Report of Investigations 2011-5

THE 2009 ERUPTION OF REDOUBT VOLCANO, ALASKA

edited by
Janet R. Schaefer

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It has received technical review and may be cited as an agency publication.

Front Cover: Redoubt Volcano as viewed toward the southeast on the afternoon of April 4, 2009. Steam rises from the crater, ash blankets the flanks, and a muddy lahar engulfs the Drift River valley. Photo by R. McGimsey. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=17860

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This report uses the International System of Units (SI) to describe units of measure such as length, area, and volume. In the case of ash cloud heights, units are given in both feet (ft) and kilometers (km) above mean sea level (ASL). For most observations, time is reported in local Alaska time; however, certain satellite and seismic data are also reported in Coordinated Universal Time (UTC). Gas measurements are reported in metric tons per day (t/d). Tephra and dome lava volumes are reported in millions of cubic meters (Mm^3).The table below provides conversions for units used in this report.

Multiply	By	To Obtain
millimeters (mm)	0.03937	inches (in)
centimeters (cm)	0.3937	inches (in)
meters (m)	3.281	feet (ft)
kilometers (km)	0.6214	miles (mi)
cubic kilometers (km^3)	0.2399	cubic miles (mi^3)
meters per second (m/s)	3.281	feet per second (ft/s)
cubic meters per second (m^3/s)	35.31	cubic feet per second (ft^3/s)

TEMPERATURE

Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by the following equation:
°F = (1.8 x°C) + 32

TIME

Alaska Standard Time (AKST) prior to March 9, 2009 at 2:00am:
AKST = Coordinated Universal Time (UTC) – 9 hours;

Alaska Daylight Savings Time (AKDT) after March 9, 2009 at 2:00am:
AKDT = UTC – 8 hours

EXECUTIVE SUMMARY

Redoubt Volcano, an ice-covered stratovolcano on the west side of Cook Inlet, erupted in March 2009 after several months of escalating unrest. The 2009 eruption of Redoubt Volcano shares many similarities with eruptions documented most recently at Redoubt in 1966–68 and 1989–90. In each case, the eruptive phase lasted several months, consisted of multiple ash-producing explosions, produced andesitic lava and tephra, removed significant amounts of ice from the summit crater and Drift glacier, generated lahars that inundated the Drift River valley, and culminated with the extrusion of a lava dome in the summit crater. Prior to the 2009 explosive phase of the eruption, precursory seismicity lasted approximately six months with the first weak tremor recorded on September 23, 2008. The first phreatic explosion was recorded on March 15, and the first magmatic explosion occurred seven days later, at 22:34 on March 22. The onset of magmatic explosions was preceded by a strong, shallow swarm of repetitive earthquakes that began about 04:00 on March 20, 2009, less than three days before an explosion. Nineteen major ash-producing explosions generated ash clouds that reached heights between 17,000 ft and 62,000 ft (5.2 and 18.9 km) ASL. During ash fall in Anchorage, the Ted Stevens International Airport was shut down for 20 hours, from ~17:00 on March 28 until 13:00 on March 29. On March 23 and April 4, lahars with flow depths to 10 m in the upper Drift River valley inundated parts of the Drift River Terminal (DRT). The explosive phase ended on April 4 with a dome collapse at 05:58. The April 4 ash cloud reached 50,000 ft (15.2 km) and moved swiftly to the southeast, depositing up to 2 mm of ash fall in Homer, Anchor Point, and Seldovia. At least two and possibly three lava domes grew and were destroyed by explosions prior to the final lava dome extrusion that began after the April 4 event. The final lava dome ceased growth by July 1, 2009, with an estimated volume of 72 Mm^3.

ERUPTION HIGHLIGHTS

PRECURSORY PHASE (JULY 2008 – MARCH 2009)

- More than seven months of precursory unrest; mainly increased glacier melting and gas emission.
- First sign of seismic unrest (short episodes of weak volcanic tremor) was detected six months prior to the first magmatic explosion.
- Aviation color code elevated to YELLOW and alert level to ADVISORY on November 5, 2008, more than four months prior to first explosion, following measurement of CO_2 emissions of $>$1,000 metric tons/day (t/d).
- A marked increase in seismicity on January 25, 2009, prompted the raising of the aviation color code to ORANGE and alert level to WATCH.
- CO_2 emissions measured from late January until the first explosion were at levels typically observed for a volcano already experiencing eruptive activity (5,000–10,000 t/d). SO_2 emissions, however, remained low until the first phreatic explosion on March 15.

EXPLOSIVE AND EFFUSIVE PHASE (MARCH 2009 – JULY 2009)

- First steam explosion on March 15 at 13:05 (for time format and units used in this report, see "SI Units and Conversion Chart," p. vi) ejected non-juvenile ash to 15,000 ft (4.6 km) ASL.
- First magmatic explosion on March 22 at 06:34 with initial ash-column height to 18,000 ft (5.5 km), building up to 44,000 ft (13.4 km) ASL in one-half hour.
- Seismicity prior to the first magmatic explosion consisted of about two days of strong, shallow swarms of repetitive events that began ~04:00 on March 20.
- Nineteen major ash-producing events in which a Volcano Activity Notification (VAN)/Volcano Observatory Notice for Aviation (VONA) was released; ash columns between 17,000 ft (5.2 km) and 62,000 ft (18.9 km) ASL.
- Explosive phase ended on April 4 with a lava-dome collapse at 05:58 and an eruption column to 50,000 ft (15.2 km) ASL.
- Pyroclastic flows were observed by remote cameras on March 23 (19:40, Event 6), March 26 (09:24, Event 8), March 27 (08:39, Event 11), March 28 (01:19, Event 15), and April 4 (05:58, Event 19).
- Two major lahars with flow run-ups to 13 m in the upper Drift River valley inundated the Drift River Terminal (DRT) on March 23 and April 4, and smaller lahars were observed on March 26, 27, and 28.
- At least two lava domes grew and were destroyed during the course of the explosive phase.
- After April 4, the final extrusive phase of dome building began, culminating growth by July 1, 2009, with a dome volume of 72 Mm^3.

IMPACTS

- Over the course of the eruption, hundreds of flights were canceled or rerouted on various carriers, including 295 Alaska Airlines flights.
- March 26 ash fall over the Kenai Peninsula forced businesses and city offices to close early.
- Trace ash fall in Anchorage on March 28 resulted in a 20-hour closure of the Anchorage Ted Stevens International Airport.
- Up to 2 mm of ash fell in Anchor Point, Homer, and Seldovia between 07:00 and 08:30 on April 4.
- Major lahars reached the Drift River Terminal on March 23 and April 4, forcing the removal of 6 million gallons of crude oil. Oil storage tanks were spared damage by a previously emplaced protective embankment, but the airstrip and surrounding facilities were flooded with water, mud, and debris up to 1.5 m deep.
- On April 5, oil production was suspended from ten Cook Inlet platforms in response to the lack of storage capability and limited tanker operations. Operations were eventually resumed when an oil transport plan was put in place to bypass the DRT tanks and transport oil directly from facilities at Granite Point and Trading Bay through the 68 km pipeline directly to tankers berthed at the Christy Lee platform, just offshore of the DRT.

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INTRODUCTION

In March 2009, after seven months of unrest and nearly 19 years since its last eruption, Redoubt Volcano began erupting explosively (fig. 1). Over the course of three weeks, at least 19 explosions sent ash into the atmosphere to heights between 17,000 and 62,000 ft (5.2 and 18.9 km) above mean sea level (ASL) (see page vi regarding units used in this report). At least two, and possibly three, lava domes grew and were destroyed during this explosive phase of the eruption. The explosions initiated several lahars—the two largest lahars reached flow run-ups of up to 13 m, moved swiftly down the 1.5-km-wide Drift River valley, and surrounded the Drift River Terminal (DRT), an oil storage and transfer facility. Trace amounts of ash (<0.8 mm) were reported as far as Fairbanks, Alaska, 550 km north–northeast of the volcano. Satellite sensors tracked sulfur dioxide (SO_2) in the atmosphere, and by March 29 the plume appeared to have circled the northern hemisphere. After the final explosive event on April 4, the last lava dome began growing in the summit crater and ceased effusion in early July.

For more than seven months prior to the onset of the explosive phase of the eruption, scientists at the Alaska Volcano Observatory (AVO) monitored the increasing unrest. Observation flights were sent to investigate reports of increased hydrogen sulfide (H_2S) emission, melting of glacial ice, and steaming; gas flights detected high levels of carbon dioxide (CO_2) and minor amounts of H_2S and SO_2; seismic instruments detected volcanic tremor, and webcam images showed vapor plumes rising from the crater. During unrest and eruption, weekly, daily, and sometimes hourly status reports and information releases warning of unrest

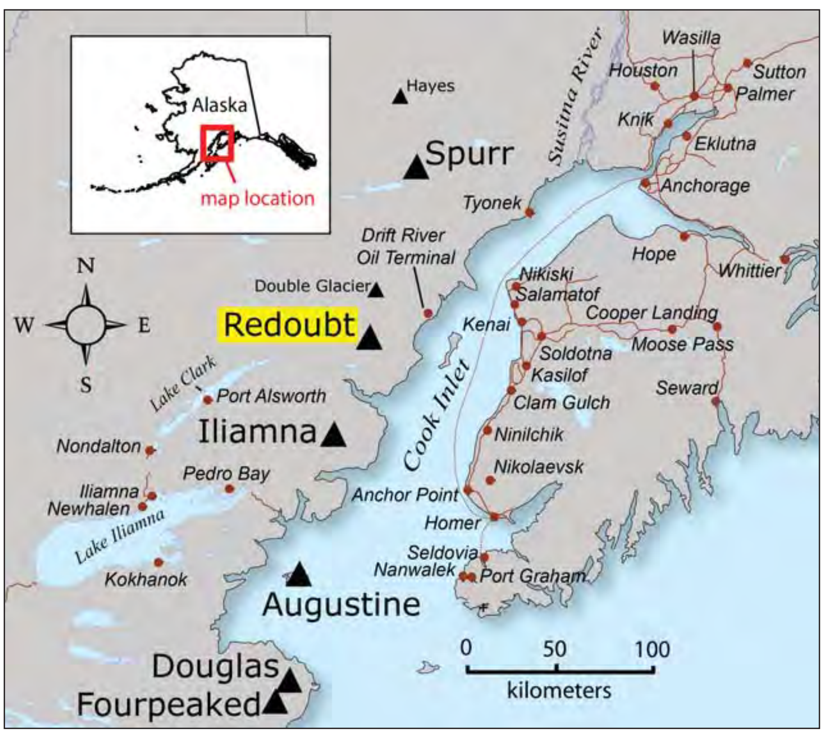

Figure 1. Location of Redoubt and surrounding volcanoes in Cook Inlet. Volcanoes are identified with black triangles. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=15524

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and providing probable eruption scenarios were sent to emergency management personnel and posted to the AVO website. Communication of the hazards was facilitated by the use of standardized Volcanic Activity Notifications (VANs) that contained details of recent observations as well as the current Volcano Alert Level and Aviation Color Code (fig. 2). The detection of early unrest, real-time evaluation of eruption onset, and immediate eruption response provide a further example of AVO's success in volcano-risk mitigation that now includes four major Cook Inlet eruptions (Redoubt, 1989–90, Crater Peak vent of Mount Spurr, 1992; and Augustine Volcano, 2006).

This report summarizes the highlights of the 2009 eruption of Redoubt Volcano from the early stages of unrest through the explosive phase and final dome-building phase. It describes AVO's operational responsibilities, including information dissemination, interagency cooperation, and monitoring. The report documents the impacts of volcanic ash on the surrounding communities, including airports, and aviation; and it describes lahars (volcanic mudflows) produced during the eruption, and their impact on the Drift River Terminal (DRT).

LOCATION AND GEOLOGIC SETTING

Redoubt Volcano is 170 km southwest of Anchorage, Alaska's largest population center, and approximately 80 km west of the Kenai Peninsula communities of Kenai, Soldotna, and Homer (fig. 1). The volcano lies just inside the eastern margin of Lake Clark National Park. Redoubt is one of five historically active volcanoes on the west side of Cook Inlet (including Spurr, Iliamna, Augustine, and Fourpeaked), and one of 52 historically active volcanoes that form the Aleutian volcanic arc. The arc comprises more than 100 volcanoes formed above the northerly directed Aleutian subduction zone. The Cook Inlet volcanoes are about 400 km northwest of the Aleutian trench axis.

Redoubt is a steep-sided, glacially dissected stratovolcano, 3,110 m high and approximately 10 km in diameter at its base. An ice-filled crater just west of the true summit hosts the vents of the most recent eruptions (fig. 3). The crater is

Volcano Alert Levels Used by USGS Volcano Observatories

Alert Levels are intended to inform people on the ground about a volcano's status and are issued in conjunction with the Aviation Color Code. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption and about potential or current hazards and likely outcomes.

Term	Description
NORMAL	Volcano is in typical background, noneruptive state or, *after a change from a higher level*, volcanic activity has ceased and volcano has returned to noneruptive background state.
ADVISORY	Volcano is exhibiting signs of elevated unrest above known background level or, *after a change from a higher level,* volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
WATCH	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, OR eruption is underway but poses limited hazards.
WARNING	Hazardous eruption is imminent, underway, or suspected.

Aviation Color Code Used by USGS Volcano Observatories

Color codes, which are in accordance with recommended International Civil Aviation Organization (ICAO) procedures, are intended to inform the aviation sector about a volcano's status and are issued in conjunction with an Alert Level. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption, especially in regard to ash-plume information and likely outcomes.

Color	Description
GREEN	Volcano is in typical background, noneruptive state or, *after a change from a higher level*, volcanic activity has ceased and volcano has returned to noneruptive background state.
YELLOW	Volcano is exhibiting signs of elevated unrest above known background level or, *after a change from a higher level*, volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, OR eruption is underway with no or minor volcanic-ash emissions [ash-plume height specified, if possible].
RED	Eruption is imminent with significant emission of volcanic ash into the atmosphere likely OR eruption is underway or suspected with significant emission of volcanic ash into the atmosphere [ash-plume height specified, if possible].

Figure 2. U.S. Geological Survey standard Aviation Color Codes and Volcanic Activity Alert Levels used to communicate the level of concern for volcanic activity at U.S. volcanoes.

breached on its north side by the informally named 'Drift glacier', which flows down into the Drift River valley and forms the informally named 'piedmont lobe.' Discharge from the glacier forms a tributary to the Drift River, which flows 43 km east through a broad valley into Cook Inlet (fig. 4).

Basement rocks underlying Redoubt Volcano comprise Jurassic quartz–diorite to tonalite intrusive rocks. The edifice consists of a ~1,500-m-thick sequence of mid Pleistocene to recent products of both explosive and effusive eruptions (Till and others, 1994). On the north side of the edifice, pyroclastic deposits overlie basement rocks directly. These deposits range from basalt to dacite in composition (53.1–68.5 wt% SiO_2), and were emplaced by pyroclastic density currents from vent explosions and lava-dome failures. A sequence of interlayered, thin, crystal-rich, basalt to basaltic andesite (49.3–59.5 wt% SiO_2) lava flows and scoria deposits as well as andesitic block-and-ash flow deposits, overlie earlier deposits on all flanks. At least three hydrothermally altered debris-flow deposits are visible in valleys to the coast on the south, east, and north sides of the edifice, indicating multiple flank-collapse events in Redoubt's history (Riehle and others, 1981; Begét and Nye, 1994).

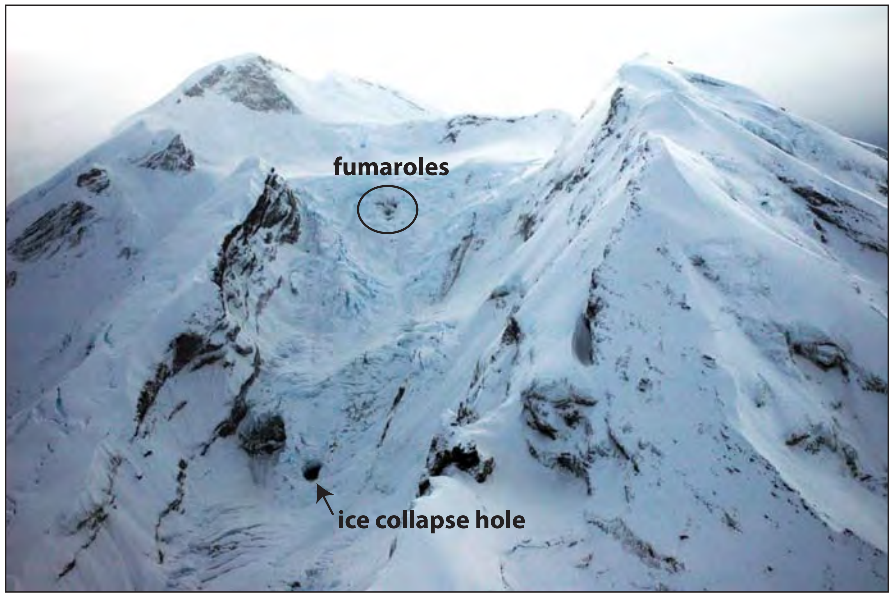

Figure 3. North flank of Redoubt Volcano, showing the ice-filled summit crater, ice collapse hole in the upper Drift glacier, and fumaroles alongside the 1990 dome in the crater. Photo by R. McGimsey, October 13, 2008. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=15778

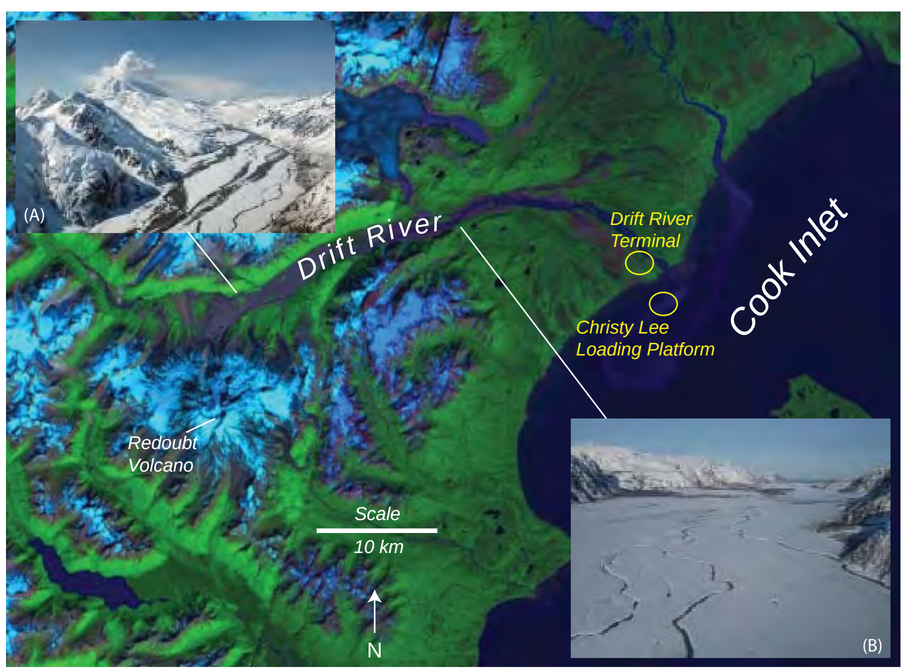

Figure 4. False-color Landsat image showing Redoubt Volcano, the Drift River valley, the Drift River Terminal, and the Christy Lee oil-loading platform in Cook Inlet. Inset (A) shows the upper Drift River valley, looking west toward steaming Redoubt Volcano. New snow covers the floor of the valley, which recently had been scoured by the April 4 lahar. Photo by R. McGimsey, April 16, 2009. http://www.avo.alaska.edu/images/image.php?id=18105. Inset (B) shows extensive pre-lahar snow and ice with open meltwater channels in the lower Drift River valley. View to the east toward Cook Inlet. Photo by M. Kaufman, March 18, 2009. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=17622

RECENT ERUPTIVE HISTORY

Redoubt has erupted more than 50 times over the past 10,000 years, and at least five times since 1700 C.E. (Begét and Nye, 1994; Till and others, 1994; Schiff and others, 2008). Recent sediment cores obtained from Cub Lake (informally named) and Bear Lake, within 25 km to the east of the summit, contain numerous tephra layers with an average tephra-fall frequency of 1.1 and 0.8 per century (>1 mm thick), respectively, over the past 3,850 years (Schiff and others, 2010).

The most recent and best documented eruptions at Redoubt occurred during 1965–68 and 1989–90. Activity between 1965 and 1968 included explosions that produced pyroclastic flows that eroded and melted 5.7 x 10^7 m^3 of snow and glacier ice from the upper Drift glacier, resulting in debris flows that inundated the Drift River valley to the coast (Sturm and others 1983; Sturm and others, 1986; Brantley, 1990). During this time, a seismic-exploration crew was evacuated from near the future site of the Drift River Terminal due to the flooding (Brantley, 1990). Effusive activity from this eruption produced at least one dome that remains and now forms a prominent ridge west of the sites of the 1989–90 and 2009 activity.

The 1989–90 eruption of Redoubt Volcano began on December 14, 1989; throughout the course of the eruption 25 explosions sent ash clouds from 26,000 ft (8 km) to over 39,000 ft (12 km) ASL. Eruptive activity included explosions, lava dome effusion, and both explosively and gravitationally driven dome collapse. The first explosion, on December 14, 1989, was preceded by ~24 hours of increased seismicity (Miller and Chouet, 1994; Power and others, 1994). Monitoring equipment placed on Redoubt's flanks just several months prior to the unrest, enabled AVO to forewarn governmental agencies to activate emergency plans. The December 14 explosion lasted 17 minutes and sent ash above 39,000 ft (12 km) ASL to the northeast. Pyroclastic flows descended from the crater, eroded ice, and deposited an ice diamict consisting of glacier ice and volcanic debris onto the lower Drift glacier (Miller and Chouet, 1994; Waitt and others, 1994; Trabant and others, 1994). This event was followed by at least five explosions over the next five days, including a prolonged 40-minute event on the morning of December 15, and steady tephra emission December 16–18. On December 15, after the 40-minute explosive event, a Boeing 747–400 aircraft encountered the ash cloud about 280 km north–northeast of Redoubt, and temporarily lost power to all four engines, eventually regaining two engines after descending ~10,700 ft (3,300 m) in four minutes. Passenger and crew were uninjured, although damage to the aircraft was estimated at $80 million (Casadevall, 1994).

Following an explosion on December 19, a dome began to grow in Redoubt's crater; it subsequently was destroyed by a major explosion on January 2, 1990 (Miller, 1994). Hot pyroclastic flows melted snow and glacial ice, creating a lahar that flowed down the Drift glacier and inundated the Drift River valley to the coast (Trabant and others, 1994). The flow came within a few meters of the top of a levee constructed around oil storage tanks at the Drift River Terminal (Dorava and Meyer, 1994).

Following the January 2, 1990, lava-dome destruction, 12 domes subsequently were emplaced, and all but the last were destroyed by explosions or collapsed gravitationally, initiating an explosion (Miller, 1994). The Drift River Terminal was flooded again on February 15 after pyroclastic flows disrupted and melted additional glacial ice and snowpack and produced significant lahars (Miller and Chouet, 1994; Gardner and others, 1994; Trabant and others, 1994; Dorava and Meyer, 1994). Between February 15 and April 21, thirteen small lava domes grew and were destroyed, and pyroclastic flows and lahars deposited debris above and onto the piedmont lobe of the Drift glacier, and lahars descended the upper part of the Drift River valley. The fourteenth and final lava dome of the eruption began growing after an explosion on April 21, partly collapsed on April 26, and effusion stopped by June 21. Post-eruption degassing and seismicity declined to background levels by July 1991 (Miller and Chouet, 1994; Brantley, 1990). Between July 1991 and October 2008, seismicity beneath Redoubt Volcano remained at or near background levels.

2008–2009 ERUPTION CHRONOLOGY

CHRONOLOGY OF UNREST: PRECURSORY OBSERVATIONS JULY 2008 – MARCH 2009

The period of unrest between July 2008 and March 2009 was documented by a variety of techniques including on-the-ground field observations, fixed-wing and helicopter-based field observations, photography, gas measurements, webcam images, pilot and resident reports, forward-looking infra-red (FLIR) measurements, meltwater chemistry, geodesy, and seismicity. The following section documents these events in a chronology of unrest leading up to the first magmatic explosion on March 22 and describes the timeline of instrument deployment and aviation color-code and volcano alert-level changes. For a more detailed discussion of the precursory seismicity, see Summary of Precursory Seismic Activity, pages 8-9.

The unrest documented between late July 2008 and late January 2009 consisted primarily of increased gas emission, melting ice, and intermittent tremor. In late July through early August 2008, AVO geologists conducting fieldwork on the volcano noted the distinct 'rotten-egg' odor of hydrogen sulfide (H_2S). A pilot flying near the volcano on September 16 also reported a strong smell of H_2S. On September 23 at 09:37–09:40 and again on September 25 at ~23:18 and September 26 at ~01:27, seismic instruments on Redoubt detected a volcanic-tremor-like signal. On September 23, AVO received this report from Melissa Sanford at Wadell Lake, 23 km east-southeast of the volcano:

> *"Hello. We have a cabin at the base of Mt. Redoubt on Wadell Lake. As we were leaving on Tuesday morning (September 23, 2008) there were five to six very loud*

explosion-type noises that came directly from the Mt. Redoubt area...sounded to us from the mountain itself."

AVO was concerned enough by these reports to conduct a gas and observation flight on September 27. Observers noted the rotten-egg odor of H_2S, increased steaming and expanding rock exposures around fumaroles, as well as a 50-m-wide ice-collapse pit on the upper Drift glacier (fig. 3). These observations set the stage for additional flights, with the purpose of monitoring the growth and expansion of these fumarolic zones and areas of melting ice.

The next gas and observational flight, on October 13, noted anomalous emission of H_2S and SO_2, and moderate levels (1,370 t/d) of CO_2. Steam had begun to rise from the melt pit and rock exposure around the fumaroles had increased (fig. 3). By November 2, more rock was exposed and gas levels of CO_2, H_2S, and SO_2 remained elevated with respect to background levels (Doukas and McGee, 2007). Based on this above-background-level activity, AVO on November 5 increased the aviation color code from GREEN to YELLOW and raised the alert level from NORMAL to ADVISORY (table 1).

Just 11 weeks later, sustained tremor beginning at 00:58 on January 25, 2009, suggested strongly that magma was on the move. A January 25 observation flight documented increased fumarolic output and the formation of a new ice-collapse pit higher on the Drift glacier. These observations on January 25 prompted AVO to change the aviation color code from YELLOW to ORANGE, the alert level from ADVISORY to WATCH, and to begin staffing the operations room 24 hours per day. By January 26, small mudflows appeared along the margin of the Drift glacier and a gas flight measured elevated levels of SO_2.

The rush to improve and augment AVO's monitoring instrumentation was on. On January 27, a webcam was installed ~12 km north of the volcano at 'Juergen's hut' and became commonly referred to as the 'hut cam.' Its unobstructed view of the crater, dome complex, and upper Drift glacier was unprecedented and proved to be an extremely valuable monitoring tool when conditions became unsafe for direct field observations. By January 27, seven seismic stations were operational: NCT, DFR, RDT, RDN, REF, RSO, and RED (fig. 5); these stations continued to record elevated seismicity. Significant melting in the crater resulted in lahars on the east and west sides of, as well as on top of, Drift glacier.

On January 29, seismicity increased and numerous small long-period (LP) events were recorded every hour on stations RSO and REF. These were followed by another marked increase that occurred late on January 29 and throughout the following day (fig. 6). Pilot reports, clear webcam views, and satellite and radar views confirmed no eruption had occurred; however, prompted by the change in seismicity, the U.S. Geological Survey (USGS) issued a news release stating, "Mount Redoubt Volcano in Alaska Likely to Erupt." In response to USGS concerns, the FAA placed a temporary flight restriction (TFR) to 60,000 ft (18.3 km) within a 16 km radius of the volcano. An observation flight was launched on January 30 to investigate what changes were taking place at the volcano in conjunction with the evolving seismicity. Observers reported that a new melt pit had opened below the 1990 dome, and a vigorous steam plume was rising to ~9,500 ft (2.9 km). Concentric crevasses on the crater floor behind the 1990 and 1966 domes formed a piston-like collapse structure, further evidence of melting beneath the ice. With news of an impending eruption, the AVO website attracted enough visitors on January 30 to overload the bandwidth, resulting in a brief interruption of web service.

A gas flight on January 31 detected greatly increased levels of CO_2 (more than 7,000 t/d), H_2S, and SO_2. The holes in the ice continued to grow, exposing more steaming rock, and two vigorous point sources of vapor and volcanic gas were

Table 1. Timeline of color code and alert level changes.

	Color Code	Alert Level	Date
	GREEN	NORMAL	Oct 3, 2008 10:37
	YELLOW	ADVISORY	Nov 5, 2008 14:52
	ORANGE	WATCH	Jan 25, 2009 02:09
	YELLOW	ADVISORY	Mar 10, 2009 09:56
	ORANGE	WATCH	Mar 15, 2009 14:50
	YELLOW	ADVISORY	Mar 18, 2009 09:41
	ORANGE	WATCH	Mar 21, 2009 22:09
	RED	WARNING	Mar 22, 2009 22:56
	ORANGE	WATCH	Mar 25, 2009 13:35
	RED	WARNING	Mar 26, 2009 08:56
	ORANGE	WATCH	Apr 3, 2009 11:44
	RED	WATCH	Apr 4, 2009 06:35
	RED	WARNING	Apr 4, 2009 06:51
	ORANGE	WATCH	Apr 6, 2009 14:55
	YELLOW	ADVISORY	Jun 30, 2009 10:20
	GREEN	NORMAL	Sep 29, 2009 10:44
	YELLOW	ADVISORY	Dec 28, 2009 09:53
	GREEN	NORMAL	Jan 5, 2010 15:32
	YELLOW	ADVISORY	Apr 5, 2010 10:59
	GREEN	NORMAL	Apr 12, 2010 12:10

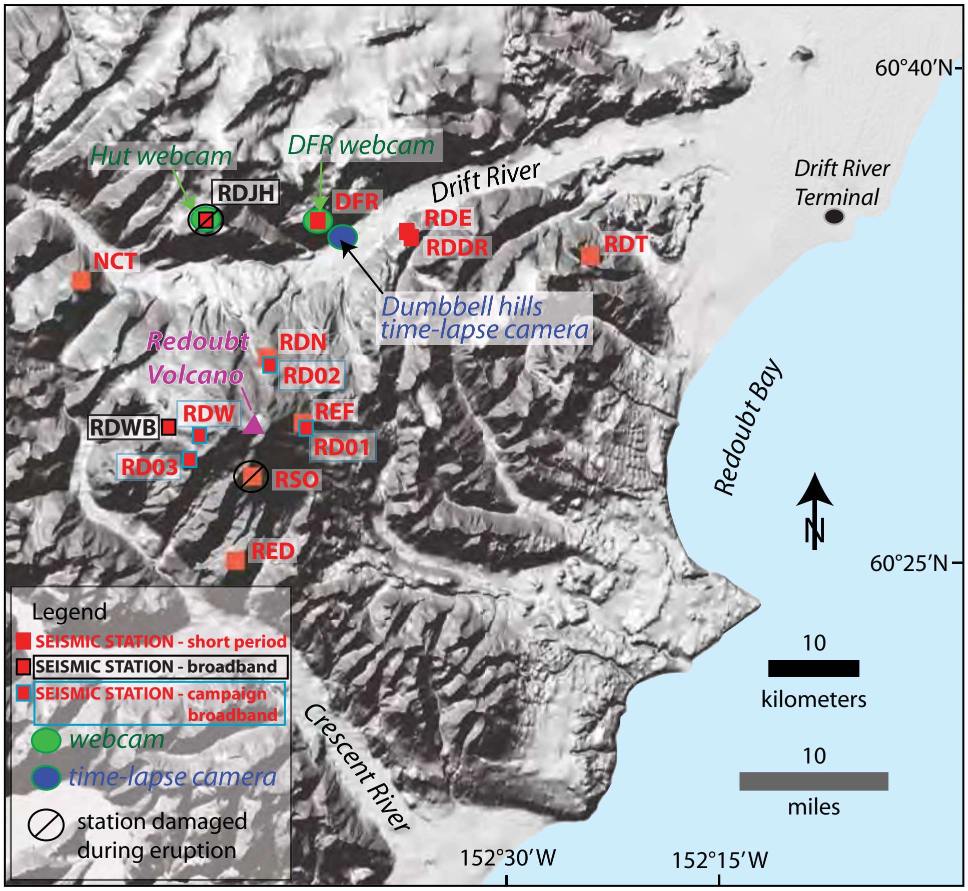

Figure 5. Seismic stations, webcams, and time-lapse camera locations.

evident at ~7,000-ft, just below the 1990 dome. Throughout February 1, seismicity remained relatively constant with several to a few dozen events detected per hour with at least two episodes of more energetic, 10- to 15-minute-duration tremor. Webcam views on February 1 showed a vapor plume rising no higher than the summit.

During the first week of February, seismicity continued to increase and gas emission remained elevated. On February 2, a 48-minute episode of repeating long-period earthquakes hinted at changes to come. On that day, the larger of the two fumaroles below the 1990 dome ceased emitting vapor, but steaming from the broad area encompassed by the 1990 dome became more apparent. On February 5, starting at 11:18, a burst of seismic energy was recorded at stations RDN, RDE, RDJH, RSO, NCT, and DFR. At stations REF and RSO, the level of background tremor following this burst was 2–3 times stronger than levels prior to the event (fig. 7). A February 7 gas flight again recorded very high levels of gas emission.

AVO expanded its monitoring toolset on February 10 with the addition of a continuous, telemetered Global Positioning System (GPS) instrument at Juergen's hut, collection of water samples from the meltwater coming off Drift glacier, and additional FLIR imagery of the dome region. The GPS station was the first telemetered station to be installed within 25 km of the vent. The only other continuous, telemetered GPS station was the Plate Boundary Observatory (PBO) station AC17, about 27 km northeast of the volcano's summit. A maximum temperature of 28°C was recorded in FLIR data from the largest area of exposed rock on the 1990 lava dome, an increase of ~16°C from November 2008 measurements. Between November 2008 and February 10, 2009, increased thermal output had melted an estimated 5–6 million cubic meters of ice in the crater (equivalent to about 2,000 Olympic-sized swimming pools).

On February 21 the ice pit doubled in size over the course of the observation flight, exposing a sub-glacial waterfall, and on February 25 a hut webcam image showed a muddy flowage deposit originating from the melt pit. A few hours later, at 15:45, seismic station RSO recorded 45 minutes of increased tremor amplitude—the strongest tremor observed since unrest began. Following this event, the character of the seismic signal changed to lower-level tremor and more discrete events. On February 26 an earthquake swarm from 17:36 to 17:54 was followed by a small lahar originating on the upper Drift glacier, as seen in the 18:04 webcam image as well as in an ASTER thermal image.

As activity ramped up at the volcano, AVO rushed to install more monitoring equipment. On February 27, field crews installed a GPS receiver and a time-lapse camera at Dumbbell hills and a GPS receiver at station RDWB. Initial

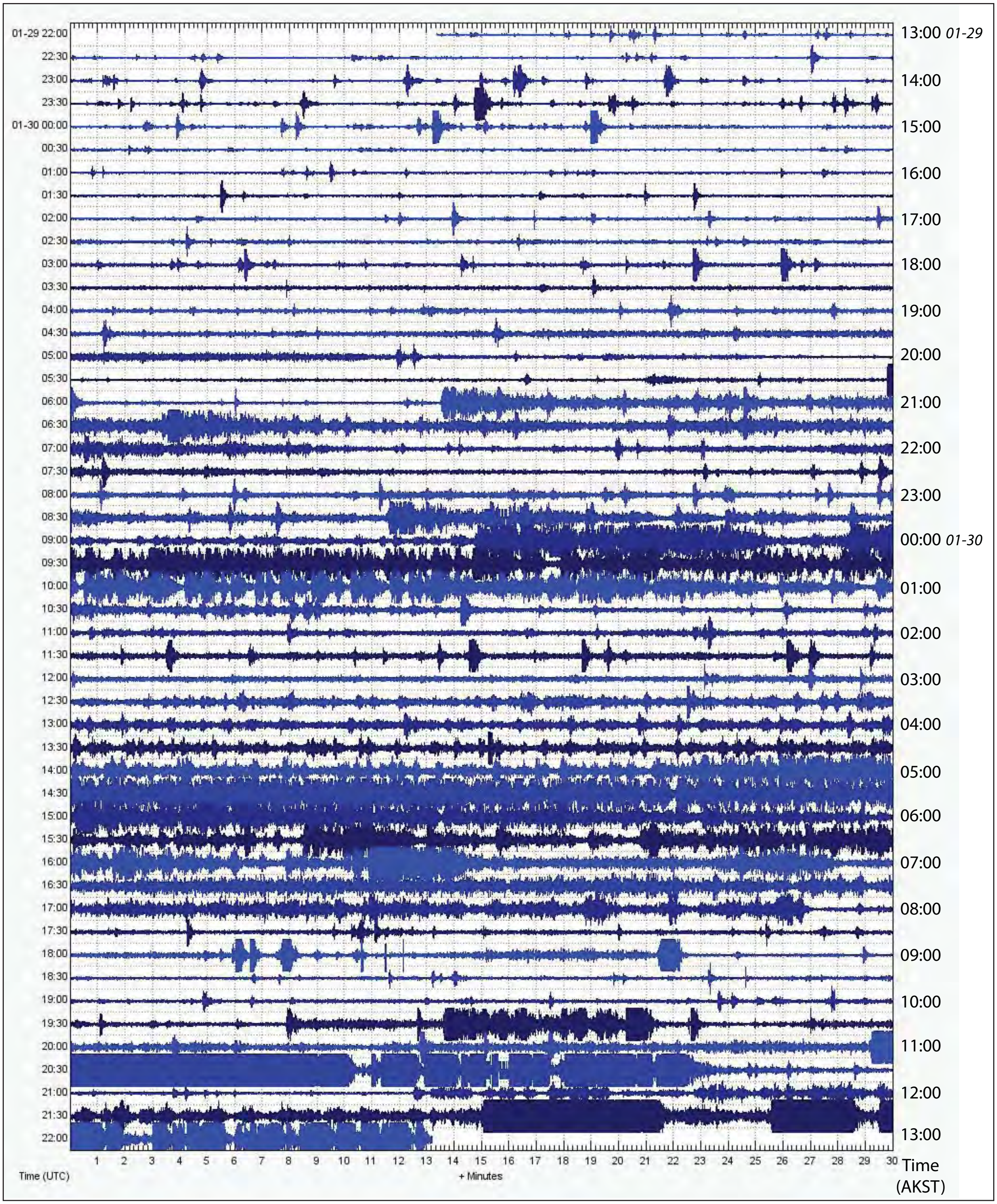

Figure 6. Seismic Station RSO helicorder plot, January 29–30, 2009, showing marked increase in seismicity seven weeks prior to the first magmatic explosion.

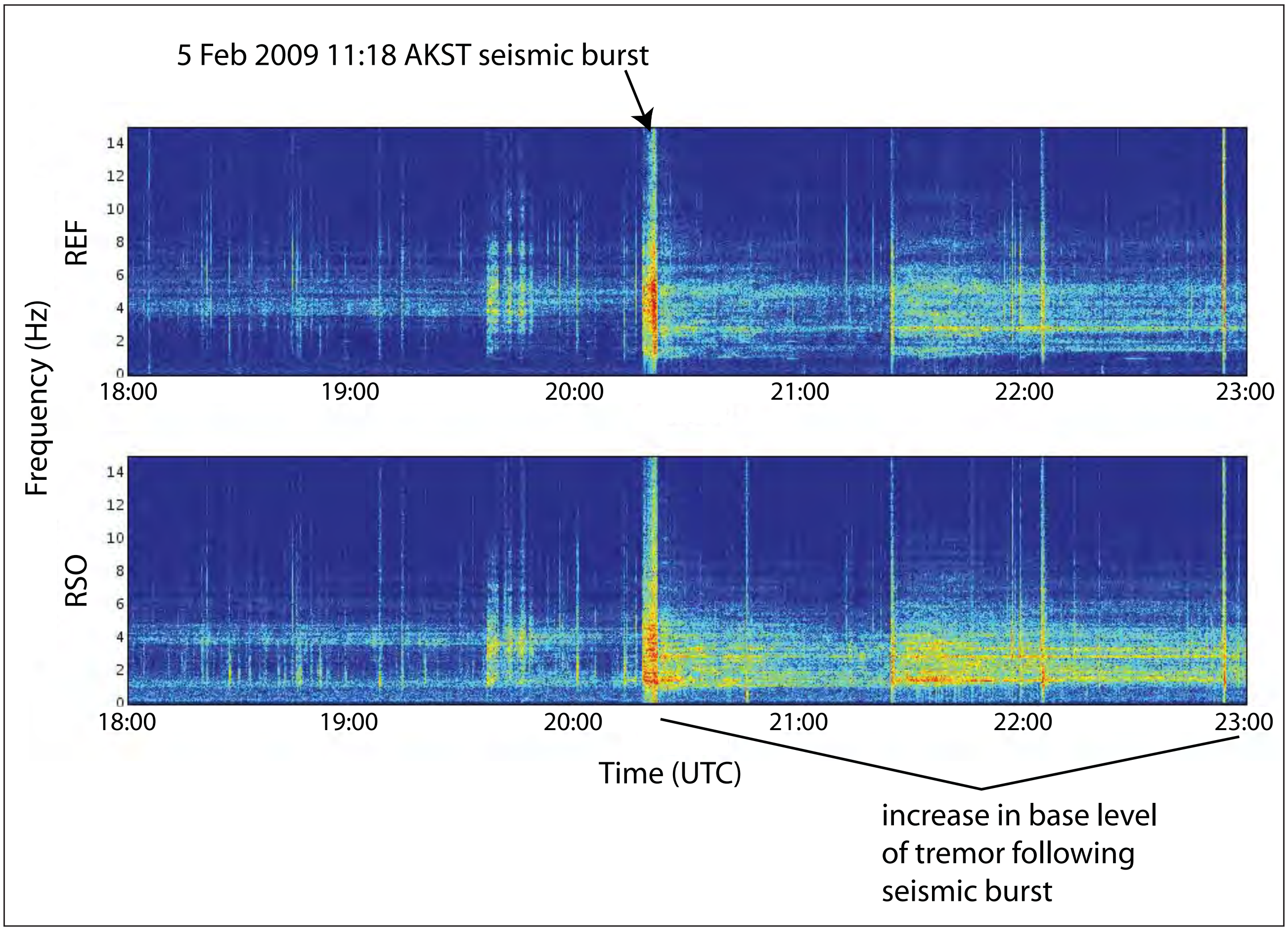

Figure 7. February 5, 2009, spectrogram showing a burst of seismic energy, followed by strong background tremor.

GPS data were inconclusive. Water chemistry of an eastern outflow stream at the base of the Drift glacier sampled on February 27, and previously on February 10 and 21, 2009 and November 7, 2008, showed a trend toward higher S/Cl ratios and lower pH, suggesting contributions of dissolved magmatic gas.

From February 25 through March 15, discrete events, rather than continuous tremor, continued to dominate the seismic character. At 13:00 on March 15, personnel conducting a gas measurement flight witnessed an explosion accompanied by a small ash emission and vigorous steam plume. Ash appeared on the snow in a small swath draped over the south crater rim. Initial observations led to speculation that this explosion was likely driven by steam from the hydrothermal system, and ejected fragments of old rock; subsequent sampling of the ash confirmed that no new magmatic material was present.

Summary of Precursory Seismic Activity

A complex protracted seismic sequence preceded the 2009 eruption, characterized by periods of tremor, volcano–tectonic (VT), long period (LP), and hybrid events at shallow depth and a more subtle sequence of LP events and VT earthquakes at depths of 20–40 km below sea level. The first anomalous seismicity identified at Redoubt prior to the 2009 eruption were three very short (minutes-long) episodes of weak volcanic tremor recorded: at 09:37 on September 23, at 23:18 on September 25, and at 10:27 on September 26, 2008. On October 5 AVO recorded a magnitude 1.6 earthquake at Redoubt roughly 20 km below sea level. This was the first event in a sequence of 31 events located in the mid to lower crust; these shocks were composed of a mix of LP events and VT earthquakes. Long-period events at mid- to lower-crustal depths are generally referred to as Deep Long-Period (DLP) events (Power and others, 2004). Waveforms of DLP events generally have emergent P- and S-phases and extended codas with peak frequencies between 1 and 4 Hz. The mid- to lower-crustal VT events generally have sharper phase arrivals and a broader frequency spectrum. These waveform characteristics for mid- to lower-crustal events have been observed at a number of volcanoes in the Aleutian arc (Power and others, 2004). No similar sequence of DLP events had been observed at Redoubt between 1989 and 2008 (fig. 8), and their occurrence is a clear precursor to the 2009 eruption (Power and others, 2009). However, it is important to note that these events followed the initial reports of increased fumarolic activity, snow melt, gas emission, and bursts of tremor observed on September 23 and 25–26, 2008.

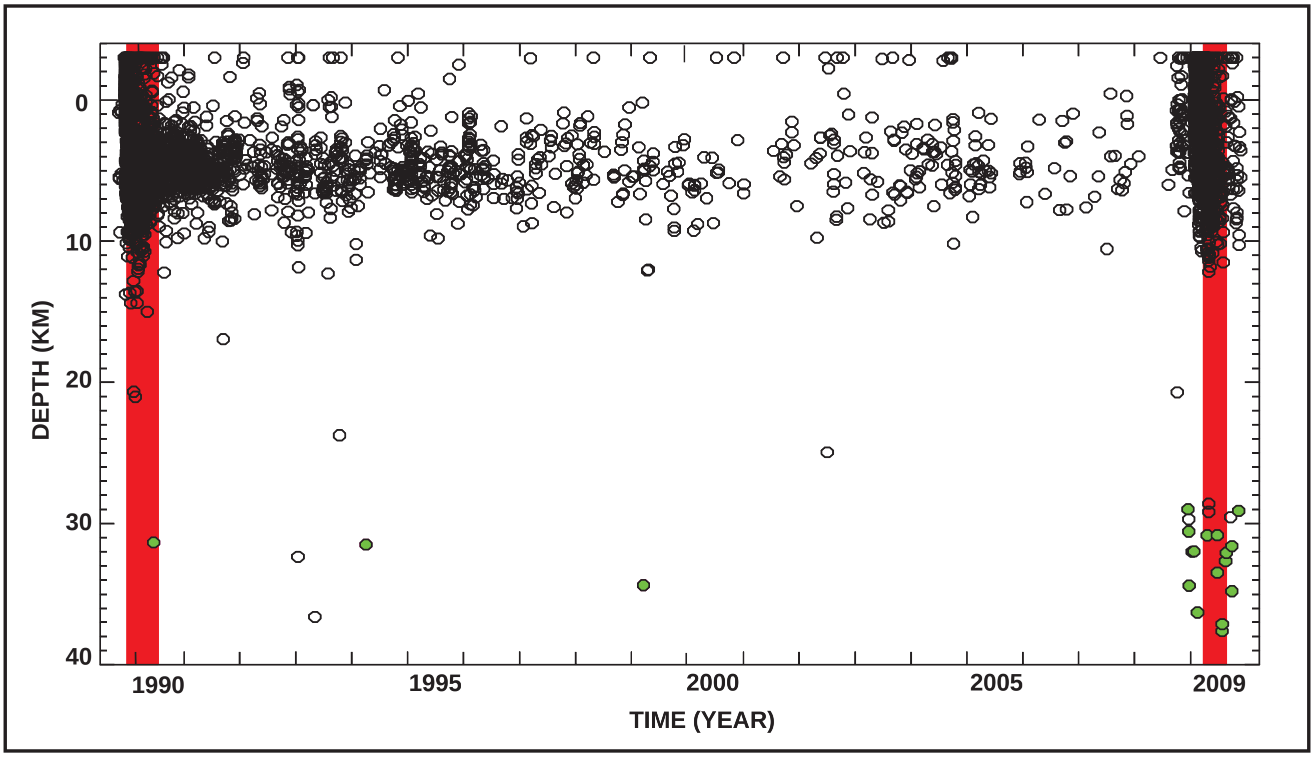

Figure 8. Plot of depth versus time for earthquakes between 1989 and 2009 with hypocenters within 7 km of the summit of Redoubt Volcano. Only hypocenters with standard horizontal and vertical location errors less than 10 km are shown. Periods of eruptive activity in 1989–90 and 2009 are shaded red. Open circles represent located events and green shaded circles represent Deep Long-Period (DLP) events.

Regardless, the occurrence of the DLP events at Redoubt factored strongly into our efforts to forecast the 2009 eruption.

Strong precursory seismicity began with a notable burst of tremor at 19:10 on January 23, 2009, that lasted for roughly 1.5 hours. This was followed by a second, stronger burst of tremor on January 24 at 17:14. A more protracted period of tremor began about 00:45 on January 25 and continued for about 4.5 hours. These three initial episodes initiated a 59-day-long sequence of shallow tremor and VT, LP, and hybrid events. Strong tremor between February 5 and 26 is illustrated nicely by Real-time Seismic Amplitude Measurements (RSAM) at station RSO (fig. 9). RSAM data represent the average amplitude and ground shaking caused by earthquakes and volcanic tremor over specified time intervals, and thus provides a useful measure of overall level of seismic activity. The strong tremor was followed by an earthquake swarm February 26–27. The onset of magmatic explosions on March 22 was preceded by a strong, shallow swarm of repetitive events that began about 04:00 on March 20, 2009.

Comparison of 1989–90 and 2009 Precursory Seismic Activity

Seismic activity prior to the 2009 eruption is much more protracted than the 1989–90 precursory seismic sequence. Between mid October and mid December 1989, a very subtle increase in shallow earthquakes and LP events was observed, as were two periods of volcanic tremor in November 1989 (Power and others, 1994). The onset of eruptive activity on December 14, 1989, was preceded by roughly 23-hour-long intense swarm of repetitive LP events located at a depth of about 1.3 km below the crater floor (Chouet and others, 1994; Lahr and others, 1994).

Several DLP events were located during and following the 1989–90 eruption (fig. 8); however, the algorithms used by AVO to detect seismic events in 1989 were likely not as well suited to triggering on the emergent waveforms typically seen in mid- to lower-crustal seismicity as those used in 2009.

Seismic Interpretation

The spatial and temporal development of earthquake hypocenters from 1989 and 2009 suggest both the 1989–90 and 2009 eruptions of Redoubt Volcano tapped a magma source area that is roughly 3–8 km below sea level (Power and others, 1994). The occurrence of precursory DLP events in 2008–2009 suggests that more mafic magma may have ascended from lower-crustal depths and interacted with magma at 3–8 km depth, thereby triggering this eruption. Shallow seismicity and tremor likely represent the transit of fluids and associated magma through a shallow system of cracks in the Redoubt edifice and upper crust as they moved toward the surface. A conceptual model showing the locations of the principal components of the Redoubt magmatic system as interpreted from the seismicity is presented in figure 10.

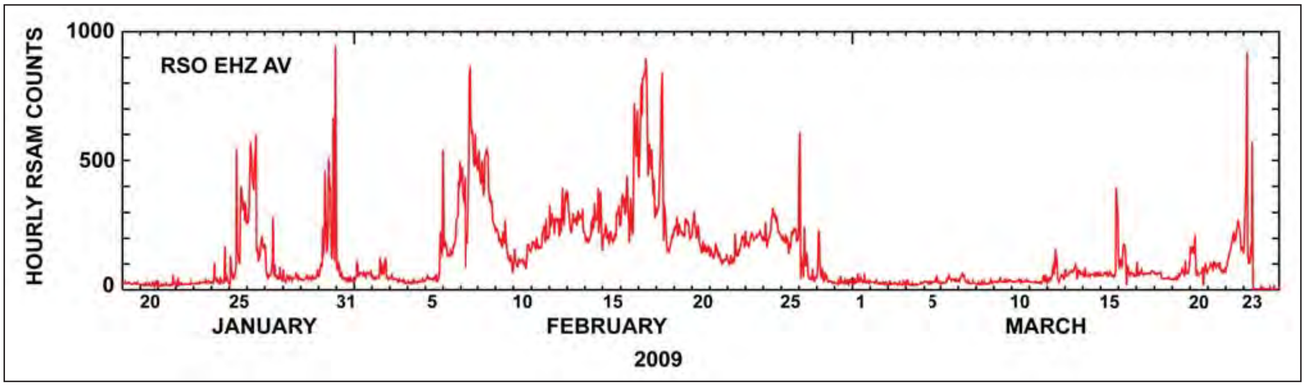

Figure 9. Hourly Real-time Seismic Amplitude Measurement (RSAM) record for station RSO from January 20 through March 24, 2009, showing the relative amplitudes of periods of tremor and shallow seismicity at Redoubt Volcano. Note that station RSO was disabled by eruptive activity on March 23.

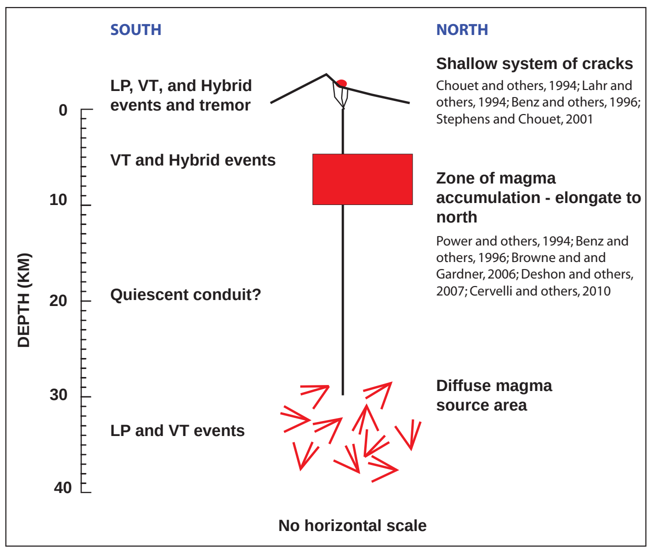

Figure 10. Schematic model of the Redoubt magmatic system inferred from the spatial and temporal development of earthquake hypocenters between 1989 and 2009. This north-south cross section shows the inferred locations of the magma source zone defined by deep long period (DLP) hypocenters located in 2009, an upper crustal magma storage area defined by volcano–tectonic (VT) hypocenters associated with the 1989–90 and 2009 eruptions, and a shallow system of cracks within the Redoubt edifice inferred from the locations of shallow seismic events in 1989–90 and 2009.

ERUPTION ONSET AND CHRONOLOGY

At 22:00 on Saturday, March 21, after a continuous increase in shallow earthquake activity (as many as 26 events per 10-minute period), AVO raised the Volcano Alert Level and the Aviation Color Code to WATCH/ORANGE (table 1). On March 22, twenty four hours later, the operations room staff watched as an emergent seismic tremor signal escalated, and by 22:34 an ash signal was detected in radar to 18,000 ft (5.5 km) ASL—the explosive magmatic phase of the eruption had begun. By 23:02, the eruption intensified, sending a plume to 44,000 ft (13.4 km) ASL. Over the course of 14 days, multiple explosions were recorded, 19 of which resulted in a formal volcano notification release (VAN/VONA), with ash plumes between 17,000 ft and 62,000 ft (5.2 km and 18.9 km) ASL (table 2). The explosions between March 22 and April 4 destroyed at least two and possibly three lava domes that were extruded in the summit crater. The explosive phase culminated with an explosion and dome collapse at 05:58 on April 4 that sent ash to 50,000 ft (15.2 km) ASL. After the April 4 explosion, another lava dome began to grow, marking the beginning of the final, uninterrupted effusive phase of the eruption that lasted until July 2009.

As the explosive phase began, and VAN/VONAs were released, AVO personnel began assigning event numbers to the major ash-producing explosions (fig. 11 and table 2). Post-event reanalysis of seismic and radar data expanded the list of explosions, but major event names are kept to facilitate communication among researchers as well as the public and media. The following section presents a chronology and description of the explosive events and intervening lava dome growth that occurred between March 22 and April 4, 2009.

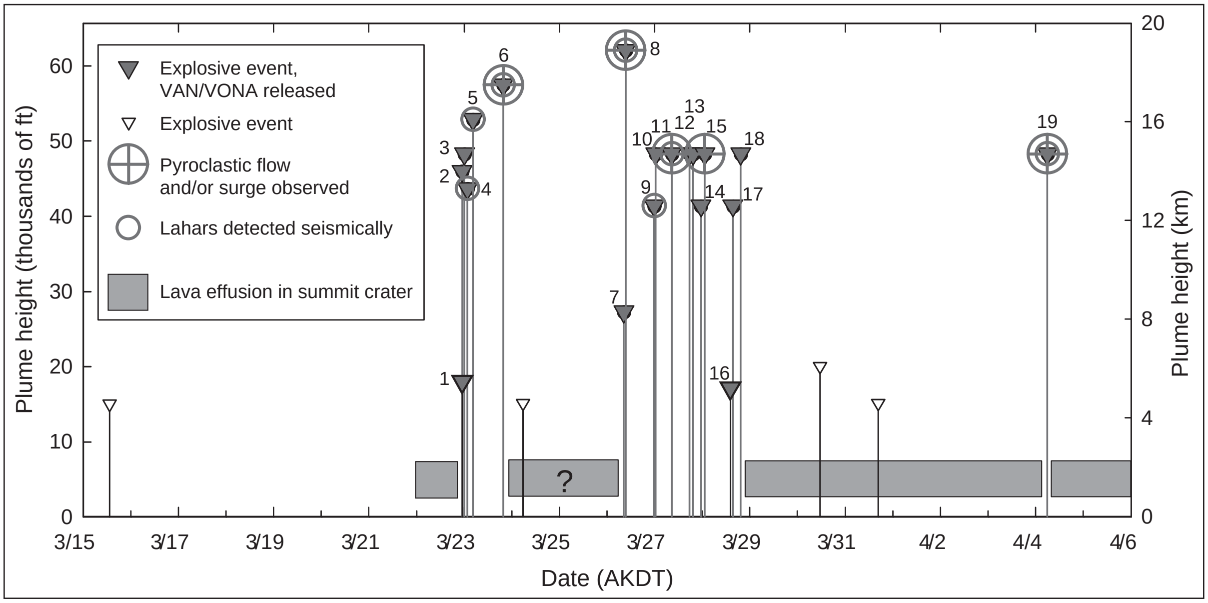

Figure 11. Time-series plot of explosive events during the 2009 eruption of Redoubt Volcano. Plume heights of significant explosions for which a Volcanic Activity Notification (VAN)/Volcano Observatory Notice for Aviation (VONA) was released are derived from USGS radar in Kenai. Plume heights for other, minor ash-producing events are from pilot reports or FAA NEXRAD weather radar. Pyroclastic flows/surges and lahars that were generated by individual explosions were determined by remote camera images and seismicity detected at stations near the Drift River valley. Lava effusion in the summit crater was recorded in satellite imagery before Event 1 and after Event 18. Although there was no visual confirmation of a dome between Events 6 and 7, the dense character of Event 7 and 8 tephra clasts and the timeframe between Event 6 and 7 explosions suggest a dome likely extruded.

March 22–23, 2009 (Events 1–6)

The first four explosions (Events 1-4; between 22:34 on March 22 and 01:38 on March 23), sent ash to between 18,000 ft and 43,000 ft (5.5 km and 13.1 km) ASL. Winds from the south sent ash to the north–northeast, sparing Anchorage and the Kenai Peninsula, but dusting areas near Skwenta and Talkeetna (fig. 12). As the ash settled from the first series of events, another explosion on March 23 at 04:30 (Event 5) sent ash to 60,000 ft (18.3 km) ASL. By this time the winds had shifted slightly and the ash cloud traveled first north then north–northeast toward and beyond Denali National Park, depositing a trace of ash (<0.8 mm) in Fairbanks, more than 500 km from the volcano. Post-event analysis of satellite imagery revealed that just prior to Event 1, a small lava dome had grown in the crater and was destroyed during the initial explosions of March 22 and 23.

The first pyroclastic flow of the eruption occurred during Event 6, which began at 19:40 on March 23. Flowage deposits were captured in the Juergen's hut webcam images starting at 19:46:01 (fig. 13). Fortuitous fresh snow that blanketed the volcano prior to the event made identification of the flow events possible. Flowage signals were detected seismically by stations DFR and RDE. The coarsest juvenile fall material of the eruption was deposited during this explosion; 10–15 cm pumice clasts were found within 3 km of the vent.

March 26–28, 2009 (Events 7–18)

Event 7 (08:34 on March 26) was relatively small, sending ash to 22,000 ft (6.7 km) ASL, but was followed within an hour by Event 8, a large explosion that lasted 14 minutes and sent ash to 62,000 ft (18.9 km) ASL. Ash from Events 7–10 was carried across Cook Inlet to the east and southeast, falling on communities along the Kenai Peninsula (minor ash fall, 0.8 to 2.0 mm).

Although Anchorage was spared the effects of the eruption through the initial eight explosions, Alaska's largest city, home to more than 250,000 residents as well as the Ted Stevens International Airport, was soon to be hit with ash as prevailing winds began blowing from the south–southwest on March 27. Plume directions during Events 11–18 (March 27–28) were all to the north and northeast of the volcano; Nikiski and Anchorage were in the plume's path and both communities received trace amounts of ash (fig. 14).

The Dumbbell hills time-lapse camera captured images of pyroclastic flows moving down the Drift River gorge during Events 11 and 15 (March 27 and 28, fig. 15). These flows traveled less than 5 km from the vent and were accompanied by increased water flow down the Drift River valley past station DFR (fig. 5). Events 17 and 18 on March 28 sent ash to 40,000–41,000 ft (12.2–12.5 km), and several minutes after the explosions, steaming lahars were seen in time-lapse images at Dumbbell hills (fig. 16). Following Event 18, on March 28, satellite imagery showed a lava dome growing in Redoubt's summit crater.

Table 2. Eruption Chronology: Explosion dates, times, durations, pressures, and maximum plume heights

Event Number[1]	Date	Time	Date	Time (official)[2]	Duration (seismic-SPU)[3]	Duration (seismic-RDT)[4]	Pressure zero to peak (DFR Pressure Sensor)	Duration (DFR Pressure Sensor)[5]	Maximum Plume Height[6]	Maximum Plume Height Data Source
	Local AKDT	*Local AKDT*	*UTC*	*UTC*	*minutes*	*minutes*	*Pa*	*minutes*	*ft*	
Event 0	3/15/2009	13:05	3/15/2009	21:05	undefined	undefined	undefined	undefined	15,000	Pilot Report
Event 1	3/22/2009	22:34:00	3/23/2009	6:34	2	<1	25	26	18,000	FAA NEXRAD radar
Event 2	3/22/2009	23:02:00	3/23/2009	7:02	7	8	151	3	44,000	FAA NEXRAD radar
Event 3	3/23/2009	0:14:00	3/23/2009	8:14	20	14	38	13	48,000	USGS radar
Event 4	3/23/2009	1:38:00	3/23/2009	9:38	38	9	70	8	43,000	FAA NEXRAD radar/USGS
reanalysis	3/23/2009	1:48:00	3/23/2009	9:48	undefined	30+	90	12	45,000	FAA NEXRAD radar
reanalysis	3/23/2009	2:52	3/23/2009	10:52	8	7	12	2	undefined	
Event 5	3/23/2009	4:30:00	3/23/2009	12:30	20	22	250	16	60,000	FAA NEXRAD radar
reanalysis	3/23/2009	4:58:00	3/23/2009	12:58	3	2	14	1	undefined	
Event 6	3/23/2009	19:40:00	3/24/2009	3:40	15	17	76	12	60,000	FAA NEXRAD radar
reanalysis	3/24/2009	5:12:00	3/24/2009	13:12	<1	<1	<1	<1	15,000	FAA NEXRAD radar
Event 7	3/26/2009	8:34:00	3/26/2009	16:34	<1	1	7	1	27,000	USGS radar
Event 8	3/26/2009	9:24:00	3/26/2009	17:24	14	14	100	7	62,000	FAA NEXRAD radar/USGS
Event 9	3/26/2009	23:47:00	3/27/2009	7:47	<1	21	31	15	41,000	USGS radar
Event 10	3/27/2009	0:28:00	3/27/2009	8:28	7	9	54	4	49,000	FAA NEXRAD radar
reanalysis	3/27/2009	0:43:00	3/27/2009	8:43	7	7	8	3	undefined	
Event 11	3/27/2009	8:39:00	3/27/2009	16:39	8	10	83	4	51,000	FAA NEXRAD radar
Event 12	3/27/2009	17:34:00	3/28/2009	1:34	2	9	146	2	48,000	USGS radar
Event 13	3/27/2009	19:24:00	3/28/2009	3:24	4	4	138	3	50,000	FAA NEXRAD radar
Event 14	3/27/2009	23:19:00	3/28/2009	7:19	2	2	78	2	48,000	USGS radar
Event 15	3/28/2009	1:19:00	3/28/2009	9:19	4	2	59	2	48,000	USGS radar
reanalysis	3/28/2009	2:00:00	3/28/2009	10:00	undefined	6	10	<1	undefined	
Event 16	3/28/2009	13:40:00	3/28/2009	21:40	6	12	28	2	17,000	FAA NEXRAD radar
Event 17	3/28/2009	15:29:00	3/28/2009	23:29	6	37+	67	3	41,000	USGS radar
Event 18	3/28/2009	19:23:00	3/29/2009	3:23	11	44	49	83	48,000	USGS radar
reanalysis	3/30/2009	9:44:00	3/30/2009	17:44	undefined	<1	1	4	undefined	
reanalysis	3/30/2009	10:50:00	3/30/2009	18:50	undefined	undefined	1	undefined	20,000	FAA NEXRAD radar
reanalysis	3/31/2009	16:07:00	4/1/2009	0:07	undefined	<1	1.9	<1	15,000	FAA NEXRAD radar
Event 19	4/4/2009	5:58:00	4/4/2009	13:58	31	75	38	31	50,000	FAA NEXRAD radar
reanalysis	4/4/2009	6:16:00	4/4/2009	14:16:00	undefined	undefined	88	undefined	50,000	FAA NEXRAD radar
reanalysis	4/5/2009	10:36:00	4/5/2009	18:36:00	3	1.5	3.7	1	undefined	

[1]Event numbers are defined by explosions where a VAN/VONA was issued; "reanalysis" refers to explosions that were interpreted by post-event reanalysis of seismic data; some reanalysis events may be considered pulses of the prior event, but others are unique events between larger signals that were buried in the data and not recognized at the time of initial analysis.

[2]Official onset times were derived from seismic signal analysis.

[3]Duration reflects the time period at distal station SPU when the signal is twice the background and is rounded to the nearest minute. This is the same referece as used in 1989-90 eruption.

[4]Duration time at proximal seismic station RDT.

[5]Duration time at pressure sensor DFR.

[6]Plume heights varied slightly depending on data source; only maximum plume heights are listed here.

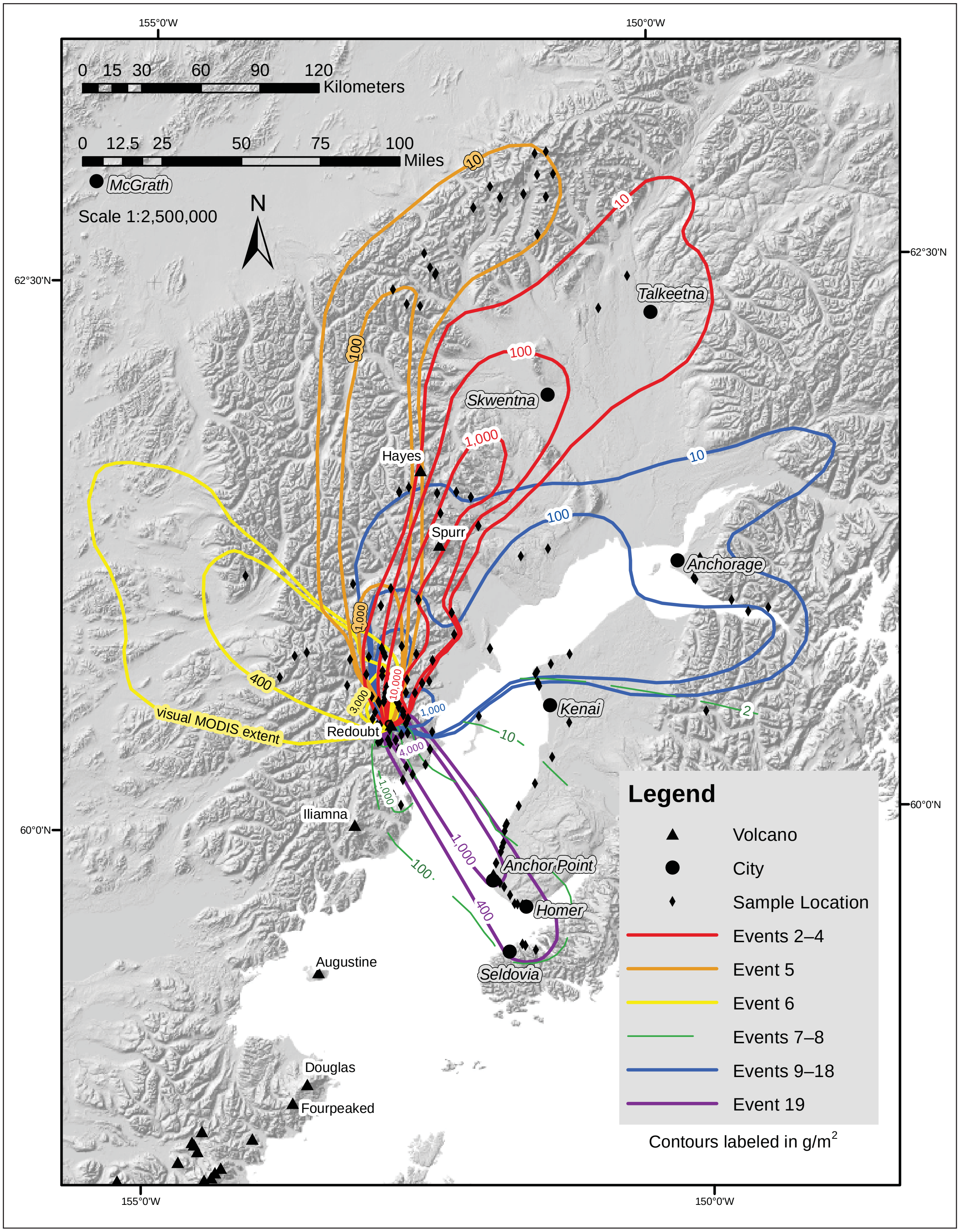

Figure 12. Map showing isomass contours of tephra fall deposits from the 2009 eruption of Redoubt Volcano. Contours that include more than one event number are composite layers; overlapping deposits or snowpack melt and subsequent combining of tephra layers prevented differentiation of the layers in the field. The outermost contour for depositional event packages 1–4, 5, 7–8, 9–18, and 19 indicates the approximate extent of ash at a concentration of 10 g/m^2; however, trace ash was deposited beyond this contour. The outermost contour of Event 6 indicates ash seen on the snow in MODIS imagery.

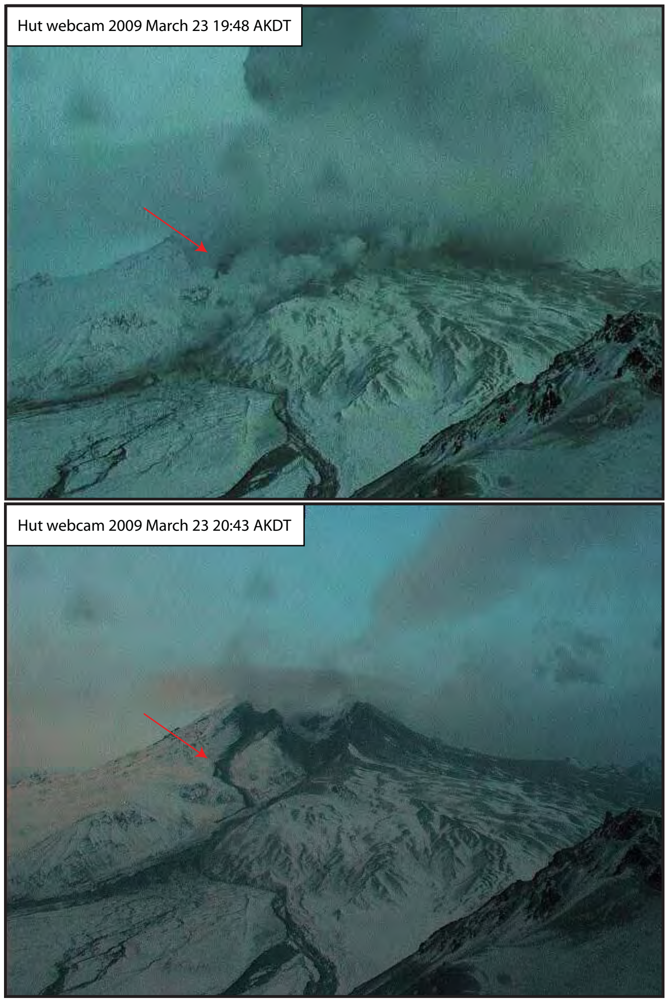

Figure 13. Juergen's hut webcam images of flowage deposit, recorded at 19:48 and 20:43 March 23. (8 and 63 minutes after the Event 6 explosion at 19:40). The arrows point to the new Event 6 flowage deposit on the upper north flank above the gorge (AVO image URL: http://www.avo.alaska.edu/images/image.php?id=36062 and http://www.avo.alaska.edu/images/image.php?id=17027)

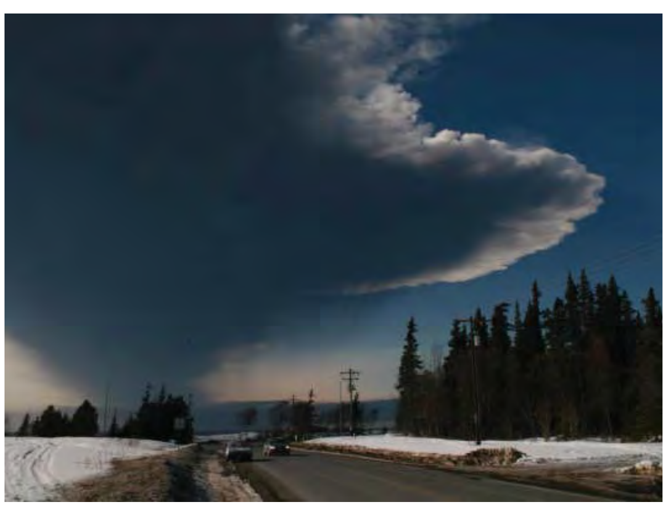

Figure 14. Ash plume over Nikiski, Event 17, March 28, 2009. Photo by Rick Monyahan. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=17355

Figure 15. Dumbbell hills time-lapse camera image showing the leading edge of a pyroclastic flow that was channeled down the Drift glacier into the Drift River valley. This flow is related to the explosive Event 11 that occurred March 27 at 08:39, one minute prior to the photo (AVO image URL: http://www.avo.alaska.edu/images/image.php?id=17878)

April 4, 2009 (Event 19)

After seven days of dome growth, Redoubt once again erupted explosively in the early morning hours of April 4. At 05:58, ash quickly rose to 50,000 ft (15.2 km), a pyroclastic flow or surge deposited a circular blanket of debris on the upper flanks of the volcano, a pyroclastic flow raced 4 km down Drift glacier, and torrents of mud and ice filled the Drift River valley, reaching the Drift River Terminal and dumping debris into Cook Inlet. A second explosive pulse at 06:16 sent another pyroclastic flow 8.5 km to the north. The winds were fast and focused toward the southeast; within three hours, morning turned to night in Homer as the ash fell from the plume passing overhead (figs. 17 and 18). The tanker, T/V Seabulk Arctic, in Cook Inlet en route to retrieve the remaining crude oil at the DRT, was turned back as the crew watched the dark ash plume rise rapidly with a spectacular display of volcanic lighting. The April 4 event was the last explosive event of the eruption; shortly thereafter the final lava dome began to form in the summit crater.

LAVA DOMES

The lava dome that was extruded after the April 4 explosion was the last of possibly four domes that were emplaced during the eruption (fig. 11). The first dome was recorded in satellite imagery shortly before Event 1 and was destroyed during the first large explosion. A second dome is believed to have grown between Events 6 and 7. Although there was no visual confirmation of a dome between Events 6 and 7, a significant proportion of dense clasts in the deposits of Events 7 and 8 and the length of time between explosive Events 6 and 7 suggest a second dome was likely extruded between Events 6 and 7 and destroyed during Events 7 and 8. Several closely spaced explosions (11 large explosions in ~58 hours) likely prevented dome growth between Events 8 and 18; however, shortly after Event 18, satellite imagery recorded a growing lava dome. This dome was destroyed during the April 4 explosion. Growth of the final dome began shortly after the April 4 explosion and continued through July 1, 2009, culminating in a final dome volume of 72 Mm^3.

Two types of lava were erupted between April 4 and July 1. Initially the lava was extruded as large, moderately vesicular, commonly flow-banded blocks (~30–45% vesicularity). On or around May 1, the dome began to extrude scoriaceous lava (~55–65% vesicularity) from the dome apex, which easily broke into smaller clasts and formed a cooler blanket over the top of the dome. A warmer, blocky dome margin

Figure 16. Event 18, Dumbbell hills time-lapse camera images taken (A) 3 minutes, (B) 18 minutes, and (C) 33 minutes after the explosion at 19:23 March 28, 2009. Steam from a warm lahar is seen traveling down the Drift River valley 18 minutes after the explosion, and new steaming deposits are seen in the image 33 minutes after the explosion.

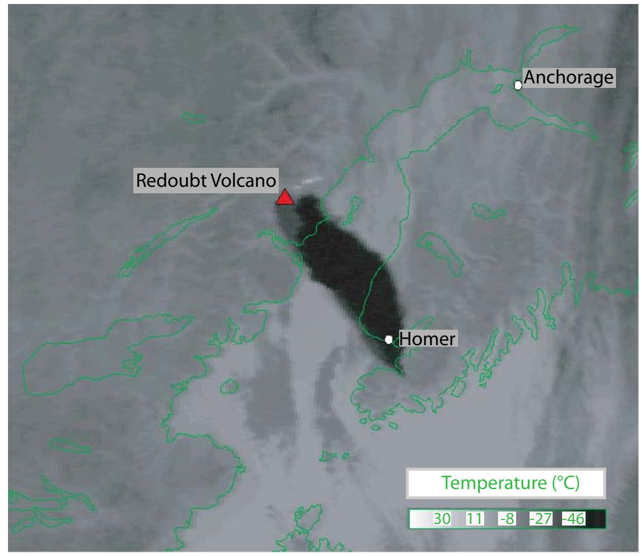

Figure 17. Infrared satellite image captured by AVHRR (Advanced Very High Resolution Radiometer) at 06:45 (14:45 UTC) April 4, 2009. The darker area is the ash cloud from Redoubt's Event 19, the explosive event that began at approximately 05:58. Image by J. Bailey, UAFGI. (AVO image URL: http://www.avo.alaska.edu/images/image.php?id=17797)

Figure 18. Photograph of Redoubt's ash cloud as seen from Homer, Alaska, during daylight hours, ~08:15 on the morning of April 4, 2009. Photograph courtesy of Larry Goode. (AVO image URL: http://www.avo.alaska.edu/images/image.php?id=17796)

expanded outward from inflationary growth, and continued to expand the dome in a radial fashion, while the scoriaceous lava effused from the top of the dome. By the end of dome growth, the warmest areas on the dome remained the blocky front and margins, and radial cracks that penetrated the scoriaceous blanket. Dome-rock compositions are similar to those of blocks sampled in the April 4 lahars, and range from 60.0 to 62.4 weight percent (wt%) SiO_2.

PRODUCTS OF THE 2009 ERUPTION

Magma that erupted in 2009 in the form of tephra and dome lavas is andesitic, ranging from 57.5 to 62.5 weight percent silica (wt% SiO_2). The 2009 eruptive deposits are geochemically similar to those from 1989–90 except that the early, low-silica andesite of 2009 is more mafic than any lava erupted in 1989–90 (fig. 19). Most 2009 lava clasts are uniformly light- to medium-gray crystal-rich andesite. A few clasts show indications of magma mixing in the form of macroscopic banding and mafic clots with quench textures. However, magma mixing features are generally much less common than in early 1989–1990 eruptive products. Plagioclase, ortho- and clinopyroxenes, amphiboles, and iron–titanium oxides are present, in order of decreasing abundance. Overall, the lavas from the most recent historical eruptions at Redoubt are more silicic than Redoubt's older lavas.

The first coarse-grained (cm-scale) vesicular juvenile tephra was erupted on March 23 during Event 5, and the coarsest tephra fall of the entire eruption was produced during Event 6 (also March 23); pumice clasts up to 11 cm in diameter were found 9 km west of the vent (figs. 20 and 21). These early explosive blasts produced predominantly medium-gray scoria with 57–58 wt% SiO_2; a small percentage of the early eruptive scoria are light gray in color and more silicic (59–62 wt% SiO_2). Dense glacial ice clasts up to 5 cm in diameter, presumably from the Drift glacier near the summit area, were found incorporated in Event 5 clasts ~12 km from the vent at Juergen's hut (seismic station RDJH, fig. 5). Ice clasts were smooth and rounded and similar in size to vesicular juvenile clasts from the same deposit (fig. 20B).

Events 7–18 (March 26–28) produced the finest-grained deposits of the eruption. The fine-grained nature of these deposits made them difficult to analyze, so no compositional data exist for these deposits.

The nature of the deposits produced by the April 4 explosion (Event 19) is notably different than those that preceded it. Event 19 produced a lithic pyroclastic-flow deposit on the north flank of the volcano that is preserved on either side of the Drift glacier gorge. This deposit is massive, poorly sorted, sandy, and contains abundant dense clasts. In addition, Event 19 generated a lahar that inundated the Drift River valley. This lahar contains abundant prismatically jointed lava clasts. Tephra-fall deposits from Event 19 are finer grained than those from earlier events. All Event 19 deposits contain primarily dense, medium- to light-gray porphyritic andesite. Vesicular scoria, such as would be produced during explosive vent eruptions, is absent. The characteristics of Event 19 deposits suggest that they were generated by collapse of a summit lava dome that grew between March 29 and April 4. Whole-rock compositions of Event 19 are different as well.

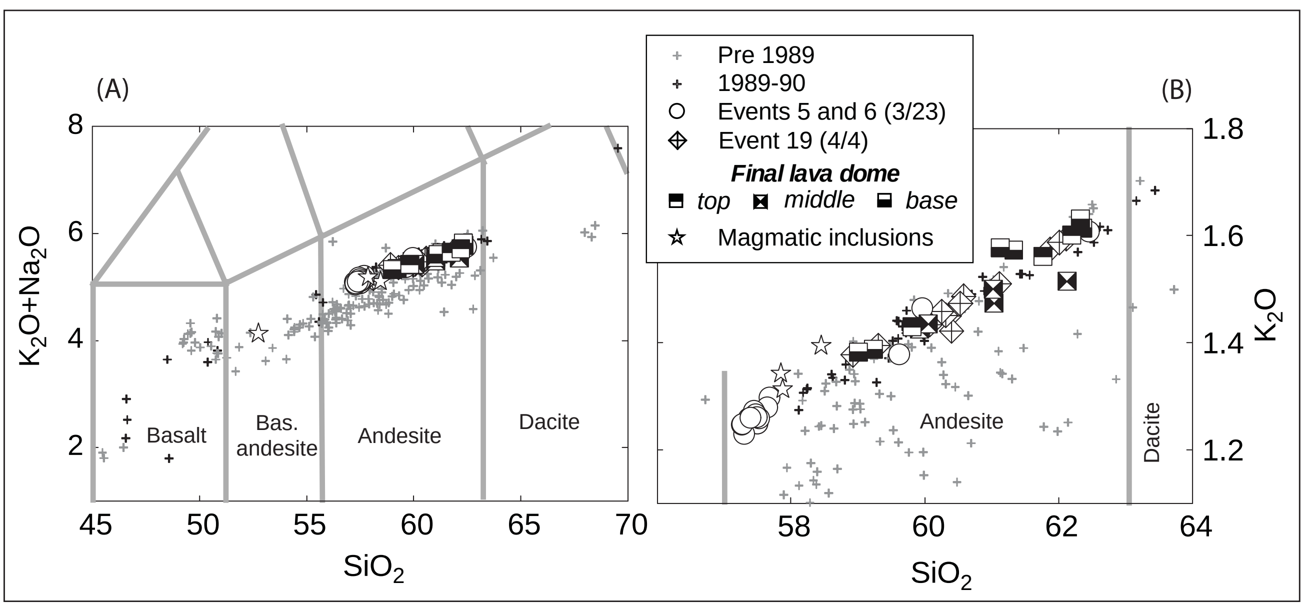

Figure 19. Geochemical variation diagrams showing compositions of erupted lavas from Redoubt Volcano. (A) SiO_2 versus total alkalis for all historic and prehistoric analyzed Redoubt samples. Note that recent lavas (including 2009 and 1989–90) are among the most evolved (high SiO_2) products of the volcano, and have higher alkalis at a given SiO_2 content. (B) SiO_2 versus K_2O for 2009 and 1989–90 samples. Note similar composition range, but a large cluster of early-erupted lavas in 2009 have lower SiO_2 contents than any 1989–90 ejecta. Redoubt 1989–90 data from Nye and others (1994).

The low-silica andesite of earlier in the sequence is absent; compositions range from 59 to 62 weight percent SiO_2, and some clasts show subtle dark and light banding.

All 2009 tephra deposits contain a significant percentage of accretionary lapilli ranging in size from 1 mm to about 2 cm. These accretionary lapilli are composed of fine-grained ash particles held together by ice particles, and thus none will be preserved in the geologic record (fig. 20). Where exposed at the surface, the lapilli layers turned into beds of mud that were then refrozen and covered with later snowfall, which formed icy mud layers in the snowpack. All fine-ash particles found within 20 km of the vent are contained in accretionary lapilli.

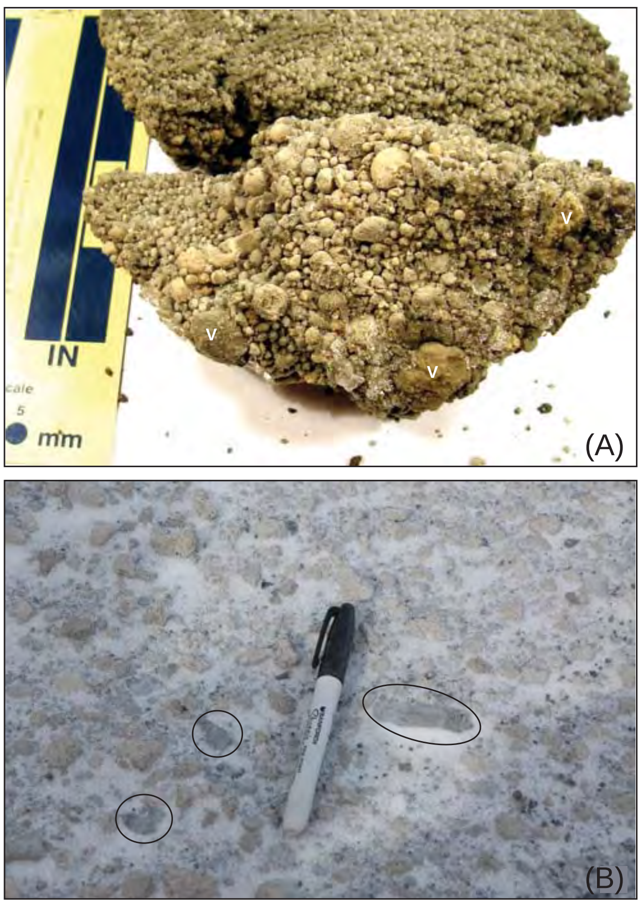

Figure 20. (A) A sample of accretionary lapilli from the March 23 eruptions. This sample was collected from Juergen's hut, about 12 km from the vent. The sample was kept frozen and photographed at the USGS in Anchorage. If left to melt, the accretionary lapilli turn into a slurry of fine ash. V = vesicular juvenile clasts. Scale to left shows a 5 mm diameter circle and the vertical scale 1 inch or 2.5 cm increments. (B) Dense glacial ice clasts, up to 5 cm in diameter (circled), found in Event 5 deposits (March 23, 04:30) 12 km from the vent.

INFORMATION DISSEMINATION

AVO OPERATIONS ROOM

The AVO operations room, located at the AVO/USGS headquarters in Anchorage, served as the data and communications center throughout the Redoubt 2008–09 volcanic unrest and eruption. Operations room staff remained aware of the volcano's activity, using 42 computer monitors to display a wide range of data, including real-time seismicity at the volcano, satellite imagery, weather and wind conditions, radar signals, models of potential ash plume migration, pilot reports, and webcam images (fig. 22). Pertinent and timely information was disseminated to federal, state, and local agencies, members of industry, the media, and the public via the AVO website, Twitter feeds, fax, and telephone. Members of cooperating agencies and the media often congregated in the operations room for debriefings or to conduct interviews. The operations room also served as the headquarters for AVO internal staff, and the base station for field activity. Staff conducted flight following of fixed-wing and helicopter-based field crews via VHF radio, satellite phone, and web-based aviation-tracking software, and could provide early warning to field crews in the event of an increase in volcanic activity.

Operations room staff posted hourly, daily, and weekly updates on the AVO website and Twitter feeds. These updates

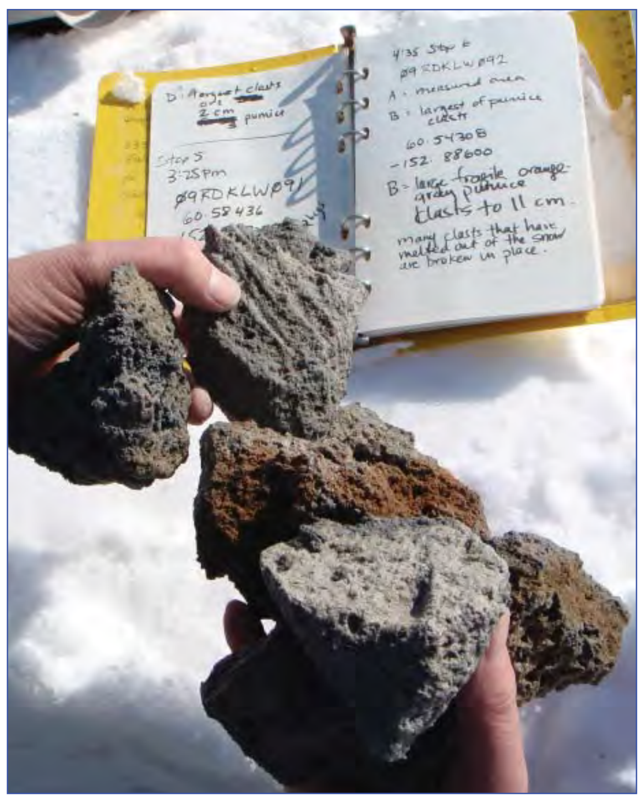

Figure 21. Event 6 (March 23, 19:40) pumice clasts up to 11 cm in diameter found 9 km west of the vent. Photo by Kristi Wallace. (AVO image URL: http://www.avo.alaska.edu/images/image.php?id=19481).

summarized the latest volcanic activity including seismicity; emission of steam, gas, and ash plumes; growth of the lava domes; observations from webcams and field crews; field crew activities; and some interpretation and forecasts of potential future activity. The operations room telephone number was publicly available, and staff fielded frequent phone calls from citizens around the country—from locals affected by ash fall, to citizens of the east coast curious to know if the volcanic activity would affect their summer travel plans to Alaska. A log was kept of all incoming phone calls. A separate phone line was maintained with a recorded summary of the latest activity, updated as conditions warranted. A dedicated private telephone line was installed to enable key government agencies to have access to the operations room in the event all public lines were in use.

At the onset of explosive events, or if an explosive event was suspected based on seismicity or other information, operations room staff immediately contacted the National Weather Service (NWS) to confirm ash plume elevation and probable direction of drift. Call-downs were conducted following established written protocols (Madden and others, 2008) to inform federal, state, and local agencies, key officials, the Drift River oil terminal facility, and the Drift River Incident Command, as well as internal staff, of the activity and color code and alert level changes. Volcanic Activity Notice (VAN) and Volcano Observatory Notification for Aviation (VONA) documents were promptly distributed to relevant staff and agencies through the web-based Hazard Notification System (HANS), email, and fax.

Figure 22. AVO seismologist John Power analyzes near-real-time seismic data in the AVO operations room in Anchorage.

During periods of ash fall, operations room staff collected ash fall information from local citizens who called in or emailed to report on ash fall in their area. This information was shared with the National Weather Service, which issued ash fall advisory messages. In later phases of the eruption, AVO staff maintained daily contact with employees on the ground at the Drift River Terminal to share information about the status of the volcano, and possible lahars and flooding downstream of the volcano.

The operations room was staffed 24 hours per day, seven days per week for more than five months, during the increase in unrest beginning January 25 until lava dome growth ended July 9. Operations room staff consisted of AVO scientists from the United States Geological Survey (USGS) in Anchorage, the University of Alaska Fairbanks Geophysical Institute (UAFGI), and the Alaska Division of Geological & Geophysical Surveys (DGGS) in Fairbanks. Visiting scientists from other USGS volcano observatories supplemented the AVO staff in running the operations room, as well as other duties.

AVO WEBSITE

Redoubt Activity Page and Twitter

During the course of unrest and eruption, the ‘Redoubt activity page’ on the AVO public website served as the hub for all information about Redoubt delivered by AVO (fig. 23). The page contained formal and informal notices (VAN/VONA, daily status reports, hourly and as-needed updates), links to webcams, webicorders, RSAM graphs, captioned images, eruption scenario information, maps, ash modeling graphics, ash fall reporting forms, ash fall collection instructions, and helpful links to other agencies.

AVO kept pace with public demands for information in the age of instant messaging by employing the microblogging technology of Twitter (http://twitter.com/alaska_avo). During the eruption, short, informal updates were published to the AVO website every few hours by AVO operations staff. These updates were coded to automatically post to AVO’s Twitter feed. Within weeks, the feed had amassed in excess of 8,000 followers. Code running the AVO image database was modified to easily push selected images to Twitpic, another social media site closely related to Twitter. These images were then linked to the alaska_avo feed on Twitter.

Web Traffic

On the morning of January 30, 2009, news of the January 25 aviation color code change from YELLOW to ORANGE was listed on various high-profile news sites, including Yahoo!, the Drudge Report, and Slashdot. The resulting load of traffic to the AVO website brought the webserver to a crawl, unresponsive to any requests. Web traffic leading up to the server crash averaged 6.8 megabits per second (ten page views per second). Within two hours, AVO's web team had the server back up and running with a very simple, low-bandwidth page. This page was text-only, and contained the minimum critical information such as the latest status report or information release, as well as the latest hourly updates.

While the server was running the low-bandwidth page, AVO implemented several solutions to reinstate the full version of the AVO website. First, a separate webserver was purchased and configured with a full copy of the website and installed at the DGGS office building. This machine served as a 'last resort' option in case the primary server was completely overwhelmed. In this case, AVO personnel would still have access to all AVO web tools and data available on the website, and could give out the address of the backup server to appropriate agencies. Caching systems were installed on the server to cache pages that were heavily database dependent, and several scripts were written to regularly transfer high-bandwidth items such as images and movies to USGS Volcano Hazard Program servers located on higher-bandwidth USGS networks in Menlo Park, California, and Seattle, Washington. With all these systems in place, the full version of the website came back online on February 2, after only four days of running in reduced bandwidth mode, and was able to continue running at full capacity throughout the remainder of the Redoubt eruption.

The 2006 eruption of Augustine Volcano in Cook Inlet was the first Alaska eruption to receive a large web presence and distribution of data, such as webcams and webicorders. The web response to this eruption was large, but was capably handled by one server, running close to its capacity. As such, AVO was able to track all the web traffic on its servers during that eruption. The busiest month of that eruption saw 23 million page views. In contrast, the 2009 eruption of Redoubt generated so much more traffic, spread amongst several servers, that AVO was unable to directly count all the traffic the servers experienced. During March 2009, traffic was estimated around 28 million page views. Another indication of web traffic is the number of emails received through the "contact AVO" link on the public website. The AVO web team received more than 3,000 emails during Redoubt's unrest and eruption, more than twice the number received during periods of quieter volcanic activity.

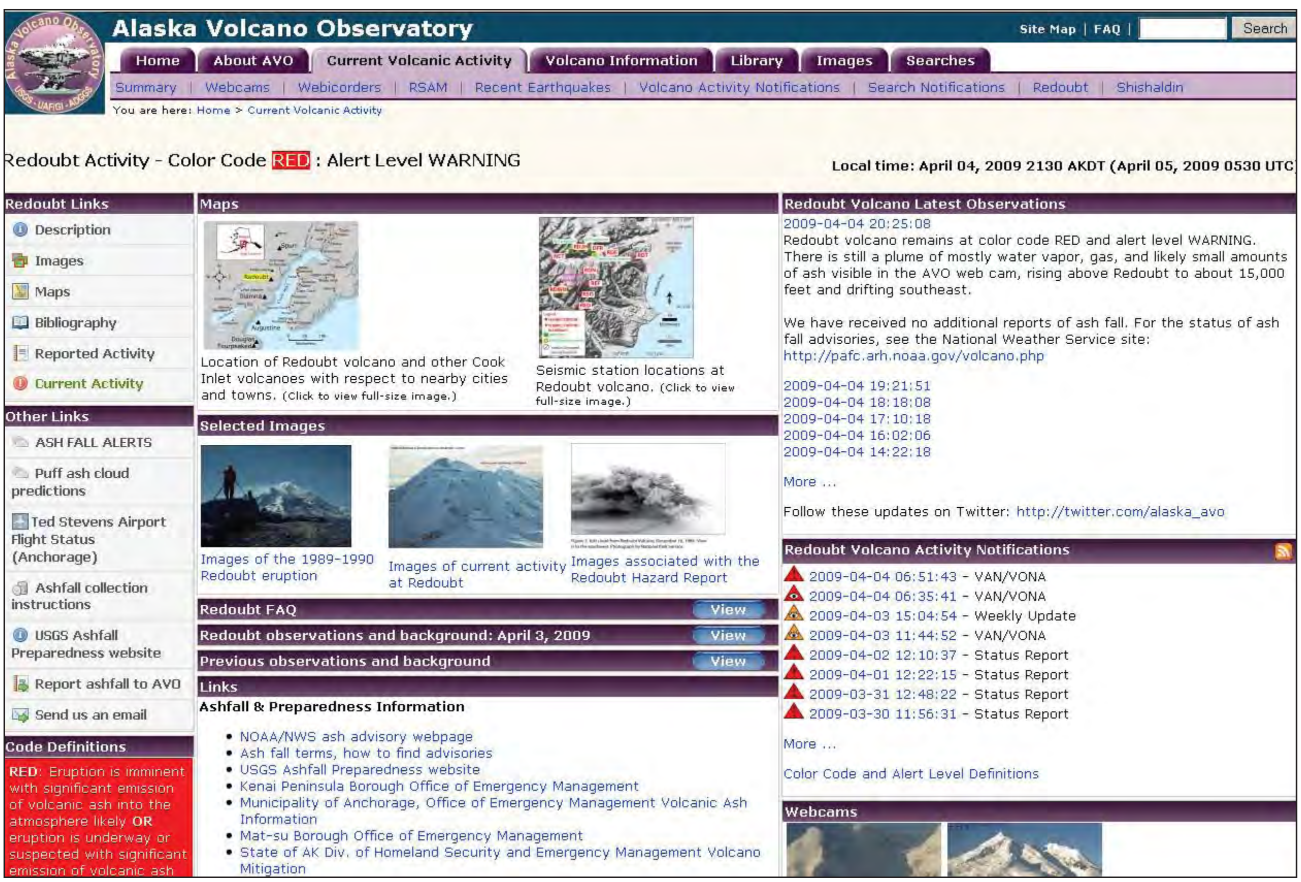

Figure 23. Redoubt activity page on the AVO public website. This page contained formal and informal notices (VAN/VONA, daily status reports, hourly and as-needed updates), links to webcams, webicorders, RSAM graphs, captioned images, eruption scenario information, maps, ash modeling graphics, ash fall reporting forms, ash fall collection instructions, and helpful links to other agencies.

Internal Web Tools

Internal communication and observations were greatly facilitated by the use of the internal logs, a web-based, database-driven, searchable message system created by AVO staff. The logs run on a password-protected internal website and are used to document and track observations of volcanic unrest and to promote informal and preliminary discussion and data sharing within AVO. Between July 2008 and August 2009, AVO staff made more than 2,000 Redoubt-specific posts to the internal logs. The internal logs work seamlessly with the internal image database, which holds more than 18,000 maps images, photographs, and illustrations, of which over 3,000 are Redoubt-related.

INTERAGENCY COOPERATION

Response to volcanic unrest is a multi-agency task involving many organizations at the Federal, State, and local level, each with their own mandate to ensure public safety and protect the environment. Much experience has been acquired by AVO regarding both aviation and ground-based ash hazards during eruptions of the past three decades at Redoubt, Augustine, Spurr, and several other Alaska volcanoes farther west. Roles and responsibilities of some of the primary participants are documented in "The Alaska Interagency Operating Plan for Volcanic Ash Episodes" (Madden and others, 2008). Signatories include U.S. Geological Survey (USGS), National Weather Service (NWS), Federal Aviation Administration (FAA), Alaska Department of Homeland Security and Emergency Management (DHSEM), U.S. Air Force (USAF), U.S. Coast Guard (USCG), and Alaska Department of Environmental Conservation Division of Air Quality (DEC/DAQ). The plan's emphasis until 2008 had been on airborne ash hazards to aviation. Following the Augustine eruption in 2006, it was expanded to include protocols related to ash fall hazards on the ground. In addition to this formal, published plan, AVO, NWS, DEC, and the Municipality of Anchorage had recently developed an additional communication protocol to ensure that agencies with air quality and ash fall alerting responsibilities would be notified.

DHSEM organized and moderated frequent interagency telephone conferences during the acute phases of eruption. AVO/USGS staff provided a quick update on the status of the volcano, usually followed by NWS commentary on the day's weather, wind field, and likely ash trajectory. Participation on these calls varied but frequently included FAA, Ted Stevens Anchorage International Airport, the affected boroughs of south central Alaska, the Municipality of Anchorage, the Alaska Department of Public Health, Anchorage and Peninsula hospitals, and others. Calls occurred with decreasing frequency as eruptive activity diminished in intensity.

Coordination between AVO and the NWS was particularly important during the 2009 Redoubt eruption in order to share information on ash-cloud height estimates and ash fall reports throughout Alaska. As in past eruptions, consolidation of public information on the Internet was a challenge; in addition to the AVO web page that hosted dynamic information on the status of the volcano, the NWS presented a Redoubt coordination page (http://pafc.arh.noaa.gov/volcano.php) that centralized all NWS warning messages for aviation, ground, and marine constituencies, and posted information and resources from other key sites such as AVO's and NOAA's hypothetical ash trajectories. Both agencies recognize that respective warning messages need to be consistent and include the most current observations from the field. Ash fall accounts in particular may be received at NWS via their weather spotter program or by AVO, requiring frequent telephone contact between agencies to coordinate messages. AVO and NWS also utilized newly developed 'ash fall severity' terms to try and standardize descriptive language in ash fall warning messages. AVO also hosted a number of press conferences at the USGS facility in Anchorage during the period of unrest leading up to the late March eruptions. These were often held in conjunction with the Unified Command for Drift River Terminal Coordination.

Unified Command—Coordination of Operations at Drift River Terminal

The threat of hazards from ash fall, lahars, and related events to the Drift River Terminal (DRT) following the lahars of March 23, 2009, prompted creation of the first of a series of interagency teams that were charged with managing and coordinating response during the eruption. The three lead agencies throughout the incident were the U.S. Coast Guard (USCG; Federal On-Scene Coordinator), Alaska Department of Environmental Conservation, Division of Spill Prevention and Response (DEC; State On-Scene Coordinator), and the Cook Inlet Pipeline Company (CIPL), which operates the terminal. The first action management plan was issued March 26. It listed the two chief objectives that dominated the agenda throughout the incident—protection of citizens and response personnel at the terminal, and protection of the environment. Work groups developed plans to begin removing the more than 6 million gallons of crude oil stored in tanks at DRT, assessed lahar damage to terminal facilities and protective dikes, assessed the potential hazards from possible future events at the volcano, activated plans to increase the ability to respond to hazardous spills, held media briefings, and started a website for public information.

On March 31, in response to increasing complexity and the need for improved coordination and planning, the Unified Command—Drift River Terminal Coordination (UC) opened an Incident Command Post in the ballroom of the Sheraton Hotel in Anchorage. The post was staffed by more than 50 personnel from numerous Federal, State, and local agencies as well as from affected companies. The primary objectives were still to ensure the protection of citizens and response personnel and the protection of the environment. To better facilitate meeting these objectives, three workgroups (Facility Restart/Oil Movement; Spill Response; and Lahar/Flood Forecasting) were established and daily Incident Action Plans were generated.

Throughout the eruption AVO was represented in the UC and its predecessors by several USGS and Alaska Division of Geological & Geophysical Survey (DGGS) scientists familiar with Redoubt Volcano and the lahar hazards of the region. The Alaska State Geologist, who is the head of DGGS in the Department of Natural Resources and a member of the State Crisis Management Team, was responsible for coordinating hazard analyses from AVO scientists and ensuring that scientific information was delivered to the UC leadership team.

Daily operations at the UC began with an all-hands meeting on the current situation, weather forecast, plans and activities, and safety issues. AVO participated by providing a briefing about volcanic activity and current hazard outlook. Throughout the day, AVO representatives consulted with the various work groups and individual agencies regarding their concerns about future potential hazards, kept the UC apprised of ongoing volcanic observations and conditions, and worked with the State Geologist on issues of interest to the leadership team. Key issues were (1) the effects of recent lahars and channel changes, (2) hazards of potential lahars and floods to the personnel, tanks, pipelines, and protective dikes at DRT, (3) the source and fate of the floating debris and sediment that lahars and river flows were delivering and their effect on safety and bottom conditions at the offshore Christy Lee loading platform (fig. 4), and (4) the effects of ash fall on terminal operations and electrostatic discharge from ash-rich plumes.

One of the methods used to assess lahar risk was the evaluation of historic and prehistoric lahars associated with prior Redoubt eruptions. These data were used to advise the UC on current state of vulnerability of the terminal. The risk was evaluated on both the altered condition of the lahar mitigation dike, and the potential of an event larger than had been witnessed during this eruption (pre April 4).

A special telephone calldown list was created for round-the-clock AVO operations to immediately notify the key UC entities in the event of eruptive activity or a change in the volcano's status. This was especially important when CIPL personnel were working at DRT to clean up, repair equipment, and prepare for tanker operations, as well as when tankers were moored at the Christy Lee loading platform offshore of DRT to load oil and oil-contaminated ballast water from the storage tanks.

Under the UC's direction, about 60 percent of the oil stored at the terminal was removed April 5–6 (table 3). Because plans had been completed for actions in the foreseeable future, the UC deactivated the command post on April 7 but continued to meet periodically. The removal of most of the remaining oil and contaminated tank ballast was completed during tanker operations in late April and early August. On August 12, 2009, the UC stood down and DEC reassumed its normal responsibility for oversight and regulation of DRT, including long-term planning for resumption of Cook Inlet oil production, storage, and shipment.

Table 3. Timeline of Unified Command (UC) actions and results of directives

March 26	First Incident Action Plan issued by joint Federal and State on-scene coordinators functioning under the Incident Command System
March 31	Incident Command Post opened at the Sheraton Hotel, Anchorage
April 5–6	3.7 of 6.2 million gallons of crude oil at Drift River Terminal (DRT) removed; seawater ballast added
April 7	Command post deactivated; 2.5 million gallons crude oil remain in tanks at DRT
April 28–30	4.2 million gallons of crude oil and seawater ballast removed; 0.8 million gallons remain
August 12	UC stood down; regulation resumed under normal Alaska Department of Environmental Conservation (ADEC) business

IMPACTS

AVIATION IMPACTS

Drifting volcanic ash clouds are a primary concern to aviation. Ingestion of volcanic ash in a jet engine can result in melting and accumulation of re-solidified ash on turbine nozzle parts, which can cause stalling or engine thrust failure, such as occurred on December 18, 1989, when all four engines of a Boeing 747-200 failed north of Anchorage upon an encounter with ash from Redoubt (Miller and Casadevall, 2000). AVO works closely with the FAA and the NWS to provide ample warning of an impending eruption so that measures can be taken to reduce ash and aviation encounters. On January 26, 2009, well before the first explosive release of ash into the atmosphere, FAA imposed a flight restriction below the 60,000-ft flight level within a 10-nautical-mile radius around Redoubt Volcano. During March and April 2009, the NWS Alaska Aviation Weather Unit (AAWU) issued 39 severe weather advisories called SIGMETS (Significant Meteorological Information) to inform the aviation community of volcanic-ash hazards (U.S. Department of Commerce, 2010).

Drifting ash clouds as well as the threat of ash fall disrupted aviation-based operations in Alaska. Ash in the atmosphere combined with ash fall in Anchorage caused the closure of the Ted Stevens International Airport for approximately 20 hours March 28–29 (Jim Iagulli, Ted Stevens International Airport Operations Manager, written commun.). During the course of the 2009 eruption, major air carriers canceled at least 295 flights, affecting more than 20,000 passengers (Murray and others, 2009). Numerous local passenger carriers canceled flights within Alaska and for much of the eruption, flying on the Kenai Peninsula was by visual flight rules (VFR) only. Ash in the atmosphere resulted in approximately 60 reroutes, 20 diversions, 10 turn-backs, and many cancellations in night operations, resulting in an ash avoidance cost to air carriers of about $400,000 (International Airways Volcano Watch Operations Group, 2010). In March 2009, Alaska Airlines had an on-time percentage of 70.2 percent, down from 78.0 percent in March 2008, which they attributed in part to disruptions caused by Redoubt (Alaska Airlines press release, April 3, 2009; http://splash.alaskasworld.com/Newsroom/ASNews/ASstories/AS_20090403_045447.asp). Starting March 22, air cargo carriers began routing through Seattle and Oakland rather than Anchorage, and some implemented temporary layoffs without pay as there was no freight to move in Anchorage. (Anchorage Daily News, March 23). An aircraft maintenance company temporarily furloughed about 50 of its 93 employees during the eruption because there were no planes to de-ice, but then changed business strategy to de-ashing to retain employees (Stapleton, 2009). At the time of this writing, the total economic impact of the Ted Stevens International Airport closure has not been assessed.

Military aviation operations were also impacted. In preparation for possible ash fall or flight restrictions from ash in the atmosphere, Elmendorf Air Force Base in Anchorage moved five C-17 aircraft and ~130 airmen to McChord Air Force Base in Washington on February 1. On February 2, they moved three additional C-130J aircraft and ~70 personnel to McChord. By March 23, Kulis Air National Guard Base had sent five C-130 Hercules and two HC-130 aircraft to Eielson Air Force Base in Fairbanks.

ASH FALL

The 2009 eruption of Redoubt Volcano included 19 major tephra-producing explosions that resulted in tephra fallout throughout south-central Alaska, affecting an estimated area of 80,000 km^2 (figs. 12 and 24). The eruption produced a total tephra-fall volume (dense-rock equivalent) of about 23 Mm^3 with a single event maximum of 6.3 Mm^3, which is comparable with historical eruptions of Redoubt Volcano (Scott and McGimsey, 1994). The potential threat of ash fall was a significant concern during the eruption, based on known impacts from historical eruptions of Redoubt and other Cook Inlet volcanoes (for examples, see Miller and others, 1998; Scott and McGimsey, 1994; McGimsey and others, 2001). Satellite imagery, NOAA HYSPLIT wind-model data, NEXRAD radar, and ash-plume and ash-fall modeling aided AVO in tracking and projecting ash-plume movement and, furthermore, assisted AVO in briefing the public about the likelihood and nature of tephra fall throughout the eruption. The long period of volcanic unrest preceding the explosive eruptions led to significant public warnings and preparations by lifeline organizations.

Heavy tephra fall (as thick as 5 cm) occurred only in locations very near the volcano (within 15 km) and posed no hazards because no infrastructure or people were present. Minor ash deposits (0.8 to 2.0 mm) occurred in communities along the Kenai Peninsula (80–100 km east–southeast), the city of Anchorage (170 km northeast) and Silver Salmon Creek Lodge (48 km south). Trace ash (< 0.8 mm) was reported as far as Fairbanks, 550 km north–northeast of the volcano. Because the eruption occurred during winter months, most ash accumulated on snow surfaces and the dark-colored ash particles absorbed solar radiation and accelerated snow melting, which effectively wetted and “locked in” the ash deposits, thus preventing significant reworking of the ash. Snowfalls that buried ash fall deposits also buried the hazard, delaying the time when dry ash could be resuspended by wind. Relatively short-duration explosions (<1 to 30 minutes) meant that ash fall on urban and rural communities was also short-lived, lasting no more than 1.5 hours (April 4), but more commonly, lasting 10 to 30 minutes. Early morning or late night ash fall events (March 23, April 4) caused fewer impacts to communities because of lack of exposure. Impacts to communities were relatively minor and more of a distraction and nuisance than a hazard, although economic losses from disruptions to airline travel were significant (see previous section).

Preparedness activities by communities and individuals significantly reduced ground-based impacts (for example, remaining indoors during ash fall, covering electronics and engine parts, suspending activities during ash fall, wearing dust masks during cleanup, etc.) (fig. 25). Local stores stocked up on emergency supplies such as dust masks, air filters, bottled water, and goggles yet sold out periodically (D’Oro, Anchorage Daily News, March 29, 2009). Nonetheless, impacts to local commerce were felt; some were positive and some negative. Significant shipping delays caused by airline flight cancellations resulted in a number of stock shortages at local stores including food supply and floral deliveries (Komarnitsky, Anchorage Daily News, March 31, 2009). Businesses trading in preparedness and cleanup supplies or services experienced retail booms (D’Oro, Anchorage Daily News, March 29, 2009). Stranded travelers caused short-term booms in businesses including rental cars, hotels, and restaurants (Mowry, Fairbanks Daily News-Miner, March 31, 2009). Closures of area clinics during ash fall in Homer on March 26 caused a spike in emergency room visits unrelated to ash fall (Klouda, Homer Tribune, April 1, 2009). Worried pet owners kept veterinary clinic phone lines busy (VCA Animal Hospitals, personal communs.). Ash leachate analyses showed that chemicals adsorbed onto the surface of ash particles that can be leached into water supplies (such as fluoride, chloride, sulfate, and nitrate) were not a significant concern to human or environmental health.

Air-quality samplers of fine particulate matter (PM) operated by the Municipality of Anchorage (MOA) and the Department of Environmental Conservation (DEC) as well as the U.S. Fish and Wildlife Service (USFWS) detected elevated levels of PM_{10} and $PM_{2.5}$ (≤10 and ≤2.5 microns, respectively) in Anchorage and Soldotna during the eruption. Nevertheless, fine particulate levels never exceeded Environment Protection Agency (EPA) 24-hour average air quality

Figure 24. Photographs showing impacts from volcanic ash fall from the 2009 eruption of Redoubt Volcano. Unless otherwise stated, all photos by Alaska Volcano Observatory staff. (A) Minor (~1 mm) ash fall deposit at Bentalit Lodge in Skwenta from the March 22 and 23 explosions. (B) Trace (<0.8 mm) ash fall deposit at the 7,000 ft above mean sea level (ASL) Denali base camp on the Kahiltna Glacier from the March 23 explosion. Solar melting of the dark-colored deposit caused the snow surface to be highly irregular, affecting climbers and ski plane services. Photograph courtesy of Lucy Tyrrell. (C) Example of reworking of ash fall by walking on dry ash in an alder stand on May 27, 2009, 2 months after the last explosion. (D) Example of reworking of fine-grained dry ash on a paved road in Nikiski just minutes after primary deposition on March 28. (E) Minor ash fall deposit (1 mm) in Anchorage on March 28. (F) Minor ash fall deposit (1.5 mm) in Homer on April 4.

Figure 25. Photographs showing examples of community eruption preparedness. (A) Billboard at the Nikiski fire station reminding people to be prepared. (B) A computer at the Soldotna Dairy Queen on March 28 covered in plastic to protect electronic parts. (C) Notice at doctor's office in Anchorage reminding patients to avoid wearing contact lenses during ash fall. (D) Stores in Anchorage such as Title Wave Books and REI have Redoubt Volcano displays and related items for sale. (E) Advertisement in the Anchorage Daily News for "volcano respirator" 3M particulate masks.

standards. Particles 10 microns (that is, PM_{10}) in diameter and smaller can be inhaled into the respiratory tract, where they can cause harm.

In summary, the most significant ash fall events in terms of ground-based impacts occurred on March 26 and 28 and April 4, mainly because these events deposited ash in the most populated regions of Alaska. On the afternoon of March 28, ash fall in Anchorage closed Ted Stevens International Airport from 17:00 until around 13:00 the next afternoon (March 29). Although the April 4 ash fall event affected a relatively narrow swath of the lower Kenai Peninsula from Anchor Point to Seldovia, up to 2 mm of ash (the thickest reported ash fall on a populated area) was deposited on snow-free surfaces causing longer-term impacts due to reworking of the ash by wind, cleanup, and normal activities.

LAHARS

Introduction

Lahars generated by the dynamic interaction of pyroclastic debris and snow and ice are common at most volcanoes in Alaska. Nearly all of the large volcanoes in the Aleutian arc have a cover of perennial snow and glacier ice. During typical eruptions, hot pyroclastic material interacts with snow and ice and leads to the rapid production of meltwater, sometimes in large quantities. Loose rock debris and sediment on the volcano flanks is entrained by this meltwater, resulting in the formation of lahars. The term 'lahar' is an Indonesian word for volcanic mudflow; such flows typically include a range of sediment–water flow types from sediment-rich debris flows to hyperconcentrated flows to sediment-laden water floods (Crandell, 1971; Pierson and Scott, 1985). Lahars follow preexisting valleys and drainages, and can travel for tens of kilometers beyond their source areas. Thus they have the potential to remain hazardous well beyond the immediate vicinity of the erupting volcano (Pierson and others, 1990).

Redoubt Volcano supports about 4 km^3 of glacier ice and perennial snow (Trabant and Hawkins, 1997), and about 1 km^3 of this amount makes up Drift glacier in the upper Drift River drainage (fig. 3). All of the known historical eruptive activity and several prehistoric eruptions have occurred from vents near the head of Drift glacier, and lahars associated with these eruptions have inundated the Drift River valley. Previous studies have identified several lahar deposits less than about 1,000 years old in the Drift River valley (Begét and Nye, 1994), including the informally named “yellow” lahar that may be as young about 900 yr. B.P. (Begét and others, 2009).

In addition to the lahars generated during the 2009 eruption, lahars also developed during the 1966–68 and 1989–90 eruptions. On January 24, 1966, Redoubt erupted explosively and a large lahar (volume unknown) was generated that inundated the Drift River valley including the site of the present-day Drift River Terminal (fig. 4). A seismic crew working along the Drift River had to be evacuated as a result of the lahar inundation, and clasts of ice many meters in diameter were transported down the Drift River valley by the lahar (Anchorage Daily News, January 26, 1966). A second lahar was generated on February 9, 1966, and this lahar apparently contained little or no ice (Riehle and others, 1981). Both lahars had flow fronts at least 4.5–6 m high, but the extent of inundation and lahar volumes are unknown.

Multiple lahars were generated during the 1989–90 eruption of Redoubt, the largest of which occurred on January 2, 1990 (Dorava and Meyer, 1994). The January 2 lahar was initiated by the collapse of a lava dome that grew in the summit crater near the head of Drift glacier. The ensuing block and ash flows that resulted from dome collapse generated significant amounts of meltwater as the flows swept across upper Drift glacier. This meltwater in turn entrained debris from the block and ash flows and available sediment on lower Drift glacier and in the upper Drift River valley to form a lahar. The January 2, 1990, lahar had an estimated peak discharge of 12,000–80,000 m^3s^{-1} (Dorava and Meyer, 1994) and it inundated the entire Drift River valley and most of the Drift River fan in the vicinity of the DRT (figure 15 of Brantley, 1990). Additional lahars were generated after the January 2, 1990, event, on February 15, March 14, and April 15, but these flows were all smaller than the January 2 lahar (Dorava and Meyer, 1994). The January 2 lahar transported clasts of ice up to 8 m in diameter about 40 km to Cook Inlet and caused the main channel of the Drift River to shift southward into the Rust Slough–Cannery Creek drainage. By the time the January 2 lahar reached the DRT, it had the properties of a hyperconcentrated flow to sediment-laden stream flow (Pierson and Scott, 1985). The peak January 2 flow inundated the DRT, and parts of the facility were flooded to depths of about 1.8 m (Dorava and Meyer, 1994).

The sediment delivered to the lower Drift River valley by the 1989–90 lahars caused significant aggradation of the valley floor and promoted rapid and unpredictable lateral shifts in the position of the active channel. During July–August 1990, the Drift River shifted northward into the drainage of Montana Bill Creek, which conveyed an estimated 70–90 percent of the flow of Drift River at that time. This resulted in significant scour of the bed of lower Montana Bill Creek and exposure of the buried oil pipeline that feeds the DRT (Dorava and Meyer, 1994).

Lahars Associated with the 2009 Eruption

Explosive eruptions between March 23 and April 4, 2009, which included the destruction of at least two lava domes, triggered numerous lahars in the Drift River valley; the largest two occurred on March 23 and April 4. Both of the large lahars inundated the Drift River valley and most of its downstream alluvial fan and introduced water, mud, and debris into and around the DRT (figs. 26 and 27).

March 23 Lahar

The second-largest lahar of the 2009 eruption was associated with Event 5 (table 2) and emplaced on the morning of March 23, 2009. An AVO observation flight late that afternoon reported an extensive area of inundation, particularly south of DRT. On the Drift River fan, the trunks of mature trees were stripped of bark to a height of several meters above the top of the lahar deposit. Farther upstream in the main Drift River valley, prominent sediment benches, mud lines, and the upper limit of snow erosion indicated lahar flow depths of 6–8 m above the valley floor (fig. 28). At Dumbbell hills (a bedrock knob in the Drift River valley about 3 km downstream from the terminus of Drift glacier) ripped-up clasts of frozen sediment were “splashed” up on the upstream (west) side of the hill, nearly reaching an equipment house on the hilltop. Maximum height of the flow run-up was later determined to be about 13 m. Large clasts of ice, many meters in length, were scattered about the valley floor, but unlike many of the 1989–90 lahar deposits, no steaming boulders were evident in the flow.

The March 23 lahar inundated an area of about 105 km^2. The lahar produced a deposit up to 5 m thick that contained predominantly river and glacier ice. The ice clasts ranged from several-meter-long tabular slabs of river ice to cobble and boulder size subrounded clasts of glacier ice. Although some rock debris was present in the lahar deposit, no juvenile material has been identified. The March 23 lahar was probably initiated by a series of vent-clearing explosions that erupted up through at least 50 m of glacier ice and snow in the summit crater, producing a voluminous release of meltwater. The resulting flood eroded and entrained snow, ice, and liquid water along its flow path. The deposit was frozen soon after it was emplaced and was later buried by the April 4 lahar deposits. As of late summer 2009, most of the deposit on the north side of the Drift River valley had melted, whereas deposits on the south side of the valley (north facing and more protected from solar heating) remained preserved.

April 4 Lahar

The lahar of April 4 was produced by a strong explosive eruption at 05:58 (Event 19) that involved a major failure of the lava dome that had grown at the mouth of the summit crater. In contrast to the March 23 lahar, the April 4 lahar contained little ice but abundant cobble and boulder size clasts of dense to slightly scoriaceous, prismatically jointed, medium to light gray andesite that appeared to be juvenile in origin. The April 4 lahar was more extensive than the

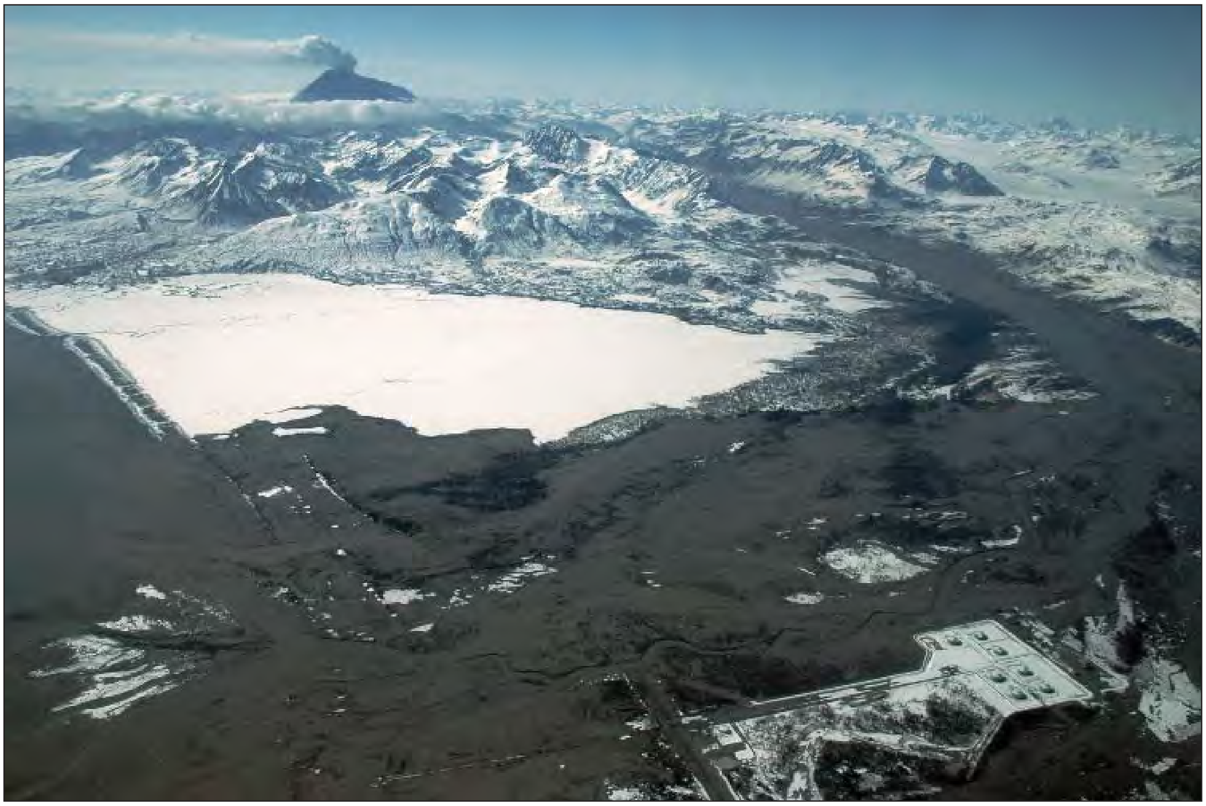

Figure 26. Lahar inundation of the Drift River valley, downstream alluvial fans, and the Drift River Terminal. Photo taken April 4, 2009, by R. McGimsey. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=41691

Figure 27. March 23, 2009, lahar inundation of the Drift River Terminal helipad, service buildings, and runway. Photo by C. Read. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=16984

Figure 28. Massive flooding in Drift River valley from the March 23, 2009, eruption of Redoubt Volcano. Prior to the lahar, the entire valley bottom was covered by snow and ice. High-water marks on the valley walls estimated to be about 6–8 m. View is up-valley from about mid valley to the Drift glacier. Photo by R. McGimsey. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=16995

March 23 lahar, inundating most of the Drift River valley and about 80 percent of the Drift River fan—in all about 130 km^3 (fig. 29).

The deposits produced by the lahar consisted of massive to faintly and horizontally stratified sand to fine gravel deposits up to 4 m thick, produced mainly by hyperconcentrated flows. Large blocks of glacier ice were scoured from Drift glacier and transported downstream almost to the DRT (fig. 30). However, in contrast to the March 23 lahar, the April 4 lahar appeared to be much more water rich. It too inundated the DRT and caused some flooding of facilities and outbuildings, and covered the airstrip with muddy sediment, trees, and other debris. The lahar also surrounded the oil storage tank farm and reached the top of, but did not breach, the containment levees.

Impacts and Hazards

The two largest lahars of the 2009 eruption were roughly comparable in volume to the largest lahar of the 1989–90 Redoubt eruption. Collectively, the 2009 lahars produced about 5–7 m of channel aggradation in the lower Drift River valley. Both the March 23 and April 4 lahars inundated portions of the DRT, and peak flows just reached the top of the containment levees surrounding the oil storage tanks. As a result of the March 23 lahar, the main channel of the Drift River in the vicinity of the DRT became choked with sediment, and all of the flow in the Drift River was diverted southward into the drainages of Rust Slough and Cannery Creek. This led to inundation of the airstrip and other parts of the DRT from overbank flows in Rust Slough. The April 4 lahar inundated all of the main drainages on the Drift River fan, including parts of the Montana Bill Creek drainage north of the DRT. Some flow was reestablished along the main stem of the lower Drift River, but most of the active flow remained in the Rust Slough drainage.

The large volume of sediment transported to the lower Drift River and Drift River fan has created a very dynamic hydrologic regime in this area. Normal fluctuations in water discharge will likely cause shifts in the position of the active channel, and it is possible for the main channel of the Drift River to be almost anywhere on the Drift River fan. Should the channel shift northward into the Montana Bill Creek drainage, it is possible that bankfull or larger flows may scour the channel bed, which could be important where a buried pipeline crosses Montana Bill Creek near the Cook Inlet coastline.

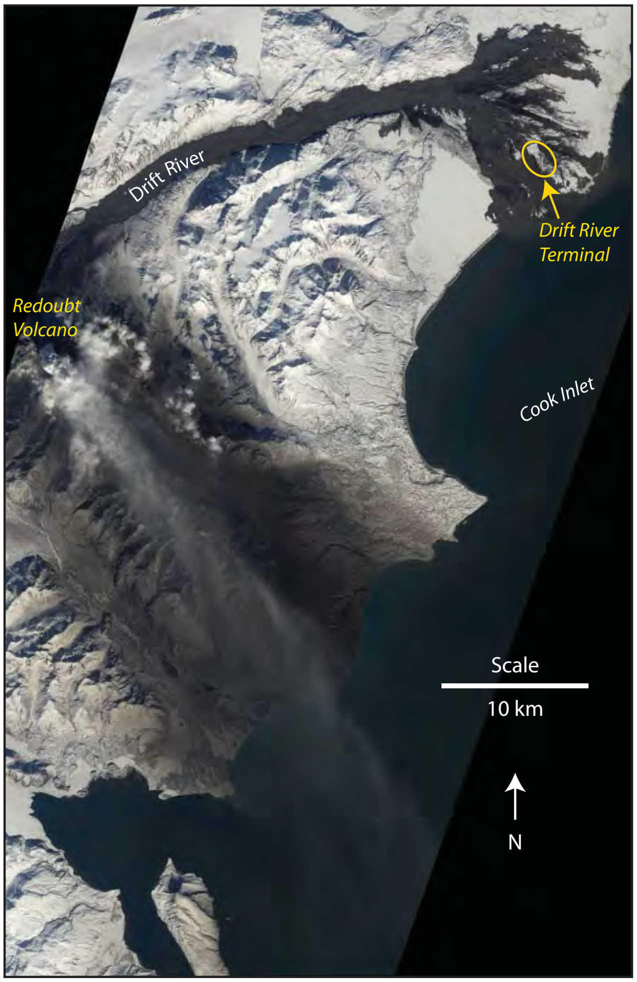

Figure 29. NASA Earth Observing-1 (EO-1) Advanced Land Imager (ALI) image showing the extent of the April 4, 2009, lahar; the muddy water and debris extend across the entire Drift River valley floor, through the Drift River Terminal area, and into Cook Inlet. The image also shows the highly directional ash fall zone to the southeast of the volcano from the April 4 eruption.

In addition to the possibility of significant lateral shifts of the active channel, Drift River will continue to erode and transport sediment emplaced during the 2009 eruption. Ultimately, much of this sediment will reach Cook Inlet, where it will accumulate in tide flats and deltas at the mouth of the Drift River drainage. It is possible that higher-than-normal sediment loads may have some impact on the aquatic environment there, which may include decreasing water depth in the vicinity of the offshore oil loading platform.

OPERATIONS AT THE DRIFT RIVER TERMINAL (DRT)

Alaska's Cook Inlet region has a number of onshore and offshore crude oil production and storage facilities and the DRT plays a key role in this oil transportation and storage system. The crude oil that is gathered from fields on the west side of Cook Inlet is carried through pipelines to staging areas at Granite Point and Trading Bay, 30 and 60 km northeast of DRT, respectively, on the western shore of Cook Inlet. Oil is then transported by pipeline to the DRT, traveling through 67.5 km of 20-inch pipe. The DRT receives and stores the oil in seven tanks with a total capacity in excess of 1 million barrels (Chevron, 2010). The oil is then delivered by pipeline to tankers berthed at the Christy Lee platform, just offshore of the DRT in Cook Inlet at the mouth of the Drift River. At the onset of the eruption in March 2009, only two of the seven tanks contained oil, and the remaining five were empty and clean. The in-service tanks, numbers one and two, each contained about 3,108,000 gallons (74,000 barrels) of crude oil. Between March 25, 2009, and August 12, 2009, the Alaska Department of Environmental Conservation, Division of Spill Prevention and Response, released 21 situation reports, documenting the events and communicating the response plans at the DRT (ADEC, 2009). The information provided below draws heavily on these reports as they relate to the impact of operations at the DRT caused by the hazards associated with the eruption of Redoubt volcano.

On the morning of March 23, following the first five explosive events and lahar, the DRT facility and pipeline were shut down and all personnel were evacuated to Trading Bay. Extensive flooding occurred at the DRT facility, covering the airstrip and surrounding the buildings with up to 1.5 m of water, mud, logs, and debris (figs. 26 and 27). The oil storage tank tertiary dike containment system suffered little damage and only a slight overflow of muddy water was observed, although lahar deposits several meters thick banked up against the outer sides of the dike, nearly to its top.

The debris from the lahar entering Cook Inlet posed a possible hurdle to tankers scheduled to dock at the Christy Lee platform and remove oil from the facility. On March 27, Cook Inlet Spill Response Inc. completed soundings of the tanker berthing area as well as the entrance and exit routes at the Christy Lee platform and observed no debris or subsurface anomalies. Cook Inlet Pipeline Company (CIPL) crews continued their work clearing access to operational buildings including metering and pump houses, in preparation for a scheduled April 4 tanker arrival to remove the crude oil. By April 1, with the closure of DRT and limited Cook Inlet crude oil storage capacity, some offshore oil production platforms had to be shut down while others scaled back production.

On the morning of April 4, eleven CIPL employees working to prepare the facility for the oil transfer to the approaching tanker were awakened by yet another explosive ash eruption and massive lahar. All employees at the facility, as well as two CIPL staff at the Christy Lee platform, moved to high-ground safe areas and remained unharmed during the event. The tanker, making its way to the platform, took shelter from ash fallout north of Augustine Island.

The ash fall, lightning associated with the ash cloud, and the lahar that accompanied the eruption made the oil transfer process too hazardous to attempt, and the crew was forced to wait out the eruption before proceeding. The lahar damaged the oil transfer pump generators, causing a failure of the oil transfer pumping system. Within a day, CIPL crews repaired the generator and pressure-tested the crude oil transfer line between the Christy Lee platform and DRT.

The final transfer of oil and ballast water from the DRT occurred in three stages. On the evening of April 5, the tanker Seabulk Arctic began receiving 3.7 of the 6.2 million gallons of crude oil stored at DRT. Both tanks at DRT storing the oil were ballasted with seawater as a precaution to prevent them from floating in the event of future flooding. Logistical challenges and personnel safety concerns delayed the removal of the remaining oil and water until April 28–30, when 4.2 million additional gallons of crude oil and previously added seawater ballast were removed, and 5 million gallons of freshwater ballast from the Columbia River were added. The final transfer of most of the remaining oil and water took place August 4–7, 2009, leaving about 160,000 gallons of oil, mostly as sludge too thick to pump, and about 390,000 gallons of water. Tanks 1 and 2 were taken out of service. In mid August, the CIPL initiated an oil transport

Figure 30. Before and after photographs in the upper Drift River valley where a large block of ice was deposited by the April 4 flood. In the upper photo, AVO volcanologists Rick Wessels (foreground) and Chris Waythomas (background) examine the flood deposits. The north shoulder of the western end of Dumbbell hills is on left side of image. The high-water mark near this site was 8.2 m. In the lower photo, taken September 22, 2009, UAF volcanology graduate student Sarah Henton is looking into the 1.5-m-deep pit left behind after the ice block melted. Photos by R. McGimsey. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=19220

plan that bypasses the DRT tanks and transports oil directly from facilities at Granite Point and Trading Bay through the 68 km pipeline directly to tankers berthed at the Christy Lee platform. At the time of this writing the DRT continues to operate under this oil bypass plan, and no new crude oil is being stored at the DRT facility.

MONITORING THE 2009 ERUPTION

INTRODUCTION

After the recent experiences gained during the 2005 eruption of Augustine Volcano, AVO scientists were well prepared for the unrest that began at Redoubt in late 2008. The ever-changing state of volcano monitoring tools requires constant testing of new technologies and implementation of new techniques. At Redoubt, several facets of advanced volcano monitoring were utilized to fully document, analyze, and understand the volcanic processes taking place, and to forecast eruptive events: fast and efficient communication pathways, improved field safety protocols, web and time-lapse camera installation and data transmission, seismic alarm systems, seismic data transfer and processing, satellite data analysis and automation, volcanic ash cloud tracking, lightning and infrasound detection, NEXRAD and C-Band Doppler radar data anlayses, and web-based communication and community outreach tools.

FIELD OBSERVATIONS

Direct field observations by AVO personnel consisted primarily of fixed-wing observational overflights and helicopter-based fieldwork. Direct observations of the vent region were hampered in the early stages of unrest and eruption because of the low winter sun angle and the fact that the crater opens to the north. During the precursory phase, field crews photo-documented the actively changing conditions of the fumarolic fields and the melting of ice in the summit crater and upper Drift glacier, and took FLIR measurements of areas in the crater. With helicopter-supported fieldwork, geologists were able to collect water samples in November 2008 and February 2009 from a stream along the east margin of the Drift glacier. Helicopter flights were conducted placing staff on the ground to repair and install seismic instruments, GPS instruments, pressure sensors, and camera equipment. During these geophysical instrument missions, conditions at the volcano were documented with photos and field descriptions. During the explosive phase of the eruption, ash in the atmosphere and the threat of additional explosions limited the amount of direct field observation, however, occasional field excursions were conducted to collect rock samples and investigate lahar impacts. During dome growth after the April 4 explosion, the stability of the dome was monitored closely with FLIR imagery to document hot spots and possible weak points on the dome that might be source areas of dome failure (fig. 31). Dome failure can result in large ash-producing eruptions and pyroclastic flows. Photogrammetric analysis of oblique digital images acquired during helicopter observation flights and fixed-wing volcanic gas surveys produced a series of digital elevation models (DEMs) of the lava dome from April 16 to September 23, 2009. The DEMs were used to estimate volume and subsequent time-averaged extrusion rates.

WEB CAMERAS

Two web cameras were operational during Redoubt's unrest and eruption, and a third web camera was installed during dome building to provide improved light sensitivity for low-light image acquisition. The first camera was located at Juergen's hut (a hut installed by geologist Juergen Kienle in 1990), near seismic station RDJH, approximately 12 km north of Redoubt. The second was located near seismic

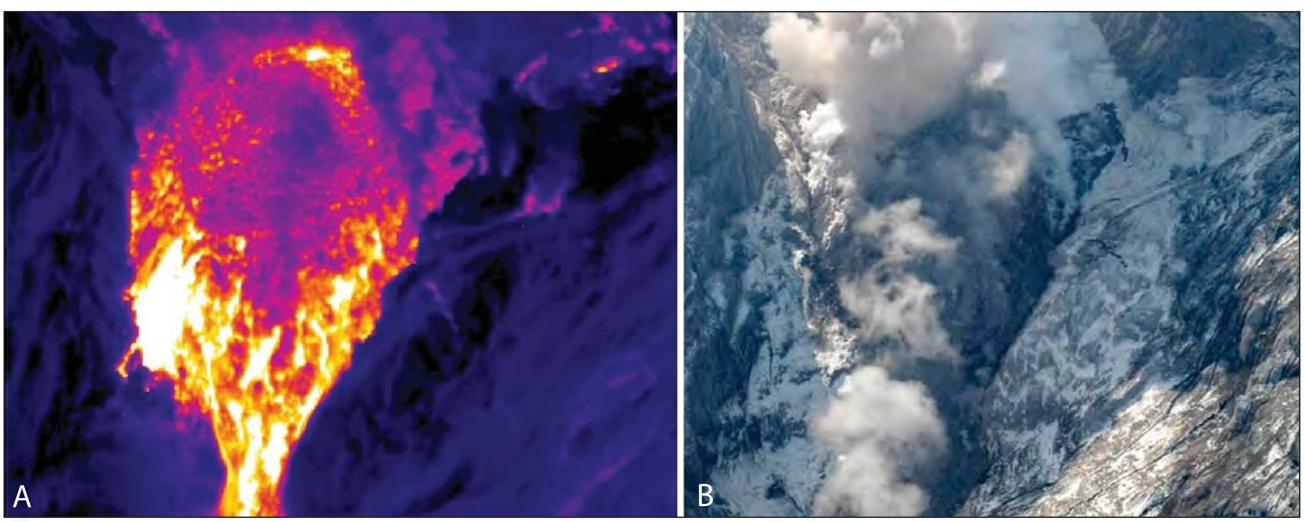

Figure 31. (A) Forward-Looking Infrared (FLIR), and (B) Photographic images taken of the Redoubt lava dome on May 8, 2009. The maximum temperature in this view was >273°C, and the average surface temperature between the vent and the toe of the lava dome was 27.9°C. FLIR image by R. Wessels, photography by K. Bull.

station DFR above the Drift River valley, approximately 12.8 km north–northwest of the volcano (fig. 5). A third, light-sensitive camera, was installed at Juergen's hut. All cameras were operated remotely from Anchorage and could be configured to optimize the available power supply. Image capture times could be set to streaming if an eruption was considered imminent, or set to select times and frequencies as conditions warranted. The web cameras were very popular with the AVO public-website viewers and proved extremely valuable to AVO scientists during precursory, explosive, and dome-building phases of the eruption.

The Juergen's hut webcam, commonly referred to as the 'hut-cam', became operational on January 27, 2009. This Stardot XL Netcam with 8mm lens, looked directly up into Redoubt's crater, and during optimum weather conditions, provided a clear view of the upper Drift glacier, crater, and dome. Precursory vapor plumes, flowage deposits, and melt holes in the glacier ice were all visible through this webcam. During the eruption, the webcam captured images of ash plumes, pyroclastic flows, and lahars (fig. 13). During post-April 4 lava dome growth, the camera was zoomed in to capture beautiful views of the growing mass of lava, which were analyzed for volume and textural changes (fig. 32). The addition of the Stardot Netcam SC low-light camera at this site temporarily in April 2009 and permanently in October 2009 helped track hot spots on the dome by recording areas of incandescence (fig. 33). Farther to the east, the DFR webcam became operational on April 1, 2009, and provided good views of the summit and northeastern flank, and was especially useful during the few times the hut-cam was not operational or was obscured by clouds (fig. 34).

TIME-LAPSE PHOTOGRAPHY

A time-lapse camera (Canon 40D with EF-S, 18–55mm zoom lens) located in the upper Drift River valley at Dumbbell hills, was installed February 27, 2009 (fig. 5). The camera was set to capture images every 5 minutes and was downloaded periodically when a crew could get to the site. Although not real-time, the time-lapse camera provided valuable retrospective images of pyroclastic flows and mudflows, helping AVO scientist interpret seismic signals and deposits associated with these events (figs. 15 and 16).

Figure 32. Images from Juergen's hut webcam, such as this August 20, 2009, image, were used to delineate textural types on the dome. T = talus; B = blocky apron, and U = upper facies.

Figure 33. Low-light images from the web camera installed at Juergen's hut helped identify and track hot spots on the dome such as this one on May 13, 2009 (lower image). The upper image was taken a few minutes prior to the lower image, without the low-light exposure feature.

Figure 34. View from DFR webcam, located 12.8 km north–northwest of Redoubt. Image taken at 15:33 on April 4, 2009.

SEISMIC MONITORING

Seismic analysis remains the primary monitoring tool for predicting a volcano's behavior. Although the first signs of unrest included visual observations of melting, elevated seismicity was soon to follow, and AVO's continual efforts to maintain an active seismic network of Cook Inlet volcanoes paid off as Redoubt began to rumble. By the time the first explosive eruption occurred, Redoubt was well covered with seismic instruments. On January 27, 2009, seven short-period seismic stations were operational, NCT, DFR, RDT, RDN, REF, RSO, and RED (fig. 5 and table 4). In February, two broadband stations were installed, station RDJH on February 3, and station RDWB on February 24. By March 22, one day prior to the first magmatic explosion, three additional broadband instruments (RD01, RD02, and RD03) had been installed and were receiving and transmitting data. These instruments allowed AVO to provide accurate and timely warning of the imminent eruption.

Seismic Analysis Software

Digital helicorder plots generated by SWARM (Seismic Wave Analysis and Real-time Monitor) software is the primary tool used by AVO scientists to track continuous seismicity. AVO uses SWARM software for the real-time display and analysis of seismic data streams from all telemetered seismic instruments. SWARM is run on individual desktop computers as well as in the operations room setting consisting of multiple wall-mounted displays. The SWARM software displays incoming seismic data as graphical helicorder plots that update once every few seconds. Signals of interest can be analyzed in detail by zooming in on the helicorder trace, which reveals the full seismic waveform. The waveforms themselves can be studied in both time and frequency domains, be filtered according to a user's specification, be compared to waveforms from nearby instruments, and be scaled and shifted to meet the user's immediate needs. While SWARM does not locate earthquakes, it does have basic GIS capabilities that provide the user situational awareness and various geographical tools, such as the ability to measure distances on a map.

Seismic Alarms

To free AVO scientists from the restrictions associated with full-time observation of the numerous seismic data streams, AVO developed alarms to automate the detection of earthquake swarms and volcanic tremor, both common precursors to volcanic eruptions. The earthquake swarm alarm (Thompson and West, 2010) is based on the continuous computation of mean and median event rates from the previous hour of data. By comparing these event rates with threshold rates, three swarm alarm conditions could be declared: a new swarm, an escalation in a swarm, or the end of a swarm. A tremor alarm was implemented with an application called IceWeb (Benoit and others, 1998), which computed reduced displacement and produced plots of reduced displacement and spectrograms that were posted every 10 minutes to the AVO internal website. Reduced displacement is a measure of the amplitude of volcanic tremor. When the reduced displacement at multiple stations exceeded predefined thresholds and there was a threefold increase in reduced displacement over the previous hour, a tremor alarm was activated. When either alarm (swarm or tremor) was triggered, an automated call-down system was initiated; observatory scientists were called in sequence until someone acknowledged the alarm via a confirmation web page.

Both alarm systems had good success during the Redoubt eruption, and there were no false alarms (Thompson and West, 2009). The tremor alarm detected pre-eruption tremor episodes as early as January 25, 2009, and detected most of the explosive events that occurred between March 23 and April 4, 2009. The swarm alarm detected all five of the main volcanic earthquake swarm episodes that occurred on February 26–27, March 21–23, March 26, April 2–4, and

Table 4. Redoubt seismic instruments and dates of operation.

Station	Latitude NAD83	Longitude NAD83	Elevation (ft)	Type	Operational Dates	Notes
BGR	60.7569	-152.4199	985	short period	July 1, 1991–present	
DFR	60.5913	-152.6883	1,090	short period	August 15, 2008–present	pressure sensor installed February 22, 2009
NCT	60.5615	-152.9316	1,120	short period	August 14, 2008–present	
RD01	60.4885	-152.7033	1,831	campaign broadband	March 22, 2009–June 9, 2009	
RD02	60.5208	-152.7373	1,401	campaign broadband	March 20, 2009–June 10, 2009	
RD03	60.4705	-152.8203	1,607	campaign broadband	March 21, 2009–June 10, 2009	
RDDR	60.5843	-152.5887	905	short period	July 1, 2009–present	
RDE	60.5869	-152.5925	571	short period	February 4, 2009–July 1, 2009	station moved and renamed RDDR on July 1, 2009
RDJH	60.5905	-152.8058	1,414	broadband	February 4, 2009–present	station hit by lightning with an outage lasting one month (March 23–April 26, 2009); station moved slightly (20m) on August 19, 2010
RDN	60.5224	-152.7402	1,400	short period	August 13, 2008–present	
RDT	60.5726	-152.4075	930	short period	August 9, 1971 –present	
RDW	60.4821	-152.8113	1,401	short period	September 7, 1990–?, 1995	
RDW	60.5208	-152.7376	1,401	campaign broadband	March 21, 2009–July 1, 2009	site reoccupied and up graded to 3 components March 21, 2009
RDWB	60.4874	-152.8423	1,546	broadband	February 24, 2009–present	station moved slightly on August 18, 2010
RED	60.4193	-152.7741	1,064	short period 3 component	November 10, 1981–present	upgraded to 3 components August 30, 1990
REF	60.4886	-152.7039	1,641	short period 3 component	March 14, 1990–present	upgraded to 3 components July 27, 1992
RSO	60.4616	-152.7561	1,921	short period	March 1, 1990–present	out March 23, 2009–April 26, 2009 due to lightning damage during eruption

May 3–7. The end-of-swarm alarms on March 23 and April 4 were particularly helpful as they were caused by transitions from swarm to tremor shortly preceding explosive eruptions.

VOLCANIC GAS MEASUREMENT

Thirty-one gas flights, using a twin-engine Navajo, flown between October 2008 and December 2009, measured CO_2 and SO_2. CO_2 was measured using a LICOR gas analyzer, and SO_2 emissions were measured using the correlation spectrometer (COSPEC). Gas measurements were made once per second along with GPS location, air temperature, and pressure. Wind data were collected at plume height to determine the speed of plume dispersion. Emission rates of both gases, calculated from the gas concentrations and wind speeds, were determined using standard techniques.

Gas emissions from Redoubt were first measured in October and November 2008 after pilot reports of a rotten-egg odor (H_2S) during flights downwind of the volcano. At that time, elevated emissions (>1,200–1,400 t/d) of CO_2 were observed, but minimal amounts of SO_2 were measured. Gas flights were conducted near the end of January, and followed an increase in seismicity. CO_2 emissions were measured between 3,500 and 9,000 t/d, but SO_2 emissions were still very low at <200 t/d. Gas emissions of CO_2 remained high through February, but SO_2 started to decrease as more ice melted in the summit region. Following the onset of the eruption in mid March 2009, the CO_2 emissions increased to 10,000–33,000 t/d, and SO_2 also quickly increased to 8,000–16,000 t/d. Emissions remained high through the middle of May, during which time there was active dome building and frequent explosions. Emissions had decreased to quiescent levels (<500 t/d for both gases) by August 2010.

SATELLITE REMOTE SENSING

Thermal activity, volcanic ash detection, and ash-cloud tracking

In the North Pacific region and across Alaska, remote-sensing data are critical in providing near-real-time data on pre-eruptive activity, eruptive events, and post-event ash-cloud tracking. During the 2009 Redoubt eruption, AVO used satellite-based, thermal infrared, visible, and ultra-violet wavelength data to analyze the volcano's activity before an eruption, during an event, and to detect and track the resulting volcanic-ash clouds (table 5).

Both Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) mid-infrared (MIR) data were used in near-real time to detect and analyze the thermal ground signals from Redoubt, providing information on surface ground temperatures and effusion rates. These were useful as complementary data to the fieldwork using FLIR cameras and dome-growth analyses.

A variety of satellite data and analytical tools help AVO detect ash in the atmosphere and determine cloud heights. AVO uses visible, single–channel, thermal infrared (TIR) data, and a brightness temperature difference (BTD) tool to detect volcanic-ash signals (fig. 35). Visible wavelength data is used, when available, to constrain ash-cloud heights using parallax and shadow methods (Holasek and others, 1996). During the Redoubt eruption, volcanic cloud heights were determined using ground-based radar, TIR data from AVHRR, MODIS, and Geostationary Operational Environmental Satellite (GOES) data. Figure 35 shows ash-cloud detection for Event 19 using AVHRR data. When an ash cloud shows a BTD (fig. 35B), then a reverse absorption tool (based on Prata [1989a, b] and shown in Webley and others, 2009) is used to detect and monitor the size and location of an ash cloud. When the ash cloud is opaque in the TIR (fig. 35C), the measured TIR brightness temperature is used along with the altitude–temperature method (Kienle and Shaw, 1979; Sparks and others, 1997) to determine cloud height. These tools are used in near-real time as soon as data become available, and the information is provided to the AVO operations room and also added to the twice-daily reports.

Table 5. Gridded North Pacific region wind fields used by the Puff model.

Wind Fields	Cell Size	Top Pressure	Approx. Max Altitude	Region
GFS	1.25 × 1.25°	70 mbar	20 km	Global
NOGAPS	1 × 1°	10 mbar	34 km	Global
NAM	45 × 45 km	50 mbar	22 km	Regional
WRF	7 × 7 km	200 mbar	16 km	Regional

GFS (NCEP Global Forecast System, NOAA)
NOGAPS (Navy Operational Global Atmospheric Prediction System, U.S. Navy)
NAM (North American Mesoscale Model, National Weather Service)
WRF (Weather Research and Forecast Model, a derivative of Mesoscale Model v.5)

AVO routinely monitors the volcanic activity across the North Pacific, 365 days a year, through automated alarms for changes in thermal activity (Dehn and others, 2000; Dean and others, 2002) and detection of ash signals from erupted clouds (Dean and others, 2002; Webley and others, 2009b). As part of its duties, the AVO remote-sensing group also carries out twice-daily monitoring shifts. Both the alarm systems and the routine monitoring remained active throughout the Redoubt eruption.

SO_2 emissions detected by the Ozone Monitoring Instrument (OMI)

The Ozone Monitoring Instrument (OMI), an ultraviolet (UV) and visible-spectrum sensor aboard NASA's AURA satellite platform, first detected SO_2 emissions from Redoubt Volcano on March 23, 2009, following the onset of explosive magmatic eruptions. The SO_2 mass emitted by Redoubt and detected by OMI on March 23 is estimated to be greater than 54,000 tonnes (t). On March 24, 2009, OMI detected an SO_2 plume from Redoubt that extended ~3,600 km east to Canada's Hudson Bay (fig. 36). The mass of SO_2 emitted

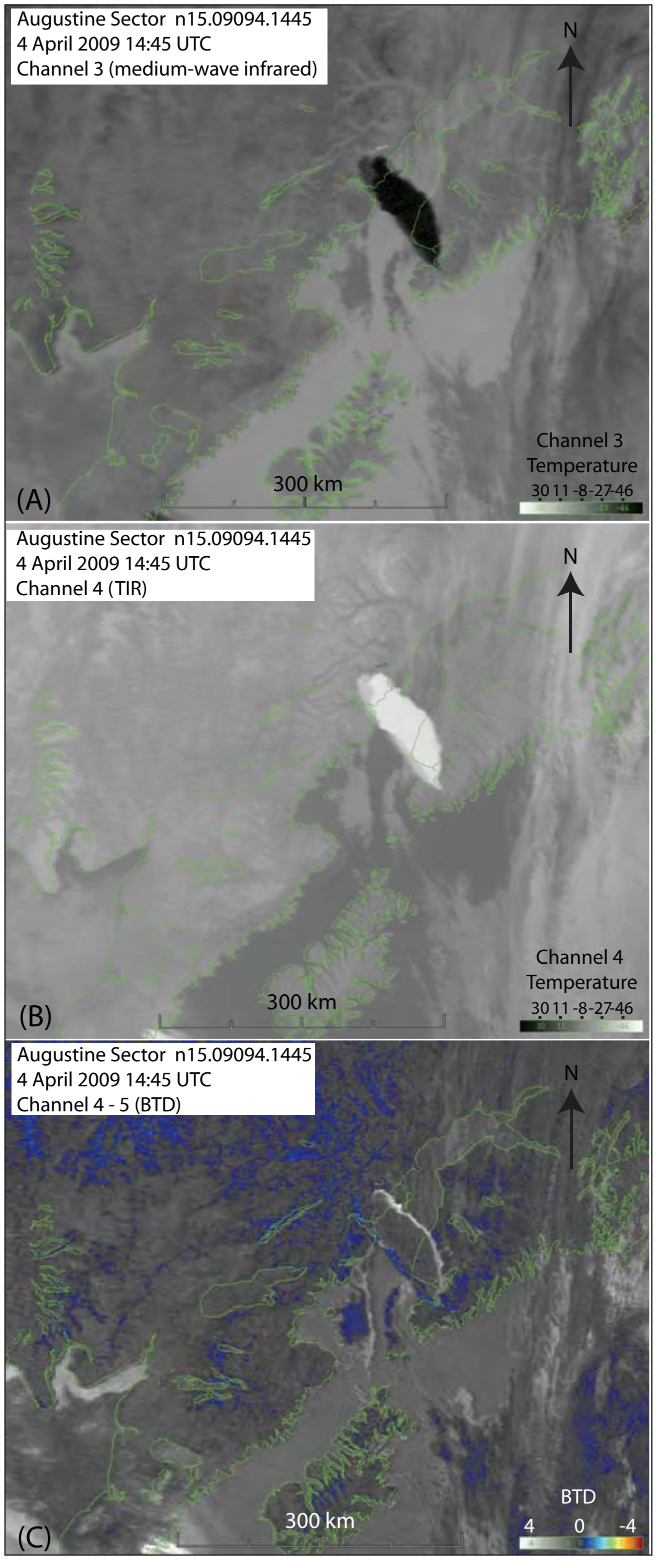

Figure 35. AVHRR image for (A) Channel 3, medium-wave infrared, (B) Channel 4, thermal infrared, and (C) Channel 4 minus 5, brightness temperature difference (BTD) for Event 19, April 4, 2009. Event 19 occurred at 00:58 (13:58 UTC), with the first polar orbiting data available at 14:45 UTC, less than an hour later. Here the plume is 51 km wide and 134 km long (northwest–southeast). The cloud-top temperature (B) in the TIR, is at -54°C, equating to 14 km ASL from altitude–temperature method using local radiosonde. In the BTD data (C) the plume is spectrally opaque in the TIR and as such there is no characteristic BTD signal indicative of volcanic ash.

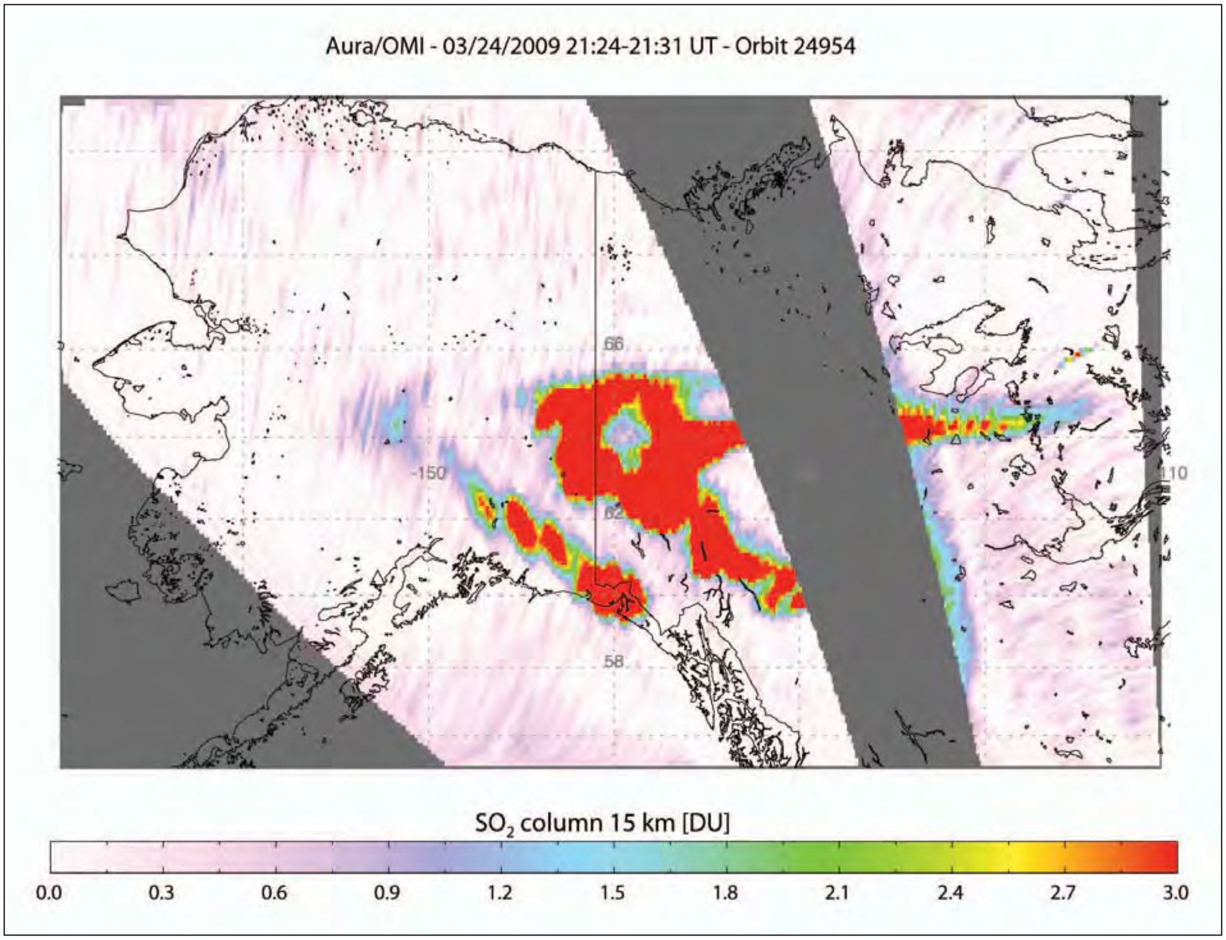

Figure 36. Ozone Monitoring Instrument (OMI) observations of Redoubt Volcano's SO_2 cloud over eastern Alaska and western Canada on March 24, 2009, at 13:24 (21:24 UTC); gray swaths indicate areas with no data. The total SO_2 mass calculated for this image was ~60 kt, the largest daily SO_2 mass observed by OMI during Redoubt's 2009 eruption.

on March 24 was ~60,000 t, the greatest daily emission mass observed by OMI for the duration of the Redoubt eruption.

OMI's combined high temporal resolution (full daily global coverage) and spatial resolution (13 km x 24 km pixel size at nadir) enable it to continually detect lower abundances of volcanic SO_2 than were previously possible from space (Carn and others, 2007). This was exemplified at Redoubt where OMI detected Redoubt SO_2 emissions on a near-daily basis for the three months following the onset of explosive magmatic eruptions, making it a useful data source to supplement the weekly to bi-weekly airborne gas measurements collected at Redoubt by AVO. Daily OMI-derived masses of SO_2 emissions from Redoubt for the period of March 23 through June 12, 2009, ranged from ~60,000 t to below detection limit, with an average daily SO_2 mass emitted of ~7,600 t and an overall decreasing trend in SO_2 emissions with time. OMI observations of the Redoubt SO_2 plume associated with the March 23 and 24 explosions were tracked in the northern hemisphere to distances of ~5,500 km on March 25, 2009, and the plume appeared to have circled the globe by March 29, 2009. The cumulative mass of Redoubt's SO_2 emissions measured by OMI for the initial three months of the eruption is about 500,000 t, of which about 290,000 t were emitted during the explosive magmatic phase alone (March 22 through April 4, 2009). This cumulative value is similar in magnitude to the cumulative SO_2 mass of 572,000–680,000 +/- 90,000 t emitted by Redoubt during the 1989–1990 period of dome growth and destruction analyzed by Casadevall and others (1994).

Puff Volcanic Ash Tracking

The Puff Volcanic Ash Tracking and Dispersion (VATD) model was used to forecast the movement of ash clouds during the 2009 Redoubt eruption. Puff, http://puff.images.alaska.edu, was initially developed solely for tracking volcanic ash (Searcy and others, 1998) but recently has been adapted to generate automated forecasts for multiple initial plume heights (Webley and others, 2009a). Puff uses Numerical Weather Prediction (NWP) data to forecast the movement of volcanic-ash particles; the NWP data can be used in real time or as an analysis tool in a research mode (Webley and others, 2010). A Puff model simulation provides the projected location of the ash particles in three dimensions at user-defined output times. Initial information includes plume altitudes, particle size distribution, vertical plume shape, eruption start time, and NWP data to be used.

During the Redoubt events, Puff was available in a multitude of modes: (1) automated forecasts, (2) online for real-time prediction and (3) as an analysis tool to compare to satellite remote-sensing data to determine ash-cloud heights. Mode 1 was the most useful application, as it provided an assessment of the ash cloud's potential location if an eruption were to occur. The Puff model was run using multiple initial plume heights from 4 to 16 km above sea level (fig. 37; real-time forecasts are online at http://puff.images.alaska.edu/watch_Redoubt.shtml). Forecast models would update automatically every three hours, allowing AVO to use the output to assess potential ash-cloud movement prior to an ash-producing explosive event. Once an event was reported, Mode 2 was implemented using the event start time obtained from seismic data and initial plume heights obtained from the TIR data and ground-based NEXRAD and C-Band radar.

LIGHTNING DETECTION

All of the large Redoubt explosive eruptions and many smaller ones were accompanied by volcanogenic lightning (fig. 38). Colleagues from New Mexico Institute of Mining and Technology, working on a collaborative National Science Foundation (NSF) grant with UAFGI, installed four lightning mapping array (LMA) stations on the east side of Cook Inlet in late January, 2009. The LMA network successfully recorded data from all the eruptions in March and April 2009, for the first time recording an entire eruption sequence from start to finish. The first eruption on March 22 was ash poor and produced only four lightning flashes, whereas the largest eruptions produced more than 10,000 lightning flashes. In general the longer-duration eruptions produced more lightning. Two main types of lightning were recorded, small and short flashes directly above the vent during ash ejections, and larger flashes in the plume as it rose above the vent and drifted downwind. The LMA network provided locations for the lightning flashes, which correlate closely with the location of the ash plume as recorded in satellite data. Lightning was especially abundant for plumes that rose to altitudes of 30,000 ft (~10 km) or more. This altitude corresponds to the tropopause, and the data suggest that fine ash particles were coated with ice and therefore concentrated positive charge. Smaller and weaker lightning flashes also occurred near the vent, and may reflect charging processes associated with colliding and fracturing ash particles.

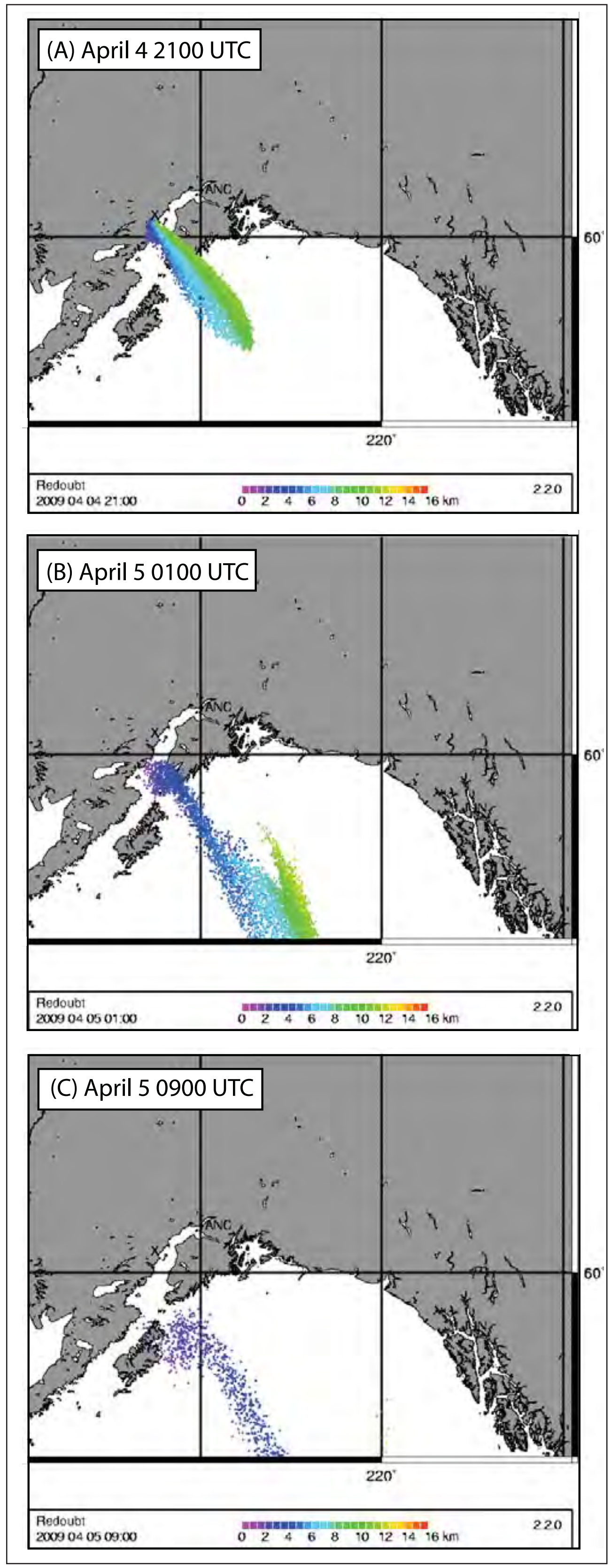

Figure 37. Ash plume forecast created April 4, 2009, by the 'Puff' automated model; start time 18:00 UTC (10:00 AKDT); initial plume height 10 km ASL. (A) April 4 at 21:00 UTC, (B) April 5 at 01:00 UTC, and (C) April 5, at 09:00 UTC. Note how the modeled forecasts propagate the ash to the southeast.

Figure 38. Lightning from Event 14 on March 27 at 23:20, photographed by Bretwood Higman. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=17283

INFRASOUND

The Redoubt explosive eruptions were well recorded on an infrasound (low frequency, <20 Hz) microphone located at station DFR, 12 km from the vent. More than 33 explosions were recorded, ranging in size from 0.5 to 171 Pascal (Pa) in pressure. All the eruptions that had pressures of 30 Pa or higher at DFR had ash columns that exceeded 30,000 ft (~10 km) in altitude. The signals lasted from <1 to 26 minutes and generally correlated with seismic signals that were also produced by the explosions. However, there are variations in the ratio of infrasound to seismic energies, suggesting variations in the source processes. Most of the larger explosive eruptions were also recorded on the I53US infrasound array in Fairbanks, 585 km north of Redoubt. Here the largest signals were 12 Pa, significantly larger than those from the 2006 eruptions of Augustine. Some lahars at Redoubt also produced small signals on the DFR pressure sensor.

NEXRAD AND C-BAND DOPPLER RADAR

Ash columns and drifting ash clouds were observed using the FAA WRS-88D NEXRAD radar, based in Kenai, 83 km east of Redoubt. When an explosive event occurred, initial cloud height estimates were made by the NWS Anchorage Forecast Office using range-height indication cross-sections and radar echo tops (table 2). The NEXRAD was operated in precipitation mode with ~5 minute scan duration. Post-event analysis of NEXRAD echo top and base reflectivity data using the publicly available “NOAA Weather and Climate Toolkit” was instrumental in ash fall mapping and ash fall collection fieldwork. All 19 ash-producing explosive events were mapped in a GIS using the NEXRAD base reflectivity data; these data were used to help target field sites for tephra collection and to interpret time–stratigraphic relationships of ash fall layers.

Another useful radar system used during the eruption was a transportable C-band Doppler radar deployed by USGS at the Kenai Municipal Airport, 82 km east of the volcano (fig. 39). This was the first deployment of this system, and it became fully operational within a day of the initial explosive events. The airport site offered an unobstructed view of Redoubt and the location was quite near the already established Kenai NEXRAD radar site. The proximity to the NEXRAD site permitted comparison of the new USGS system with an established weather-monitoring radar system (Hoblitt and Schneider, 2009). The new USGS radar system was operated remotely from the AVO operations room in Anchorage and was an extremely useful ash-cloud monitoring tool.

Unlike the NEXRAD radar that took almost 5 minutes to complete a scan of the region, the USGS radar could scan the 45-degree sector around the volcano every 60 to 90 seconds, depending on the scan parameters used. The faster scanning capability allowed for more detailed observations of pulses in activity as seen by seismic and pressure sensor data, and a quicker determination of maximum cloud height. Figure 40 shows a time sequence of reflectivity cross-sections collected by the USGS radar system on March 23, 2009. The column was imaged at 90-second intervals during this event and only some of the images are shown in this figure. Radar reflectivity is primarily a function of the sizes of the reflecting particles, their concentration, and the efficiency of the particle to reflect

Figure 39. USGS C-Band Doppler radar installed March 2009 at the Kenai Municipal Airport. AVO image URL: http://www.avo.alaska.edu/images/image.php?id=16885.

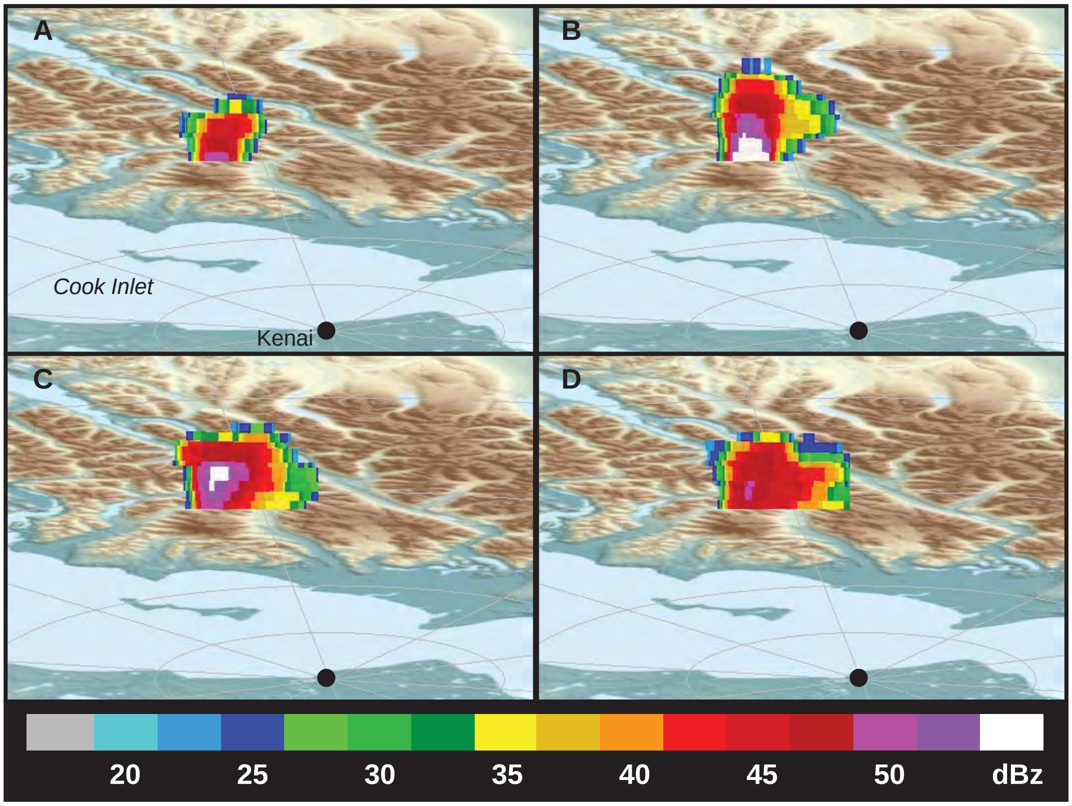

Figure 40. Radar reflectivity cross-sections of the eruption column from Redoubt Volcano as imaged by the USGS C-band radar system in Kenai. This eruptive event began on March 23, 2009, at 04:30; the view of the eruption column is from the east, with north to the right. (A) Image from 04:33:46; (B) Image from 04:36:43; (C) Image from 04:39:42; and (D) Image from 04:42:43. Location of the radar in Kenai (82 km from Redoubt) indicated by the dot. Reflectivity (a measure of the size of ash particles and their concentration) is given in dBz (decibels of reflectivity).

the radar energy. Figure 40A, acquired about 3.75 minutes after the eruption onset (at 04:30), shows a cloud rising to a height of 39,000 ft (11.9 km) ASL, increasing to 53,000 ft (16.2 km) ASL within 3 minutes (fig. 40B), and spreading laterally to the north (towards the right). High reflectivity values are observed at the vent, indicating high concentrations of large particles. Figure 40C, collected about 3 minutes later, shows the intensity of the reflectivity over the vent beginning to decrease, suggesting a decreasing mass eruption rate. After another 3 minutes (fig. 40D) the image shows a continued decrease in maximum reflectivity, suggesting decreasing ash production. During this 9 minute time period the height of the eruption column reached a maximum height of 53,000 ft (16.2 km) then dropped to 43,700 ft (13.3 km) ASL, suggesting the fallout of millimeter-sized particles.

Both the NEXRAD and USGS radar systems proved quite useful during the Redoubt eruption. The NEXRAD system has the advantage of more transmission power (750,000 watts) and is able to detect smaller-sized particles at lower concentrations than the USGS radar system (330 watts). Thus the NEXRAD radar was able to track ash clouds for greater distances. The maximum cloud heights determined by the two radars compared quite well and were typically within several thousand feet of each other. Together, the data showed that 16 explosive events reached aircraft cruise altitudes, and that many of these clouds entered the lower stratosphere (table 2). This is a region of the atmosphere where traditional satellite-based methods of estimating cloud height have large uncertainties because of the temperature inversion that occurs at the boundary between the troposphere and the stratosphere.

Post-event analysis of the USGS radar data showed a rapid decrease in the strength of the radar reflectivity (within tens of minutes of the eruption end), suggesting that the formation of accretionary lapilli (which characterizes the proximal tephra fall deposits) occurred quickly in the eruption column and the near-vent ash cloud. Understanding the rate of lapilli growth is critical, as this process removes fine-grained volcanic ash from the atmosphere more quickly than if it were to fall as single particles, thus decreasing the amount of ash to be dispersed by the prevailing winds to become an aviation hazard.

COMMUNITY ASH FALL REPORTS

The remoteness of Redoubt Volcano made direct eruption observation and real time ash fall collection challenging. As a result, AVO asked citizens positioned both near the volcano and under the path of eruption clouds to make voluntary observations and collect ash samples during the eruption.

Ash fall collection requests were made by phone, postal and electronic mailings, and by posting ash fall collection instructions on the AVO website. During the 2009 eruption of Redoubt Volcano, AVO received approximately 250 written or verbal observations and 55 physical samples from the public, including time-incremental collections during prolonged ash fall events, measured-area samples, and bulk samples (fig. 41).

When ash from the large explosions began falling on more populated communities such as Anchorage, Kenai, and Homer, reports of ash fall via phone and email began to overwhelm operations room and web team staff. To help alleviate time spent answering calls and emails, as well as to start cataloging ash fall data in a database, a web-based ash fall report form was created. This form presented several fields to the user, allowing them to enter information about the ash fall, such as the date and time, location, and amount of ash falling. If the user left contact information, AVO personnel could contact the individual, and update various fields in the database with more detailed information. These timely observations of ash fall were communicated directly to the National Weather Service so that public NWS Ash Fall Advisory statements could be updated. These observations were important, as AVO uses ash fall samples and observations to understand the composition, volume, and dispersal pattern of the ash clouds.

SUMMARY

The 2009 eruption of Redoubt Volcano shares many similarities with eruptions documented most recently at Redoubt in 1966–68 and 1989–90. In each case, the eruptive phase lasted several months, consisted of multiple ash-producing explosions, produced andesitic lava and tephra, removed significant amounts of ice from the summit crater and Drift glacier, generated lahars that inundated the Drift River valley, and culminated with the extrusion of a lava dome in the summit crater. There are dissimilarities to previous eruptions as well, with the length of pre-eruptive unrest being the most dramatic. In 1989 there was about a day of pre-eruptive seismic unrest. Prior to the 2009 explosive phase of the eruption, precursory seismicity lasted approximately six months with the first weak tremor recorded on September 23, 2008. The first phreatic explosion was recorded on March 15, and the first magmatic explosion occurred seven days later, at 22:34 on March 22. The onset of magmatic explosions was preceded by a strong, shallow swarm of repetitive earthquakes that began about 04:00 on March 20, 2009, less than three days before an explosion. Nineteen major ash-producing explosions ejected ash that reached heights between 17,000 ft and 62,000 ft (5.2 and 18.9 km) ASL. During ash fall in Anchorage, the Ted Stevens International Airport was shut down for 20 hours, from ~17:00 on March 28 until 13:00 on March 29. On March 23 and April 4, major lahars with flow run-ups to 13 m in the upper Drift River valley inundated parts of the Drift River Terminal. The explosive phase ended on April 4 with a dome collapse at 05:58. The April 4 ash cloud reached 50,000 ft (15.2 km) and moved swiftly to the southeast, depositing up to 2 mm of ash fall in Homer, Anchor Point, and Seldovia. At least two, and possibly three, lava domes grew and were destroyed by explosions prior to the final lava dome extrusion that began after the April 4 event. The final lava dome culminated its growth by July 1, 2009, with an estimated volume of 72 Mm^3.

Advanced monitoring technologies including webcams, time-lapse cameras, high-resolution satellite imagery, FLIR, gas measurements, radar, broadband seismic instruments, and seismic alarms provided AVO with data needed to properly assess the volcanic hazards, provide knowledgeable eruption scenarios, and track ash clouds. Many of these technologies were used successfully during the 2006 eruption of Augustine Volcano (Power and others, 2010). When unrest began at Redoubt, AVO staff was well prepared to initiate heightened monitoring; gas flights began early in the precursory stage, more frequent remote-sensing observations were conducted, and AVO staff were quickly able to install additional seismic stations, webcams, aerosol samplers, and time-lapse cameras. By the time the explosive phase began, Redoubt was monitored by a network of eight short-period seismometers, two broadband seismometers (RDJH and RDWB), two short-period seismometers along the Drift River to help detect mudflows (DFR and DRE), one pressure sensor (at DFR), two continuous GPS stations, two campaign GPS stations, three web cameras (one at Juergen's hut, one at DFR, and one on an oil platform in Cook Inlet not operated by AVO), one time-lapse camera at Dumbbell hills, an array of four lightning detectors along the Kenai Peninsula in collaboration with New Mexico Tech, one aerosol sampler, and a PM_{10} (particle matter of 10 microns and below) air-quality monitor in Soldotna in collaboration with USFWS.

Web-based communication played a key role in this eruption for both near-real-time monitoring information as well as public information dissemination. The AVO website served as the hub for all public information distribution including VAN/VONAs, daily status reports, hourly or more frequent updates, and links to webcams, webicorders, RSAM graphs, images, eruption scenario information, maps, volcanic-ash tracking, ash fall reporting forms, ash fall collection instructions, and helpful links to other agencies. Internal web-based tools allowed a multitude of scientists located in various geographic locations to communicate their observations and discuss probable outcomes. The web response to this eruption was huge and as demand overwhelmed the system, AVO programmers quickly responded with additional servers and advanced caching systems to maintain the website and the uninterrupted flow of volcano-hazard information.

The advanced monitoring tools used and the inter-agency cooperation during this eruption was the result of AVO's more than 20 years of experience in volcano research, monitoring, and eruption response.

Figure 41. Photographs showing various examples of community observations and ash collections submitted to AVO during the 2009 eruption of Redoubt Volcano. Unless otherwise stated, all photos by Alaska Volcano Observatory staff. (A) Ash fall collected on cookie sheets at known time intervals during the April 4 ash fall event in Homer. Photograph courtesy of Chas Stock. (B) Ash fall collected into a common soup bowl during the March 28 ash fall event in Nikiski. Photograph courtesy of Linda Vitzthum. (C) Minor (~1 mm) ash fall deposit at Bentalit Lodge in Skwenta, from the March 22 and 23 explosions. This observer cleverly marked the date of ash fall in the snow and from this photograph we can interpret percent cover (continuous in this case) and general thickness of the deposit. Photographer unknown. (D) Ash fall collected from the surface of a vehicle after the March 26 ash fall event in Homer. Photograph courtesy of DeWaine Tollefsrund. (E) Packages of ash fall samples collected throughout the eruption and sent to AVO for analysis. (F) Ash fall sample sent to AVO with detailed ash fall information written on the outside of the plastic bag. Photograph courtesy of Brian Brettschneider.

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