The 2006 Eruption of Augustine Volcano, Alaska
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Chapter 28

Hazard Information Management, Interagency Coordination, and Impacts of the 2005–2006 Eruption of Augustine Volcano

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Abstract

Dissemination of volcano-hazard information in coordination with other Federal, State, and local agencies is a primary responsibility of the Alaska Volcano Observatory (AVO). During the 2005–6 eruption of Augustine Volcano in Alaska, AVO used existing interagency relationships and written protocols to provide hazard guidance before, during, and after eruptive events. The 2005–6 eruption was notable because of the potential for volcanogenic tsunami, which required establishment of a new procedure for alerts of possible landslide-induced tsunami in Cook Inlet. Despite repeated ash-cloud generating explosions and far-traveled ash clouds, impacts from the event were relatively minor. Primary economic losses occurred when air carriers chose to avoid flights into potentially unsafe conditions. Post-eruption evaluations by agencies involved in the response indicated weaknesses in information centralization and availability of specific information regarding ash fall hazards in real time.

Introduction

The 2005–6 eruption of Augustine was the first significant volcanic event in mainland Alaska since the Crater Peak eruption of Mount Spurr Volcano in 1992 (Keith, 1995). Advances in communications technology and the explosive growth of Internet use have dramatically affected public and official expectations during volcanic eruptions, and this was reflected in the Alaska Volcano Observatory's (AVO) strategy of information management and interagency coordination during Augustine's recent eruption (Adleman and others, this volume). The importance of long-term, real-time instrumental monitoring, background geological studies, and hazard assessments at young volcanoes was underscored during the Augustine unrest, and the availability of this information profoundly influenced the accuracy of the AVO's hazard analysis before and during the eruption. Pre-event coordination among State, Federal, and local agencies was also critical in ensuring efficient flow of information during eruptive events and minimizing impacts of drifting ash clouds and ash fall.

This paper describes elements of AVO's management of volcano-hazard information during the 2005–6 Augustine eruption, as well as interagency coordination during the precursory and eruptive phases. We also summarize impacts of the Augustine eruption and key lessons learned during the post-eruption interagency after-action. This paper does not address in detail the hazard warning activities and messages of other agencies, particularly the large number of important aviation-specific warning messages issued by both the Federal Aviation Administration (FAA) and the National Weather Service (NWS).

Volcano Hazard Warning System in Alaska

Since its founding in 1988, AVO has been responsible for issuing hazard warnings pertaining to Alaska's active volcanoes. The three component agencies of AVO—the U.S. Geological Survey (USGS), the University of Alaska Fairbanks

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Geophysical Institute (UAFGI), and the Alaska Division of Geological and Geophysical Surveys (ADGGS)—all have formal mandates to mitigate hazards posed by volcanic eruptions in Alaska. The USGS has national authority and responsibility to issue disaster warnings for earthquakes, volcanic eruptions, landslides, and other geologic events as directed under the Disaster Relief and Emergency Assistance Act of 1974 (Public Law 93-288; renamed the Robert T. Stafford Act). The UAFGI is tasked with the collection and storage of seismic data pertaining to volcanic activity in support of hazard assessment and risk reduction; the UAFGI coordinates its work with other agencies and organizations to inform the public, officials, industry and citizens about volcanic hazards and associated risk (Alaska Statute 14.40.075). Finally, the Alaska State Legislature has directed the ADGGS to conduct scientific investigations to assess geologic hazards including those posed by volcanic activity to infrastructure within the State (Alaska Statute 41.08.020).

Volcano Monitoring

To meet these responsibilities, AVO uses a variety of ground-based, aerial, and satellite-based methods to detect volcanic unrest and track activity once an eruption occurs. These include real-time seismic monitoring networks, satellite remote sensing using a variety of platforms, campaign GPS deformation surveys and real-time GPS networks, fixed-wing overflights and Web cameras, airborne and ground-based thermal imaging, and airborne gas measurements. Both satellite and seismic data are analyzed at least twice daily and more often during times of heightened volcanic activity. AVO is not staffed onsite at its observatory offices around the clock unless significant unrest or eruptive activity is in progress; most data streams can be monitored remotely using the Internet. During the Augustine eruption of 2005–6, AVO increased the frequency of offsite monitoring of data streams as unrest accelerated and began continuous around-the-clock staffing in both Fairbanks and Anchorage on January 10, 2006. Onsite 24/7 staffing was discontinued on May 19, 2006 (Adleman and others, this volume).

Because of its frequent activity and proximity to major population centers, Augustine was one of the most well-monitored volcanoes in Alaska at the start of the eruption. As of mid-2005, eight seismometers (Power and Lalla, this volume) and five continuous GPS receivers (Pauk and others, this volume) were operating on Augustine Island. Additional instrumentation was added during the precursory activity and over the course of the eruption to boost monitoring capacity, replace damaged equipment, and collect geophysical data for research purposes.

Alaska Interagency Operating Plan for Volcanic Ash Episodes

Although AVO is responsible for detecting volcanic unrest and issuing notification of hazardous activity, the complete public warning process involves communication among a number of other State and Federal agencies, each of which have their own warning and information dissemination responsibilities and products (table 1). This multiagency response to volcanic activity in Alaska is documented in “The Alaska Interagency Operating Plan for Volcanic Ash Episodes” (Madden and others, 2008). In the first iteration of the plan published in 1994 after the 1992 eruptions of Mount Spurr, signatory agencies include USGS, NWS, FAA, Alaska Department of Homeland Security and Emergency Management (ADHSEM; then called the Alaska Department of Emergency Services or ADES), and the U.S. Air Force (USAF). The U.S. Coast Guard (USCG) was added in 2004 and the Alaska Department of Environmental Conservation, Division of Air Quality (ADEC/DAQ), was added in 2008. By design, the plan is updated approximately every 2 years and the 2008 revision represents the 5th edition of the plan. The purpose of this document is to summarize each agency’s key responsibilities and procedures in alerting each other and the public regarding volcano hazards. The emphasis until 2008 had been on airborne ash hazards to aviation; following the Augustine eruption, it was expanded to include protocols related to ash-fall hazards on the ground, particularly as reflected in air quality and impacts on public health. As the 2005–6 Augustine unrest progressed, the Interagency Plan was a principal organizing document that guided agency preparedness and communications. This was the first time the plan was used in response to a significant event near Anchorage.

The Level of Concern Color Code

AVO has long used a level of concern color code system to concisely communicate the degree of unrest and severity of volcanic hazard at Alaskan volcanoes. The system in place during the 2005–6 Augustine unrest was a slightly modified version of the original color code scheme developed primarily to serve the aviation community during the Redoubt eruption of 1989–90 (Brantley, 1990). Colors change in progression of increasing volcanic unrest or severity of the hazard from Green to Yellow to Orange to Red (table 2). Decisions regarding changes in colors are based on monitoring data, direct observations, and an understanding of the eruptive style of a particular volcano and similar volcanoes worldwide. We discuss how AVO applied this color code the 2005–6 Augustine eruption in a later section.

Near-real-time Hazard Information Products from AVO

AVO uses telephone call downs, written information bulletins, a Web site, and recorded telephone lines to inform the public and others about volcanic unrest, eruption notices, and hazardous conditions (Adleman and others, this volume). The telephone notifications are the most time-critical means by which AVO informs other government agencies about changes in volcano hazard conditions; a formal call-down

Table 1. Official volcano warning products in Alaska.

[Primary warning agencies in Alaska involved in volcanic eruption hazard communication and the names of public warning products for events in south central Alaska. Some messages are very specific in their intended audience (for example Notices to Airmen [NOTAMs] and Urgent Pilot Reports [UUAs] are for aviation users) and others are of broader use (for example Ashfall Advisories, Air Quality Advisories, and Information Releases). Significant redundancy is inherent in this system and proactive coordination is necessary to ensure that messages are consistent. UUAs can be issued by either FAA or NWS personnel. Not all messages will be issued for every eruption or episode of volcanic unrest. More information about current protocols for each agency can be found in the Alaska Interagency Operating Plan for Volcanic Ash Episodes (Madden and others, 2008)]

Agency	Warning Products						
Alaska Volcano Observatory (AVO)	Information Release	Weekly Report	Daily Status Report				
National Weather Service (NWS)	SIGMET (Significant Meteorologic Information)	VAA (Volcanic Ash Advisory)	MIS (Meteorologic Impact Statement)	CWA (Center Weather Advisory)	Ashfall Advisory	Marine Advisory	Special Weather or Marine Statement
Federal Aviation Administration (FAA)	NOTAM (Notice to Airmen)	UUA (Urgent Pilot Report)					
Alaska Department of Homeland Security and Emergency Management (DSHEM)	SITREP (Situation Report)	Community Alert					
U.S. Coast Guard (USCG)	Notice to Mariners						
Alaska Department of Environmental Conservation, Division of Air Quality (DEC)	Air Quality Advisory						
Alaska Department of Public Health (DPH)	Public Service Announcement						
Municipality of Anchorage	Air Quality Advisory						

procedure is documented in the Alaska Interagency Plan for Volcanic Ash Episodes (Madden and others, 2008). Written AVO communication products in 2006 included (1) Daily Status Reports issued each day for any volcanoes at level of concern Yellow or higher; (2) Weekly Updates released each Friday summarizing the week's activity in Alaska; and (3) Information Releases issued when a significant volcanic event, change in eruption conditions, or information about AVO's operational status needed to be communicated. Examples of AVO Information Releases during the Augustine eruption are shown in appendix 1.

AVO's formal written products are disseminated using three primary communication pathways: e-mail, facsimile, and internet postings. All text products are generated using a graphical interface within the AVO internal Web site. Upon completion, messages are sent nearly simultaneously to a standing e-mail list, to others via an internet-based fax service, and to the AVO and USGS Volcano Hazards Program Web site for automatic posting. AVO messages are also available in an RSS (Really Simple Syndication) feed; users can subscribe to this electronic message feed using a variety of news aggregators available on the internet.

In addition to the AVO volcano hazard text messages, other State and Federal agencies such as NWS and FAA also produce formal notification and warning products pertinent to volcanic phenomena (table 1).

Table 2. Level of concern color code changes during the 2005–2006 unrest and eruption of Augustine Volcano, Alaska.

[Compiled from Alaska Volcano Observatory web site archives, internal logs, and master AVO chronology spreadsheet.]

Date	Time local[1]	Time UTC	Color Code Assignment[2]	Reason for Color Code Change
11/29/05	12:15 p.m. AKST	2115	Yellow	Months of slowly increasing seismicity, inflation of the edifice. No surface manifestation of unrest yet detected.
1/10/06	9:10 p.m. AKST	0610	Orange	Increased seismicity beginning ~3:00 p.m. AKST. Increased likelihood of explosive eruption in hours to days.
1/11/06	05:50 a.m. AKST	1450	Red	Explosive activity onset at 04:44 a.m. AKST.
1/12/06	08:25 a.m. AKST	1725	Orange	Decreased seismicity.
1/13/06	04:00 a.m. AKST	1300	Red	Seismicity increased suddenly suggesting renewed explosive activity imminent.
1/15/06	09:45 a.m. AKST	1845	Orange	Decreased seismicity.
1/17/06	08:00 a.m. AKST	1700	Red	Increasing seismicity and explosion at 07:58 a.m. AKST.
1/18/06	09:05 a.m. AKST	1805	Orange	Decreased seismicity.
1/27/06	8:35 p.m. AKST	0535	Red	Resumed vigorous ash emission at 8:01 p.m. AKST.
2/1/06	9:45 a.m. AKST	1845	Orange	Decreasing height of ash clouds during continuous eruption phase.
4/28/06	09:45 a.m. AKDT	1745	Yellow	Lava effusion significantly diminished or stopped.
8/9/06	3:00 p.m. AKDT	2300	Green	Seismicity at background and little surface change.

[1]Times listed are formal Alaska Standard Time (AKST) or Alaska Daylight Time (AKDT) time stamps on the header of Information Release documents; these times will differ slightly from those listed on our Web page. Announcements of color code changes via our telephone call down system typically occur tens of minutes to several hours before official release of the Information Release via email, fax, and Web-posting.

[2]Color Code definitions in use during the Augustine eruption (taken from the 2004 edition of the Alaska Interagency Operating Plan for Volcanic Ash Episodes):

Green: No eruption anticipated. Volcano is in quiet, “dormant” state.

Yellow: An eruption is possible in the next few weeks and may occur with little or no additional warning.
Small earthquakes detected locally and (or) increased levels of volcanic gas emissions.

Orange: Explosive eruption is possible within a few days and may occur with little or no warning.
Ash plume(s) not expected to reach 25,000 feet above sea level.
Increased numbers of local earthquakes. Extrusion of a lava dome or lava flows (non-explosive eruption) may be occurring.

Red: Major explosive eruption expected within 24 hours. Large ash plume(s) expected to reach at least 25,000 feet above sea level.
Strong earthquake activity detected even at distant monitoring stations.
Explosive eruption may be in progress.

Late 2005–Preparations for a Possible Magmatic Eruption at Augustine

Precursory activity was first noted at in the late spring of 2005 as the daily number of located volcano-tectonic earthquakes beneath Augustine Volcano began to increase (Power and Lalla, this volume). Beginning in July and continuing over the next several months, geodetic data detected a slow inflation of the volcanic edifice (Cervelli and others, 2006; Cervelli and others, this volume). Steadily increasing daily earthquake counts combined with acceleration in deformation in late November prompted AVO's first public announcement of unrest at Augustine on November 29, when the level of concern color code was changed from Green to Yellow (table 2.) The accompanying Information Release (appendix 1*A*) described changes detected at the volcano as a departure from background conditions but stated that an eruption was not necessarily imminent. The document reviewed the range of likely volcano hazards emphasizing that for most citizens the primary concern would be ash clouds and ash fall. AVO increased its frequency of seismic data analysis in response to the sustained unrest.

Visible changes in fumarolic activity near the summit of Augustine were noted by early December. On December 2, a seismically detected explosion followed by reports of sulfur odors on the Kenai Peninsula suggested an increased likelihood of magmatic eruption. A volcanic plume was reported by pilots and seen on satellite imagery on December 12, further intensifying public interest. Although the plume was predominantly volcanic gas and water vapor, a very minor ash fall had occurred on the upper flanks of Augustine. This prompted an additional AVO Information Release that described small explosions detected seismically and discussed the hazards of increased degassing (appendix 1*B*).

In response to increasing volcanic unrest, AVO initiated discussions with interagency partners at FAA and NWS regarding the possibility of a magmatic eruption, likely scenarios, and coordination regarding warning messages. AVO staff attended a meeting with NWS on December 13 to review procedures and anticipate challenges, particularly with regard to ash-fall warning messages. On December 22, 2005, NWS and AVO cohosted an interagency press conference on the status of Augustine Volcano at the Aviation Technology Center in Anchorage. Representatives from AVO, NWS, the West Coast and Alaska Tsunami Warning Center (WCATWC), and ADHSEM spoke about their agencies' preparations and plans to respond to an Augustine eruption (Adleman and others, this volume).

Into December, AVO received numerous calls and e-mails from the public and government agencies (city offices, fire departments, hospitals, schools) inquiring about potential volcanic activity at Augustine and recommended preparations (Adleman and others, this volume). Beginning in late December, AVO staff began to use talking points and developed contact lists to refer callers to appropriate primary resources on particular topics (for example, ash-fall hazard preparedness and aviation concerns). Tsunami-specific talking points and a media management plan were prepared on December 23 following press coverage on the topic of the tsunami threat from Augustine. AVO also spoke with facilities officials from the Ted Stevens Anchorage International Airport and the USCG office in Anchorage to ensure that lines of communication were open and any uncertainties about the developing unrest were clarified. Coordination with the Anchorage office of the USCG was the first of significance since the Mount Redoubt eruption in 1989–90 when lahars threatened the Drift River Oil Terminal (fig. 1) and vessel traffic in Cook Inlet (Dorava and Meyer, 1994). AVO and the USCG discussed potential impacts of the range of eruption scenarios, reviewed estimated hazard zones depicted in the hazard report, and discussed what kind of emergency messages the USCG would issue in the event of an eruption. AVO would later work with NWS and USCG to provide draft content for Notices to Mariners.

Preparedness activities took place in communities on the lower Kenai Peninsula. By mid-December, the village of Nanwalek, located about 80 km east of Augustine and noted site of a tsunami in 1883 (Kienle and Swanson, 1985), had taken steps to stockpile emergency supplies of food, water, and other provisions; check and review emergency siren operation; and ensure that residents knew evacuation routes to safety in the event of a tsunami (Scott Waldron, Kenai Borough Emergency Management Office, oral commun., 2006).

On January 10, 2006, as monitoring parameters continued to show elevated rates of change and unrest, AVO issued an expanded public Information Release summarizing observations to date and the range of possible outcomes including the most likely eruption scenario (appendix 1*C*). Such "scenario development"—used during previous eruptions by AVO—served to capture consensus interpretations of AVO scientists and lay out the range of possible unrest progressions and their associated hazards. Throughout the precursory period, public AVO communications emphasized these scenarios and associated impacts based on a thorough understanding of historical eruptions and the prehistoric geologic record at Augustine. Unlike many other volcanoes in Alaska, Augustine had erupted twice in 30 years during a time of significant scientific investigation and instrumental monitoring of the volcano. The volcano was, in fact, one of the most heavily instrumented in the Aleutian arc. Thus, AVO scientists had the advantage of a well-documented historic eruption record when discussing scenarios.

AVO organized an interagency public meeting in Homer on the southern Kenai Peninsula in mid-January (the meeting was supposed to have occurred preeruption and was perhaps more well-attended because of the onset of explosive activity on January 11). The purpose of the meeting was to directly address citizen concerns regarding volcanic activity and associated hazards. This meeting and other public outreach events are described more fully in Adleman and others (this volume).

Command Team

In December 2005 before the onset of magmatic eruption, the AVO Scientist-in-Charge (SIC), a USGS employee, formed

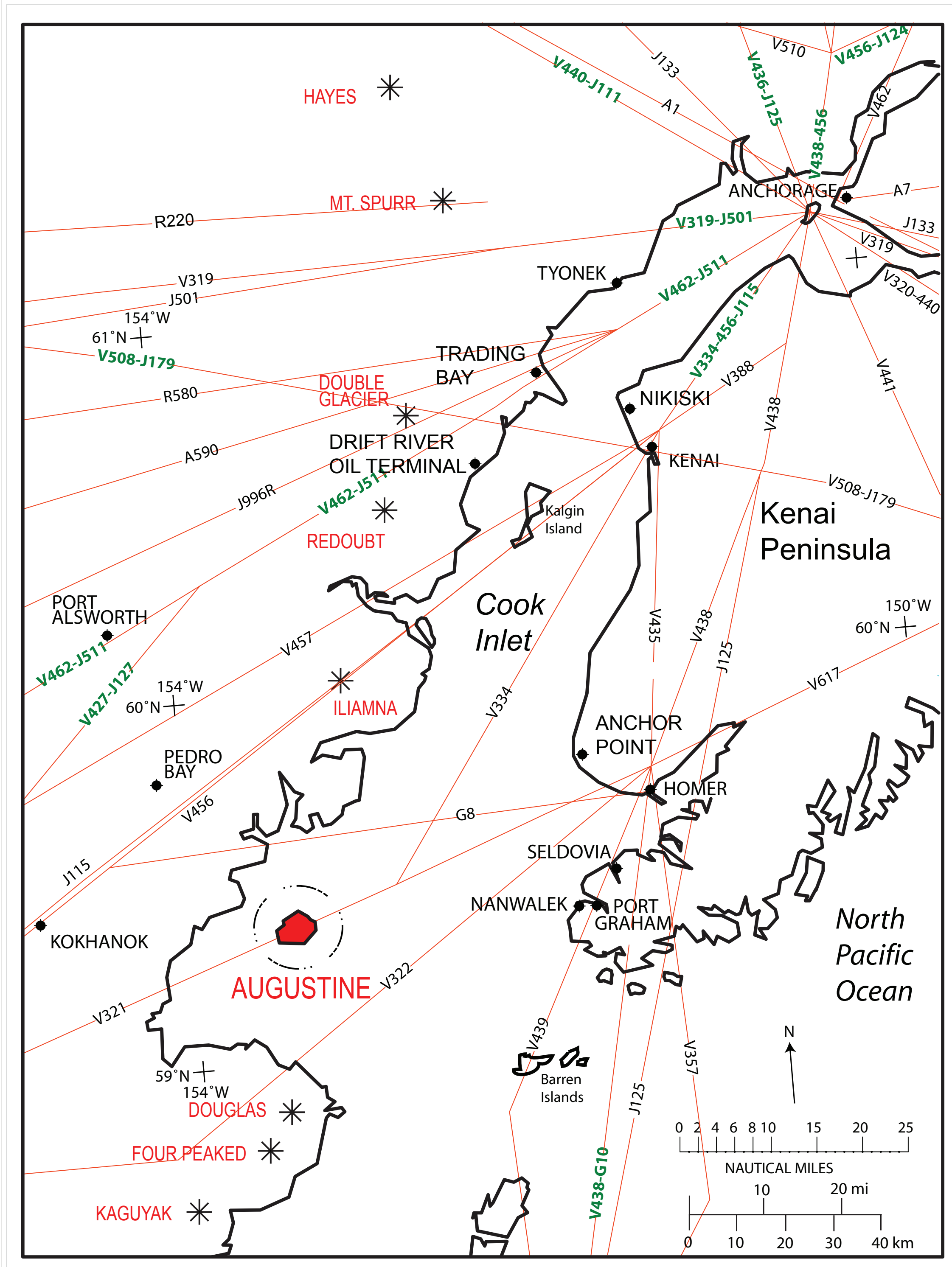

Figure 1. Map showing Cook Inlet area of south-central Alaska with principal fixed air routes (red lines). Volcanoes (asterisks), principal towns, cities, and facilities discussed in text are shown. V (victor) routes are for aircraft at and below 18,000 ft msl. All other routes are for aircraft at and above 18,000 ft. msl. Where two types of airways are superimposed, both airway labels are green. Augustine Volcano and island shown in red. The dashed circle surrounding the island is the approximate lateral extent of the Temporary Flight Restriction (TFR) put in place by the Federal Aviation Administration (FAA) on December 13, 2005. Base map (in Lambert Conformal projection) and aviation routes courtesy Walt Dotter, FAA.

a “Command Team” consisting of several AVO scientists in both the Anchorage and Fairbanks offices. The Command Team worked under the combined supervision and guidance of the SIC, the Coordinating Scientist from UAFGI, and the ADGGS Liaison. The purposes of this internal group were to clarify roles and responsibilities for managing the eruption response, to ensure adequate and coordinated operational and scientific responses, to facilitate scientific and logistical information flow within AVO, and to test a structure that could be used for all future eruption responses.

The team consisted nominally of five positions filled by AVO staff in Anchorage and Fairbanks. A “Chief of Operations” assumed responsibility for the overall response and was the primary manager of the Command Team meetings and task assignment. The Chief of Operations coordinated field and office aspects of the response including budgetary and personnel oversight in consultation with other AVO managers. In this case, the position was filled by the SIC. A “Science Coordinator” led technical discussions, maintained a synoptic view of scientific activities, data streams, analysis, and requirements to ensure accurate hazard assessment, forecasts of activity, and to maximize research opportunities. A “Media or Communications Coordinator” produced key graphics and briefing materials and oversaw the AVO Web page modifications during the eruption. This person would have been responsible for press release content development if needed. The “Information and Data Coordinator” ensured computer network health, continuity, and integration across the distributed AVO facilities. This person was also responsible for dealing with data security, data sharing protocols, and telecommunications needs. Finally, a “Hazards Information Coordinator” was responsible for developing hazard messages during the eruption. This person was the main AVO point of contact for other government agencies and addressed interagency coordination issues. Had a formal interagency Joint Information Center (JIC) been established during the eruption, the Hazards Information Coordinator would have been the primary AVO representative.

Volcano Hazard Reports for Augustine Volcano

Other important preeruption hazard resources were the published hazard reports for Augustine Volcano (Kienle and Swanson, 1985; Waythomas and Waitt, 1998). These documents, along with more dynamically updated internal talking points (see below and Adleman and others, this volume) formed the basis of the consistent public message regarding likely impacts and scenarios should an eruption occur at Augustine. As unrest progressed, AVO made frequent reference to the 1998 hazard report, which was available both on the AVO Web site and directly from the USGS. It is unknown how widely used this document was outside of AVO; an informal poll of interagency partners indicated that most knew of its existence as a key reference and many had examined it carefully. Web traffic statistics suggest at least several thousands of downloads of the 1998 hazard report in January 2006 alone (C. Cameron, ADGGS, written commun., 2007).

Hazard Information Management During the Eruption

Eruption Chronology

Following several months of precursory seismicity, deformation, increased fumarolic and degassing activity in the summit crater, and a series of small phreatic eruptions in December 2005, the main phase of the eruption began with a vent-clearing explosion on January 11 (Power and others, 2006; Cervelli and others, 2006; Neal and others, 2009). Over the next 20 days, 13 explosions sent ash between 4 and 15 km above sea level. Ash clouds drifted in all directions from the volcano, but predominantly to the northwest, northeast, east, and southeast, dusting several communities with less than 1 mm of ash (Wallace and others, this volume). On-island pyroclastic flows, surges, avalanches, ash fall, and ballistic showers impacted most of the volcano’s flanks. Interaction of hot pyroclastic debris with snow and ice on the volcano produced mixed avalanches and lahars, some of which reached the sea (Coombs and others, this volume; Vallance and others, this volume). A new lava dome was first sighted in the summit crater on January 16 (Coombs and others, this volume); however, seismicity reflective of dome growth was noted as early as January 12 (Power and others, 2006; Power and Lalla, this volume).

The eruption transitioned into a more continuous phase in late January, characterized by steady ash production and the generation of voluminous and pumiceous, high-silica andesite pyroclastic flows down the north flank of the volcano (Coombs and others, this volume). In early February, effusive activity became dominant and a new lava dome began to fill much of the summit crater. A hiatus in effusive activity occurred between about February 10 and March 3, but effusion resumed in early March with an especially vigorous period of lava effusion between March 8 and 14. Eventually, two lobes of blocky, low-silica andesite lava advanced north and northeast down the upper flank of the volcano. Intermittent shedding of hot debris from these flows produced an apron of block-and-ash avalanche deposits to the north (Vallance and others, this volume). The eruption waned by the end of March; however, the exact date effusion ceased is uncertain.

Talking Points and Expanded Information Releases

The rapid pace of information flow and intense demand that accompanies volcanic unrest and eruption are challenges for a distributed organization where any staff member may be called on to comment on hazard or status of the volcano. This is especially true as the number of real-time and near-real-time monitoring data streams increases and public expectation of current information becomes the norm. To keep AVO staff up to date on key observations, facts, and interpretations, a series of continually updated talking point documents were created in late December. Each version was shared widely within AVO (Adleman and others, this volume). Talking points were intended to be highlights of the current status of the volcano and contained key background information that staff members could use to guide response to media interviews or other outreach interactions. This was the first time during a protracted eruption that such a tool was used at AVO, although they have been used at other volcano observatories in the United States (for example, Driedger and others, 2008). Through time, talking point authors learned to anticipate media and public questions in the document which made them more useful and comprehensive. As learned during the 2004 unrest at Mount St. Helens (Driedger and others, 2008), the process of compiling such condensed statements of fact was in itself helpful in maintaining a synoptic view of the overall event. Further, the need for a sound-bite summary often helped drive science meeting discussion towards consensus interpretive statements.

On January 27, after nine explosive events, AVO issued an expanded Information Release that provided a chronologic and interpretive summary of the eruption to date, a synopsis of ongoing monitoring data and observations, and scenarios for the progression of the eruption. AVO concluded (correctly, it would turn out) that activity would likely follow the pattern of the last two historical eruptions with dome building and further explosive activity lasting months. These types of Information Releases serve two important purposes: (1) to present the consensus scientific interpretation of current and anticipated events and (2) to articulate the most important elements of ongoing volcano hazards for the public and other stakeholders.

Interagency Coordination Calls

As noted above, a number of agencies within Alaska are responsible for official response and warning messages during a volcanic event. To help ensure consistent hazard guidance to the public and keep agency representatives as up to date as possible on the state of the volcano, the ADHSEM organized and moderated frequent interagency telephone conferences during the most energetic phases of the eruption. AVO/USGS staff provided a quick update on the status of the volcano followed by NWS commentary on the day's weather, wind field, and likely ash trajectory. Additional participating agencies included FAA, Ted Stevens Anchorage International Airport, and the Alaska Department of Public Health, among others. Calls occurred with decreasing frequency as eruptive activity diminished in intensity.

Centralizing Information

Multiple messages distributed during volcanic events (table 1) can lead to confusion among the public and other entities about where to look for specific types of information. This is particularly true in the aviation and meteorology sectors where information about the status of the volcano, the presence of airborne ash, the trajectory of the cloud, ash-fall advisories, and pilot reports of ash cloud sightings are provided by different agencies in messages of varying format. To address this during the Augustine unrest, the Weather Forecast Office of the NWS in Anchorage centralized as much information as possible on an Augustine eruption coordination Web page. This page featured the full text of current ash fall warning messages, direct hyperlinks to AVO, the West Coast and Alaska Tsunami Warning Center, and the Alaska Aviation Weather Unit SIGMET pages as well as ash cloud forecast trajectory graphics produced by NOAA's Air Resources Laboratory. Had the event and associated impacts escalated (for instance, become a significantly larger, more continuous eruption or involved a tsunami-producing event), it is possible that a Joint Information Center (JIC) would have been created to help centralize and manage information flow. Discussions of such a JIC—a standard component of the Incident Command System—began in earnest on January 12 among AVO, NWS, and DHSEM; however, no firm plan was ever developed. This remains an important planning question for a future volcanic eruption (or other geologic disaster) of significance in Alaska.

Use of the Level of Concern Color Code

AVO made a total of twelve color changes during the Augustine eruption sequence as activity ramped up, became intermittently explosive, dominantly effusive, and then ceased (table 2; appendix 1*A–I*). Each color change followed internal discussion of monitoring trends and observational data in the context of what was known about the volcano's past eruptions. Some changes were urgent; for example, those following sharp accelerations in seismicity or a confirmed explosive ash producing event. Others were less time critical and were made after days of deliberation and careful crafting of accompanying language for an Information Release.

A decision to change colors always prompts a telephone call down to key agencies as outlined in the Interagency Operating Plan for Volcanic Ash Episodes (Madden and others, 2008). The call is followed by a written Information Release distributed by e-mail, fax, and Internet posting. Color codes are assigned following the generalized definitions for each color (table 2) but also take into account scientific understanding of the trend of unrest and the desired hazard message. No universal and specific data thresholds or criteria have been established for each color, in part to allow for the flexibility for each progression of volcanic unrest at individual volcanoes. These color codes are used as broad, intuitive signals reflecting the intensity of conditions at the volcano to encourage appropriate preparedness actions.

In light of this, how did AVO use the level of concern color code system to support hazard warnings during the Augustine unrest and eruption in 2005–6? The change to Yellow on November 29, 2005, was the first formal public notification of change at Augustine (appendix 1*A*). AVO had noticed and been discussing these changes internally for 4 months and, arguably, could have declared Yellow a number of weeks to several months earlier with the same impact. However, on the basis of the well-monitored status of Augustine and the precedents of the 1976 (Johnston, 1978; Kienle and Swanson 1985; Reeder and Lahr, 1987) and 1986 (Yount and others, 1987; Swanson and Kienle, 1988; Power, 1988) eruption timelines, AVO was confident that an eruption was not imminent and that further clear precursory changes would occur well in advance of actual eruption. We note that the weekly updates from AVO always include a caveat for volcanoes at the lowest level of alert "…some volcanoes may currently display anomalous behavior but are not considered to be at a dangerous level of unrest." The months of low-level unrest at Augustine could reasonably fall into this category.

AVO raised the color code to Orange in the evening of January 10, about 7 hours before the first significant explosion of the eruption, in response to a clear increase in seismicity (appendix 1*D*). Over the next 3 weeks, AVO assigned Red (table 2) just before or immediately following explosive events at Augustine, each time basing the decision primarily on interpretation of seismic signals with occasional corroborating evidence of high-altitude (greater than 30,000 ft asl) ash columns from radar (appendix 1*E*; Schneider and others, 2006) or pilot reports. The longest time period at Red was during the end of the explosive and beginning of the continuous eruption phase between January 27 and February 1, when the volcano was in an unstable pattern of nearly continuous ash emission and block-and-ash-flow production punctuated by explosions (appendix 1*F*). As ash cloud production decreased in intensity (and column heights became consistently below about 25,000 ft), AVO reverted to Orange and remained there for the duration of the eruption. We now know that this included a nearly one-month-long hiatus in effusion followed by a pulse of lava dome and flow activity that continued into mid-March (Coombs and others, this volume; appendix 1*G*).

As with many eruptive events, determining exactly when the eruption ended was difficult. AVO remained at Orange on the basis of continued or renewed lava extrusion and the potential for a sudden explosion or explosive collapse of the lava dome. The downgrade to Yellow on April 28 occurred nearly 7 weeks following the cessation of repetitive, shallow earthquakes and frequent rockfalls related to lava effusion (appendix 1*H*; Power and Lalla, this volume). The Information Release announcing Yellow, as well as subsequent weekly updates, continued to emphasize ongoing hazards from rockfalls, avalanches, and sudden explosions and also noted the possibility that eruptive activity could resume, although with likely precursory increases in seismicity, gas output, or deformation.

AVO ended 24-hour staffing of the Observatory on May 19, 2006, but remained at color code Yellow for Augustine until August 9. At that time, the consensus among AVO staff was that seismicity had returned to background levels and other monitoring data (deformation, gas, thermal) indicated a slowly stabilizing, post-eruptive system. No data suggested new magma ascent, decreasing the possibility that eruptive activity would resume. In addition, AVO field crews working on the volcano in early August observed no changes that would be indicative of renewed activity, further contributing to the decision to downgrade to Green. The Information Release accompanying this declaration emphasized again continuing hazards from sudden rockfalls, avalanches, and gas emissions (appendix 1*I*).

In the fall of 2006, the USGS instituted a new alert code system that retains Aviation Color Codes for aviation hazards but adds a parallel term—Volcano Alert Level—that integrates both aviation and ground-based hazards (Gardner and Guffanti, 2006). An important aspect of this new system is the ability of Volcano Observatories to decouple the Aviation Color Codes and the Volcano Alert Levels; for example, when a fluid lava flow eruption poses little threat to aviation but presents a significant threat on the ground. In such a case, the designation may be Yellow/Watch or even Orange/Warning. Evaluating the use of this new system retrospectively for the Augustine events of 2005–6, it is hard to see the need to decouple the two systems at any time. Even during the dominantly effusive phase of late February and March, 2006 when minimal ash was present in the atmosphere, the possibility of sudden explosive events remained high (an Orange/Watch situation). For Alaskan volcanoes, nearly all of which are capable of expelling ash into the atmosphere to altitudes of concern to aviation, it is likely the Aviation Color Codes and Volcano Alert Levels will always move together.

Tsunami Hazard and Protocols for Early Warning of Volcanogenic Tsunami

Augustine Volcano has a history of large debris avalanches that can produce tsunami in lower Cook Inlet (Begét and Kienle, 1992; Siebert and others, 1995; Waythomas and Waitt, 1998). In 1883, a 6 to 8 m wave associated with a large explosive eruption and sector collapse was reported at Port Graham (now called Nanwalek) and English Bay on the west shoreline of the lower Kenai Peninsula (Kienle and Swanson, 1985). Geologic evidence suggests that in the last few thousand years, about a dozen similar debris-avalanche events have occurred (Begét and Kienle, 1992; Siebert and others, 1995). Tsunamis associated with these events are not well understood, and geologic evidence for tsunami inundation is equivocal. Modeling studies of tsunami generation indicate that a moderate but potentially damaging wave is possible, with lead times of about 27 to 125 minutes for the shorelines of lower Cook Inlet from the Barren Islands to Kalgin Island (fig. 1; http://wcatwc.arh.noaa.gov/Augustine/AugustineWeb.htm, last accessed January 2008). Compared to other hazardous volcanic phenomena, the likelihood of a tsunami during a typical eruptive sequence and subsequent period of quiescence at Augustine is considered low (Waythomas and Waitt, 1998). Despite this, local consequences of such an event could be high, and, in 2006, the tsunami threat from Augustine was on the minds of many residents of the coastal portions of the Kenai Peninsula.

Before the first major explosions in January, AVO and the WCATWC developed a strategy to deal with potential volcanogenic tsunami and required public warnings. In the United States, tsunami warnings are the responsibility of the National Oceanic Atmospheric Administration's (NOAA) two regional Tsunami Warning Centers in Alaska and Hawaii. Tsunami warnings are issued via the Emergency Alert System, NOAA's Weather Radio, and other NOAA dissemination channels. In Alaska, warnings are also issued through State and local channels to key areas on the Kenai Peninsula and other communities and to civil authorities in Alaska. In addition, for isolated communities, such as Nanwalek and Port Graham, siren systems are activated by the issuance of an alert.

Historically, NOAA's primary responsibility has been to issue warnings for earthquake-induced tsunami. Tsunami initiated by volcanic processes (flank failure, flowage deposits, and others) require NOAA and volcano observatories to work together to effectively issue warning messages, and Augustine provided an opportunity to refine this cooperation.

The NOAA-AVO approach for Augustine took into account the most likely scenario for generation of tsunami from the volcano—a debris avalanche into Cook Inlet. Such an event was expected to be accompanied by a strong and unique seismic signal produced by a large-volume (0.1 to 0.5 km^3) flank failure and landslide event. If Augustine's level of concern color code was Orange or Red and a shallow earthquake occurred near Augustine Island with a magnitude greater than 4.5, a tsunami warning would have been issued immediately by the WCATWC for coastlines of the lower Cook Inlet. The WCATWC would then consult with AVO by phone to evaluate the event and other data streams (for example, WEB cameras, pressure sensors, on-island seismic network, their own regional seismic network) to refine or cancel the alert. In this way, given the short travel times, potentially affected communities would receive warnings with as much lead time as possible.

When the level of concern color code for Augustine reverted to Yellow or Green, WCATWC would call AVO before issuing any alert in order to evaluate the likelihood of a tsunami. The WCATWC was also added to the list of key government agencies on AVO's initial telephone call down list in the event of an explosive or significant event at Augustine. This would enable WCATWC staff to be on heightened alert for the possibility of tsunami following significant activity and production of pyroclastic flows or other flowage events that reached the sea.

Although the system was not tested during the 2005–6 eruption by earthquakes fitting the preestablished criteria, participants feel it was a successful approach to this difficult to forecast and confirm process. The many island volcanoes subject to flank failure in Alaska (Coombs and others, 2007) and other parts of the world (for example, the Marianas) suggests this approach, the first of its kind in the U.S., may be viable for other similarly situated volcanoes with sufficient seismic monitoring. Each volcano would require an independent analysis of flank failure scenarios, resultant wave travel time to vulnerable coastlines, and likely seismicity and detection thresholds for varying seismic station density. Interagency alert protocols for other volcanic phenomena such as pyroclastic flows, which can also produce tsunami, have yet to be discussed. Finally, although the emphasis of concern in this system has been on the coastal population centers, impacts of volcanically generated tsunami on marine vessel traffic and the required messaging to warn this constituency should also be considered. This will require close coordination with the USCG or other maritime authorities.

Impacts of the 2005–2006 Eruption

Impacts of this eruption were not rigorously tracked and much information presented here is anecdotal or collated from reports in the popular media.

General

According to news reports, preeruption publicity prompted a spike in local purchases of dust masks and automobile air filters and other emergency preparedness supplies throughout south-central Alaska. Both personal and institutional checking of disaster preparedness and plans was also widely reported. The Anchorage School District (ASD) administration reviewed emergency preparations in the event of an ash fall and sent information to parents outlining ASD preparedness, protocols for school closures, and other issues. Following the January 13 ash-producing events, Ninilchik elementary and Homer high schools closed early due to expected ash fall. Other closures occurred sporadically throughout January in anticipation of ash fallout. In Homor, the South Peninsula Hospital constructed a special prefilter apparatus for their building air intakes. Cancellation of Kodiak-based filming for a major motion picture was a significant economic blow to the Kodiak Borough.

In hindsight, some of these very proactive preparedness efforts were perhaps overly conservative given the magnitude of resulting ash fall and the severity of actual impacts. However, with no operational ash fall model in place and given the inherent uncertainty of an evolving eruptive event, it was difficult for AVO and NWS to provide specific guidance to emergency managers and the public regarding the amount of ash to expect. Further challenges are posed by the required style of NWS ash fall messages; these are highly formatted communications that are referenced to established zones that include large areas of Alaska. Thus, when ash fall was possible in a portion of a zone, the entire area is featured on warning graphics inadvertently depicting a much broader area of potential impact than is necessary.

In addition to limitations in accurate warning messages, incomplete public understanding of ash-fall events and likely impacts may have contributed to aggressive preparedness efforts. Residents of south-central Alaska had not experienced volcanic ash fall since the 1992 Mount Spurr eruption, and it is likely that many residents of the Kenai Peninsula were unacquainted with what to expect—the population of the Kenai Peninsula Borough increased by more than 25 percent (or 10,000 people) during the period 1990–2006 (http://www.borough.kenai.ak.us/econ/1S_P%20data/Demographics/PopulationOverview.htm, last accessed August 13, 2009). In addition, the last eruption to affect the Kenai Peninsula, the 1989–90 eruption of Redoubt Volcano, also occurred in midwinter and had significant impacts on the western Kenai on several occasions (Scott and McGimsey, 1994). Thus, a lack of experience with ash fall by some combined with others' memories of hardships during the last fallout event may have contributed to an extra-heightened sense of concern.

Aviation Sector

Significant interruptions of air travel into and out of Anchorage and other communities in south-central Alaska occurred during the explosive phase. Following several explosions, vulnerable air routes were modified or cancelled. Some airlines elected to bypass Anchorage or move aircraft out of concern for potential ash fall. Special Military Operations Areas were closed temporarily. One nondamaging encounter with an apparent volcanic gas cloud occurred on January 14 about 800 km downwind, and one other unconfirmed minor encounter on January 30 was reported. A summary of known aviation impacts is found in table 3.

To provide a safe operating environment for AVO field crews and to reinforce concerns about sudden explosive activity, a Temporary Flight Restriction (TFR) was put in place by FAA on December 13, 2005, following the December 12 plume and discussions with AVO about the possibility of further small explosions and minor ash falls near Augustine. This initial TFR—communicated to aviation interests through the national Notice to Airmen or NOTAM system—prohibited aircraft from flying within a 5-nm radius of the summit to 6,000 ft asl (fig. 1). The TFR also cautioned pilots operating near or downwind of the volcano. The TFR was expanded on January 11 following the first significant explosive event to include a cylinder with radius of 5 nm from the summit extending from sea-level up to but not including 50,000 ft asl. The TFR remained in effect until April 28, 2006, when AVO lowered the level of concern color code to Yellow.

Airport and Aviation Facility Closures

Kienle (1994) reviewed the impacts of the 1976 and 1986 eruptions of Augustine Volcano, which included damage to a number of aircraft due to ash encounters and many flight cancellations and diversions. While forecasting and communication of hazards to aircraft has vastly improved in the intervening decades, the number of aircraft at risk has grown immensely. By 2006, annual aircraft landings at Ted Stevens Anchorage International Airport had nearly tripled from 1976 levels to 100,496 landings and total passengers had almost doubled to 5,043,147 (http://dot.alaska.gov/anc/business/airServiceDevelopment/statistics/AnnualStats_1957-2007.pdf, last accessed August 21, 2009). Because of the very small amounts of ash fall on populated areas, there were no closures of any airfields or airports during the 2005–6 Augustine eruption, in contrast to the 1992 Spurr eruption (Casadevall and Krohn, 1995). The only known impact to an air traffic control facility was closure of the Homer Flight Service Station for part of January 13 due to concern for ash fall in the area. Anchorage International had no significant take-off or landing delays during January resulting from activity at Augustine (G. Howard, FAA, written commun., 2006).

Aircraft Encounters with Volcanic Clouds

We are aware of no damaging encounters between aircraft and volcanic ash from Augustine in 2005–6 despite more than a dozen explosive eruptions producing drifting ash clouds that traveled through air traffic corridors at night and in bad winter weather. This success can be attributed to a much broader awareness across the aviation sector regarding volcano hazards, a vastly improved warning network that links real-time volcano monitoring, ash-cloud detection, tracking, and forecasting across several Federal agencies, and clarified communication pathways. In addition, the short duration of the explosive events at Augustine meant that ash clouds were small and became rapidly diffuse downwind.

Two nondamaging encounters between aircraft and a volcanic cloud from Augustine came to the attention of AVO. The first and more costly occurred on January 14 about 800 km downwind of the volcano in the vicinity of Yakutat on the Gulf of Alaska coastline. A full Boeing 737 flying in daylight conditions from Anchorage to Seattle entered a suspicious cloud described as a brown-colored stratified layer at 31,000 ft. The crew noted a "dirty," musty odor lasting about 8 to 10 minutes. After climbing to 33,000 ft and deviating to the northeast into clear air, the layer was distinctly visible below the aircraft. On landing, the plane was taken out of service for 2 days and thoroughly inspected; no damage was found. Before this encounter, five discrete explosions at Augustine had produced small volume ash clouds to altitudes of greater than 30,000 ft estimated from both pilot reports and NWS radar (Schneider and others, 2006; Bailey and others, this volume). All clouds drifted southeast and then northeast over the Gulf of Alaska

Table 3. Summary of principle aviation impacts from the 2006 eruptive activity at Augustine Volcano.

[Data courtesy Greg Howard, Federal Aviation Administration, and Alaska Volcano Observatory records. ANC, Anchorage Ted Stevens International Airport; FAI, Fairbanks International Airport; PACOTS, Pacific Organized Track System; ATC, Air Traffic Control; ZAN, Anchorage Center; MOA, Military Operations Area; USAF, U.S. Air Force]

Date	Impact	Comment
11 Jan	Some flights from Anchorage to Homer cancelled or delayed until daylight allowed better visibility of ash cloud.	
11 Jan	Minor radio interference reported by one aircraft operating near the volcano.	
13 Jan	Six aircraft inbound to ANC from Asia choose to divert to FAI to avoid the risk of ash exposure on the ground.	This decision was made by individual air carriers based on forecast winds and ash trajectory models.
13 Jan	Air Cargo operators at ANC expedite turnaround to minimize ground time for aircraft.	
13 Jan	Westbound PACOTS moved to the south; 10 aircraft chose this route to avoid potential ash.	This action was done by Anchorage Center Traffic Management in consultation with Oakland Center.
13 Jan	Separation between aircraft inbound for Anchorage from Asia temporarily increased as a precaution.	
13 Jan	One westbound PACOTS track cancelled.	
14 Jan	PACOTS tracks moved south to avoid projected ash trajectory; this moved all eastbound PACOTS south of Alaska airspace.	Oakland ATC was advised to build tracks to remain south of 53N145W to avoid projected ash dispersion.
13–15 Jan	Several airlines cancelled or rescheduled a total of ~35 flights, primarily to avoid operations in the area of projected ash during hours of darkness.	
14 Jan	Boeing 737 briefly encounters volcanic cloud 800 km downwind.	Flight crew deviated to clear air; aircraft inspection shows no damage
14 Jan	Temporary ground-stop (no departures) in southeast Alaska due to pilot report of ash over Yakutat and ATC workload managing requests for reroutes.	
14–15 Jan	Route restrictions coordinated between Anchorage and Canadian Air Traffic Control Centers as the ash cloud entered Canada.	This action was based on forecast motion of the volcanic cloud into Canadian airspace.
14–15 Jan	Staffing at ZAN increased temporarily in anticipation of increased workload.	
17 Jan	PACOTS track moved to the south.	
17 Jan	Military exercises in NAKNEK and STONY MOAs delayed 5.5 hours due to ash cloud and need for a contingency air corridor in case inbound flights to ANC required diversion; USAF cancels 6 training sorties and 3.5 hours of flight training. Air National Guard moved 7 aircraft to Fairbanks.	Ash projected to move to the northeast from Augustine following significant explosive event.
17 Jan	Minor reroutes at pilot requests; one regional carrier flight from ANC to Kodiak returned to ANC after seeing brown haze.	
28–31 Jan	Low level ash emission January 28-31 resulted in numerous flight cancellations or re-routes based on SIGMET descriptions of ash cloud position and motion.	
30 Jan	Piper Cherokee encountered very fine ash in southwest Alaska; also reported a burning in nose and eyes.	No damage reported.

until they could no longer be seen on satellite. This aircraft may have entered an extremely ash-poor aerosol cloud from one or both of the last two explosions of January 13 (at 0140 and 0358 UTC, January 14) based on an analysis of PUFF model output with respect to the likely time and location of the encounter (P. Webley, written commun., 2007).

The second encounter on January 30 remains ambiguous, and we were not able to reach the pilot for careful followup. According to the original report, a Piper Cherokee aircraft flying between Togiak and Dillingham in southwest Alaska encountered very fine ash and possibly volcanic gas from the ground to an altitude of 7,000 ft. The report indicates fine ash accumulated on the windscreen—presumably when the plane was on the ground at Togiak—and the pilot reported a burning sensation in the nose and eyes. As the flight approached Dillingham, the pilot noted that the air cleared abruptly. Easterly winds did occur during the continuous phase of the eruption from January 28–31 and so a diffuse ash and gas cloud in the Togiak area is plausible (Wallace and others, this volume). Also on January 30, AVO received reports from St. George Island (1,000 km west-southwest of Augustine) of fine dust and an odd taste and smell in the air. This report was unsubstantiated by sampling or other means; however, it is consistent with forecast trajectories of the Augustine plume tracking to the west from the island and out over the Bering Sea. Both incidents occurred in areas where satellite imagery could no longer detect the fine ash and aerosol clouds from these short-lived explosions, illustrating current limitations on providing accurate tracking and long-term forecast of diffuse volcanic clouds. Two years later, several aircraft encounters with far-traveled, ash-poor volcanic clouds from Okmok and Kasatochi volcanoes again underscored the challenge of providing operationally helpful warnings and clear guidance on the severity of this hazard to the aviation sector (Osiensky and others, 2008).

Marine Sector

Cook Inlet surrounding Augustine Island is an economically important shipping corridor for cargo vessels to and from the Port of Anchorage, the Nikiski oil refinery and liquefied natural gas (LNG) facility on the west coast of the Kenai Peninsula, and petroleum production and storage sites at Trading Bay and Drift River on the west side of Cook Inlet (fig. 1). LNG-loaded tankers alone make about 40 round trip transits from Nikiski to Tokyo each year (http://www.kenailng.net/go/doc/1067/143609/). Sixteen oil and gas platforms are located in upper Cook Inlet between Kenai and Tyonek. Additionally, Cook Inlet is a rich commercial and subsistence fishing area and is also used mostly during summer months for recreational boating and fishing. According to the U.S. Coast Guard (USCG), most deep-draft vessels traveling north or south in Cook Inlet remain far to the east of Augustine Island to follow more direct, deep water routes, thus mitigating impacts from Augustine activity. Despite this, following discussions with AVO and after the onset of explosive activity, the USCG office in Anchorage took steps to ensure the safety of mariners in the vicinity of Augustine. First, a warning to mariners was issued describing activity at the volcano and possible hazards to boats including ash fall and debris in the water. Secondly, on January 18, the USCG issued a temporary safety zone around Augustine Island prohibiting vessel traffic within one nautical mile of the shoreline (Federal Register, 2006). This rule went into effect following a number of explosive events at Augustine and was to remain in effect until September 1, 2006, or until cancelled. We are not aware of any direct impacts on vessels from the eruption. Other than light ash fall and possible minor nearshore disturbance as lahars reach the coastline on a number of occasions, there would have been no significant harm to boat traffic during the 2005–6 activity. AVO did receive a number of inquiries from the fishing community about the state of the volcano and possible hazards at sea.

Ash Fall Impacts

The explosive and continuous phases of the eruption produced at least 13 drifting ash clouds. The majority of ash fallout occurred on Augustine Island and into Cook Inlet, but on a number of occasions, trace amounts of ash did fall on inhabited areas (Wallace and others, this volume). We are aware of no significant property damage or adverse health affects due to fallout, consistent with the very short duration and small volume of the individual ash falls. There were, as discussed above, indirect impacts and costs due to precautionary closures of schools and other facilities, effort expended to repeatedly cover computers and other sensitive electronics, and other actions taken out of concern for the potential of ash fall. Finally, a significant number of public inquiries to AVO and other agencies referred to ash fall likelihood and expected impacts (Adleman and others, this volume).

Eruption Interagency After Action and Lessons Learned

In April 2006, barely a month after the cessation of lava effusion at Augustine, AVO and NWS organized an interagency after-action review to gather lessons learned and identify ways to improve future eruption response efforts. Before the meeting, a questionnaire was sent to participants which included AVO, NWS, FAA, WCATWC, USCG, ADHSEM, the Alaska Department of Environmental Conservation, the U.S. Air Force, Kenai Borough Emergency Services, the Municipality of Anchorage, and contacts in several communities on the southern Kenai Peninsula (appendix 2). A similar questionnaire was also sent by e-mail to police, fire, and other officials in some affected communities to solicit feedback on the effectiveness of warning messages. A summary of the meeting was shared among the agency attendees. Many constructive suggestions contributed to the update of the Alaska

Interagency Plan in 2008 (Madden and others, 2008). Several key conclusions of the evaluation are below.

"Balkanization" of information—People expressed frustration at having to go to multiple Web sites for complete information on the status of the volcano and current warning messages. A one-stop Web page that includes current volcano hazard information and links to all formal warning messages—even more comprehensive than the National Weather Service Augustine coordination page developed during this eruption—is needed.

Joint Information Center (JIC)—A JIC formed under principles of incident command, although perhaps not required during this relatively low-impact eruption, may become necessary in the future. It is not clear how one will be created during a significant volcanic incident in the State of Alaska but a preliminary plan for JIC formation should be in place prior to such an event (Driedger and others, 2008).

Ash-fall hazard information—Initial public advisories were not specific enough in terms of the likely severity of impact (amounts and duration) and the areas where ash fall could be anticipated. Both the message content and dissemination pathways need improvement. More public health expertise is required in developing ash-fall warning guidance.

Conclusions

AVO applied experience gained during recent eruptions in Cook Inlet (Miller and Chouet, 1994; Keith, 1995), other parts of the Aleutian arc, and at Mount St. Helens, Washington (Driedger and others, 2008) to provide volcano hazard information during the 2005–6 unrest and eruption at Augustine Volcano. The Augustine activity occurred during an era of improved interagency coordination and advanced communications technology, both major contributors to effective response. The existence of an interagency coordination plan and well-established relationships among AVO and key Federal, State, and local agency representatives contributed to efficient and timely hazard messages before, during, and after the eruption. A lack of any significantly damaging aircraft encounter with ash, despite more than a dozen ash clouds in the greater Cook Inlet region, can be attributed in part to a properly functioning ash and aviation hazard mitigation network in Alaska and an informed aviation sector. Overall, eruption impacts were limited primarily to unknown economic losses due to flight cancellations and other decisions to avoid travel or other activities out of concern for potential impacts.

The Augustine eruption highlighted ongoing challenges to the interagency management of volcano hazard information. In particular, volcanology and meteorology communities have yet to make fully operational ash-fall forecasting and visualization tools to address fallout, one of the most important primary hazards of explosive volcanic eruptions. Similarly, hazards posed by ash-poor volcanic aerosol clouds to aircraft operations remain poorly understood. Effective operational guidance to the aviation sector regarding these distal cloud hazards remains an important goal.

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Appendix 1. Excerpts from key Alaska Volcano Observatory Information Releases during the Augustine Volcano eruption on November 29, 2005, December 12, 2005, January 10, 2006, January 11, 2006, April 28, 2006, and August 9, 2006

[Some header and footer information has been deleted for brevity]

A. First announcement of significant unrest.

Tuesday, November 29, 2005 12:15 PM AKST (2115 UTC)

AUGUSTINE VOLCANO (CAVW#1103-01-)
59.3633°N 153.4333°W, Summit Elevation 4134 ft (1260 m)
Current Level of Concern Color Code: **YELLOW**
Previous Level of Concern Color Code: **GREEN**

AVO has detected important changes in earthquake activity and ground deformation at *Augustine* Volcano in southern Cook Inlet. These data are consistent with renewed volcanic unrest. AVO is therefore raising the level-of-concern color code from green to **YELLOW** and will continue to monitor activity closely. There is no indication that an eruption is imminent or certain.

Beginning in May 2005, there has been a slow increase in the number of earthquakes located under Augustine Volcano. The earthquakes are generally small (less than magnitude 1.0) and concentrate roughly 1 km below the volcano's summit. These earthquakes have slowly increased from 4-8 earthquakes/day to 20-35 earthquakes/day. Additionally, data from a 6-station Global Positioning System (GPS) network on Augustine Volcano indicate that a slow, steady inflation of the volcano started in mid-summer 2005 and continues at present. The GPS benchmark located nearest the summit has moved a total of 2.5 cm (1 inch). This motion is consistent with a source of inflation or pressure change centered under the volcano. This is the first such deformation detected at Augustine Volcano since measurements began just prior to the 1986 eruption.

No reports of increased steaming have been received by AVO, nor have satellite data shown increased thermal activity.

Historic eruptions of Augustine typically begin with explosive bursts that may send plumes of ash to 30,000-40,000 feet above sea level. The primary hazards to communities, aviation, and mariners in Cook Inlet and parts of south-central Alaska from an Augustine eruption are ash fall and drifting ash clouds. In 1986, 6 mm (0.25 inch) of ash fell in Homer, 120 km (75 mi) east of Augustine and light ashfall was recorded in Anchorage, 290 km (180 mi) away. Hot, ground-hugging flows of volcanic rock debris called pyroclastic flows may form during an eruption and could be hazardous to people, aircraft, or boats on or in the immediate vicinity of the island.

Island volcanoes can generate tsunamis by collapse into the sea. There is no evidence that conditions are developing that would lead to a major volcanic landslide or similar event at Augustine that, upon entering Cook Inlet, could generate a tsunami. No tsunami waves were generated during any of the last five eruptions of Augustine Volcano.

B. Discussion of first visible plumes and sulfur odors following explosions.

Monday, December 12, 2005 3:05 PM AKST (0005 UTC)

Current Level of Concern Color Code: **YELLOW**

A steam plume extending at least 75 km (45 mi) SE from *Augustine* Volcano is clearly visible by satellite and has also been reported by local pilots. Images in the web camera also show a plume. The plume appears to be primarily steam.

During the past several days, AVO has detected changes in the style of earthquake activity and received other information about gas emissions and steaming at Augustine Volcano. Two seismic events on Friday evening (12/9/05), and Sunday evening (12/11/05) may have perturbed the hydrothermal system, initiating steam explosions. These events are consistent with reports of steaming at the summit observed on Saturday (12/10/05), and distinct sulfur smell ("like from a sewer") in the air on Sunday evening (12/11/05) at Nanwalek and Port Graham, approximately 80 km (50 mi) east of the volcano. Collectively, these events are signs of continued and elevated level of volcanic unrest, but do not indicate that an eruption is imminent in the next few days to weeks. The level-of-concern color code remains at Yellow and AVO will continue to monitor activity closely.

Depending on the direction of the wind and the amount of gas emitted at the volcano, sulfur odors may persist. Periods of foul smelling air may accompany the present level of unrest at Augustine, but these periods should be relatively brief and are not expected to be a significant health concern. Humans can detect at very low concentrations the volcanic gases sulfur dioxide and hydrogen sulfide. At higher concentrations (or if a person has respiratory problems) the gases can irritate the eyes and respiratory system. People with respiratory problems should take reasonable precautions as they would for dealing with other types of slightly unhealthy air. See *http://www.ivhhn.org/* "guidelines and databases" for more information.

C. Expanded Information Release discussing possible outcomes and hazards.

Tuesday, January 10, 2006 1:05 PM AKST (2205 UTC)

Current Level of Concern Color Code: **YELLOW**

Since last spring, the Alaska Volcano Observatory (AVO) has detected increasing volcanic unrest at Augustine Volcano in lower Cook Inlet. Based on all available monitoring data AVO regards that an eruption similar to those in 1976 and 1986 is the most probable outcome. We expect such an eruption to occur within the next few weeks or months. There is currently no indication that an eruption will occur within the next few days and Augustine remains at color code **Yellow**.

Observations and Background:

Rates of earthquake occurrence increased slowly from an average rate of 1 to 2 per day in early May, to 3 to 4 per day in October and 15 per day in mid-December. These earthquakes are occurring directly beneath the mountain's summit at depths close to sea level. The largest event located to date is a magnitude 1.2. Concurrent with this increase, we have also detected a small uplift of the volcano using Global Positioning Systems (GPS) instruments permanently installed on the mountain. The total swelling to date is approximately 2 inches (5 cm). In early and mid December, a number of small steam explosions were recorded by seismic instruments on the volcano. Views of the summit following these explosions revealed new steaming cracks and localized deposits of debris. In addition, airborne gas measurements and thermal imaging measurements have shown an increase in the output of volcanic gas and heat at the summit of the volcano. The highest temperature recorded, on January 4, was 390 C (750 F). AVO interprets these changes as a sign that new magma is accumulating beneath the volcano's summit. Based on an analysis of past and current earthquake locations, GPS, gas, and heat data, this new magma may have risen to sea level or higher.

C. Expanded Information Release discussing possible outcomes and hazards.—Continued

In response to this activity, AVO has deployed additional seismometers, GPS receivers, an infrasound sensor, and time lapse cameras on the flanks of the volcano, and established a web-based camera system. Further deployment of additional monitoring equipment is ongoing. We plan continued visual and infrared surveillance of the volcano's summit and frequent measurements of gas output.

The most recent eruptions of Augustine were characterized by an initial explosive phase lasting from 4 to 14 days. The explosive phase produces large ash plumes, that depending upon the prevailing winds and height of the eruptive column, can be carried hundreds to thousands of miles. Most communities in south-central Alaska experienced some ash fall with accumulations of several millimeters during both the 1976 and 1986 eruptions (Anchorage received 0.12 inches (3 mm) in 1976 and less than 0.04 inches (1 mm) in 1986; Homer received about 0.2 inches (5 mm) in 1976 and 1986). During the explosive phase of the eruption, many portions of Augustine Island are also overrun by pyroclastic flows (fast flowing mixtures of hot volcanic gasses, steam, rock and ash) and mud flows (fast moving mixtures of volcanic rock, ash and water). The explosive phase is generally followed by the extrusion of a lava dome which is generally accompanied by smaller explosions and pyroclastic flows. Communities in south-central Alaska may again experience minor ash fall during these later phases of the eruption.

Interpretation and Hazards:

Based on our current understanding of Augustine's past eruptions and our analysis of the current episode of unrest, AVO considers the following future scenarios as possible:

1) **Failed Eruption:** No eruption occurs as magma does not reach the surface. Earthquake activity, ground deformation, gas output, and steaming slowly decrease over several weeks or months.
2) **Eruption similar to those of 1976 and 1986:** Unrest continues to escalate culminating in an eruption that is similar to those that occurred in 1976 and 1986. An eruption such as this would likely spread volcanic ash throughout and perhaps beyond Cook Inlet depending upon the prevailing winds. Much of Augustine Island would be inundated by pyroclastic flows, mud flows, ash fall, and ballistic showers.
3) **Larger Explosive Eruption:** A significantly larger eruption could occur, perhaps similar to eruptions that are thought to have taken place prehistorically. Such an eruption might involve the production of larger ash plumes, significant modification of the island's summit, and large pyroclastic flows and mud flows on the island.
4) **Flank Collapse:** The intruding magma or other processes could destabilize a portion of the Augustine cone that could result in a large landslide. If this landslide entered Cook Inlet, a localized tsunami could be generated. Such a landslide and tsunami were associated with the 1883 eruption of Augustine Volcano. It is also likely that a landslide of this type would be accompanied by an eruption.

Based on all available monitoring data AVO, regards scenario number two, an eruption similar to those in 1976 and 1986, as the most probable outcome at this time. At this time scenarios one, three and four are considered less likely.

Comparing the time frame of pre-eruptive activity in 1976 and 1986 with the current unrest, we would expect such an eruption to occur within the next few weeks or months. There is currently no indication that an eruption will occur within the next few days. Both the 1986 and 1976 eruptions were preceded by short-term (hours to days) increases in seismic activity. Should earthquake activity or other monitoring data suggest that an eruption is expected within hours or days, AVO would move Augustine from its current level of concern color code Yellow to Orange or Red.

AVO will continue to monitor the volcano closely. We plan to add additional instrumentation on the volcano to help us better understand the nature of this unrest. New data and observations may lead us to change our assessment. Any changes would be announced in a subsequent Information Release.

Further information on Augustine Volcano and related hazards and response plans can be found at the following web sites:

C. Expanded Information Release discussing possible outcomes and hazards.—Continued

Alaska Volcano Observatory: Most recent information on Augustine Volcano
www.avo.alaska.edu

U.S. Geological Survey: Hazards associated with volcanic ash fall
http://volcanoes.usgs.gov/ash/

NOAA National Weather Service: Ash cloud trajectories and aviation warnings
http://pafc.arh.noaa.gov/augustine.php

NOAA West Coast and Alaska Tsunami Warning Center: Tsunami issues related to Augustine
http://wcatwc.arh.noaa.gov/Augustine/AugustineWeb.htm

Alaska Division of Homeland Security and Emergency Management: Community preparedness
http://www.ak-prepared.com/plans/mitigation/volcano.htm

D. Marked increase in seismicity and likelihood of explosive eruption.

Tuesday, January 10, 2006 9:10 PM AKST (610 UTC)

Current Level of Concern Color Code: **ORANGE**

The level of Concern Color Code for *Augustine* Volcano is now **ORANGE** .

Over the past six hours, earthquake activity beneath Augustine has increased markedly. AVO considers this activity indicative of a heightened possibility of an explosive eruption within hours to days.

AVO is monitoring the situation closely and will issue further updates as new information and analyses become available. Onsite staffing at AVO has now expanded to 24 hour operations.

E. Notice of first major explosive event.

Wednesday, January 11, 2006 5:50 AM AKST (1450 UTC)

Current Level of Concern Color Code: **ORANGE**
The level of Concern Color Code for *Augustine* Volcano is now **RED**

At 4:44 a.m. (AKST) this morning, AVO began recording seismic signals interpreted as explosions at the summit of Augustine Volcano that likely mark the onset of an eruption. The current activity may be emitting ash, steam, and volcanic gases.

If the volcano follows a pattern similar to the 1976 and 1986 eruptions, we would expect a further intensification of seismic activity prior to a larger explosive event. It is also possible that an explosive eruption could occur with little or no warning.

AVO is monitoring the situation closely and will issue further updates as new information and analyses become available.

F. Description of continuous phase.

Monday, January 30, 2006 9:15 AM AKST (1815 UTC)

Current Level of Concern Color Code: **RED**

Augustine volcano has been in a state of continuous eruption since 14:30 AKST (2330 UTC) January 28. Overflight observations on January 29 suggest that pyroclastic flows are being produced. Larger seismic signals were detected at 11:17 AKST (2017 UTC) on January 29, and 03:25 AKST (1225 UTC) and 06:21 AKST (1521 UTC) on January 30. National Weather Service radar indicates that ash clouds from these events rose to 25,000 feet above sea level. In general, other than during these three events, an ash-rich plume is rising to about 14,000 feet above sea level. For up-to-date Ashfall Advisories and wind trajectories, please refer to the latest National Weather Service website: *http://pafc.arh.noaa.gov/augustine.php*.

Thermal anomalies (measured by satellite-based instruments) persist, both at the summit of Augustine and on the northern flank, consistent with continuing eruption and hot pyroclastic flow deposits on the volcano.

G. Increased seismicity interpreted as increased extrusion rate.

Thursday, March 9, 2006 9:05 AM AKST (1805 UTC)

Current Level of Concern Color Code: **ORANGE**

Beginning at approximately 0530 AKST (1430 UTC) March 8, 2006, seismicity at *Augustine* Volcano increased markedly; as of about midnight AKST (0900 UTC) March 9, 2006 it became more or less continuous.. The amplitude of the seismicity is high, with the signal nearly saturating several instruments. Imagery from a low light camera in Homer show two distinct bright spots, the first at the summit, the second approximately midway down the north flank. Satellite imagery shows thermal anomalies at Augustine, as it has for the last several weeks. There are no indications of substantial ash emissions at this time.

Taken together, these data probably indicate accelerated rates of magma extrusion, in the form of increased dome growth, vigorous lava flows, or a combination of both. Extrusion of this kind creates local hazard, but is not likely to generate explosions, significant ash emissions, or a tsunami.

H. Downgrade to Yellow, first time at Yellow since January 10, 2006.

Friday, April 28, 2006 9:45 AM AKDT (1745 UTC)

Current Level of Concern Color Code: **YELLOW**
Previous Level of Concern Color Code: **ORANGE**

Based on the current level of activity at *Augustine*, we are lowering the Level of Concern Color Code from **ORANGE** to **YELLOW**.

Data and observations currently indicate that the growth of the summit lava dome and lava flows has stopped, or continues only at a very low rate. Seismic data show that rock fall and avalanche events are still occurring, but at a diminished level. Visual observations and satellite data show that there have not been any detectable changes at the summit over the last few weeks.

Despite the apparent cessation of lava dome growth, the new dome and lava flows are still highly unstable, and rock falls and avalanches are still occurring and may continue for several weeks or months. The north flank of the

H. Downgrade to Yellow, first time at Yellow since January 10, 2006—Continued

island is the area most susceptible to rock falls and avalanches, and the steep ends of the lava flows are also places where rock fall activity may continue. These areas are considered very hazardous. Small, dilute ash clouds produced by rock falls and avalanches may still develop, but these ash clouds are unlikely to extend beyond Augustine Island.

Some indicators suggest that magma is still present at shallow levels. AVO will continue to make volcanic gas measurements and recent measurements indicate that levels are still above background and likely indicate degassing of shallow magma. Weak thermal anomalies persist in satellite data, consistent with slow cooling of the lava dome and continued venting of hot gases.

Despite the volcano's current quiet state, renewed eruptive activity is possible. AVO expects that a renewal of explosive activity or lava extrusion would likely be preceded by increases in seismicity, gas output, and deformation.

Brief, unexpected explosions are still possible if hot gas and rocks interact with groundwater, but such explosions are unlikely to produce ash that would travel far beyond the island.

AVO continues to monitor Augustine closely and the observatory will remain staffed 24/7 until conditions at the volcano approach background levels.

I. Return to Green, normal, non-eruptive state.

ALASKA VOLCANO OBSERVATORY
Information Release
Wednesday, August 9, 2006 3:00 PM AKDT (2300 UTC)

AUGUSTINE VOLCANO (CAVW#1103-01-)
59°21'48"N 153°26'W , Summit Elevation 4134 ft (1260 m)
Current Level of Concern Color Code: **GREEN**
Previous Level of Concern Color Code: **YELLOW**

Based on the current level of activity at *Augustine* Volcano, we are lowering the Level of Concern Color Code from **YELLOW** to **GREEN**.

Seismic data and observations made by AVO geologists working on the volcano indicate that activity has decreased to background levels. Visual observations and satellite data show that there have been no detectable changes at the summit over the last few months.

Despite the cessation of lava dome growth, the new dome and lava flows are still unstable, and small rock falls and avalanches may occur for several months, especially on the north flank of the volcano. The steep ends of the lava flows are also places where rock fall activity may continue. These areas are still considered hazardous to anyone visiting the island.

The Augustine summit area continues to emit noxious volcanic gases. A gas-rich plume is often present and areas downwind of the summit may be engulfed by variable amounts of volcanic gas. Where the plume hugs the ground near the volcano, the gases can cause eye irritation and respiratory problems. Gases can accumulate in low-lying or confined areas of the summit and lava flows, and it is possible, but not likely, that the concentration of gases in these areas could reach levels dangerous to humans.

Though the volcano is currently quiet, renewed eruptive activity is possible. AVO expects that a renewal of explosive activity or lava extrusion would likely be preceded by increases in seismicity, gas output, and deformation.

Appendix 2. Interagency After-Action Premeeting Questionnaire

PRE-MEETING ASSIGNMENT TO PARTICIPANTS:

Please use the attached forms to submit the following information to no later than COB April 14. Responses will help guide the discussion and ensure we address key issues.

- **A. AGENCY GOALS FOR THE AFTERACTION**: what does your agency hope to get out of this meeting?
- **B. SUCCESSES**! What specific actions, policies, procedures, etc. were effective? These may be from your own agency or from any part of the interagency effort. What can we learn from this?
- **C. CHALLENGES!** What actions, policies, procedures, etc. were lacking in effectiveness and require improvement. How can we accomplish this?

PLEASE ANSWER THESE QUESTIONS prior to the meeting and be prepared to discuss:

- A. Did you or your agency make use of the published U.S. Geological Survey Volcano Hazard Assessment for Augustine Volcano? If not, why? If so, was it helpful?
- B. Were the daily coordination conference calls effective? How can they be improved?
- C. Was information about likely impacts of eruptive activity easy to obtain?
- D. Was there a good balance between Internet-based and other forms of communication?
- E. How did you receive the most critical information (phone? E-mail? Other?)
- F. Should a Joint Information Center have been established? If so, what would this look like, what is its purpose, and who would lead the JIC?
- G. What were the primary concerns of your agency and constituency and were these adequately addressed?

DO YOU HAVE ANY SPECIFIC QUESTIONS THAT YOU WOULD LIKE TO DISTRIBUTE TO THE GROUP PRIOR TO THE MEETING?