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2009 Volcanic Activity in Alaska, Kamchatka, and the Kurile Islands—Summary of Events and Response of the Alaska Volcano Observatory

Scientific Investigations Report 2013–5213

U.S. Department of the Interior
U.S. Geological Survey

Cover: Steam plume rises from Redoubt Volcano following the early morning explosive eruption on April 4, 2009. Pyroclastic flow and lahar deposits are visible on the lower north flank, upper piedmont glacier, and upper Drift River valley. Aerial view is from the northeast. Located in Lake Clark National Park & Preserve, Redoubt is built upon the expansive Aleutian Mountain Range, visible in upper right background. Photograph by Game McGimsey, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17861.

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By Robert G. McGimsey, Christina A. Neal, Olga A. Girina, Marina Chibisova, and Alexander Rybin

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U.S. Department of the Interior
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Conversion Factors and Datum

Conversion Factors

Inch-Pound

Multiply	By	To obtain
acre	4,047	square meter (m^2)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
foot (ft)	0.000305	kilometer (km)
foot (ft)	0.3048	meter (m)
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
inch (in.)	1.609	kilometer (km)
ton per day (ton/d)	0.9072	metric ton per day

SI to Inch-Pound

Multiply	By	To obtain
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	3,281	foot (ft)
meter (m)	3.281	foot (ft)
centimeter (cm)	0.3937	inches (in.)
metric ton per day	1.1022	ton per day (ton/d)
millimeter (mm)	0.03937	inch (in.)
square meter (m^2)	0.0002471	acre

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Datum

Altitude and elevation as used in this report, refer to distance above sea level, unless otherwise noted.

2009 Volcanic Activity in Alaska, Kamchatka, and the Kurile Islands—Summary of Events and Response of the Alaska Volcano Observatory

By Robert G. McGimsey[1], Christina A. Neal[1], Olga A. Girina[2], Marina Chibisova[3], and Alexander Rybin[3]

Abstract

The Alaska Volcano Observatory (AVO) responded to eruptions, possible eruptions, volcanic unrest, and reports of unusual activity at or near eight separate volcanic centers in Alaska during 2009. The year was highlighted by the eruption of Redoubt Volcano, one of three active volcanoes on the western side of Cook Inlet and near south-central Alaska's population and commerce centers, which comprise about 62 percent of the State's population of 710,213 (2010 census). AVO staff also participated in hazard communication and monitoring of multiple eruptions at ten volcanoes in Russia as part of its collaborative role in the Kamchatka and Sakhalin Volcanic Eruption Response Teams.

Introduction

The Alaska Volcano Observatory (AVO) monitors, reports, and studies volcanic unrest at Alaskan volcanoes. The year 2009 was dominated by the eruption of Redoubt Volcano in Cook Inlet. AVO also responded to volcanic unrest at several other volcanoes in Alaska, including Fourpeaked, Aniakchak, Veniaminof, Shishaldin, Okmok, and Cleveland, as well as non-volcanic activity mistakenly attributed to Mount Sanford, an inactive volcano, by local residents (fig. 1).

Of the more than 50 historically active volcanoes in Alaska (Cameron and others, 2008), 31 were monitored in 2009 with a network of seismometers sufficiently reliable in their operation to consistently track earthquake activity (fig. 1; table 1); on November 17, 2009, four volcanoes—Fourpeaked, Aniakchak, Veniaminof, and Korovin—were delisted because their seismic networks had become non-functional, reducing the seismically monitored volcanoes to 27. Seismic stations are in place at two additional volcanoes (Little Sitkin and Semisopochnoi (fig. 1); however, telemetry links are intermittent and background seismicity has not been confidently determined. Thus, AVO does not yet consider these volcanoes formally monitored with seismic instrumentation. AVO's routine monitoring program includes twice-daily analysis of seismicity and satellite imagery, web cameras, occasional overflight observations and airborne-gas measurements, and compilation of pilot reports and observations of local residents and mariners. Additionally, AVO receives real-time deformation information from permanent Global Positioning System (GPS) stations at four Alaska volcanoes (Okmok, Augustine, Akutan, and Spurr). In recent years, periodic analysis of Interferometric Synthetic Aperture Radar (InSAR) imagery also has been used to detect deformation at volcanoes in Alaska (Lu and others, 2003; Lu, 2007; Lu and others, 2007).

AVO continues to participate by formal agreement with the Kamchatkan Volcanic Eruption Response Team (KVERT; Kirianov and others, 2002) and the Sakhalin Volcanic Eruption Response Team (SVERT; Rybin and others, 2004) to aid in satellite monitoring of Russian volcanoes and support dissemination of hazard information. In 2009, AVO assisted in broadcasting alerts about eruptive activity at eight Russian volcanoes in Kamchatka and Northern Kuriles (Sheveluch, Klyuchevskoy, Bezymianny, Kizimen, Karymsky, Koryaksky, Gorely, and Ebeko), and two in the Central Kuriles (Sarychev and Raikoke).

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[3]Sakhalin Volcanic Eruptions Response Team, Institute of Marine Geology and Geophysics, Nauki Street, Yuzhno-Sakhalinsk, Russia 69302.

Figure 1. Historically active volcanoes in Alaska along with place names used in this report. From January 1, 2009, through November 16, 2009, 31 of the volcanoes were considered seismically monitored (red and orange triangles). On November 17, 2009, four volcanoes—Fourpeaked, Aniakchak, Veniaminof, and Korovin (orange triangles)—were delisted because their seismic networks had become non-functional. Following the established criteria of Cameron and others (2008), historically active volcanoes are considered to be those that have had an eruption or period of intense deformation, seismic or fumarolic activity that is inferred to reflect the presence of magma at shallow levels beneath the volcano. The "historical" period in Alaska is considered post mid-1700s when written records of volcanic activity began. Note that Mount Sanford volcano is not considered historically active; local residents often report activity they mistake is volcanic in origin. Map is modified from Schaefer and others (2009). Shaded relief from Riehle and others (1997). Bathymetry from Smith and Sandwell (1977).

Table 1. History of seismic monitoring of Alaskan volcanoes from August 1971 through December 2009.

[History of seismic monitoring compiled by J. Dixon, U.S. Geological Survey (2009). “First station installed” is defined as the receipt of real-time data from the station. This date can be many months following initial fieldwork at the volcano. Alaska Volcano Observatory (AVO) considers the seismic network “complete” following installation and data transmission from a minimum of four seismic stations. Typically, AVO seismologists wait about six months or more to understand background rates of seismicity before formally declaring a volcano seismically monitored and adding it to the monitored list. We note here the first mention of the seismic status of each monitored volcano in the AVO weekly update. Regularly issued written information statements began during the Redoubt eruption in 1989-90 and were expanded to include all Cook Inlet volcanoes in April 1991. The Magnitude of Completeness is the lowest magnitude that can confidently be located for activity detected in 2009. For more information on specific network histories, readers are referred to the series of annual seismic summaries prepared by AVO (for example, Dixon and others, 2010)]

Volcano	Approximate start date of seismic monitoring	Magnitude of completeness
Wrangell	First station installed – July 2000 Network complete – **August 2001** Added to monitored list in weekly update – November 2001	1.0
Spurr	First station installed – August 1971 Network complete – **August 1989** Added to monitored list in weekly update – April 1991	0.1
Redoubt	First station installed – August 1971 Network complete – **August 1988** Added to monitored list in weekly update – April 1991	0.4
Iliamna	First station installed – September 1987 Network complete (Min 4 stations) – **September 1994** Added to monitored list in weekly update – April 1991	0.3
Augustine	First station installed – October 1970 Network complete – **August 1978** Added to monitored list in weekly update – April 1991	-0.1
Fourpeaked	First station installed – September 2006 Network complete – **October 2006** Added to monitored list in weekly update – July 2007 Removed from monitored list in November 2009	1.0
Katmai-North (Snowy)	First station installed – August 1988 Network complete – **October 1998** Added to monitored list in weekly update – December 1998	0.9
Katmai-Central (Griggs, Katmai, Novarupta, Trident)	First station installed – August 1988 Network complete (Min 4 stations) – **July 1991** Added to monitored list in weekly update – November 1996	0.4
Katmai-South (Martin, Mageik)	First station installed – August 1988 Network complete – **July 1996** Added to monitored list in weekly update – November 1996	0.4
Ukinrek Maars/ Peulik	First station installed – March 2005 Network complete (Min 4 stations) – **March 2005** Added to monitored list in weekly update – April 2005	0.9
Aniakchak	First station installed – July 1997 Network complete – **July 1997** Added to monitored list in weekly update – November 1997 Removed from monitored list in November 2009	1.3
Veniaminof	First station installed – February 2002 Network complete – **February 2002** Added to monitored list in weekly update – September 2002 Removed from monitored list in November 2009	1.4
Pavlof	First station installed – July 1996 Network complete – **July 1996** Added to monitored list in weekly update – November 1996	1.9

Table 1. History of seismic monitoring of Alaskan volcanoes from August 1971 through December 2009.—Continued

[History of seismic monitoring compiled by J. Dixon, U.S. Geological Survey (2009). "First station installed" is defined as the receipt of real-time data from the station. This date can be many months following initial fieldwork at the volcano. Alaska Volcano Observatory (AVO) considers the seismic network "complete" following installation and data transmission from a minimum of four seismic stations. Typically, AVO seismologists wait about six months or more to understand background rates of seismicity before formally declaring a volcano seismically monitored and adding it to the monitored list. We note here the first mention of the seismic status of each monitored volcano in the AVO weekly update. Regularly issued written information statements began during the Redoubt eruption in 1989-90 and were expanded to include all Cook Inlet volcanoes in April 1991. The Magnitude of Completeness is the lowest magnitude that can confidently be located for activity detected in 2009. For more information on specific network histories, readers are referred to the series of annual seismic summaries prepared by AVO (for example, Dixon and others, 2010)]

Volcano	Approximate start date of seismic monitoring	Magnitude of completeness
Dutton	First station installed – July 1988 Network complete – **July 1996** Added to monitored list in weekly update – November 1996	0.6
Shishaldin (and Isantoski)	First station installed – July 1997 Network complete – **July 1997** Shishaldin added to list in weekly update – November 1997 Isantoski added to list in weekly update – December 1998	1.0
Westdahl (and Fisher)	First station installed – August 1998 Network complete – **October 1998** Added to monitored list in weekly update – December 1998	0.8
Akutan	First station installed – March 1996 Network complete – July 1996 Added to monitored list in weekly update – November 1996	0.7
Makushin	First station installed – July 1996 Network complete – **July 1996** Added to monitored list in weekly update – November 1996	1.2
Okmok	First station installed – January 2003 Network complete – **January 2003** Added to monitored list in weekly update – January 2004	1.2
Korovin	First station installed – July 2004 Network complete – **July 2004** Added to monitored list in weekly update – December 2005 Removed from monitored list in November 2009	0.3
Great Sitkin	First station installed – September 1999 Network complete – **September 1999** Added to monitored list in weekly update – December 1999	0.6
Kanaga	First station installed – September 1999 Network complete – **September 1999** Added to monitored list in weekly update – December 2000	1.5
Tanaga	First station installed – August 2003 Network complete – **August 2003** Added to monitored list in weekly update – June 2004	1.2
Gareloi	First station installed – August 2003 Network complete – **September 2003** Added to monitored list in weekly update – June 2004	1.6
Semisopochnoi (Cerberus)	First station installed – September 2005 Network complete – **September 2005** Added to monitored list in weekly update – not yet added	0.8
Little Sitkin	First station installed – September 2005 Network complete – **September 2005** Added to monitored list in weekly update – not yet added	0.7

This report summarizes volcanic activity in Alaska, Kamchatka, and the Kuriles in 2009 and briefly describes AVO's operational response. Descriptions are presented in geographic order from northeast to southwest along the Aleutian Arc, and north to south in Kamchatka and the Kuriles. Each event summary ends with a paragraph providing a background narrative of the volcano in question. Information is derived primarily from AVO daily status reports, weekly updates and special information releases/statements, internal bimonthly reports, AVO email and internal electronic logs, and the Smithsonian Institution Global Volcanism Network Bulletins that are available at URL: http://volcano.si.edu/reports_bgvn.cfm. Table 1 is a history of seismic monitoring of Alaska volcanoes from August 1971 through December 2009. Table 2 summarizes 2009 volcanic activity in Alaska. Table 3 summarizes changes in Aviation Color Codes in 2009 for Alaskan volcanoes. Table 4 presents cross-referenced lists of volcanic activity by year and by volcano for all previous reports (1992–2009).

Only activity that resulted in a significant investment of staff time (defined here as several hours or more for reaction, tracking, and follow-up) is included. Where more extensive published documentation for an episode of unrest exists, we provide key references. Over the course of the year, AVO typically receives dozens of reports of steaming, unusual cloud sightings, or false eruption reports. Most of these are resolved very quickly and are not tabulated here as part of the response record.

Some activity included in AVO's annual summaries is reported to occur at volcanoes that are not considered historically active (see "What is an Eruption?", for definition of "historically active"). The "unusual" phenomenon typically is observed and reported by local residents, and considered by them to be signs of unrest or eruptive activity. The 2009 activity reported at Mount Sanford is such an example.

On rare occasions, AVO issues an information statement to dispel rumors of volcanic activity. In years past, we have used the phrase "suspect volcanic activity" (SVA) to characterize unusual activity that is subsequently determined to be normal or merely enhanced fumarolic activity, weather-related phenomena, or other non-volcanic events. Beginning with the 2006-year report, we have ceased using this term as it has presented us with problems of consistency.

Altitudes and elevations reported are in feet and/or meters above sea level (ASL) unless noted, and time is reported as Alaska Standard Time (AKST), Alaska Daylight Time (AKDT), Kamchatkan Standard Time (KST), or Kamchatkan Daylight Time (KDT) as needed, with Coordinated Universal Time (UTC) in parentheses. For most satellite or geophysical instrumentation references, times are given in UTC. We preserve English or Inch-Pound units of measurement especially where they reflect the primary observations of distance or altitude such as those commonly received via pilot reports and aviation authorities in the United States. Elsewhere, measurements are presented in International System of Units (SI) with Inch-Pound Units in parentheses for convenience. Volcano locations in latitude and longitude and summit elevations are taken from the Alaska Volcano Observatory database and may differ slightly from previously published compilations.

Increasing monitoring, increasing information, more to report

As AVO has expanded instrumental monitoring and made use of the increasing number of high-resolution satellite platforms, the threshold of detection of volcanic unrest in Alaska has lowered considerably. In addition, increasing air and marine-vessel traffic in the Aleutians along with improved Internet and other telecommunications infrastructure in remote Alaska, and the highly visible web presence of AVO may contribute to the increased number of reports of volcanic activity we receive, evaluate, and log. The focus of this report is on volcanic activity that represents a significant departure from 'background', a somewhat loosely defined state of quiet at a given volcano. For a more quantitative picture of the level of seismic unrest, readers are referred to the catalog of seismicity at Alaska volcanoes, also produced on an annual basis (for example, Dixon and others, 2010).

What is an "eruption"?

The specific use of the term 'eruption' varies from scientist to scientist and there is no universally agreed-upon definition. Here, we adopt usage of the Smithsonian Institution's Global Volcanism Program, which defines eruptions as, "…events that involve explosive ejections of fragmental material, the effusion of liquid lava, or both. This fragmental material may be old as well as new; the explosive interaction of volcanically generated heat and near-surface water can cause dramatic eruptions without any fresh volcanic material reaching the surface" (http://www.volcano.si.edu/faq.cfm#q2). The element of this definition we wish to emphasize are the verbs 'eject' and 'effuse,' which refer to dynamic surface processes that pose some level of hazard. The presence or absence of often ambiguous 'juvenile material' or fresh magma is not relevant to this use of the term eruption, particularly when communicating a potential hazard, which makes no distinction between juvenile and non-juvenile eruption products. This definition would not, however, include passive volcanic degassing or hydrothermal-fluid discharge unless accidental solid fragments are entrained.

What is an "historically active volcano"?

AVO defines an "active" volcano as a volcanic center that has had an eruption (see above) or period of intense seismic or fumarolic activity that is inferred to reflect magma at shallow levels within the volcano. The "historic" period in Alaska is considered post mid-1700s when written records of volcanic activity were first compiled. We include some volcanoes on our list of 'potentially active' volcanoes that do not exactly fit these criteria because geologic evidence suggests that they have been active within the last few thousand years and as such, although not historically active, they retain a potential for hazardous activity that requires careful monitoring. As geologic understanding of Alaska's volcanoes improves through additional fieldwork and modern radiometric-dating techniques, our list of "active" volcanoes will undoubtedly evolve. A case in point from 2006: Fourpeaked Mountain, thought not to have erupted in the Holocene, produced a phreatic eruption in the fall of 2006. It now ranks as a historically active volcano, despite not appearing on the list prior to 2006. The AVO annual summary often contains information about reports of unusual activity—non-volcanic in nature, but mistaken by local observers to be volcanic activity—at volcanoes that are not considered "historically active"; they are included because AVO staff spent significant time responding to the reports/observations. The activity at Mt. Sanford, described in this summary report, is an example.

Table 2. Summary of 2009 volcanic activity in Alaska, including actual eruptions, possible eruptions, unusual increases in seismicity or fumarolic activity, or, in the case of Sanford, non-volcanic activity that resulted in a response from AVO.

[Location of volcanoes shown in figure 1]

Volcano	Date of activity	Type of activity
Sanford[1]	March 18–19, 2009	Persistent anomalous cloud originating at summit.
Redoubt	January 1–July 1, 2009; Dec. 28, 2009	Precursory activity leads to major eruption; 20 explosive events, growth of 3–4 domes, production of ash clouds, voluminous lahars generated.
Fourpeaked	Variously throughout 2009	Continued decline of steam and gas emission.
Aniakchak	February–June 2009	Anomalous seismicity; low-frequency events.
Veniaminof	Intermittently throughout 2009	Diffuse steaming from intracaldera cone; increase in seismicity.
Shishaldin	January–October 2009	Increased seismicity, small steam and ash plumes, thermal anomalies.
Okmok	March, May, 2009	Tremor bursts, uplift of crater floor.
Cleveland	Intermittently throughout 2007	Intermittent explosions, thermal anomalies, minor ash and gas emission.

[1]Not one of the historically active volcanoes in Alaska.

Table 3. Alaskan volcanoes with Aviation Color Code changes in 2009.

[Description of Level of Concern Color Codes is shown in appendix 1. Local times are only shown where color code changes were short-lived during rapidly evolving events. Volcanoes that do not have a real-time seismic network are not assigned a color code **GREEN** because without seismic data, Alaska Volcano Observatory has no definitive information that the level of activity at the volcano is at background. For these volcanoes, AVO uses the designation **UNASSIGNED.** Fourpeaked, Aniakchak, Veniaminof, and Korovin volcanoes go from **GREEN** to **UNASSIGNED** due to failure of their seismic networks]

Color Code	Date of change
REDOUBT	
YELLOW	January 1–January 25
ORANGE	January 25–March 10
YELLOW	March 10–March 15
ORANGE	March 15–March 18
YELLOW	March 18–March 21
ORANGE	March 21–March 22
RED	March 22–March 25
ORANGE	March 25–March 26
RED	March 26–April 3
ORANGE	April 3–April 4
RED	April 4–April 6
ORANGE	April 6–June 30
YELLOW	June 30–September 29
GREEN	September 29–December 28
YELLOW	December 28–December 31
FOURPEAKED	
GREEN	January 1–November 17
UNASSIGNED	November 17–December 31
ANIAKCHAK	
GREEN	January 1–November 17
UNASSIGNED	November 17–December 31
VENIAMINOF	
GREEN	January 1–May 7
YELLOW	May 7–May 26
GREEN	May 26–November 17
UNASSIGNED	November 17–December 31

Color Code	Date of change
SHISHALDIN	
GREEN	January 1–January 6
YELLOW	January 6–February 11
GREEN	February 11–July 10
YELLOW	July 10–October 19
GREEN	October 19–December 31
OKMOK	
GREEN	January 1–March 2
YELLOW	March 2–March 20
GREEN	March 20–December 31
CLEVELAND	
YELLOW	January 1–May1
UNASSIGNED	May 1–June 25
ORANGE	June 25–June 27
YELLOW	June 27–July 15
UNASSIGNED	July 15–October 3
ORANGE	October 3–October 5
YELLOW	October 5–October 19
UNASSIGNED	October 19–December 31
KOROVIN	
GREEN	January 1–November 17
UNASSIGNED	November 17–December 31

Table 4a. Compilation by year of volcanoes included in an Alaska Volcano Observatory Annual Summary, 1992–2009.

[Volcanoes are presented in geographical order from northeast to southwest along the Wrangell-Aleutian volcanic arc and north to south along Kamchatka and the Kurile Islands. Prior to 1995, Alaska Volcano Observatory did not report on Russian volcanoes]

Volcanoes mentioned	
Alaskan	**Russian**
1992	
Spurr/Crater Peak	
Iliamna	
Redoubt	
Mageik (Katmai Group)	
Westdahl	
Akutan	
Bogoslof	
Seguam	
1993	
Churchill	
Sanford	
Spurr/Crater Peak	
Veniaminof	
Shishaldin	
Makushin	
Seguam	
Kliuchef (Atka)	
Kanaga	
1994	
Sanford	
Iliamna	
Katmai Group (Martin, Mageik, Trident)	
Veniaminof	
Kupreanof	
Shishaldin	
Makushin	
Cleveland	
Kanaga	
1995	
Katmai Group (Martin)	Bezymianny
Veniaminof	Karymsky
Shishaldin	
Makushin	
Kliuchef (Atka)	
Kanaga	
1996	
Wrangell	Klyuchevskoy
Iliamna	Bezymianny
Katmai Group (Martin, Mageik, Trident, Mount Katmai)	Karymsky
Pavlof	Avachinsky
Shishaldin	Mutnovsky
Westdahl	Alaid (Kurile Islands)
Akutan	
Amukta	
Korovin (Atka)	
Kanaga	
1997	
Wrangell	Sheveluch
Sanford	Klyuchevskoy
Shrub Mud	Bezymianny
Iliamna	Karymsky
Katmai Group (Martin, Mageik, Snowy, Kukak)	Alaid (Kurile Islands)
Chiginagak	
Pavlof	
Shishaldin	
Okmok	
Cleveland	
Amukta	
1998	
Shrub Mud	Sheveluch
Augustine	Klyuchevskoy
Becharof Lake	Bezymianny
Chiginagak	Karymsky
Shishaldin	
Akutan	
Korovin (Atka)	
1999	
Wrangell	Sheveluch
Shrub Mud	Klyuchevskoy
Iliamna	Bezymianny
Veniaminof	Karymsky
Pavlof	
Shishaldin	
Vsevidof	
2000	
Wrangell	Sheveluch
Katmai Group (Snowy)	Klyuchevskoy
Chiginagak	Bezymianny
Shishaldin	Karymsky
	Mutnovsky
2001	
Katmai Group (Snowy/Kukak)	Sheveluch
Pavlof	Klyuchevskoy
Frosty	Bezymianny
Shishaldin	Karymsky
Makushin	Avachinsky
Okmok	
Cleveland	
Great Sitkin	

Table 4a. Compilation by year of volcanoes included in an Alaska Volcano Observatory Annual Summary, 1992–2009.—Continued

[Volcanoes are presented in geographical order from northeast to southwest along the Wrangell-Aleutian volcanic arc and north to south along Kamchatka and the Kurile Islands. Prior to 1995, Alaska Volcano Observatory did not report on Russian volcanoes]

Volcanoes mentioned	
Alaskan	**Russian**
2002	
Wrangell	Sheveluch
Katmai Group (Martin, Mageik)	Klyuchevskoy
Veniaminof	Bezymianny
Mt. Hague (Emmons Lake Caldera)	Karymsky
Shishaldin	
Great Sitkin	
2003	
Wrangell	Sheveluch
Redoubt	Klyuchevskoy
Iliamna	Bezymianny
Augustine	Karymsky
Katmai Group (Mageik)	Alaid
Veniaminof	Chikurachki
Pavlof	
Mt. Hague (Emmons Lake Caldera)	
Shishaldin	
Akutan	
2004	
Mt. Crillon (non-volcanic peak)	Sheveluch
Mount Spurr	Klyuchevskoy
Katmai Group (Martin)	Bezymianny
Veniaminof	Karymsky
Shishaldin	Chirinkotan (Kuriles)
Westdahl	
2005	
Mount Spurr	Sheveluch
Iliamna	Klyuchevskoy
Augustine	Bezymianny
Katmai Group (Martin, Mageik, Trident)	Karymsky
Chiginagak	Avachinsky
Aniakchak	Mutnovsky
Veniaminof	Ebeko
Pavlof/Mt. Hague	Chikurachki
Shishaldin	
Cleveland	
Korovin	
Kasatochi	
Tanaga	
2006	
Klawasi	Sheveluch
Mount Spurr	Klyuchevskoy
Augustine	Bezymianny
Fourpeaked	Karymsky
Katmai Group (Martin, Mageik, Trident)	Ebeko
Veniaminof	Severgin
Cleveland	Berga
Korovin	
Kasatochi	
2007	
Wrangell	Sheveluch
Redoubt	Klyuchevskoy
Augustine	Bezymianny
Fourpeaked	Karymsky
Veniaminof	Gorely and Mutnovsky
Pavlof	Chikurachki
Akutan	Berga
Cleveland	
Korovin	
2008	
Redoubt	Sheveluch
Aniakchak	Klyuchevskoy
Veniaminof	Bezymianny
Shishaldin	Karymsky
Unalaska Bay, near Makushin	Koryaksky
Okmok	Gorely and Mutnovsky
Cleveland	Chikurachki
Kasatochi	Tyatya
2009	
Sanford	Sheveluch
Redoubt	Klyuchevskoy
Fourpeaked	Bezymianny
Aniakchak	Kizimen
Veniaminof	Karymsky
Shishaldin	Koryaksky
Okmok	Gorely
Cleveland	Ebeko
	Sarychev
	Raikoke

Table 4b. Compilation by volcano for particular years included in an Alaska Volcano Observatory Annual Summary, 1992–2009.

[Suspect Volcanic Activity (SVA) is defined as a report of eruption or possible eruption that is normal fumarolic activity or non-volcanic phenomena, such as weather related. PIREP, pilot weather report. AVO stopped using this designation in 2006]

Volcano	Year mentioned	Type of activity
	Alaska (east to west)	
Churchill	1993	SVA, anomalous seismicity
Wrangell	1996	SVA, steam plume
	1997	SVA, steam plume
	1999	SVA, steaming and phreatic ash emission
	2000	SVA, steam plumes
	2002	SVA, suspicious clouds, redistributed ash
	2003	SVA, anomalous clouds
	2007	Triggered seismicity; steam plumes and redistributed ash
Sanford	1993	SVA, reported vapor plume likely from avalanche
	1994	SVA, reported vapor plume likely from avalanche
	1997	SVA, large vapor cloud from SW face
	2009	Persistent anomalous cloud
Shrub Mud	1997	Eruption; energetic ejection of saline mud and CO_2
	1998	Eruption continues; ejection of saline mud and CO_2
	1999	Eruption continues; ejection of saline mud and CO_2
Klawasi Mud	2006	Possible new mud vent
Spurr	1992	Subplinian eruptions; ash, pyroclastic flows, lahars
	1993	SVA, glacial outburst produces seismicity
	2004	Heat flux to summit; lahars; cauldron develops
	2005	Continued heat to summit; cauldron evolves
	2006	Continued heat to summit; cauldron evolves
Redoubt	1992	SVA, steam plume from still-cooling dome
	2003	SVA, anomalous weather cloud
	2007	First signs of precursory activity leading to eruption in 2009
	2008	Pre-eruption increase in gas emissions and thermal flux from summit crater
	2009	Eruption, dome building/destruction, lahars, ashfall
Iliamna	1992	SVA, PIREP of large steam plume, media frenzy
	1994	SVA, vigorous steam plume, avalanche
	1996	Intense seismicity related to magmatic intrusion
	1997	SVA; anomalous seismic swarm; avalanche
	1999	SVA, avalanche
	2003	SVA, avalanche
	2005	SVA, rock avalanche
Augustine	1998	1986 dome spine partially collapses, generates mudflow
	2005	Precursory activity prior to eruption in early 2006
	2006	Explosive and effusive eruption
	2007	Strong seismic events; reports of steam plumes
Fourpeaked	2006	Phreatic eruption
	2007	Ongoing fumarolic emissions
	2009	Continued decline of steam and gas emissions

Table 4b. Compilation by volcano for particular years included in an Alaska Volcano Observatory Annual Summary, 1992–2009.—Continued

[Suspect Volcanic Activity (SVA) is defined as a report of eruption or possible eruption that is normal fumarolic activity or non-volcanic phenomena, such as weather related. PIREP, pilot weather report. AVO stopped using this designation in 2006]

Volcano	Year mentioned	Type of activity
Alaska (east to west)—Continued		
Katmai Group		
Mageik	1992	SVA, anomalous cloud
Martin/Mageik/Trident	1994	SVA, plume-like cloud
Martin	1995	SVA, large steam plume
Martin/Mageik/Trident/Mount Katmai	1996	SVA, anomalous seismicity
Martin/Mageik/Snowy/Kukak	1997	SVA, PIREPS of ash and steam plumes
Snowy	2000	SVA, steaming hole in glacier
Snowy/Kukak	2001	SVA, steaming hole in glacier
Martin/Mageik	2002	SVA, steam plume
Mageik	2003	SVA, steaming, large cloud of re-suspended ash
Martin	2004	SVA, large steam plume
Martin	2006	Earthquake swarm
Martin/Mageik/Trident	2005	SVA, steam cloud, re-suspended ash, new crater?
Becharof Lake	1998	SVA, intense seismic swarm and inflationary episode
Chiginagak	1997	Minor eruptive activity, new fumarole field
	1998	SVA, continuation of increased fumarolic activity
	2000	SVA, steam emissions from fumarole field
	2005	Heat to summit; acidic flood; cauldron develops
Aniakchak	2005	SVA, anomalous seismicity, thermal anomaly
	2008	Anomalous seismicity, weather related
	2009	Anomalous seismicity
Veniaminof	1993	Low-level eruption and lava flows
	1994	Strombolian eruption and lava flows
	1995	Strombolian eruptions
	1999	SVA, extreme discharge and turbid river
	2002	Low-level phreatic eruptions
	2003	Low-level phreatic eruptions
	2004	Weak phreatic and Strombolian eruption
	2005	Intermittent phreatic and Strombolian eruption
	2006	Intermittent phreatic and Strombolian eruption
	2007	Weak phreatic emissions and vapor plumes
	2008	Minor phreatic (?) eruption
	2009	Minor phreatic eruptions
Kupreanof	1994	SVA, PIREP of unusual steam plume
Pavlof	1996	Strombolian eruption
	1997	Strombolian eruption concludes
	1999	SVA, summit snow melt, ash dustings, steam plumes
	2001	SVA, steaming, possible ash, sulfur smell
	2005	SVA, mis-located steam plume
	2007	Strombolian eruption
Hague (Emmons Lake Caldera)	2002	SVA, increase in fumarolic activity in summit crater
	2003	SVA, crater lake drains, refills, drains
	2005	SVA, steam plume
Frosty	2001	SVA, rock fall avalanches

Table 4b. Compilation by volcano for particular years included in an Alaska Volcano Observatory Annual Summary, 1992–2009.—Continued

[Suspect Volcanic Activity (SVA) is defined as a report of eruption or possible eruption that is normal fumarolic activity or non-volcanic phenomena, such as weather related. PIREP, pilot weather report. AVO stopped using this designation in 2006]

Volcano	Year mentioned	Type of activity
	Alaska (east to west)—Continued	
Shishaldin	1993	Minor phreatic
	1994	SVA, PIREP of minor steam/ash
	1995	Minor eruptive activity, steam/ash
	1996	Eruption; steam/ash and thermal anomaly
	1997	Minor eruptive activity, steam/ash
	1998	Minor eruptive activity, steam/ash
	1999	Strombolian eruption
	2000	Minor eruptive activity, steam/ash
	2001	Minor unrest, seismicity increase, steam clouds
	2002	SVA, shallow seismicity; PIREP of possible eruption
	2003	SVA, steam plumes
	2004	Small steam and ash plumes
	2005	SVA, increased seismicity, steam plumes prompt PIREPS
	2008	Minor phreatic ash (?) emission events
	2009	Increased seismicity, small steam plumes, thermal anomalies
Westdahl	1992	Fissure eruption, lava fountains, ash clouds, lava flow
	1996	SVA, suspicious weather cloud on satellite image
	2004	SVA, seismic swarm
Akutan	1992	SVA, steam/ash emissions
	1996	Intensive seismicity, ground cracking
	1998	SVA, tremor-like seismicity
	2003	SVA, anomalous steam plume
	2007	Triggered seismicity; inflation; anomalous steaming on lower east flank
Makushin	1993	Minor phreatic
	1994	SVA, PIREP of minor steam/ash
	1995	SVA, steam plume
	2001	SVA, increase in seismicity
	2008	Unalaska Bay; discolored seawater/bubbles likely due to groundwater discharge; not volcanic
Bogoslof	1992	Dome extrusion, ash and steam emissions
Okmok	1997	Strombolian eruption
	2001	SVA, seismic swarm
	2008	5 weeks of phreatomagmatic eruption from numerous vents on caldera floor; substantial to severe ash fall on Umnak Island
	2009	Bursts of tremor, crater floor inflation
Vsevidof	1999	SVA, sighting of ash after regional earthquake
Cleveland	1994	SVA, possible steam/ash emission
	1997	Minor eruption, steam/ash
	2001	Eruption; gas/ash, lava/debris flows
	2005	Intermittent explosions
	2006	Intermittent explosions
	2007	Intermittent explosions, small ash clouds
	2008	Intermittent explosions; ash clouds, thermal anomalies, flowage deposits
	2009	Intermittent explosions, thermal anomalies, minor ash and gas emission
Amukta	1996	Small eruption; ash emission
	1997	SVA, PIREP of small ash eruption
Seguam/Pyre Peak	1992	Minor eruptive activity, steam/ash emissions
	1993	Fissure eruption produces lava flow and ash cloud
Kliuchef (Atka)	1993	SVA, audible rumbling, strong sulfur odor
	1995	SVA, large steam plume, strong sulfur odor

Table 4b. Compilation by volcano for particular years included in an Alaska Volcano Observatory Annual Summary, 1992–2009.—Continued

[Suspect Volcanic Activity (SVA) is defined as a report of eruption or possible eruption that is normal fumarolic activity or non-volcanic phenomena, such as weather related. PIREP, pilot weather report. AVO stopped using this designation in 2006]

Volcano	Year mentioned	Type of activity
	Alaska (east to west)—Continued	
Korovin (Atka)	1996	SVA, PIREP of ash cloud, suspicious cloud on satellite image
	1998	Eruption; explosions and ash fall
	2005	Minor eruption, steam and ash
	2006	Seismic swarms, uplift, increased fumarolic activity
	2007	Seismic swarm; continued fumarolic activity; inflation rate decreases
Kasatochi	2005	SVA, unusual bubbling; floating scum on crater lake
	2006	Continued bubbling in intracaldera lake
	2008	Significant explosive eruption; ash clouds, ash fall, inundation of entire island by pyroclastic flows
Great Sitkin	2001	SVA, anomalous seismicity
	2002	SVA, seismic swarm, tremor
Kanaga	1993	SVA, increased steaming
	1994	Eruption; steam/ash and lava flow
	1995	Minor eruptive activity, steam/ash and lava
	1996	Possible eruption and ash emission
Tanaga	2005	SVA, anomalous seismicity, including a period of tremor
	Kamchatka and northern Kurile Islands (north to south)	
Sheveluch	1997	Lava dome growth, pyroclastic avalanches, ashfalls
	1998	Lava dome growth, explosions, ash plumes, pyroclastic avalanches, ashfalls
	1999	Lava dome growth, explosions, ash plumes, pyroclastic avalanches, ashfalls
	2000	Lava dome growth, explosions, pyroclastic avalanches, ash plumes, ashfalls
	2001	Lava dome growth, strong explosions, pyroclastic flows, lahars, ash plumes, ashfalls
	2002	Lava dome growth, explosions, ash plumes, pyroclastic avalanches, ashfalls
	2003	Lava dome growth, explosions, ash plumes, pyroclastic avalanches, ashfalls
	2004	Lava dome growth, strong explosions, dome collapse, pyroclastic flows, lahars, ash plumes, ashfalls
	2005	Lava dome growth, strong explosions, dome collapse, pyroclastic flows, ash plumes, ashfalls
	2006	Lava dome growth, explosions, ash plumes, pyroclastic avalanches, ashfalls
	2007	Lava dome growth, explosions, ash plumes, pyroclastic avalanches, ashfalls
	2008	Lava dome growth, explosions, ash plumes, pyroclastic avalanches, ashfalls
	2009	Lava dome growth, explosions, pyroclastic flows, ash plumes, ashfall
Klyuchevskoy	1996	Strombolian and Vulcanian, ash explosions, ash plumes, ashfalls
	1997	Strombolian and Vulcanian, ash explosions, ash plumes, ashfalls
	1998	Strombolian and Vulcanian, ash explosions, ash plumes, ashfalls
	1999	Strombolian and Vulcanian, ash explosions, ash plumes, ashfalls
	2000	Vulcanian explosions
	2001	Fumarolic plume
	2002	Elevated seismicity, gas-rich explosion
	2003	Strombolian and Vulcanian, ash explosions, ash plumes, ashfalls
	2004	Strombolian and Vulcanian, ash explosions, ash plumes, ashfalls
	2005	Strombolian and Vulcanian explosive eruptions, phreatic explosions, lava flows, lahars, ash plumes, ashfalls
	2006	Increased seismicity, thermal anomaly, no eruption
	2007	Strombolian and Vulcanian explosive eruptions, phreatic explosions, lava flows, lahars, ash plumes, ashfalls
	2008	Strombolian and Vulcanian explosive eruptions, phreatic explosions, lava flows, lahars, ash plumes, ashfalls
	2009	Strombolian and Vulcanian explosive eruptions, phreatic explosions, lava flows, lahars, ash plumes, ashfalls

Table 4b. Compilation by volcano for particular years included in an Alaska Volcano Observatory Annual Summary, 1992–2009.—Continued

[Suspect Volcanic Activity (SVA) is defined as a report of eruption or possible eruption that is normal fumarolic activity or non-volcanic phenomena, such as weather related. PIREP, pilot weather report. AVO stopped using this designation in 2006]

Volcano	Year mentioned	Type of activity
Kamchatka and northern Kurile Islands (north to south)—Continued		
Bezymianny	1995	Explosive eruption, pyroclastic flows, ash plumes, ash falls
	1996	Lava flow effusion, fumarolic activity
	1997	Two explosive eruptions, pyroclastic flows, ash plumes, ash falls
	1998	Lava flow effusion, degassing and spalling of new dome
	1999	Explosive eruption, pyroclastic flows, ash plumes, ash falls
	2000	Two explosive eruptions, pyroclastic flows, ash plumes, ash falls
	2001	Two explosive eruptions, pyroclastic flows, ash plumes, ash falls
	2002	Explosive eruption, pyroclastic flows, ash plumes, ash falls
	2003	Explosive eruption, pyroclastic flows, ash plumes, ash falls
	2004	Two explosive eruptions, pyroclastic flows, ash plumes, ash falls
	2005	Two explosive eruptions, pyroclastic flows, ash plumes, ash falls
	2006	Two explosive eruptions, pyroclastic flows, ash plumes, ash falls
	2007	Three explosive eruptions, pyroclastic flows, ash plumes, ash falls
	2008	Explosive eruption, pyroclastic flows, ash plumes, ash falls
	2009	Explosive eruption, pyroclastic flows, ash plumes, ash falls
Kizimen	2009	Increased seismicity and fumarolic activity; no eruption
Karymsky	1995	Increased seismicity
	1996	Explosive eruption, ash plumes, ash falls
	1997	Low level Strombolian and Vulcanian eruptions, ash plumes, ash falls
	1998	Low level Strombolian and Vulcanian eruptions, ash plumes, ash falls
	1999	Low level Strombolian and Vulcanian eruptions, ash plumes, ash falls
	2000	Low level Strombolian and Vulcanian eruptions, ash plumes, ash falls
	2001	Low level Strombolian and Vulcanian eruptions, ash plumes, ash falls
	2002	Low level Vulcanian and Strombolian eruptions, ash plumes, ash falls
	2003	Vulcanian and Strombolian eruptions, lava flows, ash plumes, ash falls
	2004	Low level Vulcanian and Strombolian eruptions, ash plumes, ash falls
	2005	Low level Vulcanian and Strombolian eruptions, ash plumes, ash falls
	2006	Low level Vulcanian and Strombolian eruptions, ash plumes, ash falls
	2007	Strombolian/Vulcanian eruption, ash plumes, ash fall
	2008	Strombolian/Vulcanian eruption, ash plumes, ash falls
	2009	Strombolian/Vulcanian eruption, ash plumes, ash falls

Table 4b. Compilation by volcano for particular years included in an Alaska Volcano Observatory Annual Summary, 1992–2009.—Continued

[Suspect Volcanic Activity (SVA) is defined as a report of eruption or possible eruption that is normal fumarolic activity or non-volcanic phenomena, such as weather related. PIREP, pilot weather report. AVO stopped using this designation in 2006]

Volcano	Year mentioned	Type of activity
Kamchatka and northern Kurile Islands (north to south)—Continued		
Koryaksky	2008	Phreatic explosions and ash emission
	2009	Increased fumarolic output, phreatic explosions, ash plumes, ash falls
Avachinsky	1996	Increased seismicity
	2001	Increased seismicity, phreatic explosion, ash plume, ash fall
	2005	Increased seismicity, thermal anomaly
Gorely	2007	Increased seismicity and fumarolic activity; no eruption
	2008	Increased seismicity; no eruption; uncertain source with Mutnovsky
	2009	Increased fumarolic activity and seismicity; no eruption
Mutnovsky	1996	Fumarolic plume
	2000	Gas and steam explosion
	2005	Fumarolic activity
	2007	Increased seismicity – phreatic explosion, ash plume, ash fall
	2008	Fumarolic activity
Alaid (Kurile Islands)	1996	Ash plume
	1997	SVA
Ebeko	2005	Increased fumarolic activity and phreatic eruptions
	2006	Increased fumarolic activity
	2009	Increased fumarolic output, small phreatic explosions
Chikurachki	2002	Stombolian and Vulcanian eruption, ash plumes, ash falls
	2003	Stombolian and Vulcanian eruption, ash plumes, ash falls
	2005	Brief explosion produces ash and ash fall
	2007	Two short Vulcanian eruptions, ash plumes, ash falls
	2008	Vulcanian eruption, ash plumes, ash falls
Severgin	2006	Phreatic or fumarolic activity
Chirinkotan	2004	Brief, low-level steam, gas, and ash emission
Raikoke	2009	Fumarolic emission and possible phreatic ash
Sarychev	2009	Significant explosive eruption; ash clouds, pyroclastic and lava flows
Berga	2006	Phreatic or fumarolic activity
	2007	Possible eruption or gas outburst
Tyatya	2008	Increased fumarolic output; no eruption

Table 4c. Citations for Alaska Volcano Observatory Annual Summary reports, 1992–2008.

Year	Citation	URL
1992	McGimsey, R.G., Neal, C.A., and Doukas, M.P., 1995, Volcanic activity in Alaska: Summary of events and response of the Alaska Volcano Observatory 1992: U.S. Geological Survey Open-File Report 95-83, 26 p.	http://pubs.er.usgs.gov/usgspubs/ofr/ofr9583
1993	Neal, C.A., McGimsey, R.G., and Doukas, M.P., 1996, 1993 Volcanic activity in Alaska: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 96-0024, 21 p.	http://pubs.er.usgs.gov/publication/ofr9624
1994	Neal, C.A., Doukas, M.P., and McGimsey, R.G., 1995, 1994 Volcanic activity in Alaska: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 95-0271, 18 p.	http://pubs.er.usgs.gov/publication/ofr95271
1995	McGimsey, R.G., and Neal, C.A., 1996, 1995 Volcanic activity in Alaska and Kamchatka: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 96-0738, 22 p.	http://pubs.er.usgs.gov/publication/ofr96738
1996	Neal, C.A., and McGimsey, R.G., 1997, 1996 Volcanic activity in Alaska and Kamchatka: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 97-0433, 34 p.	http://pubs.er.usgs.gov/publication/ofr97433
1997	McGimsey, R.G., and Wallace, K.L., 1999, 1997 Volcanic activity in Alaska and Kamchatka: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 99-0448, 42 p.	http://pubs.er.usgs.gov/publication/ofr99448
1998	McGimsey, R.G., Neal, C.A., and Girina, Olga, 2003, 1998 Volcanic activity in Alaska and Kamchatka: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 03-0423, 35 p.	http://pubs.usgs.gov/of/2003/of03-423/
1999	McGimsey, R. G., Neal, C. A., and Girina, Olga, 2004a, 1999 Volcanic activity in Alaska and Kamchatka: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report OF 2004-1033, 49 p.	http://pubs.usgs.gov/of/2004/1033/
2000	Neal, C.A., McGimsey, R.G., and Chubarova, Olga, 2004, 2000 Volcanic activity in Alaska and Kamchatka: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 2004-1034, 37 p.	http://pubs.usgs.gov/of/2004/1034/
2001	McGimsey, R.G., Neal, C.A., and Girina, Olga, 2004b, 2001 Volcanic activity in Alaska and Kamchatka: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 2004-1453, 53 p.	http://pubs.usgs.gov/of/2004/1453/
2002	Neal, C.A., McGimsey, R.G., and Girina, Olga, 2005, 2002 Volcanic activity in Alaska and Kamchatka: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 2004-1058, 51 p.	http://pubs.usgs.gov/of/2004/1058/
2003	McGimsey, R.G., Neal, C.A., and Girina, Olga, 2005, 2003 Volcanic activity in Alaska and Kamchatka: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 2005-1310, 58 p.	http://pubs.usgs.gov/of/2005/1310/
2004	Neal, C.A., McGimsey, R.G., Dixon, J.P., and Melnikov, Dmitry, 2005, 2004 Volcanic activity in Alaska and Kamchatka: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Open-File Report 2005-1308, 67 p.	http://pubs.usgs.gov/of/2005/1308/
2005	McGimsey, R.G., Neal, C.A., Dixon, J.P., Ushakov, Sergey, 2007, 2005 Volcanic activity in Alaska, Kamchatka, and the Kurile Islands: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Scientific Investigations Report 2007-5269, 94 p.	http://pubs.usgs.gov/sir/2007/5269/
2006	Neal, C.A., McGimsey, R.G., Dixon, J.P., Manevich, Alexander, and Rybin, Alexander, 2009, 2006 Volcanic activity in Alaska, Kamchatka, and the Kurile Islands: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Scientific Investigations Report 2008-5214, 102 p.	http://pubs.usgs.gov/sir/2008/5214/
2007	McGimsey, R.G., Neal, C.A., Dixon, J.P., Malik, Nataliya, and Chibisova, Marina, 2011, 2007 Volcanic activity in Alaska, Kamchatka, and the Kurile Islands: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Scientific Investigations Report 2010–5242, 112 p.	http://pubs.usgs.gov/sir/2010/5242/
2008	Neal, C.A., McGimsey, R.G., Dixon, J.P., Cameron, C.E., Nuzhdaev, A.E., and Chibisova, M., 2011, 2008 Volcanic activity in Alaska, Kamchatka, and the Kurile Islands: Summary of events and response of the Alaska Volcano Observatory: U.S. Geological Survey Scientific Investigations Report 2010–5243, 94 p.	http://pubs.usgs.gov/sir/2010/5243/

Volcanic Activity in Alaska, Northeast to Southwest along Aleutian Arc

Mount Sanford Volcano

CAVW# 1105-01-

62°13'N 144°08'W
4,949 m (16,237 ft)

Copper River Basin

PERSISTENT ANOMALOUS CLOUD WORRIES LOCAL RESIDENTS
Unusual orographic cloud originating at Sanford.

On March 18 and 19, 2009, local Copper River Basin residents observed a large, unusual cloud emanating from the summit of Mount Sanford volcano (figs. 2–4). AVO was alerted on March 19 because the cloud had persisted for more than 24 hours and some residents were concerned that the cloud indicated volcanic activity. The cloud was reported to extend for more than 50 km (30 mi). The plume was visible March 19 on a webcam located at the High Frequency Active Auroral Research Program (HAARP) facility, 29 km (18 mi) north of Glennallen, Alaska, but the view was "all clear" at Sanford from this camera on March 20. From the vantage point of most residents of the Copper River Basin, this cloud appeared to be a feature unique to Sanford; however, AVO remote sensing specialists examining satellite images of the region reported that this was one of several orographic clouds streaming off the higher mountain peaks in the area. AVO issued an Information Statement on March 20 to report and explain the observations.

Figure 2. Mount Sanford, a large, glacier-covered Pleistocene shield volcano in the Wrangell-St. Elias National Park and Preserve of eastern Alaska. Wrangell volcano to the right. View is to the southeast across the Copper River. Photograph by Don Richter, USGS, August 1981. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=303.

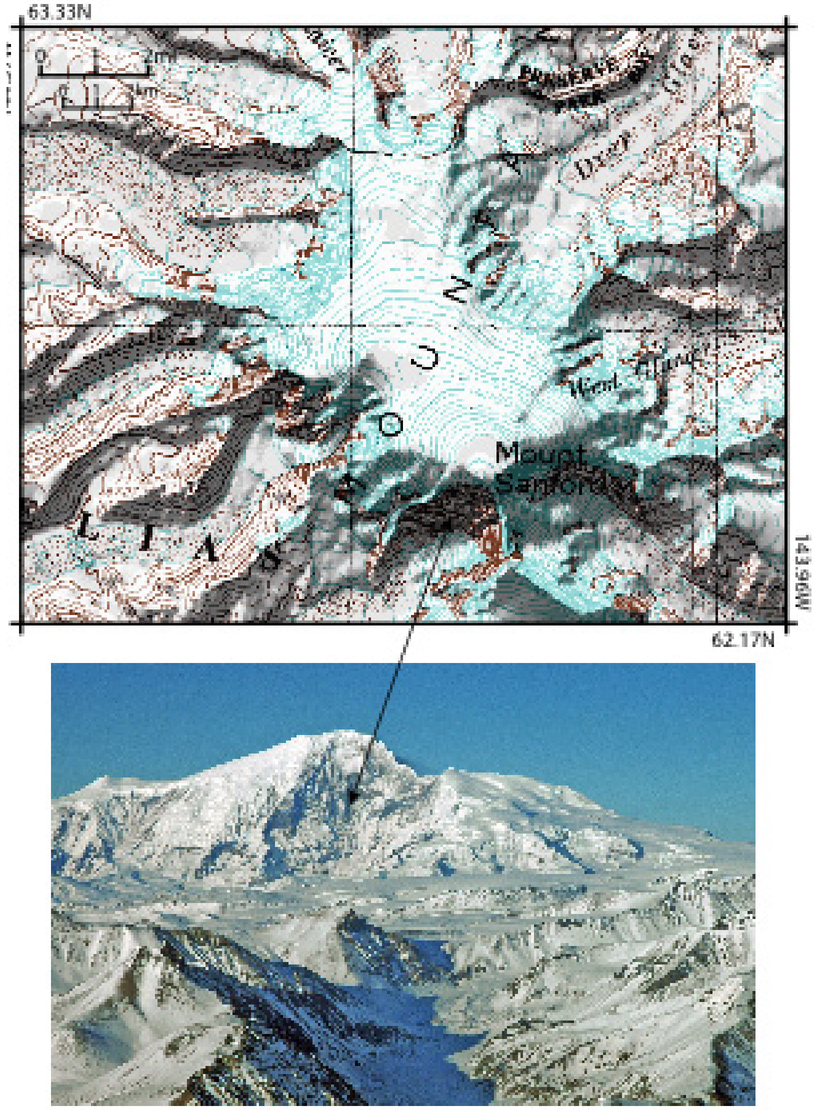


Figure 3. Shaded-relief topographic map of Mount Sanford (top) and oblique aerial photograph (bottom) showing the shear southern face with vertical relief of about 2,400 m (8,000 ft), which is the site of almost constant rock-, snow-, and ice-falls onto the Sanford Glacier. The anomalous vapor plume shown in figure 4 is seemingly originating from a point near the top of this wall. Map courtesy of Cheryl Cameron, AKDGGS/AVO; AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=2965. Photograph by Suzanne McCarthy, Prince William Sound Community College, March 17, 2005; AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=46781.

Mt. Sanford, located 72 km (45 mi) east of Glennallen, Alaska, is a large, glacier-covered, complex, Pleistocene andesite shield volcano in the Wrangell-St. Elias National Park and Preserve of eastern Alaska (Richter and others, 1995). At 4,949 m (16,237 ft), Sanford is the second highest volcano in the Wrangell volcanic field. In addition to the orographic clouds formed when moist air rises and cools over the summit Sanford, anomalous plumes also form from rock-, snow-, and ice-falls. The southwestern face is a shear wall with vertical relief of about 2,400 m (8,000 ft) (fig. 3), and is the site of almost constant rock-, snow-, and ice-falls onto the Sanford Glacier, activity which on occasion is energetic enough to produce anomalous vapor plumes mistaken by local residents to be steam clouds (Neal and others, 1995, 1996; McGimsey and Wallace, 1999). There is no record of historical eruptive activity at Mt. Sanford, and the youngest lava flows are estimated to be 100,000 years old (Richter and others, 1995).

Figure 4. Anomalous cloud streaming southwest from the summit of Mount Sanford volcano on March 19, 2009. The cloud was reported to extend for more than 50 km (30 miles). View is to the east from the Gulkana air field 16 km (10 mi) north of Glennallen. Mt. Drum volcano to the right. Photograph by Copper Center resident Ronald Simpson. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=46791.

Redoubt Volcano

CAVW# 1103-03

60°29'N 152°45'W
3,108 m (10,197 ft)

Cook Inlet

UNREST LEADS TO ERUPTION
Seven weeks of strong, shallow tremor culminates in 20 explosive events over a 21-day period, sending plumes to heights between 15,000 and 62,000 ft (4.6 and 18.9 km) ASL, and extrusion of 3 lava domes; causes disruption of regional commerce, closure of Ted Stevens International Airport for 20 hours, and interruption of Cook Inlet oil and gas production.

After a nearly 19-year hiatus since last active, the Cook Inlet Redoubt Volcano erupted (cover photograph). The unrest at Redoubt documented in 2007 and 2008 (McGimsey and others, 2011; Neal and others, 2011) culminated in a 21-day period of explosive eruptions in 2009 that dispersed ash over a sizeable swath of southcentral Alaska, closed Ted Stevens International Airport for 20 hours, and generated massive flooding of the Drift River valley, which seriously impacted oil production, storage, and transport in Cook Inlet (Schaefer, 2012; Bull and Buurman, 2013). The eruption produced 20 explosive events and extrusion of 3 lava domes (table 5; fig. 5). Schaefer (2012) contains greater details on impacts and AVO response to the eruption, and a special issue of the Journal of Volcanology and Geothermal Research contains a collection of comprehensive topical papers.

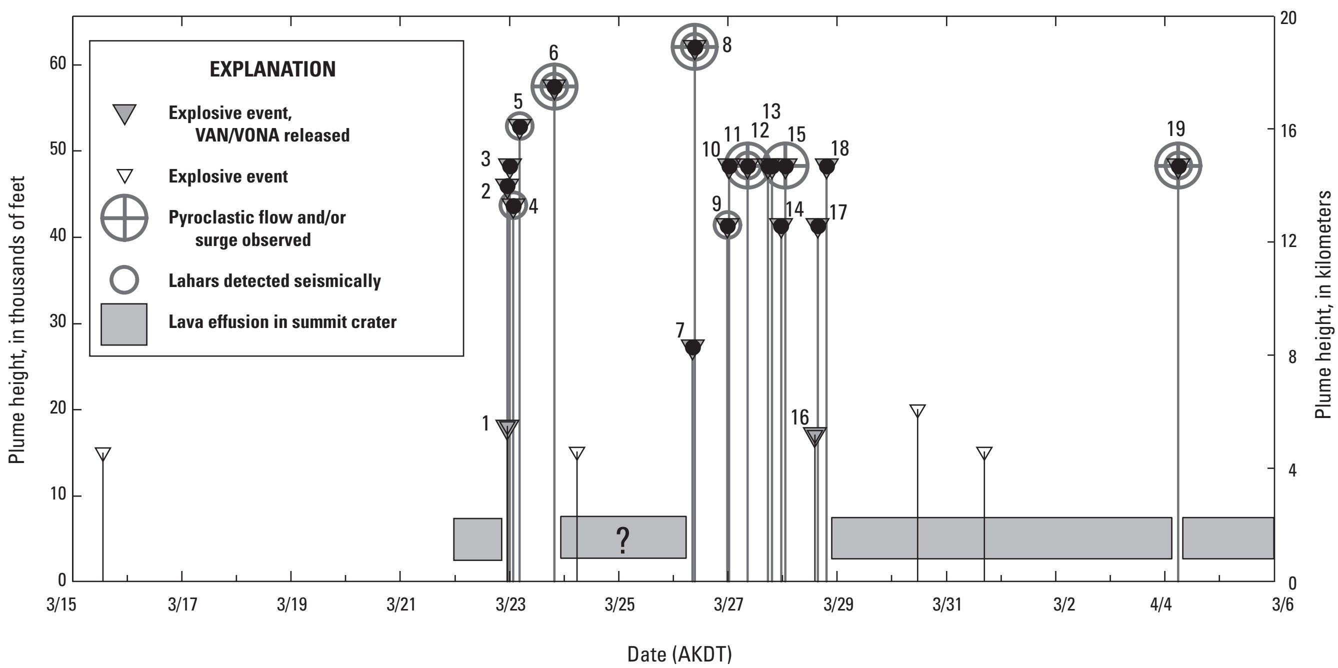


Figure 5. Time-series plot of explosive events during the 2009 eruption of Redoubt Volcano. Plume heights of significant explosions for which a Volcanic Activity Notification (VAN)/Volcano Observatory Notice for Aviation (VONA) was released are derived from USGS radar in Kenai, Alaska. Plume heights for other, minor ash-producing events are from pilot reports or FAA NEXRAD weather radar. Pyroclastic flow/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 (table 5). Despite 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 Events 6 and 7 explosions suggests a dome was likely extruded (from Schaefer, 2012, fig. 11).

Table 5. Redoubt eruption chronology: Explosion dates, times, durations, pressures, and maximum plume heights.

[From Schaefer (2012). **Event No.:** 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. **Official time:** Official onset times were derived from seismic signal analysis. **Duration, seismic SPU**: 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 reference as used in 1989–90 eruption. **Duration, seismic RDT**: Duration time at proximal seismic station, RDT. **Duration, DFR pressure sensor**: Duration time at pressure sensor DFR. **Maximum plume height:** Plume heights varied slightly depending on data source; only maximum plume heights are listed here. –, no data]

Event No.	Date (local AKDT)	Time (local AKDT)	Date (UTC)	Time, official (UTC)	Duration, in minutes: Seismic SPU	Duration, in minutes: Seismic RDT	DFR pressure sensor: Pressure zero to peak (Pa)	DFR pressure sensor: Duration (minutes)	Plume height: Maximum, in feet	Plume height: Data source
0	03-15-09	13:05	03-15-09	21:05	undefined	undefined	undefined	undefined	15,000	Pilot report
1	03-22-09	22:34:00	03-23-09	6:34	2	<1	25	26	18,000	FAA NEXRAD radar
2	03-22-09	23:02:00	03-23-09	7:02	7	9	151	3	44,000	FAA NEXRAD radar
3	03-23-09	0:14:00	03-23-09	8:14	20	14	38	13	48,000	USGS radar
4	03-23-09	1:38:00	03-23-09	9:38	38	9	70	8	43,000	FAA NEXRAD radar/USGS
reanalysis	03-23-09	1:48:00	03-23-09	9:48	undefined	30+	90	12	45,000	FAA NEXRAD radar
reanalysis	03-23-09	2:52	03-23-09	10:52	8	7	12	1	undefined	–
5	03-23-09	4:30:00	03-23-09	12:30	20	22	250	16	60,000	FAA NEXRAD radar
reanalysis	03-23-09	4:58:00	03-23-09	12:58	3	2	14	1	undefined	–
6	03-23-09	19:40:00	03-24-09	3:40	15	17	76	12	60,000	FAA NEXRAD radar
reanalysis	03-24-09	5:12:00	03-24-09	13:12	<1	<1	<1	<1	15,000	FAA NEXRAD radar
7	03-26-09	8:34:00	03-26-09	16:34	<1	1	7	1	27,000	USGS radar
8	03-26-09	9:34:00	03-26-09	17:24	14	14	100	7	62,000	FAA NEXRAD radar/USGS
9	03-26-09	23:47:00	03-27-09	7:47	<1	21	31	15	41,000	USGS radar
10	03-27-09	0:28:00	03-27-09	8:28	7	9	54	4	49,000	FAA NEXRAD radar
reanalysis	03-27-09	0:43:00	03-27-09	8:43	7	7	8	3	undefined	–
11	03-27-09	8:39:00	03-27-09	16:39	8	10	83	4	51,000	FAA NEXRAD radar
12	03-27-09	17:34:00	03-28-09	1:34	2	9	146	2	48,000	USGS radar
13	03-27-09	19:24:00	03-28-09	3:24	4	4	138	3	50,000	FAA NEXRAD radar
14	03-27-09	23:19:00	03-28-09	7:19	2	2	78	2	48,000	USGS radar
15	03-28-09	1:19:00	03-28-09	9:19	4	2	59	2	48,000	USGS radar
reanalysis	03-28-09	2:00:00	03-28-09	10:00	undefined	6	10	<1	undefined	–
16	03-28-09	13:40:00	03-28-09	21:40	6	12	28	2	17,000	FAA NEXRAD radar
17	03-28-09	15:29:00	03-28-09	23:29	6	37+	67	3	41,000	USGS radar
18	03-28-09	19:23:00	03-29-09	3:23	11	44	49	83	48,000	USGS radar
reanalysis	03-30-09	9:44:00	03-30-09	17:44	undefined	<1	1	4	undefined	–
reanalysis	03-30-09	10:50:00	03-30-09	18:50	undefined	undefined	1	undefined	20,000	FAA NEXRAD radar
reanalysis	03-31-09	16:07:00	04-01-09	0:07	undefined	<1	1.9	<1	15,000	FAA NEXRAD radar
19	04-04-09	5:58:00	04-04-09	13:58	31	75	38	31	50,000	FAA NEXRAD radar
reanalysis	04-04-09	6:16:00	04-04-09	14:16:00	undefined	undefined	88	undefined	50,000	FAA NEXRAD radar
reanalysis	04-05-09	10:36:00	04-05-09	18:36:00	3	1.5	3.7	1	undefined	–

Redoubt Volcano is a glacier-clad, steep-sided stratovolcano, with an ice-filled summit crater widely breached to the north where a deeply incised valley glacier (Drift glacier) drains the crater to the Drift River valley (figs. 6–7). The volcano is large (30–35 km^3; 7.2–8.4 mi^3), and built upon Mesozoic granitic rocks of the Alaska-Aleutian Range batholith that rise 1,200–1,500 m (about 3,900–4,900 ft) above sea level (Till and others, 1993, 1994). Located on the western side of Cook Inlet within Lake Clark National Park and Preserve, the volcano is 170 km (106 mi) southwest of Anchorage and 82 km (51 mi) west of Kenai (fig. 1). The most recent prior eruptive activity occurred December 14, 1989 through April 1990, and was characterized by 23 episodes of dome construction and destruction—some explosively, and some by gravitational collapse. The resulting pyroclastic flows mixed with ice and snow to produce voluminous lahars that threatened the oil storage and loading facility (Drift River Oil Terminal [DROT]) located along the western shore of Cook Inlet, 35 km (22 mi) downstream along the Drift River (fig. 6) (Miller and Chouet, 1994).

The 2009 eruption of Redoubt is divisible into three distinct phases: Precursory, Explosive/Effusive, and Effusive (Schaefer, 2012; Bull and Buurman, 2013).

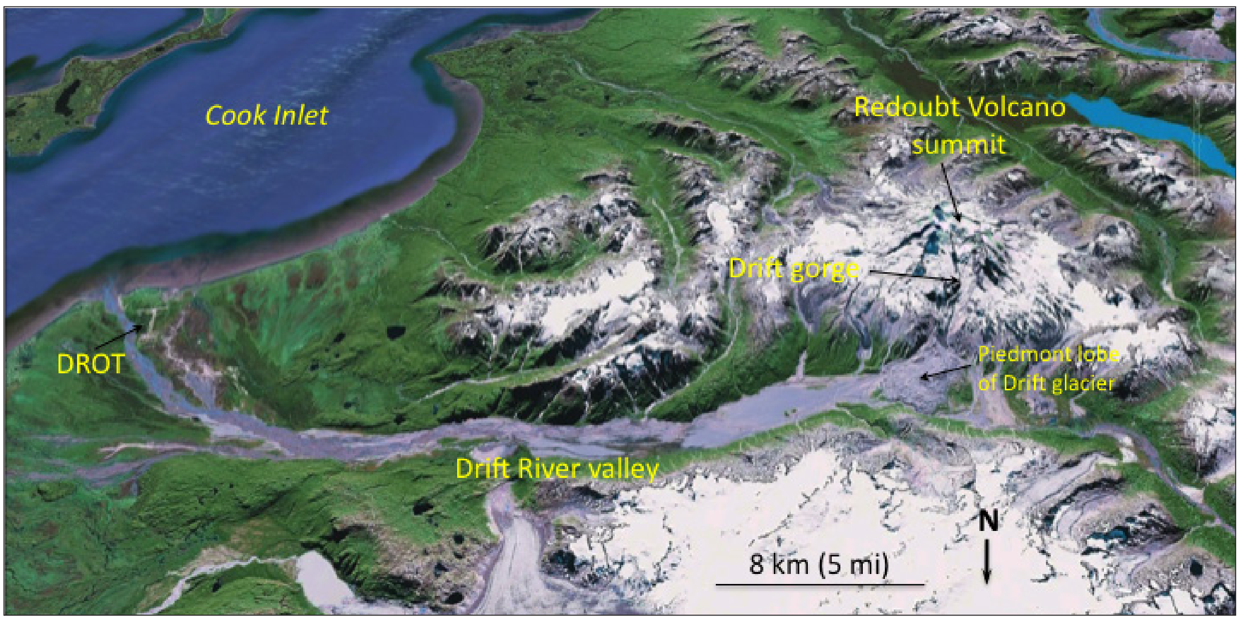


Figure 6. Oblique Google© Earth image of Redoubt Volcano and the Drift River valley. View is to the south. The oil storage and loading facility near Cook Inlet is DROT. Distance from the terminus of the piedmont lobe of Drift glacier down the Drift River valley to Cook Inlet is about 35 km (22 mi). Image is from 2008.

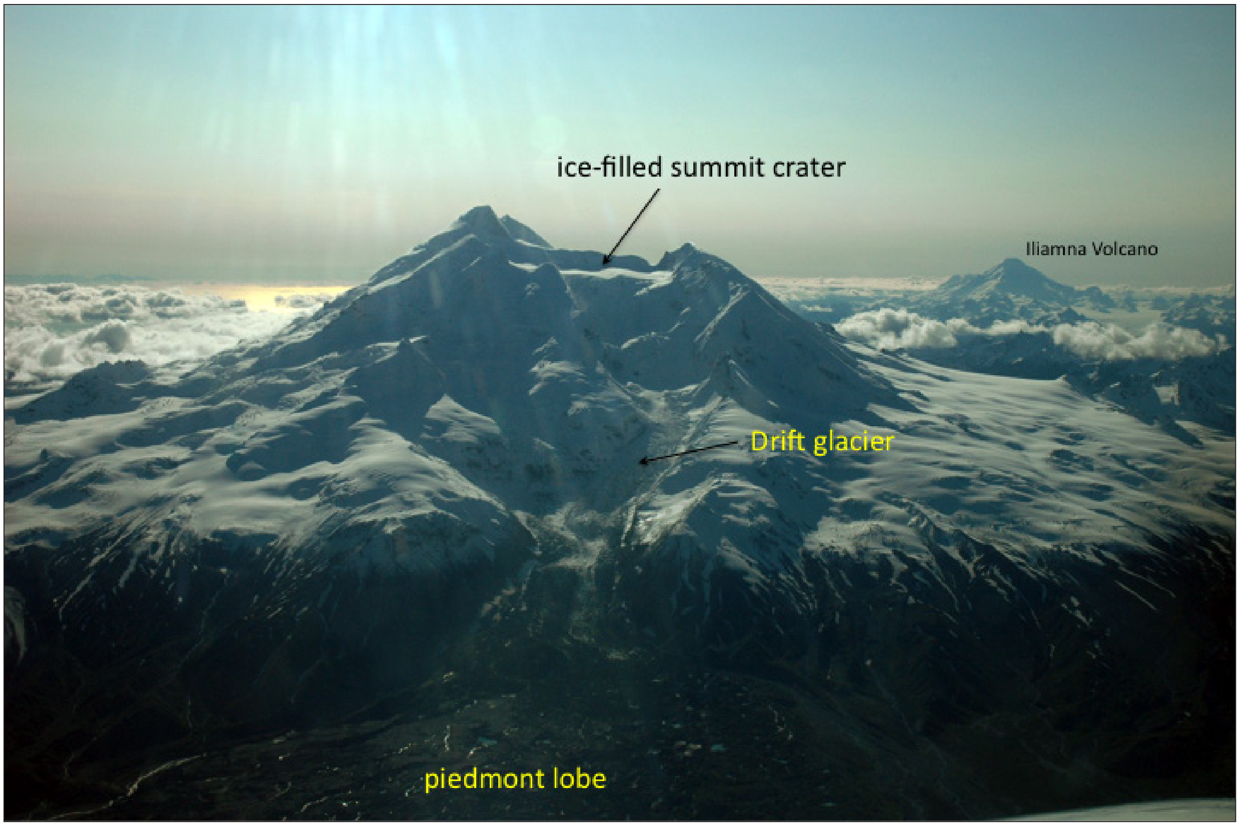


Figure 7. Oblique aerial view from the north of Redoubt Volcano. The ice-filled summit crater is breached to the north and feeds the Drift glacier, which flows down the northern flank through Drift gorge, and spreads into a piedmont lobe across the upper Drift River valley. Iliamna Volcano in distance to the right. Photograph by Game McGimsey, AVO/USGS, September 27, 2008. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=47111.

Precursory Phase—2007–March 15, 2009

In retrospect, the first indication of unrest occurred in early 2007 with the appearance of warm, vaporous, bare ground on the ice-covered 1990 lava dome (McGimsey and others, 2011, figs. 7 and 10; Neal and others, 2011), an indication of heat rising to the summit area. Ascent of magma from deep to shallow levels in the crust beneath the volcano occurred prior to May 2008 as implied from retrospective analysis of geodetic data (Grapenthin and others, 2013). During a late September 2008 overflight, a vigorous summit fumarole and melt holes were observed, including a prominent skylight above a 100-m-high (328 ft) waterfall concealed beneath the glacier (fig. 8). In October 2008, consistent with magma ascent, AVO gas monitoring determined that emissions of CO_2, SO_2, and H_2S had significantly increased to levels not observed since the 1989–90 eruption series (Werner and others, 2012). Surface deformation and multiple large melt holes soon developed in ice of the summit crater and Drift gorge, and increasing volumes of warm melt-water flowed into the upper Drift River valley. Anomalous seismicity was soon detected, and all signs pointed to a steady escalation of activity, prompting AVO on November 5, 2008, to upgrade the Aviation Color Code/Volcano Alert Level to **YELLOW/ ADVISORY**; Aviation Color Code status of the volcano had been at **GREEN** since March 5, 1993.

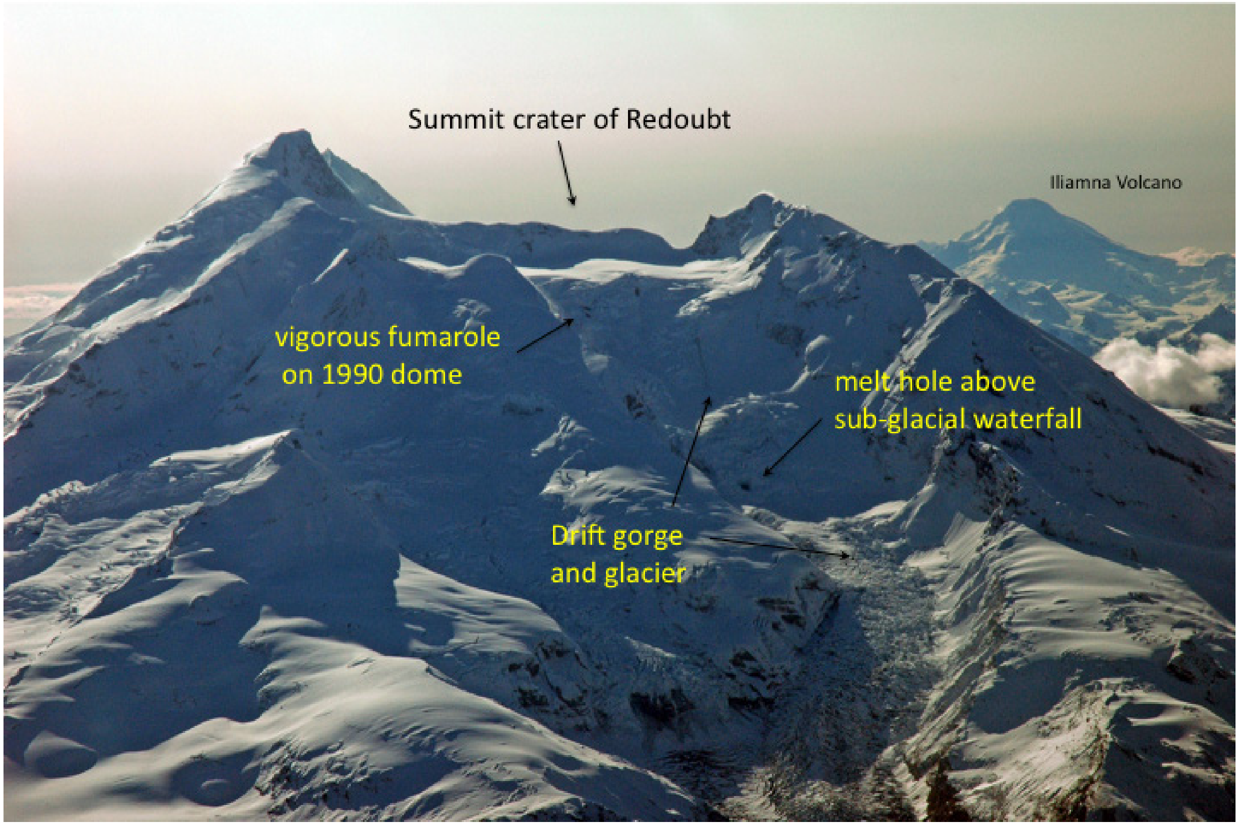


Figure 8. Oblique aerial view of Redoubt Volcano from the north. The ice-filled summit crater is breached to the north and feeds the Drift glacier down the northern flank through Drift gorge to the upper Drift River valley (out of view beyond bottom of photograph). The 1990 dome is buried in summit ice, although several steaming melt holes have developed, and a vigorous fumarole is present in one. Iliamna Volcano is in the distance. The melt hole midway down the Drift glacier developed sometime between the end of August and September 27, 2008, and is a skylight above a 100-m-high (328 ft) waterfall beneath the glacier. Photograph by Game McGimsey, AVO/USGS, September 27, 2008. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=47101.

Heat supply to the summit crater continued and gas emissions steadily increased over the next couple of months. On January 25, 2009, a sudden, striking increase in seismicity prompted AVO to upgrade the Aviation Color Code/Volcano Alert Level to **ORANGE/WATCH** (fig. 9). The summit fumarole, first documented in 2007 (McGimsey and others, 2011), had become quite vigorous and continued to enlarge the surrounding melt-hole, and on January 30, AVO staff onboard an overflight observed and photographed a prominent, roughly circular, 150-m-diameter (500 ft) piston-like subsidence structure within the crevassed ice plateau above the 1990 dome, further signs of intense thermal activity and generation (and possible storage?) of melt water in the summit crater (fig. 10); this ice cauldron would eventually enlarge to 225 m (750 ft) across and 100 m (330 ft) deep (Bleick and others, 2013). Seismicity continued to increase and during the first week of February, a nearly hour-long episode of repeating long-period events occurred followed by high levels of gas emission (Schaefer, 2012). Tremor continued at intermittent levels through February 25. A protracted decrease in seismic activity for the next 13 days led to lowering the activity levels to **YELLOW/ADVISORY** on March 10 (fig. 11).

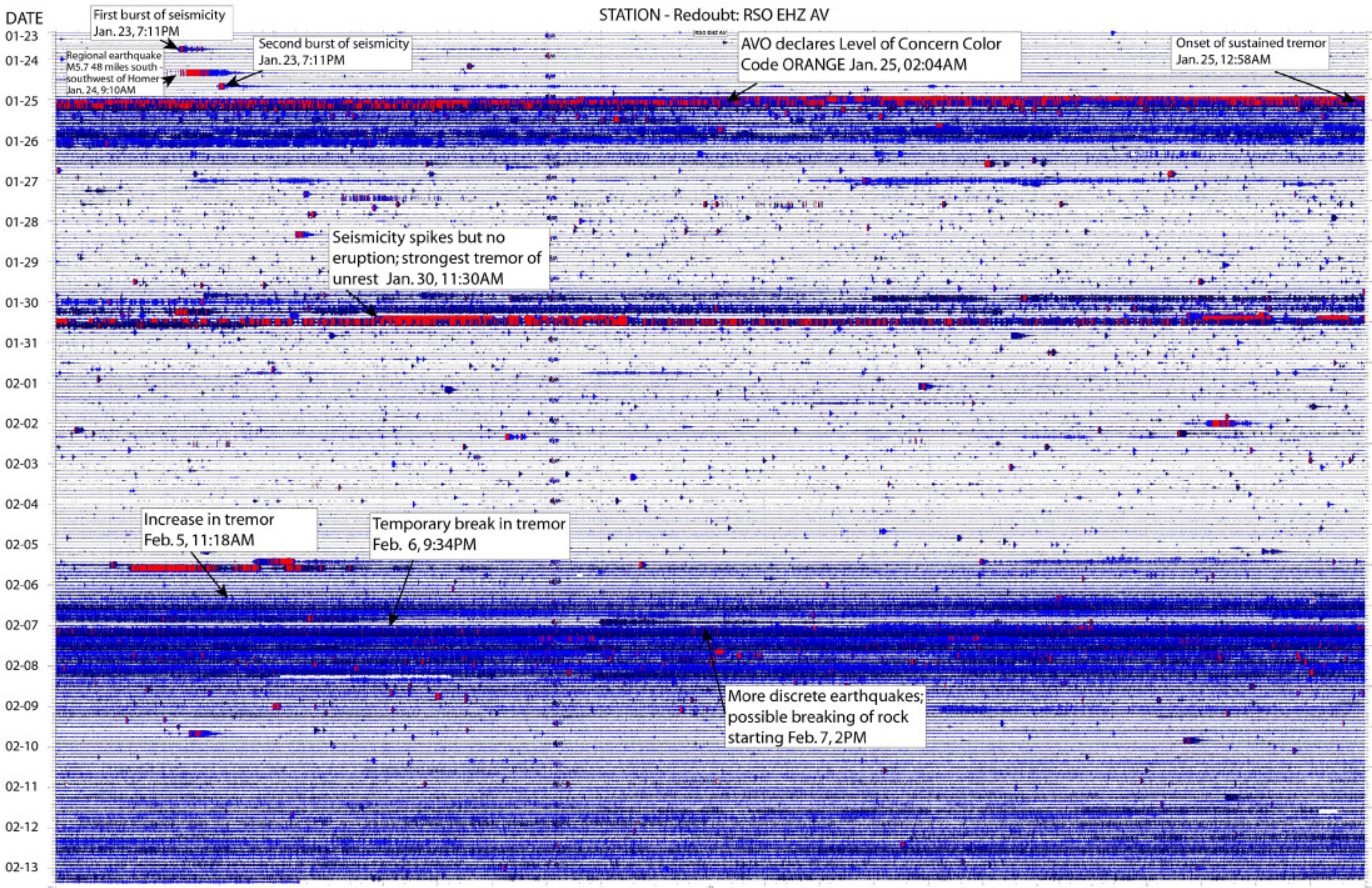


Figure 9. Annotated helicorder record for Redoubt seismic station RSO from January 23 to February 13, 2009, showing precursory activity. Location of station RSO can be seen in figure 48. A sudden increase in seismicity on January 25 prompted AVO to upgrade the Aviation Color Code/Volcano Alert Level to **ORANGE/WATCH**.

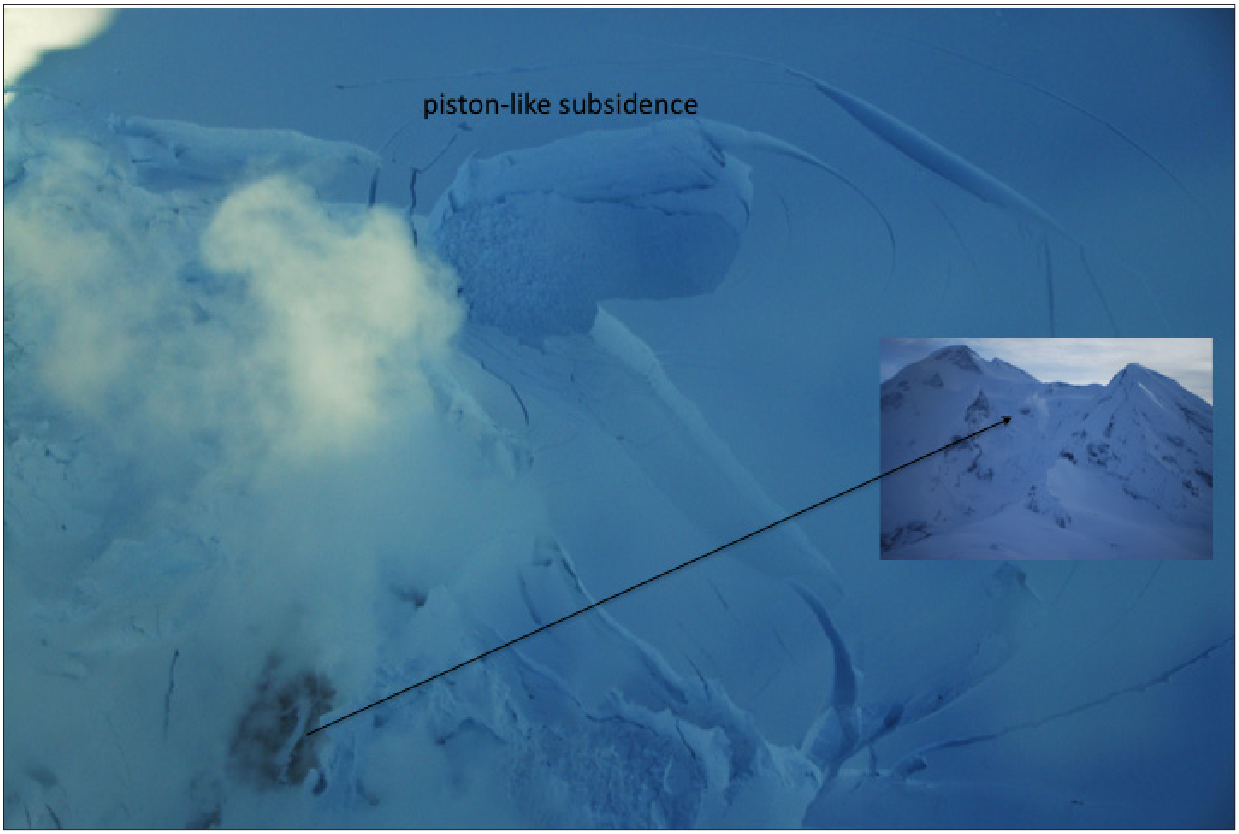


Figure 10. Plateau area in the summit crater of Redoubt above the 1990 dome. Note piston-like collapse feature and area of general subsidence of the snow/ice. These features were first observed on January 30, 2009, and had enlarged slightly by January 31. The bare area partly obscured by steam is the location of the 1990 dome. Photograph by Chris Waythomas, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=16407. Inset image shows the location of the fumarole and ice collapse pit in summit crater of Redoubt. Photograph by Heather Bleick, AVO/USGS, January 26, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=16316.

Explosive and Effusive Phase—March 15–April 4, 2009

Seismicity remained unchanged for the next 5 days until the afternoon of March 15, 2009 (fig. 11), when, with little seismic precursory activity, a phreatic explosion through the summit crater ice occurred at the southern margin of the 1990 lava dome, followed 7 days later by the first of 19 magmatic (juvenile-ash-producing) explosions that would be recorded during the subsequent 14 days (table 5; fig. 5). Associated ash clouds reached heights between 17,000 and 62,000 ft (5.2 and 18.9 km) ASL (Schaefer, 2012). Eruptive activity during this period was characterized by explosions (referred to as “Events” in table 5 and fig. 5), and intervening lava effusion.

Three main episodes of closely spaced magmatic explosions occurred: March 22–23 (Events 1-6); March 26–28 (Events 7-18); and April 4 (Event 19) (fig. 5). The explosive events on March 22–23 destroyed the existing1990 lava dome and excavated $0.5–1.5 \times 10^8$ m^3 of ice and snow from the upper Drift glacier and summit crater (Waythomas and others, 2013), sent ash clouds to 60,000 ft (18.3 km) ASL, and generated two large lahars that swept the Drift River valley wall to wall, inundating portions of the Drift River Oil Terminal (DROT) (figs. 12–15). High-water marks on the valley walls indicated a maximum flow depth of 6–8 m (20–26 ft) and peak discharge was estimated to range from 20,000 to 120,000 m^3/s

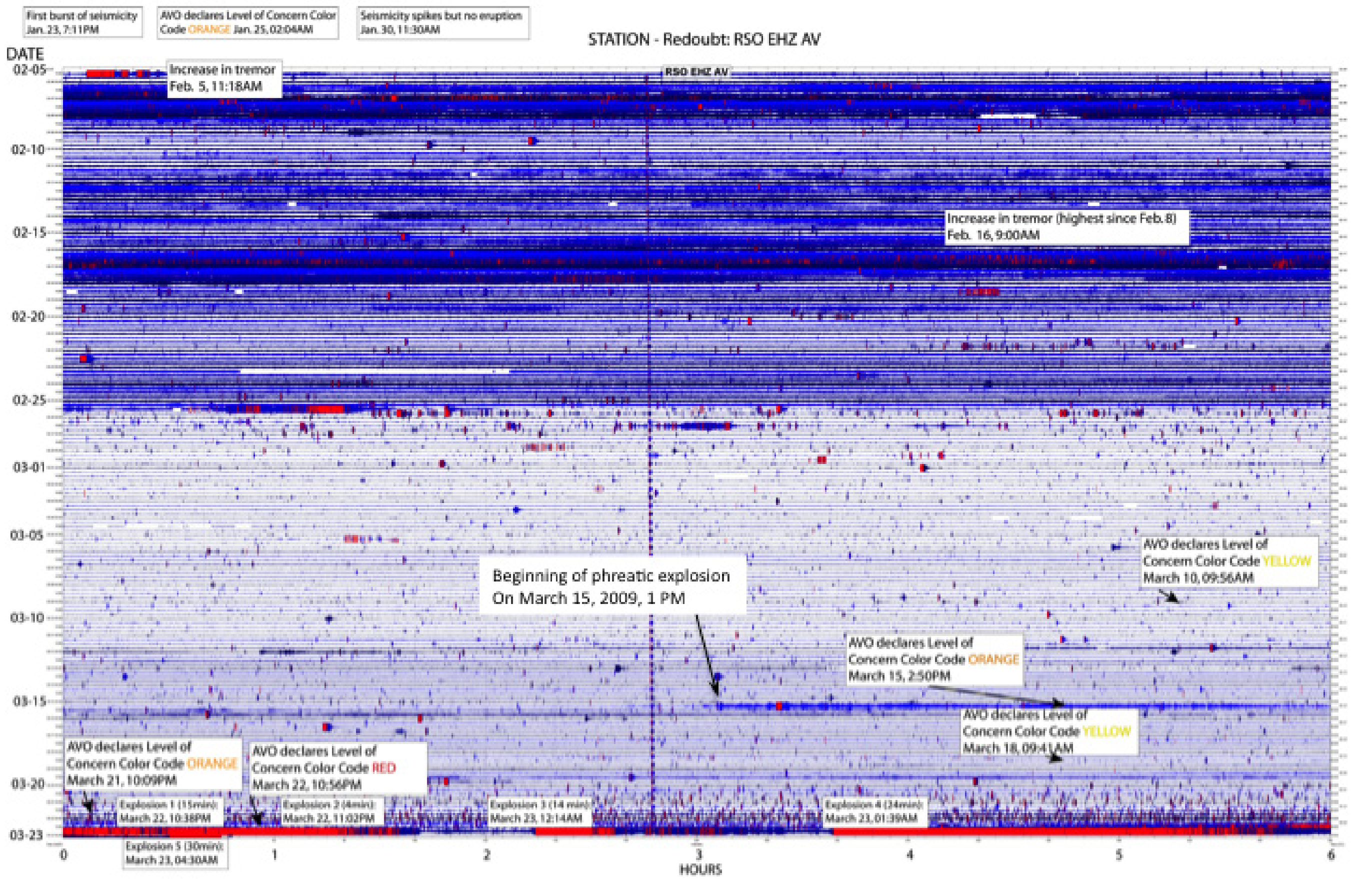


Figure 11. Annotated helicorder record from February 5 to March 23, 2009. A protracted decrease in seismic activity from February 26 to March 10, 2009, prompted AVO to decrease the Aviation Color Code/Volcano Alert Level to **YELLOW/ADVISORY.**

(Waythomas and others, 2013). Southerly winds carried the ash northward over the remote and sparsely populated Alaska Range (fig. 16). Retrospective analysis of satellite imagery revealed that new lava was extruded in the summit crater prior to the initial explosion on March 22; areal dimensions were 115 × 75 m (377 × 246 ft), with an estimated volume (inflated) of 6.5×10^6 m^3 (8.5×10^6 yds^3) (Bull and Buurman, 2013). This dome was short-lived, being destroyed by the five explosions on March 23. Event 6 produced the first pyroclastic flow of the eruption, which was caught on Web camera images (fig. 17).

No significant explosions were recorded from March 24–25, and renewed lava extrusion during this period is inferred based on seismicity (potentially dome #2), although there was no visual confirmation. Then began a 3-day period—March 26 through 28—during which 12 explosions occurred, with the largest, Event 8 (table 5), producing a lahar down the Drift River (figs. 18–19), and sending ash up to 62,000 ft (18.9 km) ASL. Events 7–10 produced ash that was carried east and southeast, and fell in minor amounts (< 2 mm) on communities of the Kenai Peninsula (fig. 16). The explosions on March 27–28, Events 11–18, produced ash plumes that were conveyed by winds aloft north and northeast of the volcano; Event 11 also produced a pyroclastic flow that descended onto the piedmont lobe of Drift glacier (fig. 20). Event 13 on March 27 sent an eruption cloud to 50,000 ft (15.2 km) and was widely viewed by residents on the Kenai Peninsula (fig. 21).

Figure 12. View down the Drift River valley of the massive—wall to wall—lahar inundation resulting from the March 22–23, 2009, eruption of Redoubt Volcano (Events 2–5, table 5). Point A is the location for figure 13, which shows the high-water mark along the base of the southern valley wall. Photograph by Game McGimsey, AVO/USGS, March 23, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=16997.

Figure 13. High-water mark (6–8 m; 20–26 ft; Waythomas and others, 2013) above the active channel on the southern wall of Drift River valley about midway downstream from the volcano resulting from the March 22–23, 2009, eruption of Redoubt Volcano (see fig. 12, point A for location). Drift River runs about 35 km (22 mi) from the volcano to the shore of Cook Inlet. Photograph by Cyrus Read, AVO/USGS, March 23, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17016.

Figure 14. Lahar deposits from the March 22–23, 2009, eruption of Redoubt Volcano that surround the oil storage tank farm at DROT. View is to the southeast toward the shore of Cook Inlet. The main channel of Drift River is left of the tanks. Rust Slough—overwhelmed by lahar deposits—is flowing adjacent to the protective dike right of the tanks; channel modifications directed the main flow of all subsequent lahars down this drainage. The debris in the foreground accumulated nearly to the top of the protective dike, which prior to the eruption was 6 m (20 ft) high. Minor lahar spillage over the dike occurred from flow down Rust Slough (right side of tanks). Point A is the location for the photograph in figure 15. Photograph by Game McGimsey, AVO/USGS, March 23, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=16985.

Figure 15. View to the west across the debris-laden airstrip at DROT showing lahar inundation of facilities (up to 2 m, 6.5 ft) resulting from the March 22–23, 2009, eruption of Redoubt Volcano, about 35 km (22 mi) up the Drift River valley. The oil storage tank farm shown in figure 14 is just visible at top of the image. Photograph by Game McGimsey, AVO/USGS, March 23, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=47131.

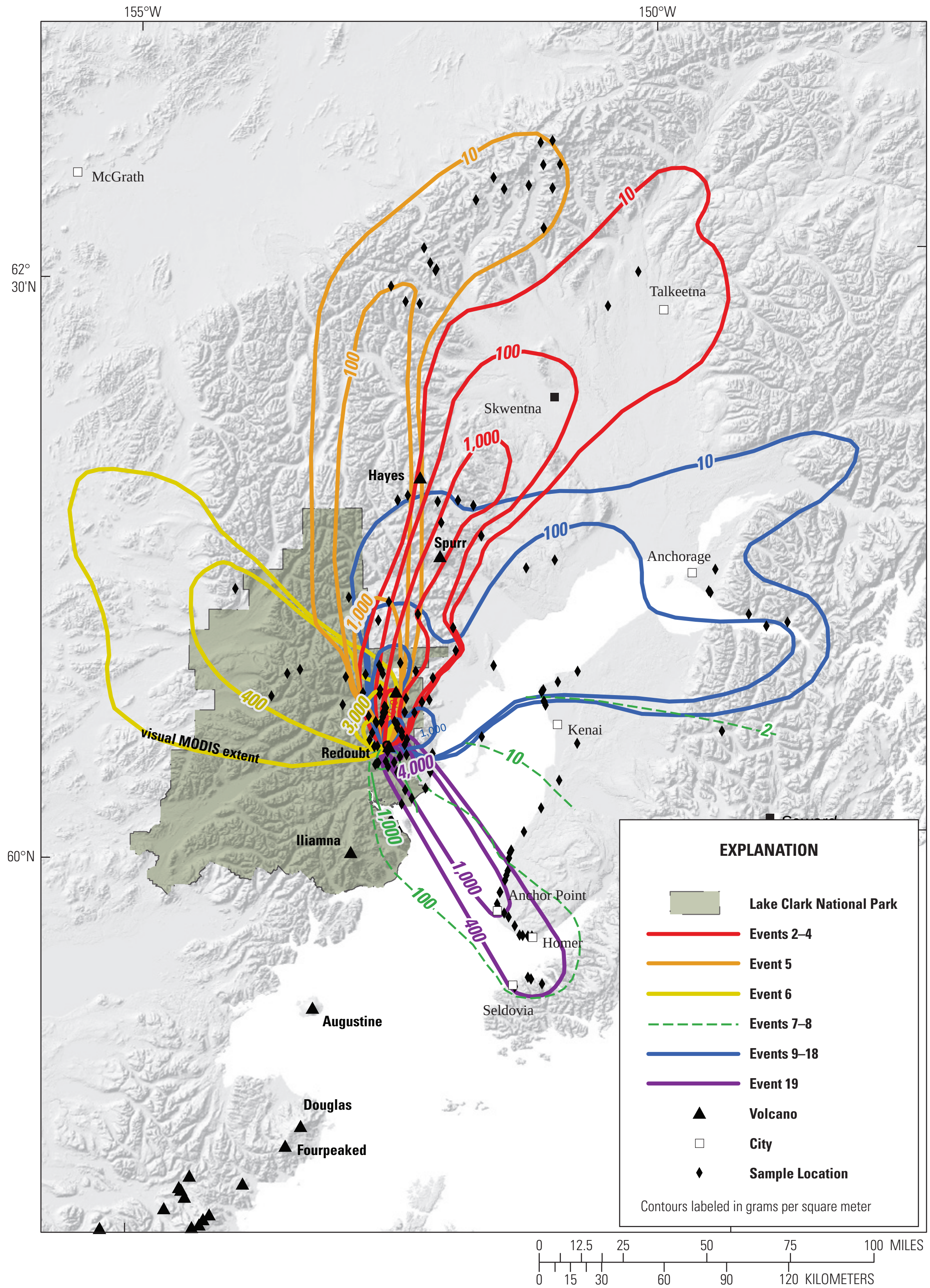


Figure 16. Ash distribution and isomass contours of tephra fall deposits from the 2009 eruption of Redoubt Volcano. Isomass contours (lines delineating areas of equal mass) are in grams per square meter with the outermost (minimum) line shown of 10 g/m^2 except for Event 6 where the outermost contour indicates ash visible on the snow in MODIS satellite imagery. Trace amounts of ash were deposited beyond all 10 g/m^2 contours. Figure 12 in Schaefer (2012); Schaefer and Wallace (2012); Wallace and others (2013).

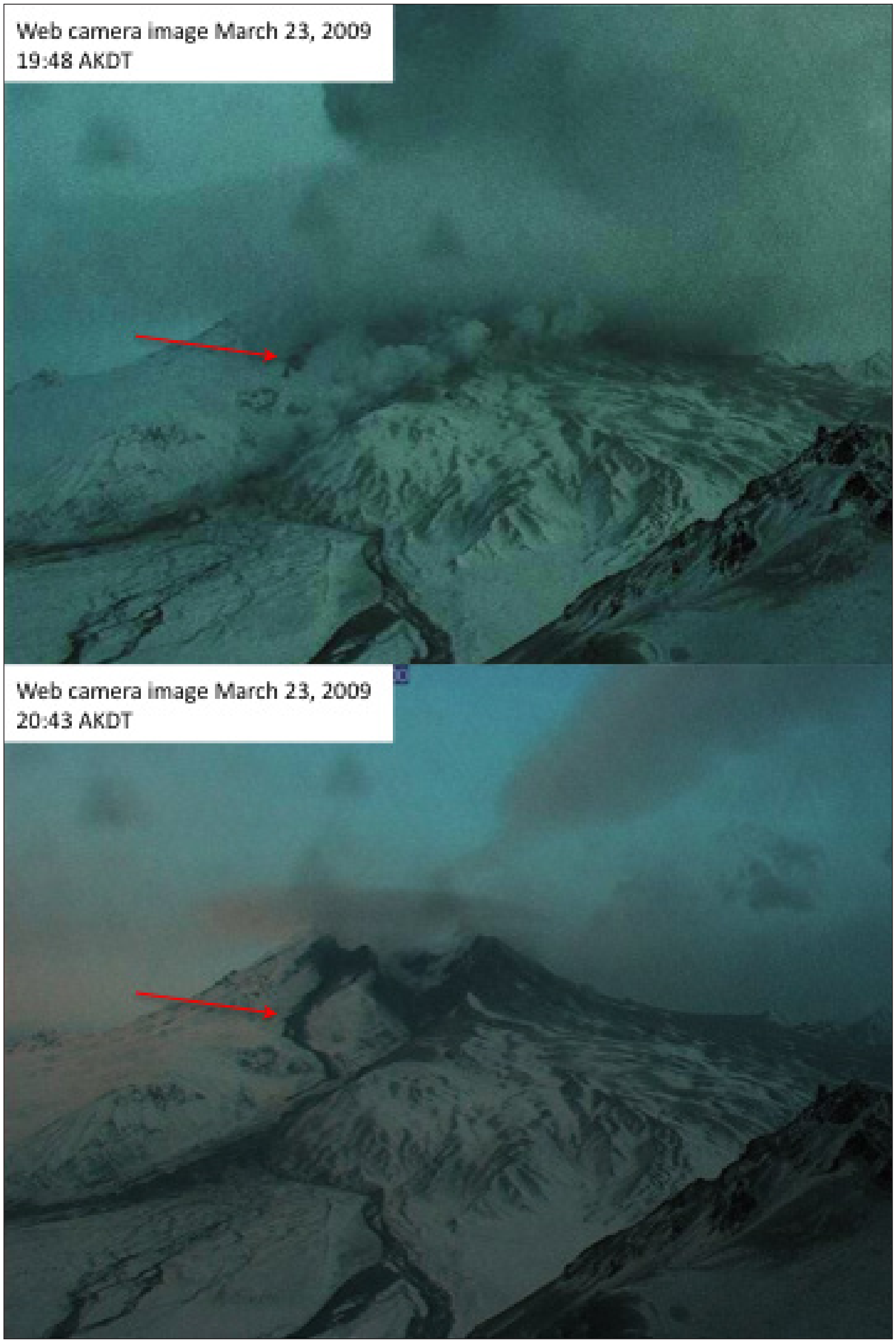


Figure 17. Photographs taken from the Web camera located at the AVO monitoring hut (known informally as Juergen's Hut), located on a ridge 11 km (6.8 mi) north of Redoubt, captured the first pyroclastic flow of the 2009 Redoubt eruption on the afternoon of March 23, 2009. In the upper image, taken at 19:48 AKDT, the red arrow points to the flow front 8 minutes after the onset of Event 6. In the lower image, taken at 20:43 AKDT after the eruption cloud has dissipated, the red arrow points to the same location. The pyroclastic flow overtopped the east summit ridge as seen in the lower image, and the flow advanced down the flank and merged onto the Drift glacier. AVO database images URL: http://www.avo.alaska.edu/images/image.php?id=36062 and http://www.avo.alaska.edu/images/image.php?id=17027.

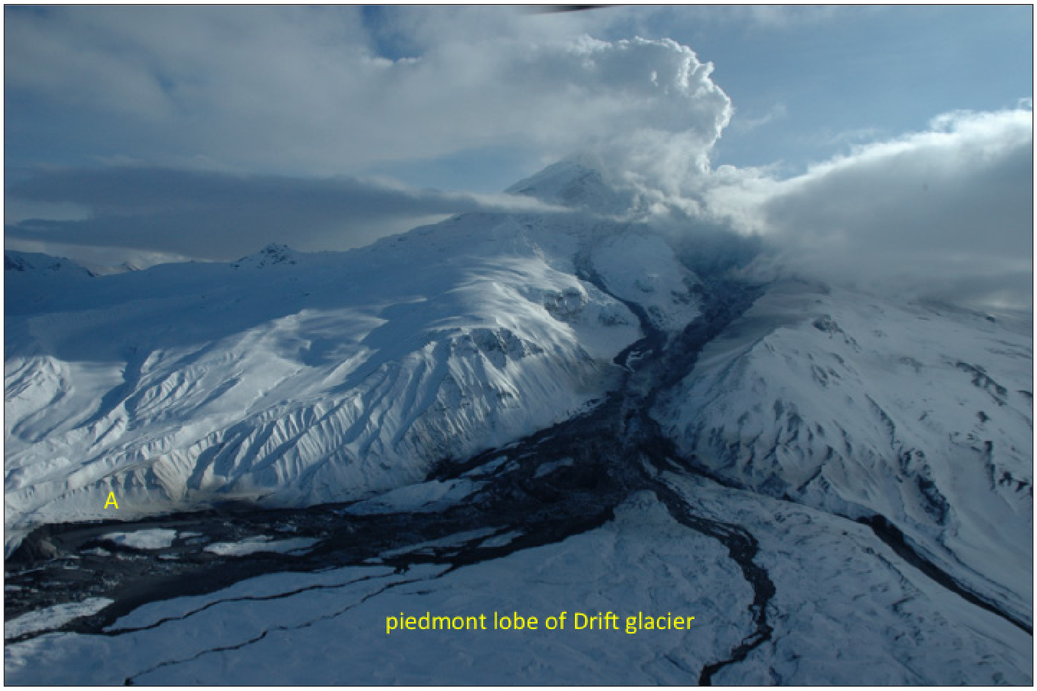


Figure 18. Flow channels and deposits down the Drift gorge and onto and across the piedmont lobe of Drift glacier resulting from the eruptions of March 26, 2009 (Events 7 and 8). View is from the north. Point A corresponds to A′ in figure 19. Photograph by Game McGimsey, AVO/USGS, March 26, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=47241.

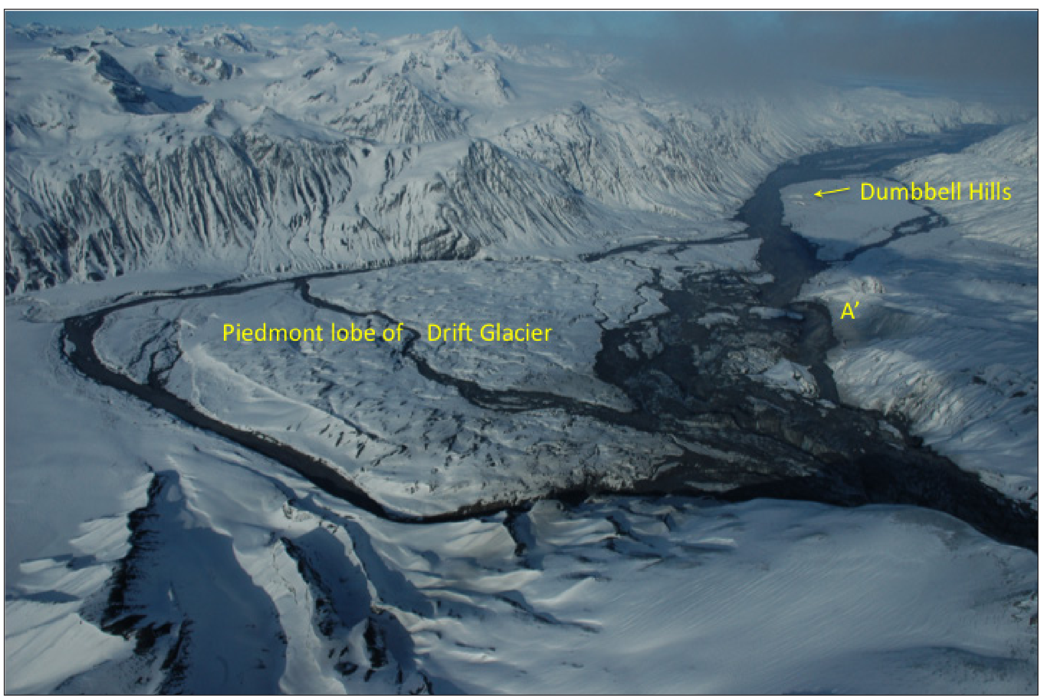


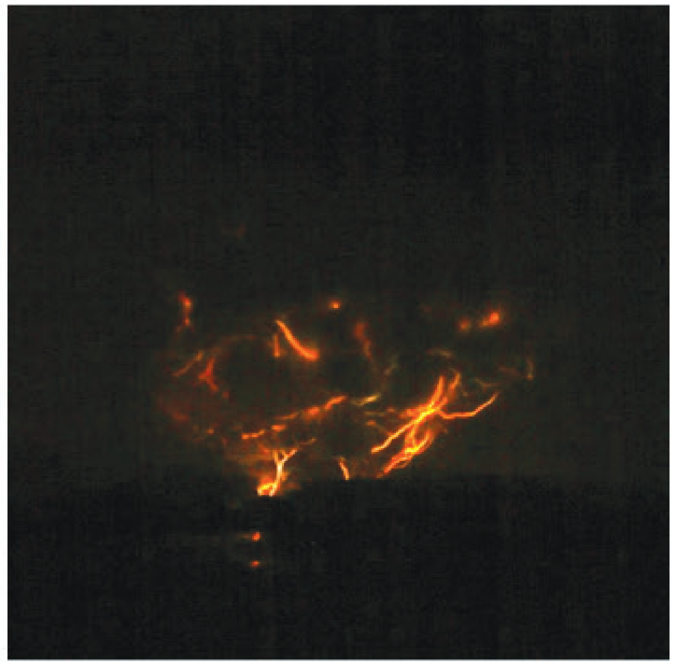
Figure 19. Piedmont lobe of Drift glacier down the Drift River valley with flowage channels and deposits resulting from explosive Events 7–8 on March 26, 2009. View is from the east. The lahars and flood waters have deeply incised the eastern (right) side of the piedmont lobe. Point A′ corresponds to point A in figure 18. Redoubt is out of the field of view off the right side of image. For scale, the valley is 2 km (1.25 mi) wide at Dumbbell Hills. Photograph by Game McGimsey, AVO/USGS, March 26, 2009. AVO image database URL: http://www.avo.alaska.edu/images/image.php?id=47251.

Figure 20. Pyroclastic flow descending from Redoubt's summit down Drift gorge and glacier on the northern flank and onto the piedmont lobe of Drift glacier during the eruption of March 27, 2009 (Event 11). Photograph taken by an AVO time-lapse camera located on Dumbbell Hills, a bedrock island in the upper Drift River Valley (see fig. 19 for location of Dumbbell Hills). AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17878.

Figure 21. Ash column and cloud from the Event 13 eruption of Redoubt on March 27, 2009, 19:24:00 AKDT. Photograph courtesy of Dennis Anderson, http://auroradude.zenfolio.com/. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17278.

Events 14 and 15, during the nights of March 27 and 28, produced spectacular lightning in the ash plumes (fig. 22). Clear views on the afternoon of March 28 provided observations of the pyroclastic deposits blanketing the summit of Redoubt following Event 15 (fig. 23). Event 17 (March 28, 15:29 AKDT) sent a plume to 41,000 ft (12.5 km) and southwesterly winds carried the ash over the northern Kenai Peninsula and Anchorage (figs. 16, 24). Trace amounts of ash fell on Anchorage resulting in closure of the Ted Stevens International Airport for 20 hours and disruption of commercial air traffic (figs. 25–26). The final eruption of this period (Event 18) occurred in the early evening of March 28, 2009, sending a plume to 48,000 ft (14.6 km) that was carried to the northeast; no communities were impacted (Wallace and others, 2013).

A



B

Figure 22. Photographs showing A. Lightning generated during Event 14 eruption of Redoubt, March 27, 2009, 23:19:00 AKDT and B. Lightning generated during Event 15, March 28, 2009, 01:19:00. Both photographs courtesy of Bretwood Higman. AVO database images at URL: A. http://www.avo.alaska.edu/images/image.php?id=17283; B. http://www.avo.alaska.edu/images/image.php?id=17288.

Figure 23. Southwest flank of Redoubt Volcano covered in pyroclastic deposits from the Event 15 eruption, 01:19 AM AKDT on March 28, 2009. Center in view is the Crescent glacier. Note the lighter-colored, still-steaming pyroclastic deposit on the west (left) margin of the glacier. The pyroclastic deposits likely formed from low-height column collapse because they are about equally distributed and draped around the upper flanks. The ash plume from this event was directed north. Photograph courtesy of Jeff Duft. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17665.

Figure 24. March 28, 2009, eruption cloud from Redoubt (Event 17) as seen from the highway between Kenai and Nikiski, Alaska on the northern Kenai Peninsula (see fig. 16 for location). This cloud eventually dropped minor amounts of ash in Anchorage, closing Ted Stevens International Airport for 20 hours. Photograph courtesy of Leigh Hagstrom-Sanger. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17562.

Figure 25. Impact from volcanic ash fall in Nikiski, Alaska (see fig. 16 for location). This ash was generated during Event 17 explosive eruption of Redoubt Volcano on March 28, 2009, at 15:29 AKDT and began falling here at approximately 16:16 AKDT, lasting about 5 minutes. Fine ash is re-suspended as vehicles drive over the recently deposited ash fall deposit. Photograph by Kristi Wallace, AVO/USGS, March 30, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17536.

For the next 7 days, a new lava dome grew in the summit crater, punctuated by several minor explosions (fig. 5). This dome had final areal dimensions of 700 × 330 m (2,297 × 1,083 ft), and an estimated volume (inflated) of 3.9×10^7 m^3 (5.1×10^7 yds^3) (Bull and Buurman, 2013). Seismicity during this period varied and included two distinct seismic swarms. On the morning of March 29, a 1-hour-long swarm occurred that consisted of 37 repeating earthquakes, and was followed by 20 hours of high-amplitude spasmodic tremor that was associated with continuous, low-level ash emissions (Buurman and others, 2013; Schneider and Hoblitt, 2013). Then, on April 2, a 43-hour swarm of repeating earthquakes began that culminated in the final explosive event (Event 19) of the 2009 eruption early on the morning of April 4, 2009 (Buurman and others, 2013). The lava dome collapsed and was destroyed, ash clouds rose to 50,000 ft (15 km) (fig. 27), and satellite images revealed that a deep, wide crater was excavated around the summit vent. A pyroclastic flow of hot dome debris cascaded down the Drift gorge, spilling over the lower west shoulder, and onto the upper half of the piedmont lobe of Drift glacier (figs. 28–29). A massive lahar was generated and coursed bank-to-bank down the Drift River valley further inundating the DROT facilities (fig. 29). The lahar was primarily a hyperconcentrated flow, rich in sand, with a peak discharge of 60,000–160,000 m^3/s (Waythomas and others, 2013); in comparison, the largest lahar of the 1989–90 eruption—generated on January 2, 1990—had a peak discharge of about 80,000 m^3/s (Dorava and Meyer, 1994). Average flow depths were 2–5 m (6.6–16.4 ft) with 10 m (33 ft) flow run-up 14 km (8.7 mi) downstream from the terminus of Drift glacier, and maximum run-up near Dumbbell Hills of 27 m (89 ft) (figs. 30–31) (Waythomas and others, 2013). The lahar spread widely once it exited the confines of the valley, surrounding and partially inundating DROT, and entering Cook Inlet (figs. 32–33).

Figure 26. Volcanic ash from the March 28, 2009, eruption of Redoubt (Event 17) in Anchorage, Alaska. Upper photograph shows field maintenance crews at Ted Stevens International Airport on March 29, 2009, plowing and blowing snow that was mixed with ash to facilitate removal. Trace amounts of ash (<1 mm) fell in Anchorage prompting closure of the airport for 20 hours. Lower photograph shows heavy vehicle traffic on Tudor Road on March 31, 2009, that stirred and re-suspended ash resulting in poor air quality. Both photographs taken by Bill Roth, and provided courtesy of the Anchorage Daily News. Used with permission.

Figure 27. Eruption of Redoubt Volcano on April 4, 2009, 05:58 AKDT (Event 19). Lightning arcs through the ash plume. The cloud rose to 50,000 ft (15.2 km) and was carried southeast over Cook Inlet and the lower Kenai Peninsula (fig. 36). Copyrighted photograph courtesy of Marco Fulle–Stromboli Online. Used with permission.

Figure 28. Redoubt Volcano viewed from the northwest following the April 4, 2009, eruption (Event 19). Steam rises from the summit crater, pyroclastic flow and surge deposits drape the flanks and shoulders of Drift gorge, and lahar deposits cover the Drift River valley. Photograph by Game McGimsey, AVO/USGS. AVO image database at URL: http://www.avo.alaska.edu/images/image.php?id=17860.

Figure 29. Aftermath of the April 4, 2009, eruption of Redoubt (Event 19). The upper image is the view from the east showing steam rising from the summit crater, pyroclastic flow and surge deposits on the northern flank and onto the piedmont lobe of Drift glacier, and lahar deposits in the upper Drift River valley. The lower image was taken from the west and shows pyroclastic flow and surge deposits on the lower northern flank of Redoubt and the wall-to-wall lahar inundation of Drift River valley out to the coast. The valley is approximately 2 km (1.25 mi) wide at the location of Dumbbell Hills. Lahar deposits from this event overtopped and covered all prior lahar and flood deposits in the valley. For reference, point A marks the same location in each image. Both photographs by Game McGimsey, AVO/USGS. AVO database images at URL: Upper. http://www.avo.alaska.edu/images/image.php?id=17849. Lower. http://www.avo.alaska.edu/images/image.php?id=47141.

Figure 30. Lahar and flood deposits in the Drift River valley from the April 4, 2009, eruption of Redoubt Volcano. The location is on the northern side of the valley where the Drift River lobe of Double Glacier enters the valley, about 14 km (8.7 mi) downstream from the terminus of the Drift glacier. The flow ran up onto, and through low points on the terminal moraine shown above. High water mark on the trees was 10 m (33 ft) above the active channel, though average flow depths were estimated to have been 2–5 m (6.6–16.4 ft) (Waythomas and others, 2013). Photograph by Willie Scott, CVO/USGS, April 17, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=18170.

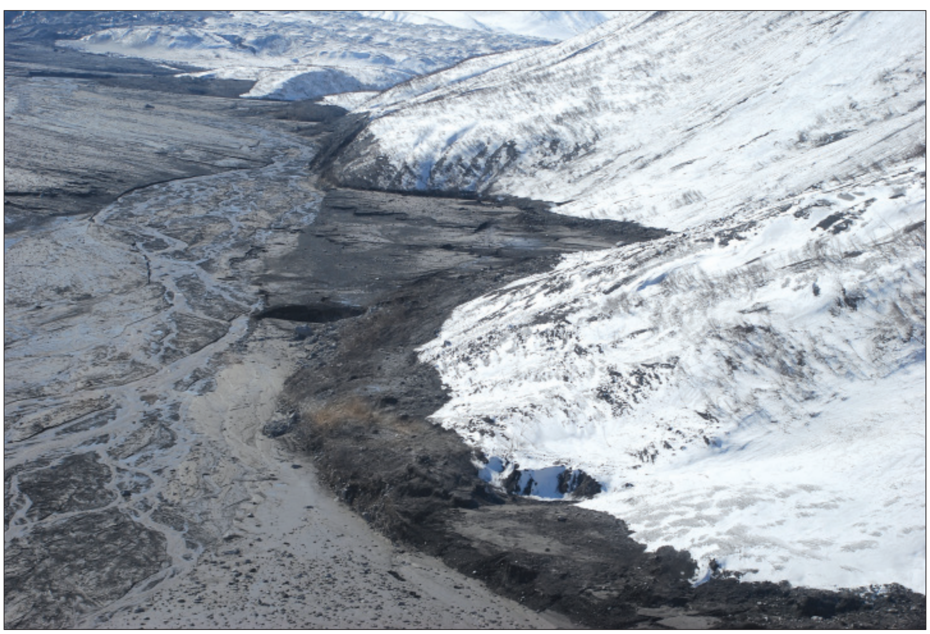


Figure 31. Upper Drift River valley and lahar run-up onto the northern valley wall, across from Dumbell Hills (see fig. 29) from the April 4, 2009, eruption of Redoubt Volcano. The maximum vertical run-up at this location was about 27 m (89 ft; see fig. 13 of Waythomas and others, 2013); the flow, advancing down the Drift gorge, was directed diagonally across the valley and “sloshed” up against this northern valley wall, producing higher run-up than locations farther down valley. The high-water mark in straight sections of this part of the upper Drift valley was 13 m (43 ft; Waythomas and others, 2013). Photograph by Kate Bull, AVO/AKDGGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17806.

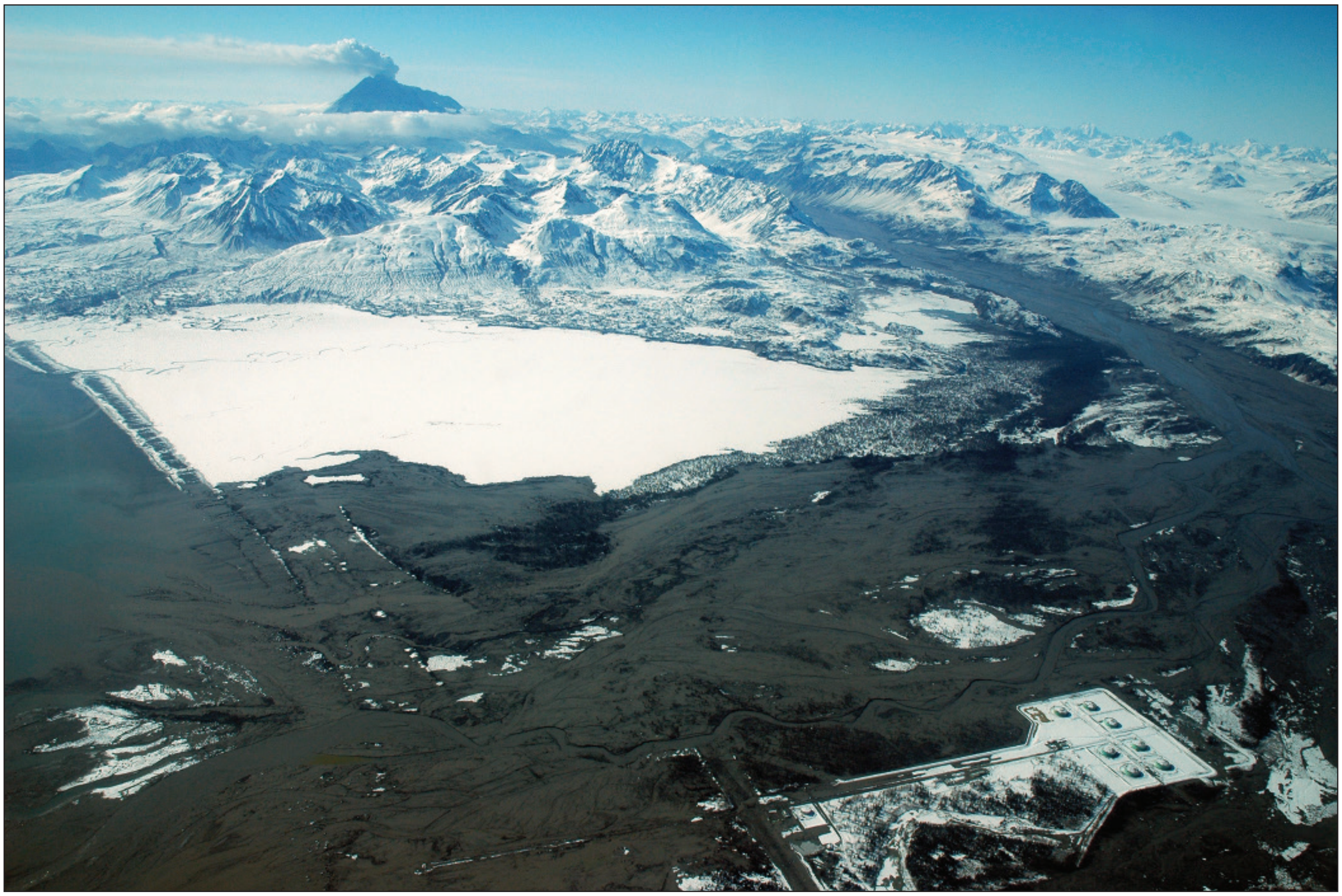


Figure 32. Steaming Redoubt Volcano and lahar debris from the April 4, 2009, eruption (Event 19) that inundated the Drift River valley, impacting part of the DROT facility (lower foreground), and extending into Cook Inlet. View is from the east. Photograph by Game McGimsey, AVO/USGS, April 4, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=47191.

Figure 33. Panoramic view from the south of lahar debris from the April 4, 2009, eruption of Redoubt Volcano (Event 19). The flow emerged from the Drift River valley (left), engulfed the DROT, and then entered Cook Inlet. Image by Game McGimsey, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17863.

A peculiar phenomena was observed offshore where the lahar debris entered Cook Inlet (fig. 34). Although the April 4, 2009, lahar deposit was quite ice-poor (Waythomas and others, 2013), the flow itself carried large blocks of ice—both river channel and glacier—and frozen, ice-rich deposits from previous lahars. The ice and frozen debris floated upon entering Cook Inlet. An ebbing tide (National Oceanic and Atmospheric Administration, 2008) presumably interacted with the flow entering the Inlet to spiral the material into a large, vorticular mass about 760 m (2,500 ft) in diameter. Floating ice blocks are up to 14–15 m (46–49 ft) across, and comparable to large blocks left stranded in the Drift River valley (fig. 35).

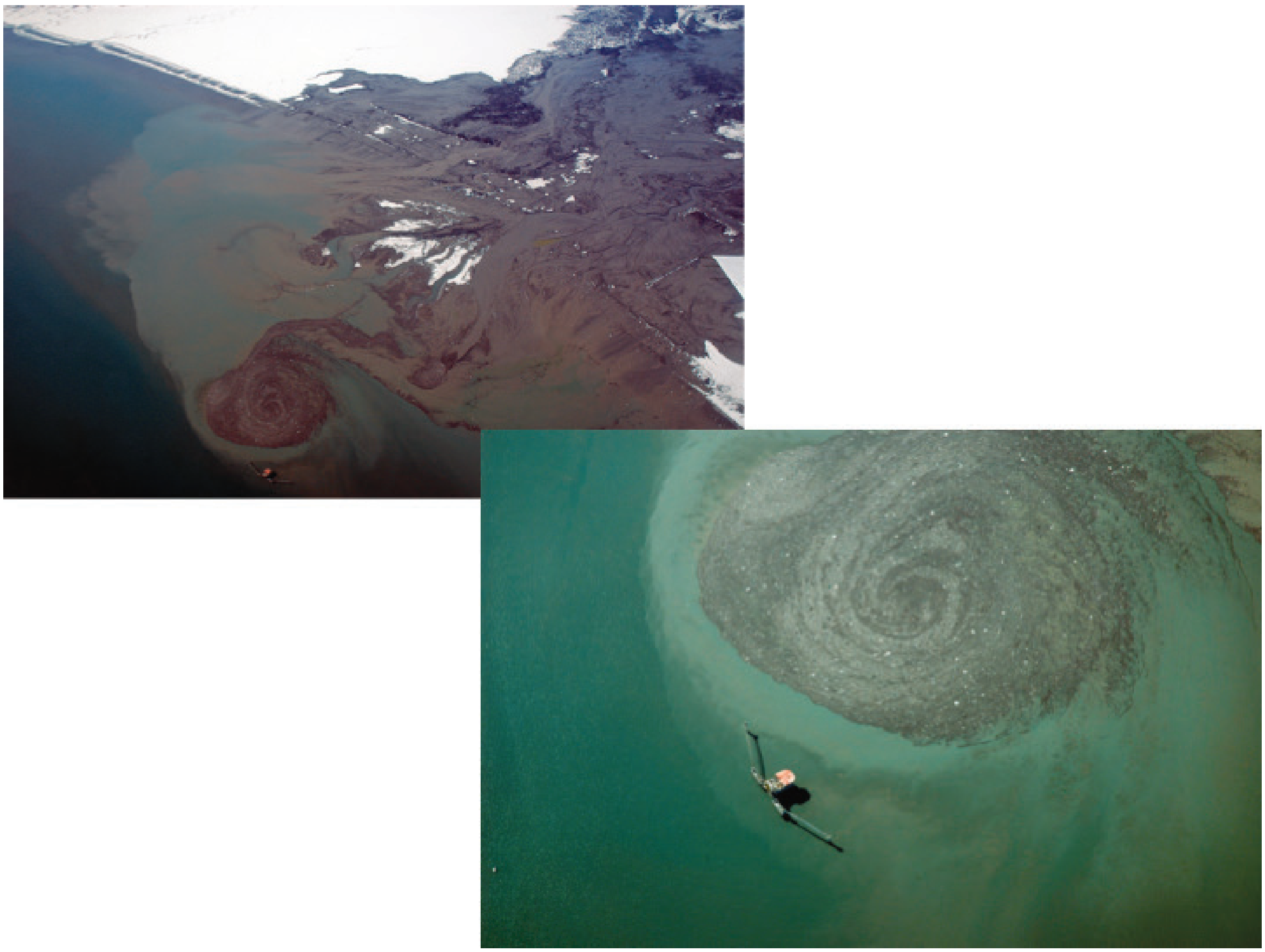


Figure 34. Lahar debris from the April 4, 2009, eruption of Redoubt Volcano entering Cook Inlet. A large vorticular mass of ice blocks and debris (frozen?) developed at the flow front. The largest ice blocks are 14–15 m (46–49 ft) across. These photographs were taken at 15:12 AKDT, about 2 hours into an ebb tide (National Oceanic and Atmospheric Administration, 2008). The structure immediately outboard of the mass is the Christy Lee oil-loading platform, part of the DROT operations. Both photographs by Game McGimsey, AVO/USGS. AVO database images at URL: http://www.avo.alaska.edu/images/image.php?id=47161 (top image), and URL: http://www.avo.alaska.edu/images/image.php?id=47171 (bottom image).

Figure 35. Large block of glacier ice carried either from the summit crater of Redoubt or plucked from the Drift glacier and carried to this location by the lahar produced from the April 4, 2009, eruption of Redoubt (background). This block is 12 m (40 ft) across and 10 m (33 ft) tall (lowest portion obscured in photograph) on April 30, 2009, when this photograph was taken. The ice block was likely larger when left stranded adjacent to Dumbbell Hills 26 days earlier (see fig. 29 for location), 4 km (2.5 mi) from the terminus of Drift glacier. Geologist Rick Wessels examines the block and geologist Chris Waythomas (in distance) stands near another large ice block. The high-water mark near this site was 8.2 m (27 ft). Photograph by Game McGimsey, AVO/USGS, April 30, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=19218.

The ash cloud produced by the April 4, 2009 eruption (Event 19) was carried southeasterly over the mountains of the Aleutian Range, across Cook Inlet, and then over the southern Kenai Peninsula where 1–2 mm of ash fell on local communities (cover photograph, figs. 16, 36–39) (Wallace and others, 2013). A day later, another, although much smaller, steam and ash emission was observed.

Figure 36. View from the west of Redoubt Volcano following the April 4, 2009, eruption (Event 19). The ash cloud produced from this event was carried to the southeast (same direction as the steam plume in image) over Cook Inlet and the southern Kenai Peninsula. Panoramic photograph by Game McGimsey, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=47151.

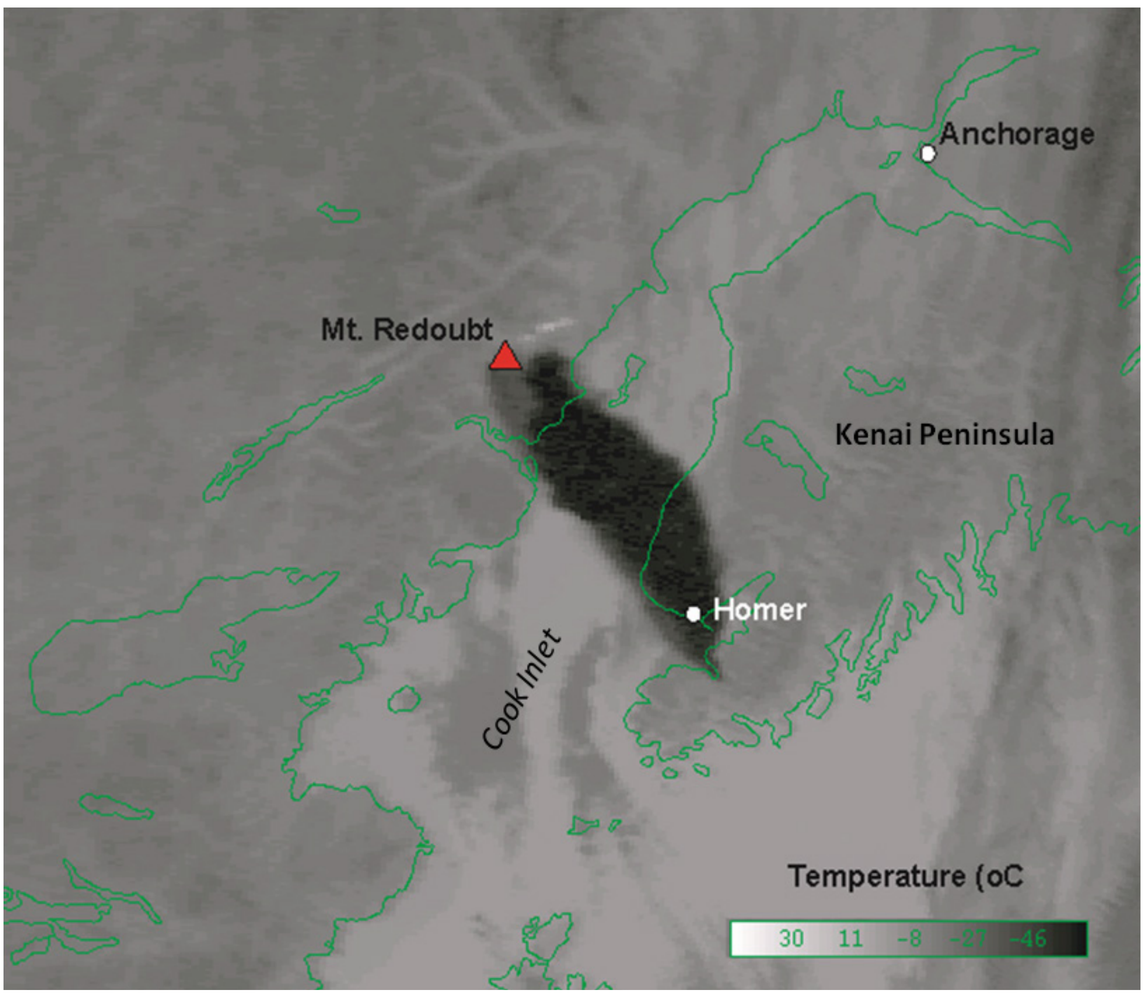


Figure 37. Infrared satellite image captured by AVHRR (Advanced Very High Resolution Radiometer) at 14:45 UTC (06:45 AM AKDT) on April 4, 2009. The darker area is the ash cloud emitted from Redoubt Volcano during explosive Event 19 that began at 05:58 am AKDT. The gray area immediately south of the volcano is the ash deposit that fell on the snow-covered mountains (see cover photograph). Image created by John Bailey, AVO/UAF-GI. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17797.

Figure 38. Ash from the early morning April 4, 2009, eruption of Redoubt (Event 19) covering the windshield and hood of a vehicle in Homer, Alaska. Up to 2 mm of ash fell across the southern Kenai Peninsula (Wallace and others, 2013). Photograph courtesy of Chas Stock. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17820.

Figure 39. Ash from the early morning eruption of Redoubt on April 4, 2009, covering the snow in Homer, Alaska. Up to 2 mm of ash fell on the southern Kenai Peninsula. Photograph courtesy of Terry Thompson. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17825.

On the morning of April 5, 2009, AVO received a call and photograph from a resident on the Kenai Peninsula who witnessed an unusual phenomena at Redoubt. A dark plume rose more than several thousand feet from a location far removed from the summit and at a much lower elevation on the northern flank of Redoubt (fig. 40). Informally referred to as “Jr. Plume,” the activity was determined to result from hot pyroclastic debris, which had spilled over the western shoulder of Drift gorge onto glaciers of the northern flank during the April 4, 2009 eruption; the debris was sifting down into crevasses, interacting with glacier ice, and producing intermittent phreatic explosions and small plumes of steam and possibly entrained ash. Plumes were not continuous, and the activity was monitored with images acquired from a nearby Web camera (located at seismic station DFR) on a ridge northeast of Drift glacier (fig. 41). The anomalous activity occurred intermittently from April 5–10, 2009. On April 16, an AVO field crew verified that activity has ceased, photographed the rootless vent, and landed by helicopter to collect samples (fig. 42).

Figure 40. Redoubt Volcano viewed from the east. The dark, vertical column rising right (north) of the volcano is from a “rootless” phreatic eruption where pyroclastic debris channeled down the Drift glacier during the April 4 eruption overflowed laterally onto a deeply crevassed flank glacier. The hot debris flowed into several closely spaced crevasses and came in contact with ice creating an intermittent, vigorous steam plume (known informally as Jr. Plume). Photograph courtesy of Scott Lawrence. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=17979.

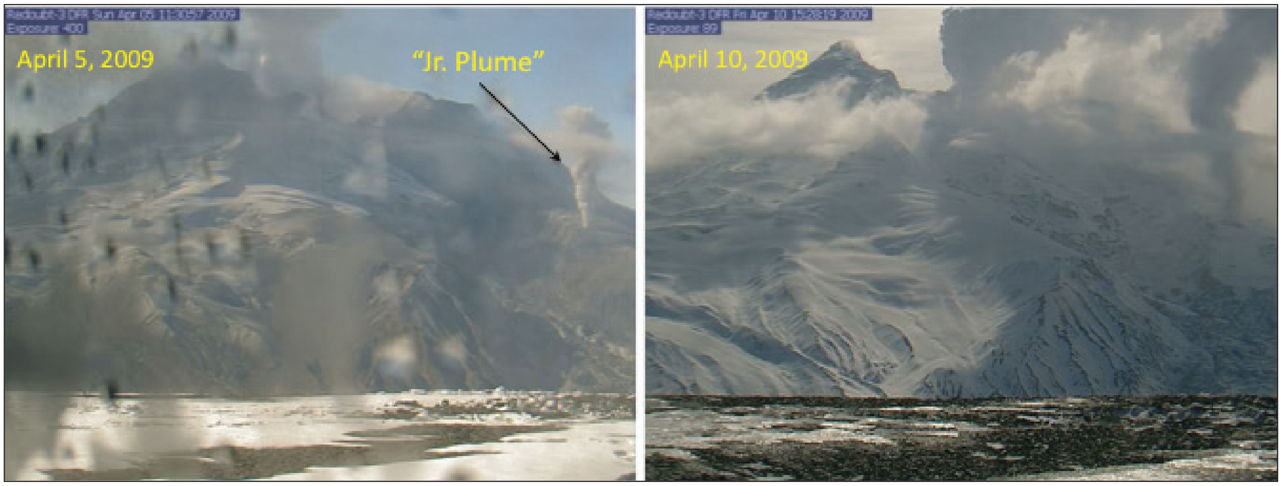


Figure 41. Images from the Web camera installed at seismic station DFR, 9 km (5.6 mi) northeast of the steam and ash plume rising from the western shoulder of Drift gorge (see fig. 50 for camera location). Image on left shows a robust dirty steam plume rising several thousand feet about midday on April 5, 2009. Image on right shows continued activity from the same location on the afternoon of April 10, 2009. The plume was generated by hot pyroclastic debris of the April 4, 2009, eruption sifting down into crevasses and interacting with glacier ice. The activity was intermittent between April 5 and 10, 2009. Image on left in AVO database at URL: http://www.avo.alaska.edu/images/image.php?id=47261. Image on right in AVO database at URL: http://www.avo.alaska.edu/images/image.php?id=18026.

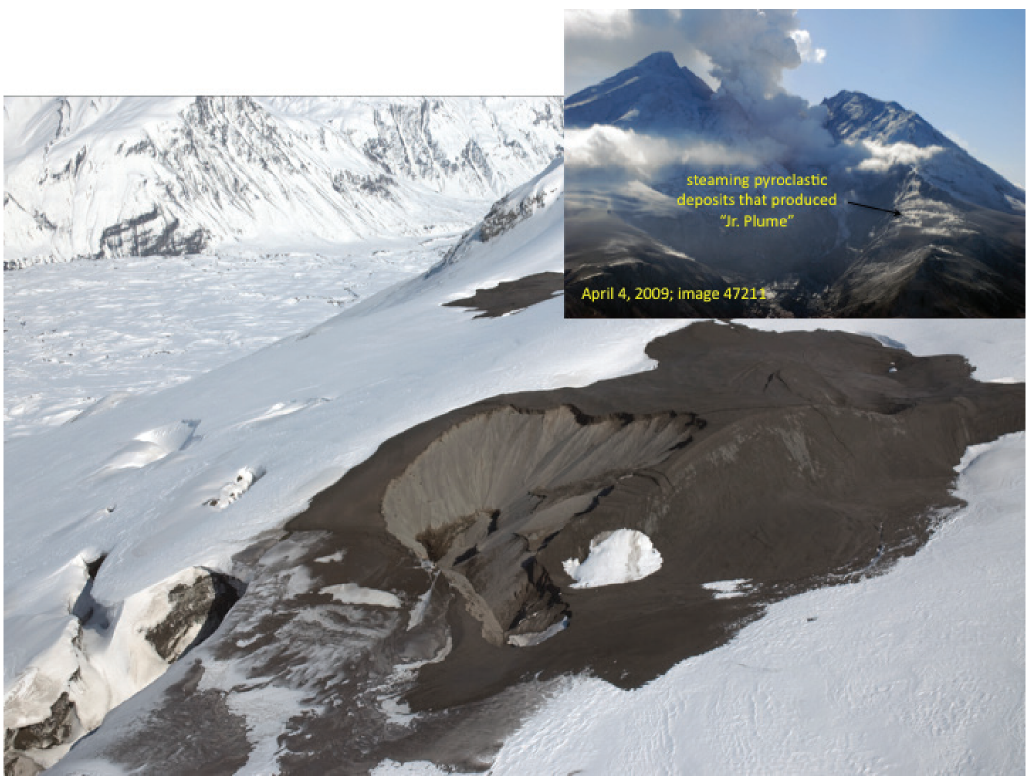


Figure 42. Site on the lower northern flank of Redoubt Volcano where pyroclastic debris from the April 4 eruption overflowed the western shoulder of Drift gorge and sifted into deep crevasses, generating intermittent phreatic plumes that rose 500–600 meters. The plumes were intermittently visible in Web camera images (inset) as well as from the east (fig. 40) between April 5 and 10. This photograph taken April 16, 2009, by Game McGimsey, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=18107. The inset photograph on top right shows hot pyroclastic deposits on the west (right) shoulder of Drift gorge. Photograph by Kate Bull, AKDGGS; AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=47211.

Effusive Phase—April 4–July 1, 2009

With cessation of explosive activity on the morning of April 4, 2009, the eruption entered a prolonged effusive phase characterized by continuous extrusion of the final lava dome over the following 3 months (fig. 43; table 6). Photogrammetric analysis of successive series of oblique digital images during this time period produced an accurate measurement of dome growth (Diefenbach and others, 2013). By July 1, 2009, the dome had reached what would be the maximum dimensions, 950 × 485 m (3,117 × 1,591 ft) and volume (inflated), 72×10^6 m^3 (94×10^6 yd^3). The dome volume and dimensions decreased slightly after July 1, 2009, as effusion subsided, and the dome began cooling and contracting. The highest effusion rate (35 m^3/s) occurred in the first 2 weeks of dome growth, and the lowest (2.2 m^3/s) occurred in early summer 2009 (table 6) (Diefenbach and others, 2013).

Monitoring the growth and evolution of the final lava dome was accomplished with analysis of time-sequenced oblique-aerial, Web-camera, and Forward Looking Infrared (FLIR) images (figs. 43–47). The first month of dome growth was endogenous and produced a rounded structure with a coarse, blocky texture consisting of intermediate to high–silica andesite lava (fig. 44) (Bull and others, 2013). About May 1, a finely fragmented and scoriaceous lava of about the same composition appeared at the top of the dome and spread divergently toward the outer margins, eventually covering 36 percent of the dome surface (figs. 45–47) (Bull and others, 2013). The change in surface texture began commensurate with an increase in seismicity—a 5-day final tremor swarm—and gas emissions (Buurman and others, 2013; Lopez and others, 2013; Werner and others, 2013). Dome growth continued for another 2 months with cessation determined to be about July 1, 2009. Over the next few months, as the dome slowly began cooling, contraction reduced the volume to about 70×10^6 m^3 (table 6). By December 31, 2009, the dome was largely snow-covered, although steam persistently rose from the top of the dome (fig. 48).

Table 6. Redoubt 2009 final dome volume and effusion rates.

[From Diefenbach and others (2013). Dome volume and effusion rate calculations syn- (April–July) and post-eruption (August–September) at Redoubt. Associated error estimates are rounded to one significant figure]

Date	Observation platform	Dome volume (10^6 m^3)	Effusion rate (m^3/s)
04-04-09	Dome 4 effusion begins		
			35 ± 1.0
04-16-09	Helicopter	36 ± 1.0	
			4.2 ± 0.8
05-04-09	Fixed-wing	42 ± 0.6	
			14 ± 2.0
05-08-09	Helicopter	47 ± 0.6	
			14 ± 4.0
05-14-09	Fixed-wing	54 ± 1.8	
			27 ± 12
05-16-09	Helicopter	59 ± 1.0	
			4.7 ± 1.0
05-26-09	Fixed-wing	63 ± 0.6	
			3.8 ± 0.6
06-09-09	Helicopter	68 ± 0.4	
			2.2 ± 0.4
07-01-09	Helicopter	72 ± 0.6	
08-20-09	Helicopter	71 ± 2.0	–
09-23-09	Helicopter	70 ± 0.3	–

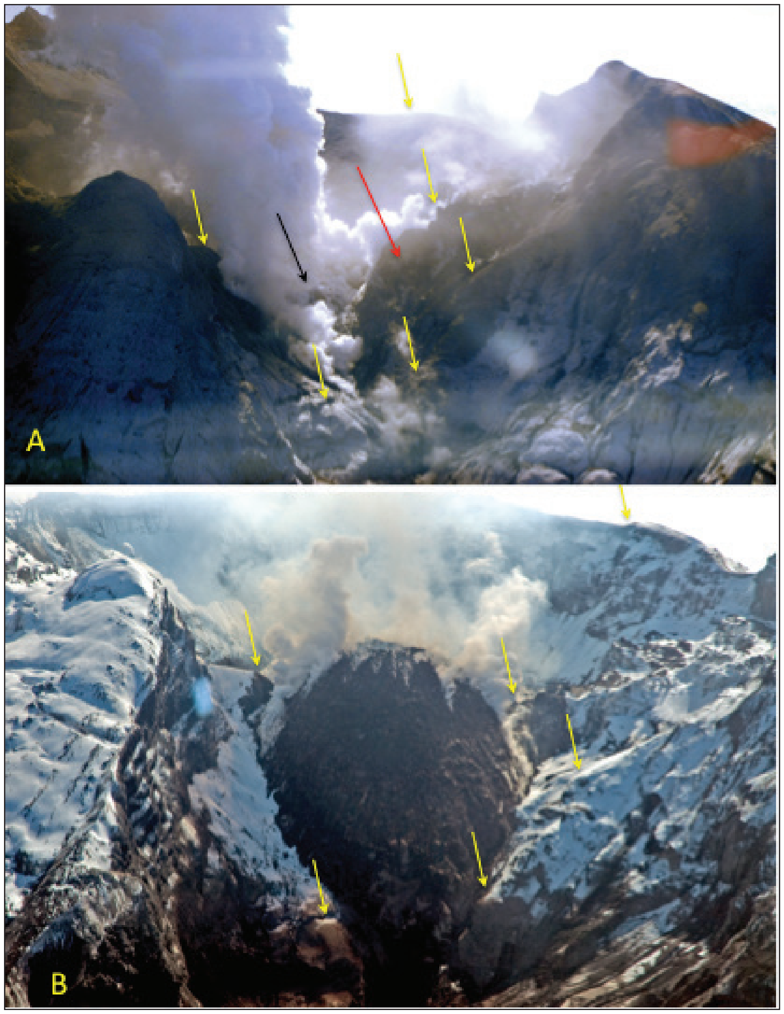


Figure 43. Photographs showing A. Summit crater of Redoubt taken on April 5, 2009, 1 day after the final explosive event (Event 19, April 4, 2009). The eruption has entered the Effusive Phase and the final lava dome is being extruded, with only a small portion visible at the base of the steam column (black arrow). Yellow arrows point to locations identifiable in photograph B. Taken August 20, 2009, after the lava dome has stopped growing and reached its maximum volume of 72×10^6 m^3 (94×10^6 yd^3). As the lava dome grew, it enveloped a substantial portion of the 1965–68 dome remnant (red arrow). Photograph A by Heather Bleick, USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=47221. Photograph B by Game McGimsey, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=19133.

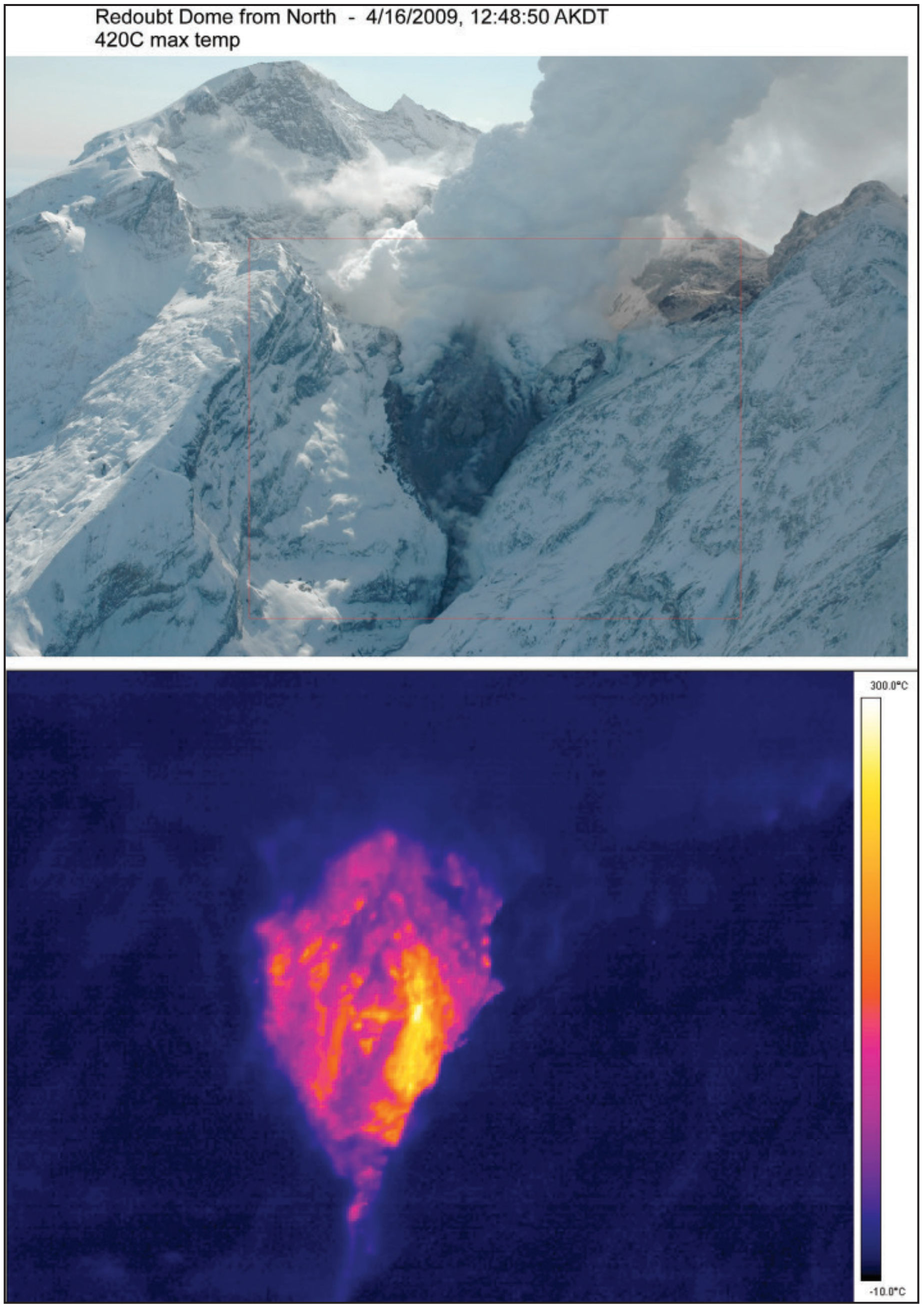


Figure 44. Redoubt Volcano active lava dome viewed from the north on April 16, 2009. The upper image is an aerial oblique photograph and the lower shows the FLIR thermal image of the inset box above. Maximum temperature of the dome surface indicated by FLIR is 420 °C. At this phase, the dome is growing endogenously and has a coarse, blocky surface texture. Upper photograph by Game McGimsey, AVO/USGS; lower image created by Rick Wessels, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=18095.

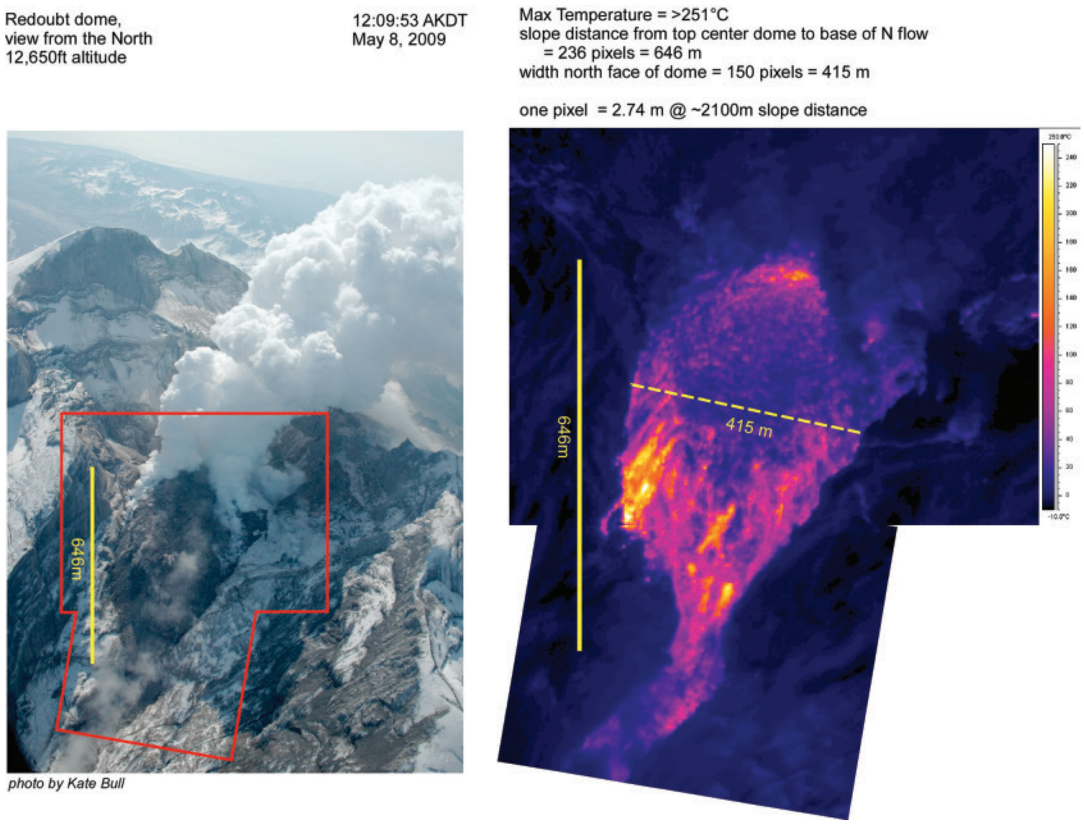


Figure 45. Aerial oblique photograph and FLIR thermal camera image of the final lava dome growing in the summit crater of Redoubt Volcano. The dome began growing April 4, 2009, reaching its final size and volume by July 1, 2009. The FLIR image shows maximum temperatures of the surface have cooled to about 251 °C. The finely fragmented scoreaceous texture that began developing at the top of the dome about May 1, 2009, is visible here as the mottled, cooler (darker color) top of the dome. The solid yellow scale shows the approximate slope length from the top of the lava dome to the active toe of the northern extension, based on FLIR images. The dashed yellow scale shows the approximate width of the narrower portion of the dome. Both images were taken on May 8, 2009. Oblique aerial photograph by Kate Bull, AVO/DGGS; FLIR image by Rick Wessels, AVO/USGS. This figure created by Rick Wessels, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=18571.

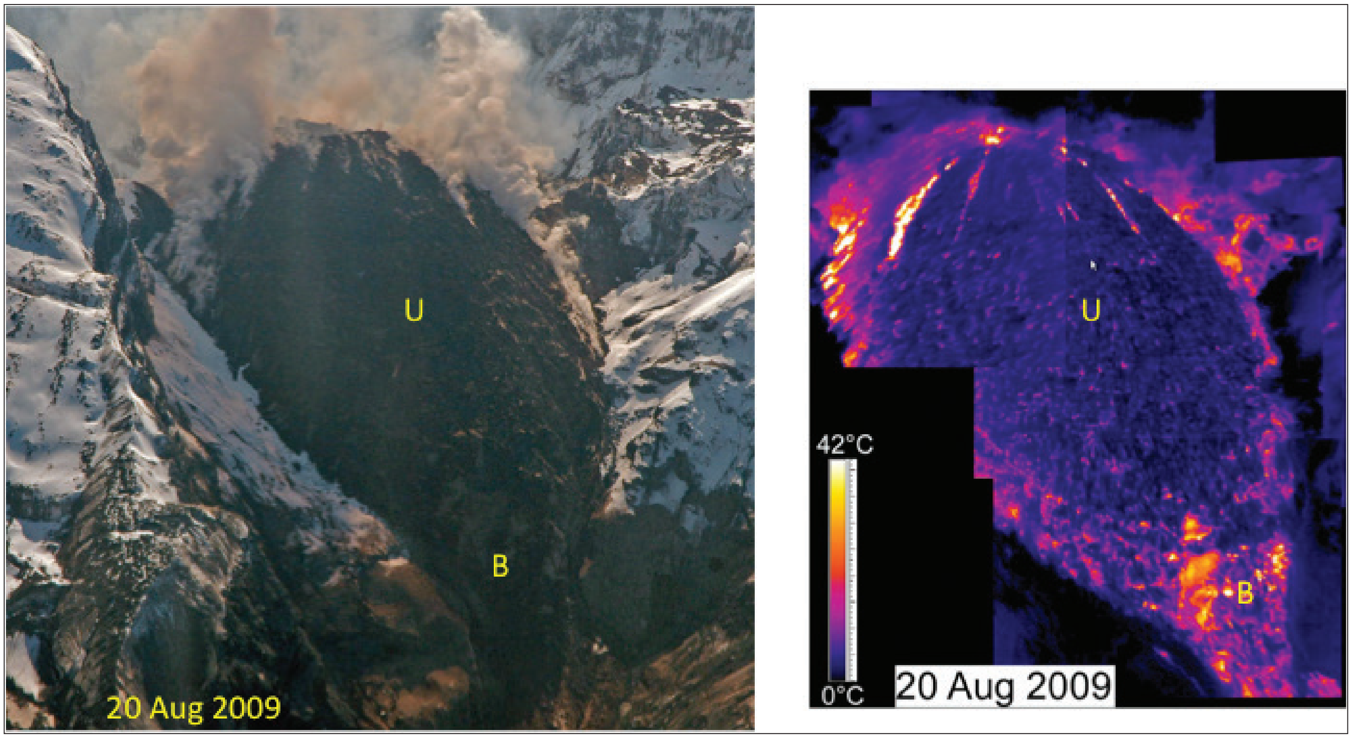


Figure 46. Oblique aerial and FLIR images of the final lava dome of the 2009 Redoubt eruption. Growth of the dome was complete by July 1, 2009. These images were taken on August 20, 2009, and the surface of the dome has cooled substantially compared with measurements taken earlier in the summer (see figs. 44–45), with only a few areas showing maximum temperatures of 60 °C. The fine, fragmented, scoreaceous lava texture (U) that began developing about May 1, 2009, covers much of the upper half of the northern side of the dome and is mottled and cooler (darker color). The blocky (B) portion of dome is along the margins. Aerial oblique photograph by Game McGimsey, AVO/USGS; AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=47231. FLIR image by Rick Wessels, AVO/USGS.

Figure 47. Final dome of the 2009 eruption of Redoubt Volcano. Extrusion of this last dome began on April 4 and was complete by July 1, 2009. The dome measures roughly 950 m (3,117 ft) by 485 m (1591 ft), and has a volume (inflated) of approximately 71 million m^3 (table 6) (Diefenbach and others, 2013) when this photograph was taken on August 20, 2009. Surface of the upper two-thirds or so of the dome displays a finely fragmented texture that began developing after May 1, 2009, while the outer margins remain blocky (Bull and others, 2013). View is from the northwest. Photograph by Game McGimsey, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=47201.

Figure 48. 2009 Redoubt dome on December 31, 2009. The lower, outer surface has cooled sufficiently to accumulate snow. Active fumaroles at the top continue to issue voluminous steam clouds. Photograph by Christina Neal, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=19458.

The formerly ice-filled summit crater of Redoubt was dramatically altered during the 2009 eruption (fig. 49). Ice lost during the 1989–90 eruption had largely been replenished by 2005 (McGimsey and others, 2011, fig. 7). The 2009 eruption melted and explosively excavated a large portion of Drift glacier ice from the crater and the Drift gorge amounting to an estimated 1–2.5 $\times 10^8$ m^3 (Waythomas and others, 2013). The amount of ice removed during the 1989–90 eruption was 2.9 $\times 10^8$ m^3 (Trabant and Hawkins, 1997). Although somewhat more ice was lost in 1989–90 than in 2009, most of it came from ice in the Drift gorge, which was originally about 100 m thick, and during the eruption was stripped completely bare from the top of the beheaded piedmont lobe up to the lava dome. The 2009 eruption resulted in a greater volume of ice removed from the summit crater through explosion and reaming of a larger initial vent, while a substantial amount remained intact in the gorge.

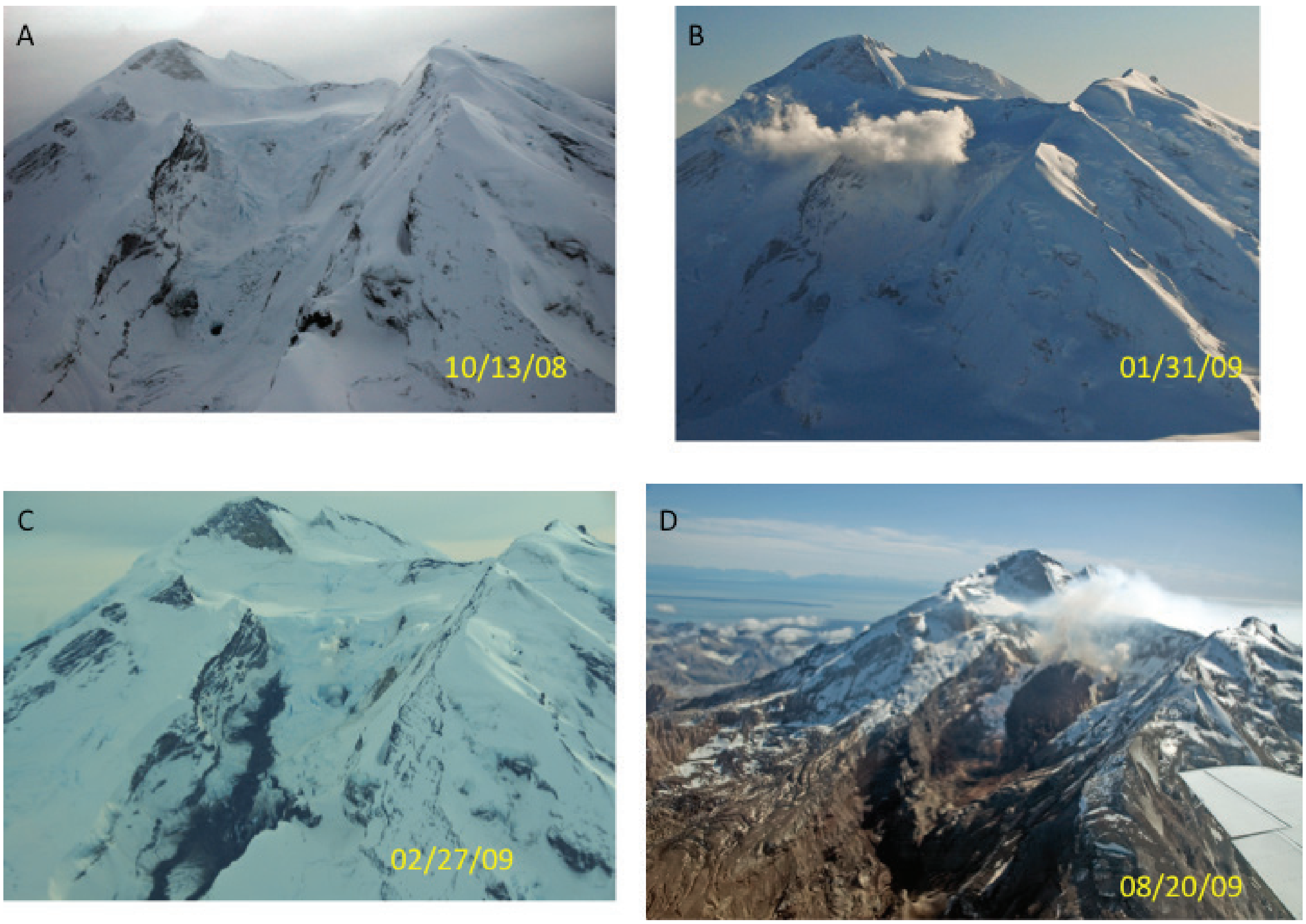


Figure 49. Succession of similar-perspective photographs from October 2008 to August 2009 showing impact on the Redoubt summit crater and Drift glacier (upper gorge) from the 2009 eruption. The total volume of ice and snow lost (removed) from the crater and gorge by the eruption is estimated to be about 1–2.5 $\times 10^8$ m^3 (fig. 2, Waythomas and others, 2013). Photograph A by Game McGimsey, AVO/USGS, AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=15778. Photograph B by Chris Waythomas, AVO/USGS, AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=16404. Photograph C by Chris Waythomas, AVO/USGS, AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=16740. Photograph D by Game McGimsey, AVO/USGS, AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=19134.

From January 25 to December 28, 2009, the Aviation Color Code changed 14 times (table 3). On April 6, 2009, following the explosive events of April 4, the Aviation Color Code/Volcano Alert Level was downgraded from **RED/WARNING** to **ORANGE/WATCH**, and then to **YELLOW/ADVISORY** on June 30, 2009. The round-the-clock staffing of the AVO Operations Center that began on Sunday, January 25, 2009, was reduced to extended hours (6 a.m. to 9 p.m., 7 days per week) on July 9, 2009, and then back to regular business hours, 5 days per week, on Friday July 31, 2009. Seismicity and gas emissions continued to decrease and with no further indications of unrest, the volcano was returned to **GREEN/NORMAL** status on September 29, 2009.

On the afternoon of December 27, 2009, after 6 months of declining activity, a series of small, repetitive earthquakes abruptly began in the vicinity of Redoubt's summit. Because similar seismicity had been precursory to eruptive activity, AVO upgraded the Aviation Color Code/Volcano Alert Level to **YELLOW/ADVISORY** on the morning of December 28, 2009. Satellite and Web camera views were obscured by clouds. On December 29, a clear Cook Inlet Web camera image showed no unusual activity or vapor plume, and a pilot reported no plume over the volcano. By December 29, the shallow swarm of earthquakes had decreased markedly, and continued to decrease into early January 2010. Redoubt finished out 2009 at Aviation Color Code/Volcano Alert Level of **YELLOW/ADVISORY**.

The 1989–90 and 2009 eruptions of Redoubt were comparable in total erupted volume (McGimsey and others, 2009). Discrepancies exist in published reports between 2009 eruption volumes and there is uncertainty about the number of domes produced in 2009 (3 or 4).

Compared to the 1989–90 eruption of Redoubt, the 2009 eruption was smaller in total volume of all erupted material; estimated total DRE volume for 1989–90 was about 0.18 km^3 (180×10^6 m^3), and about 0.08–0.12 km^3 (79–120×10^6 m^3) for 2009 (Miller, 1994; Bull and Buurman, 2013).

AVO used a variety of tools and methods to monitor the unrest and eruption of Redoubt Volcano. Although some additional instruments were installed as the activity increased, most equipment was already established and operational. By March 22, 2009, 12 seismic stations, 2 Web cameras, 1 time-lapse camera, and 5 continuously recording GPS stations were installed and collecting data (fig. 50); 4 GPS stations at campaign seismic stations immediately prior to the March eruptive activity, and a fifth station 28 km (17 mi) northeast of the volcano operated by the Plate Boundary Observatory.

During the 2009 Redoubt unrest and eruption, several monitoring and research techniques were used to document and understand volcanic processes and to better forecast eruption scenarios:

- Daily (and often, hourly) analysis and evaluation of seismic data (Buurman and others, 2013; Hotovec and others, 2013; Ketner and Power, 2013).
- AVO conducted 29 airborne measurements of gas emissions (Kelly and others, 2013; Lopez and others, 2013; Pfeffer and others, 2013; Werner and others, 2013).
- Collected and analyzed local and regional GPS data to establish geodetic trends (Grapenthin and others, 2013).
- Monitored infrasound signals (Fee and others, 2013).
- Collected and analyzed meltwater samples originating in the summit and Drift glacier (Werner and others, 2012).
- Acquired and analyzed FLIR and satellite imagery to evaluate thermal characteristics in the summit area prior to and during the eruption and to track ash clouds (Wessels and others, 2013).
- Used Doppler weather radar to evaluate eruption plumes and clouds (Schneider and Hoblitt, 2013).
- Analyzed satellite data to track and evaluate eruptive clouds (Webley and others, 2013).
- Applied photogrammetric techniques to calculate dome dimensions and volumes (Diefenbach and others, 2013).
- Collected and evaluated tephra fall deposits (Wallace and others, 2013).
- Documented and analyzed the character and deposits of the numerous lahars that inundated the Drift River valley and impacted the DROT (Waythomas and others, 2013).
- Characterized eruptive products (Coombs and others, 2013).

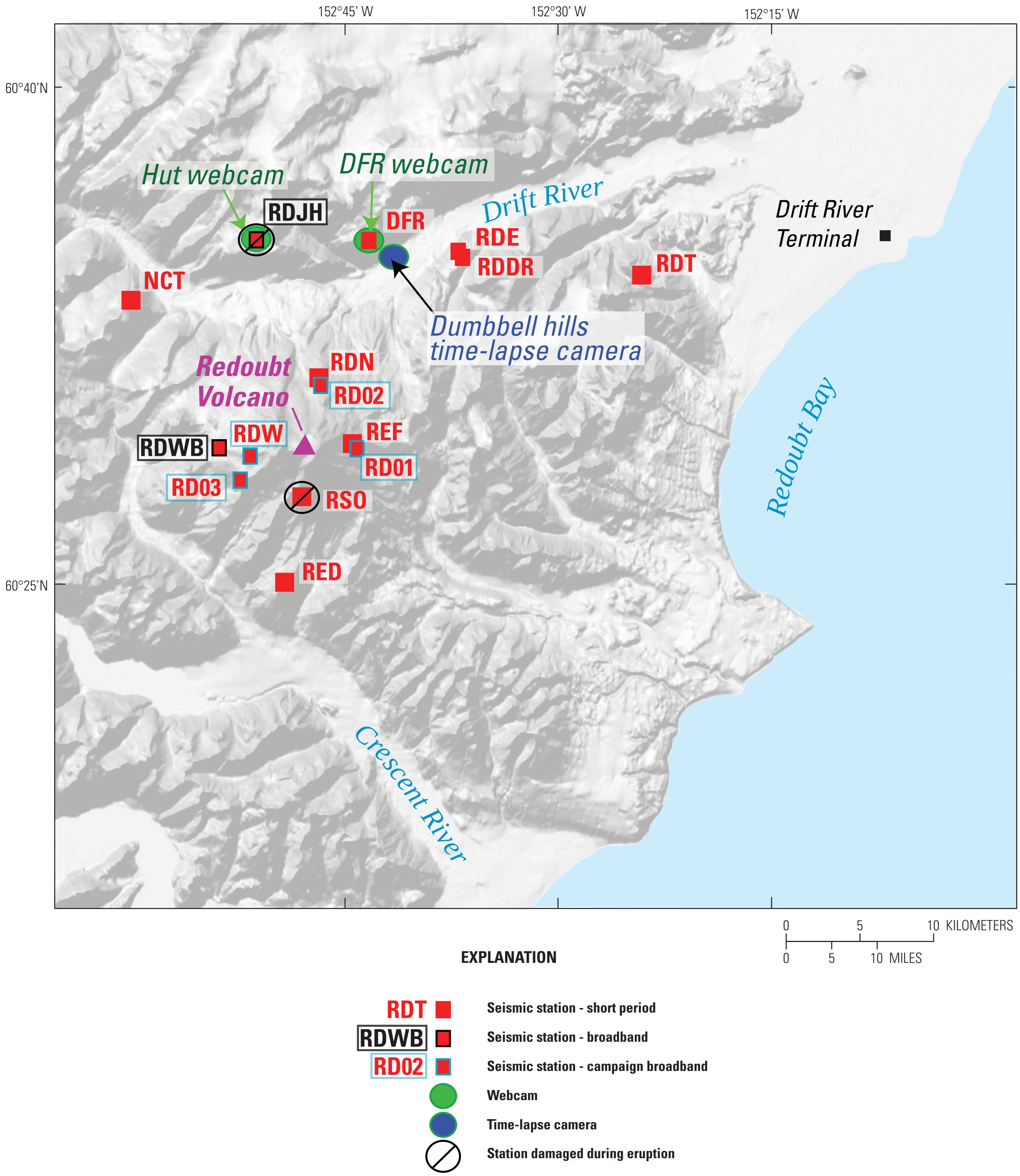


Figure 50. Annotated image showing AVO monitoring equipment at Redoubt during the 2009 eruption. Seismic stations, Web cameras, and time-lapse camera locations. From Schaefer (2012).

Photography, overflight observations, pilot reports, and field crew reports also contributed to the flow of information used by AVO to assess and respond to the activity. AVO issued VANs, VONAs, Daily Status Reports, Information Releases, and the AVO public website (http://www.avo.alaska.edu) to disseminate information and warnings.

Lahars produced by the March 22–23, 2009, explosions damaged the facilities at DROT and the threat of further hazards prompted creation of a series of interagency teams, formed into a Unified Command (UC) that managed and coordinated Federal, State, and local response to the eruption (Schaefer, 2012). The primary objectives were to ensure safety and protection of citizens and response personnel, and to protect the environment with regards to hazards related to lahar risk to the DROT. Daily Incident Action Plans were generated and issued, often in the presence of the media. AVO scientists actively participated in the UC to provide scientific information and hazard analyses. The UC directed removal of most of the oil from DROT; 60 percent on April 5–6, and the remaining by the end of April. The UC stood down on August 12, 2009, and returned regulation to the Alaska Department of Environmental Conservation.

The impacts and costs to the aviation industry resulting from the 2009 explosive eruptions of Redoubt are well summarized in Schaefer (2012). Following upgrade of the Aviation Color Code to **ORANGE** on January 25, the FAA imposed a flight restriction around Redoubt on January 26, 2009, encompassing a 10-nautical-mile radius and 60,000-ft flight level. Between March 22, 2009 and April 5, 2009—the period of explosive events and resulting ash clouds—60 planes were re-routed, 20 were diverted, 10 were turned back, and many airport night operations were cancelled in Anchorage. Additional costs to the air carriers from the eruption were conservatively estimated to be $400,000 (International Airways Volcano Watch Operations Group, 2010). Other disruptions included flight delays, temporary furlough of aircraft maintenance employees, and a 20-hour closure of the Ted Stevens International Airport prompted by the March 28 eruption and subsequent ash cloud that passed over Anchorage. Military aircraft and personnel were temporarily moved to bases in Washington and Fairbanks to avoid potential ash hazards.

Fourpeaked Volcano

CAVW# 1102-26-
58°46'N 153°40'W
2,104 m (6,903 ft)

Cook Inlet/Alaska Peninsula

CONTINUED DECREASE OF STEAM AND GAS EMISSIONS
Downgraded to **UNASSIGNED** due to inability to assess seismicity as equipment fails.

The abrupt phreatic eruption and glacial outburst flood at Fourpeaked volcano in September 2006 raised general interest in the previously inactive and non-instrumented volcano (Neal and others, 2009a; Gardine and others, 2011). A four-station seismic network, pressure sensors, and a Web camera were installed after the eruption to monitor the activity. Throughout the rest of 2006 and the first half of 2007, seismicity gradually decreased along with steam and gas emissions from a train of closely spaced melt pits near the summit. Status of the volcano was downgraded to Aviation Color Code/Volcano Alert Level of **GREEN/ADVISORY** on June 6, 2007 (McGimsey and others, 2011).

Steam and gas emissions were frequently observed in Web camera images and during routine gas measurement flights through the first half of 2008, and were visible to an AVO field crew on Augustine Volcano in July 2008 (AVO internal log entries). Activity continued to decrease into, and through 2009.

Steam plumes were visible in the Web camera on February 8, 2009, and during gas measurement flights on June 6, 2009, and November 2, 2009 (fig. 51); during the November overflight, no gas was detected (M. Doukas, U.S. Geological Survey, written commun., 2012). As the phreatic activity diminished, the melt holes began filling with snow and fumarolic activity was observed only from a single vent (figs. 52–53).

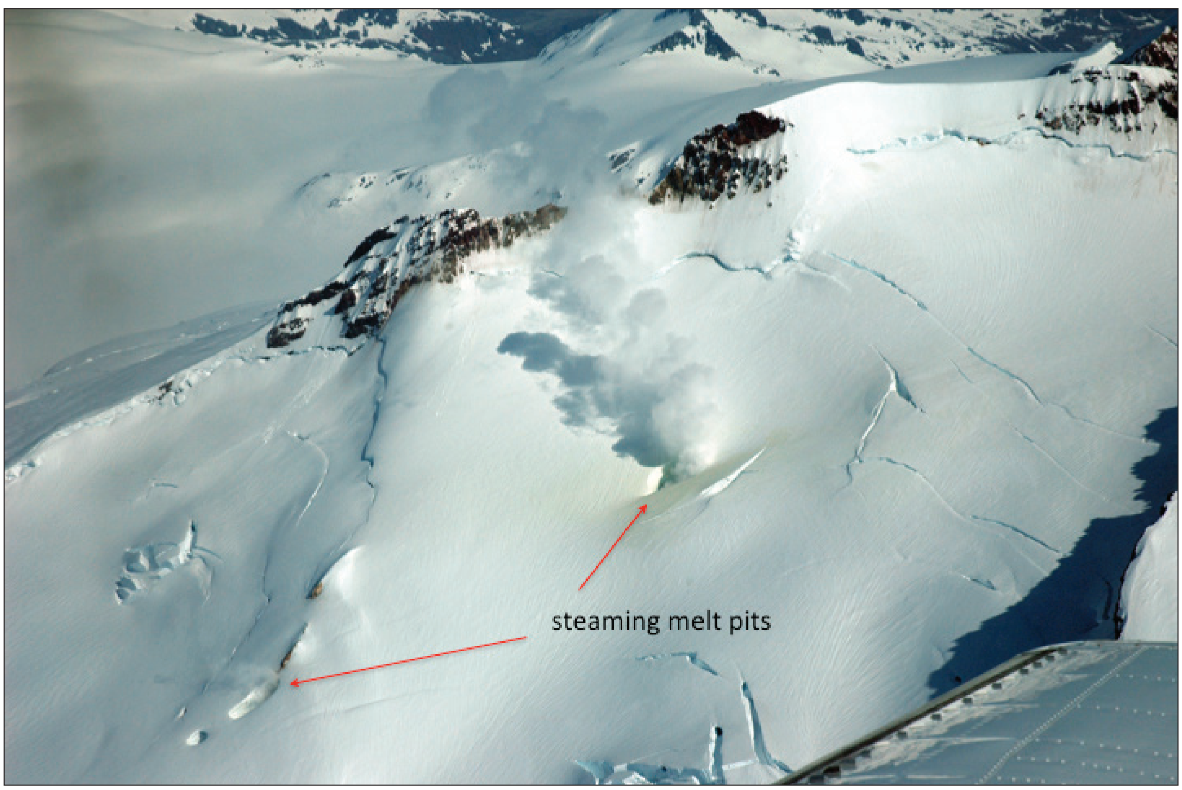


Figure 51. Steam and gas rise from two melt pits near the summit of Fourpeaked volcano on June 6, 2009. Yellow discoloration surrounds the larger pit; the smaller, second pit is down slope (lower left in photograph). View is from the west-northwest. Photograph by Michael Doukas, CVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=46801.

Figure 52. Steam and gas rise from a lone melt pit near the summit of Fourpeaked volcano on November 2, 2009. View is from the west. Photograph by Game McGimsey, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=19371.

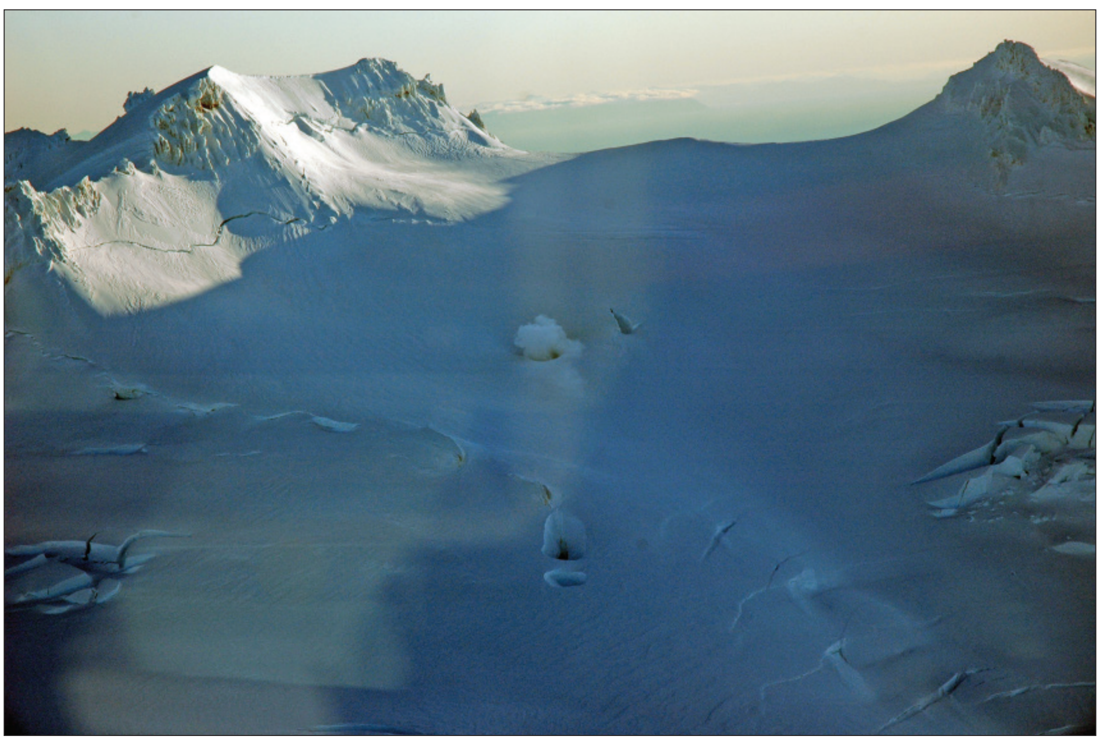


Figure 53. Steam and gas rise from a melt pit near the summit of Fourpeaked volcano on November 2, 2009. View is from the northwest. The lower melt pit that was active in June 2009 was cold. Photograph by Game McGimsey, AVO/USGS. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=19372.

The seismic and infrasound networks, and the Web cam, were serviced in the summer of 2008, and a year later, as the batteries drained, the instruments stopped recording data. On November 17, 2009, prompted by the network outage and inability to assess the level of seismic activity, AVO issued a Volcanic Activity Notice and an Information Release downgrading Fourpeaked from Aviation Color Code **GREEN** and Volcano Alert Level **NORMAL**, to **UNASSIGNED**, thus removing it from the list of seismically monitored volcanoes.

Fourpeaked volcano lies within the northeastern corner of Katmai National Park and Preserve on the Alaska Peninsula, 12 km (7.5 mi) southwest of Mount Douglas (fig. 1). The edifice is defined by "four peaks," which are isolated, eroded exposures of lava flows along ridge crests and cliff faces that radiate out from the ice-covered summit (J. Fierstein, U.S. Geological Survey, written commun., 2007). The source areas (pits and vents) for the recent activity extend linearly from high in the summit crater (or cirque), northward for about 1,250 m (4,100 ft). Until late 2006, no historical activity was recorded for this volcano. The age of the last significant eruption is not known but considered to be pre-Holocene (>10,000 years). On September 17, 2006, two large steam plumes were observed rising from Fourpeaked to an altitude of about 6,000 m (about 20,000 ft) above sea level (Cervelli and West, 2007). An ensuing glacial outburst flood scoured a steep-walled canyon more than 100 m (330 ft) deep and moved a mixture of water and fine-grained to boulder-sized ice and debris at least 6 km (4 mi) down slope (Neal and others, 2009a). Subsequent gas measurements showed a significant amount of SO_2 issuing from the volcano. Following the eruption, a report surfaced of a similar steam and gas plume observed by a mariner during the summer of 1965.

Aniakchak Volcano

CAVW# 1102-09-

56°54'N 158°13'W

1,341 m (4,400 ft)

Alaska Peninsula

ANOMALOUS SEISMICITY

Downgraded to **UNASSIGNED** due to network outage.

Following several episodes of anomalous seismicity in 2008 (Neal and others, 2011), deep, low-frequency seismic events continued to be recorded at Aniakchak Volcano through the first half of 2009 while the seismic network was still operating. On February 27 and 28, 12 low-frequency events were located that had magnitudes of ML 1.0–2.1 and hypocentral depths of about 15–28 km (9.3–17.4 mi), and another sequence of events occurred on March 4 with one locatable low frequency event about 7 km (4.4 mi) depth (fig. 54). (Scott Stihler, U.S. Geological Survey, written commun., 2011). Another burst of low-frequency events occurred at Aniakchak on June 3, 2009.

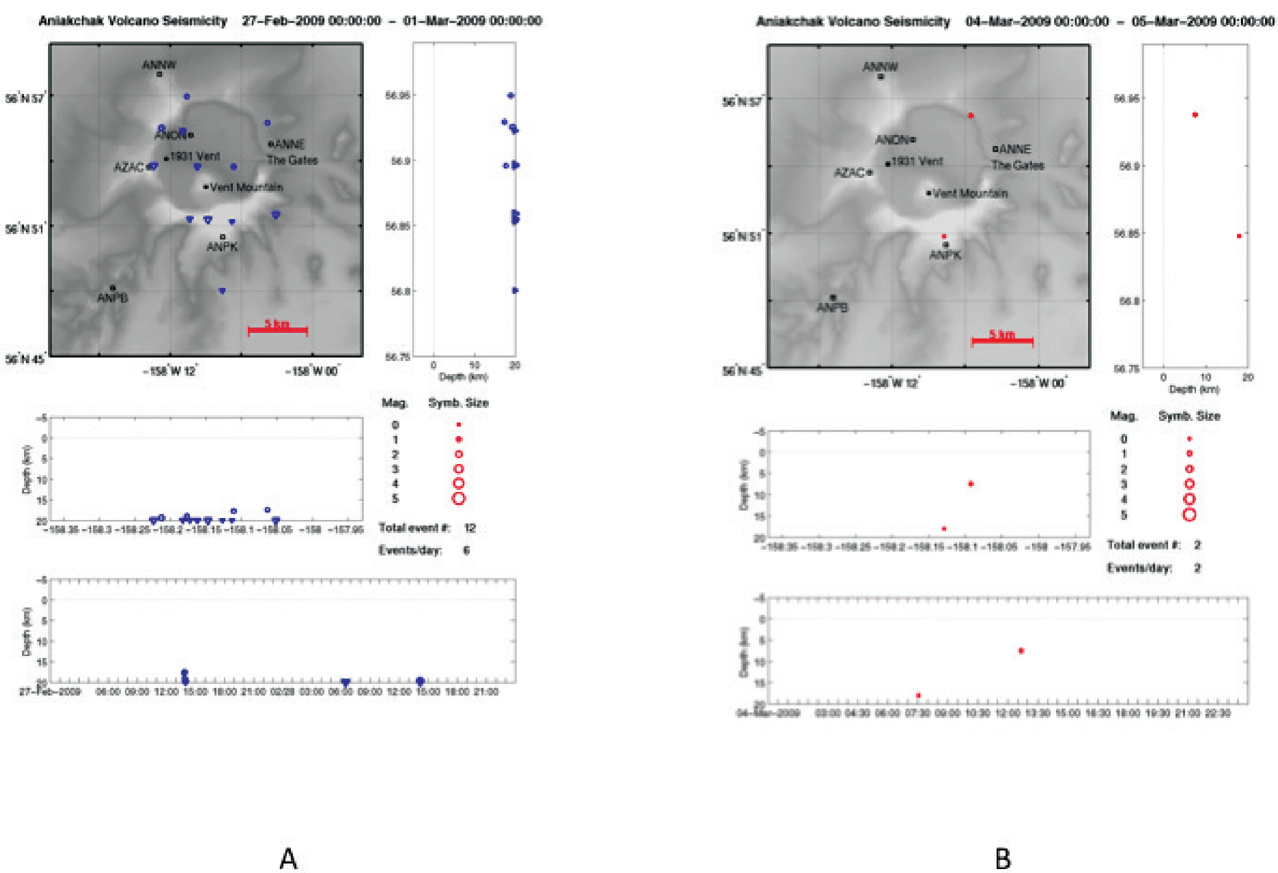


Figure 54. (A) Swarm of low-frequency earthquakes beneath Aniakchak Volcano on February 27 and 28, 2009. Magnitudes ranged from ML 1.0–2.1 and depths of about 15–28 km (9.3–17.4 mi). (B) Several located low-frequency events at Aniakchak on March 4, 2009, located about 4 km (2.5 mi) south-southeast of Vent Mountain at a hypocentral depth of about 18 km (11.2 mi), and another about 7 km (4.4 mi) north-northeast of Vent Mountain at a depth of about 7 km (4.4 mi).

By September 2009, chronic station outages and data interruption prompted AVO to include Aniakchak in the list of four volcanoes considered for downgrading to **UNASSIGNED**. On November 17, AVO issued a Volcanic Activity Notice and an Information Statement formally declaring that Aniakchak and three other volcanoes: Veniaminof, Fourpeaked, and Korovin were no longer seismically monitored due to seismic station outages, and thus were changed from volcano alert level **NORMAL** and Aviation Color Code **GREEN** to **UNASSIGNED**. Two seismic stations at Aniakchak became operational by December 8, 2009, but would again go out in early 2010. The network would eventually become operational again during the summer of 2010.

Aniakchak is a circular caldera 10 km (6.2 mi) in diameter and as deep as 1 km (3,280 ft) from the rim to the caldera floor. The caldera formed during a catastrophic eruption 3,400 years ago (Miller and Smith, 1987; Dreher and others, 2005). Numerous lava domes, lava flows, and scoria cones are situated around the caldera floor (Neal and others, 2001); the largest intracaldera cone is Vent Mountain, 2.5 km (1.5 mi) in diameter and rising 430 m (1,410 ft) above the floor of the caldera. The only historical eruption of Aniakchak occurred in 1931, and was a powerful explosive event that blanketed a large portion of the eastern Alaska Peninsula with ash (Nicholson and others, 2011).

Mount Veniaminof Volcano

CAVW# 1102-07

56°12'N 159°24'W
2,507 m (8,225 ft)

Alaska Peninsula

MINOR PHREATIC ERUPTIONS; LOWERING OF STATUS
Mostly diffuse steam rising from the intracaldera cone; network outage

The long-term, low-level eruptive activity at Veniaminof Volcano, having waxed and waned since 2002, continued intermittently throughout 2009. Following periods of elevated seismicity and minor steam and ash emissions in February 2008 (Neal and others, 2011), the volcano entered 2009 in Aviation Color Code/Volcanic Alert Level of **GREEN/NORMAL.** On January 8, 2009, a pilot reported seeing a wispy, light-gray plume between 6,500 and 10,500 ft (1,980 and 3,200 m), and extending 28 km (15 mi) downwind from the volcano. A passenger in an aircraft took a photograph of the plume (fig. 55). The AVO/USGS Web camera located at nearby Perryville also captured the plume that day (fig. 56).

AVO remote sensing experts interpreted the "gray tone" attributed to the plume to be backscatter shadow from the plume rather than ash content. Similar steaming was recorded in Web camera images most of the previous week and again during the week of March 17. The Web camera became inoperative on March 17 due to relocation of the village office hosting the camera. The camera would not come back online until May 27, 2009.

In response to an increase in seismic activity across the entire network, AVO issued a VAN on May 7, 2009, elevating the Aviation Color Code/Volcanic Alert Level **to YELLOW/ ADVISORY.** Because the Web camera was inoperative,

Figure 55. Steam plume rising from the central cone within Veniaminof caldera and extending 28 km (15 mi) downwind. View is from the north-northeast. Photograph by Ernest Weiss, January 8, 2009. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=16219.

calls to local observers on May 9 produced reports of a "steady stream of light steam, with occasional small puffs." Low-level tremor was recorded the week of May 18, but the activity soon diminished, and with no further visual reports of activity, on May 26, 2009, AVO issued a VAN downgrading the volcano to **GREEN/NORMAL**. A few days later, on May 29, tremor returned and abruptly increased later in the day. The Web camera was once again operating, but the view on this day was obscured by clouds. Nothing unusual was noted in satellite images. Tremor continued through May 30, 2009, but at a lower amplitude than previously recorded, and then diminished entirely. Thus, no change in status was forthcoming.

On June 23–24, 2009, a small swarm of low-frequency earthquakes was recorded at Veniaminof, the last of the calendar year as the network began deteriorating. On the morning of October 19, 2009, a U.S. Coast Guard flight crew flying over Bristol Bay reported "steady smoke and ash" coming from the center of Veniaminof. Web camera images at the time showed a voluminous, low-level steam plume over the volcano, but no indication of ash (fig. 57).

On November 17, 2009, due to continued station outage, reducing the network to only a single station, AVO issued a VAN downgrading the volcano from Aviation Color Code/ Volcanic Alert Level **GREEN/NORMAL to UNASSIGNED**, and delisting it from the inventory of seismically monitored Alaska volcanoes. The volcano would remain at this status through the remainder of 2009.

Veniaminof, an ice-clad, about 350-km^3 (about 84-mi^3) andesite and dacite stratovolcano, is one of the largest and most active volcanoes of the Aleutian Arc (Miller and others, 1998; Bacon and others, 2007). Located 775 km (482 mi) southwest of Anchorage and 35 km (22 mi) north of Perryville (fig. 1), the summit hosts an ice-filled, 10-km diameter (6.2-mi) caldera. Two Holocene caldera-forming eruptions are recorded in extensive pyroclastic-flow deposits around the volcano (Miller and Smith, 1987). Low-level, largely phreatic ash explosions from the approximately 350-m-high (about 1,150 ft) intracaldera cone have occurred intermittently since 2002, while the last significant magmatic eruption occurred in 1993–95 (Neal and others, 1995; McGimsey and Neal, 1996; Neal and others, 1996). This eruption was characterized by intermittent, low-level emissions of steam and ash, and production of a small lava flow that melted a pit in the caldera-ice field. During the more significant historical eruptions, ash plumes reached about 7,800 m (about 26,000 ft) ASL and produced ash fallout within about 40 km (about 25 mi) of the volcano. In early 2009, the volcano was monitored by a network of eight seismometers. Outages reduced the network to one operable station by mid-November 2009.

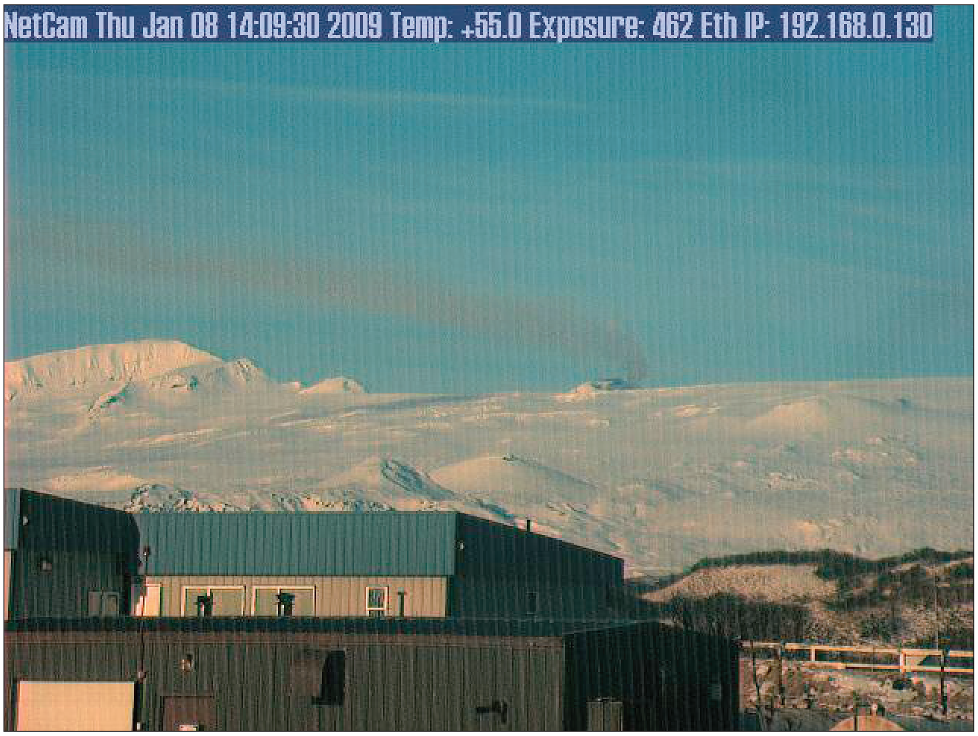


Figure 56. AVO/USGS Web camera image from Perryville showing a persistent steam plume emanating from the central cone within Veniaminof caldera. The village is about 35 km (22 mi) south of Veniaminof Volcano. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=46841.

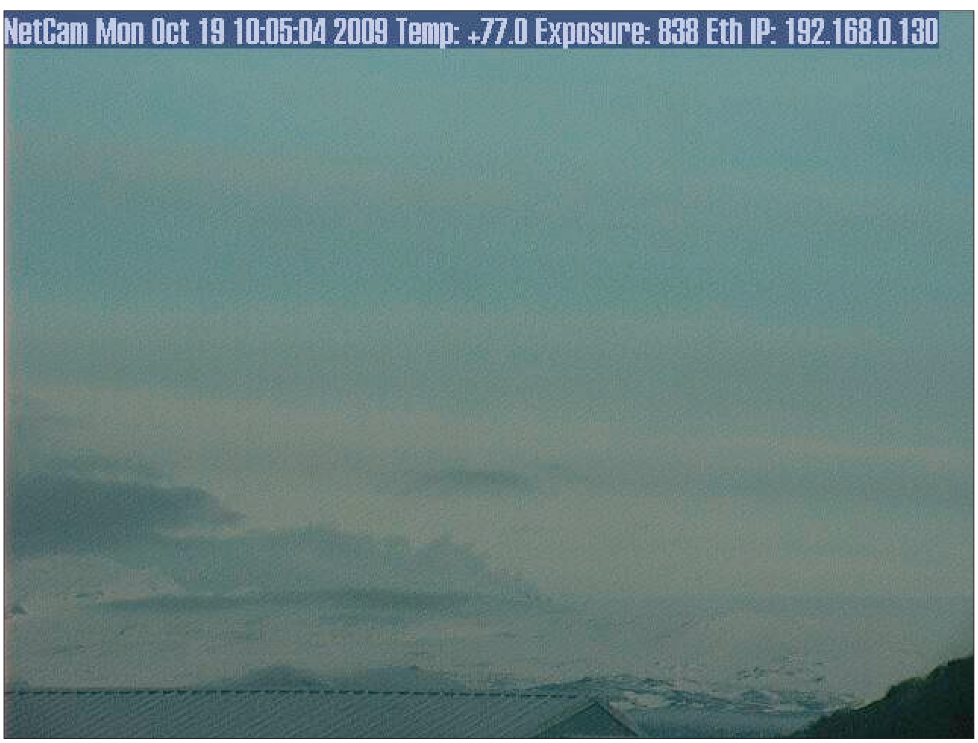


Figure 57. AVO Web camera image of voluminous steaming from the intracaldera cone in the Veniaminof caldera. The Web camera is situated in Perryville, 35 km (22 mi) south of the central cone. This Web camera image was taken on October 19, 2009, at 10:05:04 a.m. AKDT. The steam plume was first reported by a Coast Guard crew flying over Bristol Bay. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=46851.

Shishaldin Volcano

CAVW# 1101-36-
54°45'N 161°58'W
2,857 m (9,373 ft)

Unimak Island, eastern Aleutian Islands

INCREASED SEISMICITY, SMALL STEAM PLUMES, THERMAL ANOMALIES

Shishaldin Volcano is one of the most active volcanoes of the Aleutian arc. Minor unrest and eruptive activity have been documented for all but a couple of the past 20 years (table 4b). In 2008, Shishaldin maintained the pattern of producing steam plumes, occasionally with minor phreatic ash emissions (Neal and others, 2011). Thermal anomalies (TA) were observed on September 5 and December 18, 2008. This activity increased in early 2009 with the occurrence of a significant 2-pixel thermal anomaly and a slight increase in seismicity on January 5 (fig. 58). AVO issued a VAN the following day upgrading the Aviation Color Code/Volcano Alert Level to **YELLOW/ADVISORY**. That day, pilots and ground observers reported a constant steam plume rising about 1,000 ft (about 300 m) above the summit and trailing off 16–25 km (10–15 mi) to the southeast. Satellite views on January 8 showed a steam-filled crater and no ash on the snow-covered flanks, and a pilot's photograph taken January 11 shows a pulsing steam plume (fig. 59). A few days later, on January 13, AVO seismologists identified low-amplitude, minor tremor in the seismicity at Shishaldin, which continued for several weeks and then apparently faded out.

On January 17, the on-island Shishaldin Web camera, which had been out of service since October 22, 2008, was made operational again, although images were not recorded until February 20. Over the next couple of weeks, thermal anomalies were few, seismicity remained low, and although the reports of steaming continued, steam emissions from Shishaldin are considered normal. The return to background conditions prompted AVO to downgrade the Color Code/Alert Level to **GREEN/NORMAL** on February 11, 2009. A February 28 Web camera image shows a modest steam plume rising from the summit (fig. 60). Image quality problems with the Web camera in March and April led to the camera being taken off-line on April 30.

Over the next 7 weeks, occasional thermal anomalies were observed along with continuous low-level tremor, which was not considered unusual activity for Shishaldin. Then, on April 7, a PenAir pilot reported Shishaldin streaming more vigorously than in the previous 16 months of observing during his weekly flights by the volcano. A thermal anomaly was reported in satellite imagery that day as well. Activity continued during the next couple of weeks, and on April 20, thermal activity at the summit spiked with the recording of multiple thermal anomalies having saturated pixels, indicative of high ground temperatures (more than 300 °C; about 600 °F). This level of thermal activity was last observed at Shishaldin during the run-up to the 1999 eruption (J. Dehn, AVO UAFGI, 2009 internal log entry 31659). A pilot reported steaming on May 5, and an observer on a different flight that day reported also seeing dark colored, linear features on the northern side of the summit. These would later be interpreted to be minor streams of “dirty” water; no significant deposits were produced (fig. 61).

Throughout June, thermal anomalies were detected on about one-third of the days, with a particularly strong anomaly noted on June 9; no unusual seismicity was detected. A clustering of thermal anomalies appeared to coincide with favorable vertical view angles. On the night of June 25, an ASTER thermal infrared satellite image showed a thermal anomaly and a 22-km-long (14 mi) steam plume extending east-northeast from Shishaldin (fig. 62). Clouds blanketed most of Unimak Island, but the top of Shishaldin was visible above the cloud deck. An observer in Cold Bay, Alaska, called on June 29 to report increased steaming at Shishaldin during the previous couple of days. During the first full week of July, thermal anomalies increased in strength, with a return of saturated pixels (high ground temperatures). Based on this trend, as well as the persistence of the thermal anomaly, AVO elevated the Color Code/Alert Level to **YELLOW/ADVISORY** on July 10, 2009. Neither seismicity nor deformation had changed appreciably, and satellite data showed no significant sulfur dioxide gas emissions.

Airborne emissions were detected in the daily analysis of satellite imagery on July 13, which was a day of rare, cloud free conditions, and a pilot also reported a steam plume rising 2,000 ft (600 m) above Shishaldin and moving to the northwest. Then, on July 15, the Ozone Monitoring Instrument (OMI) satellite imagery appeared to show a small plume-like cloud rich in SO_2 originating at Shishaldin; a PUFF simulation using current winds supported the emission source as being Shishaldin (fig. 63).

During the remainder of July and the first half of August, weather permitting, views of Shishaldin showed steaming from the summit. Thermal anomalies were observed in satellite images, particularly in August. A Plate Boundary Observatory (PBO) crew working on Unimak Island replaced the AVO Web camera for Shishaldin, and it began recording images on August 10 (fig. 64); the Web camera would go off-line again on October 11, 2009.

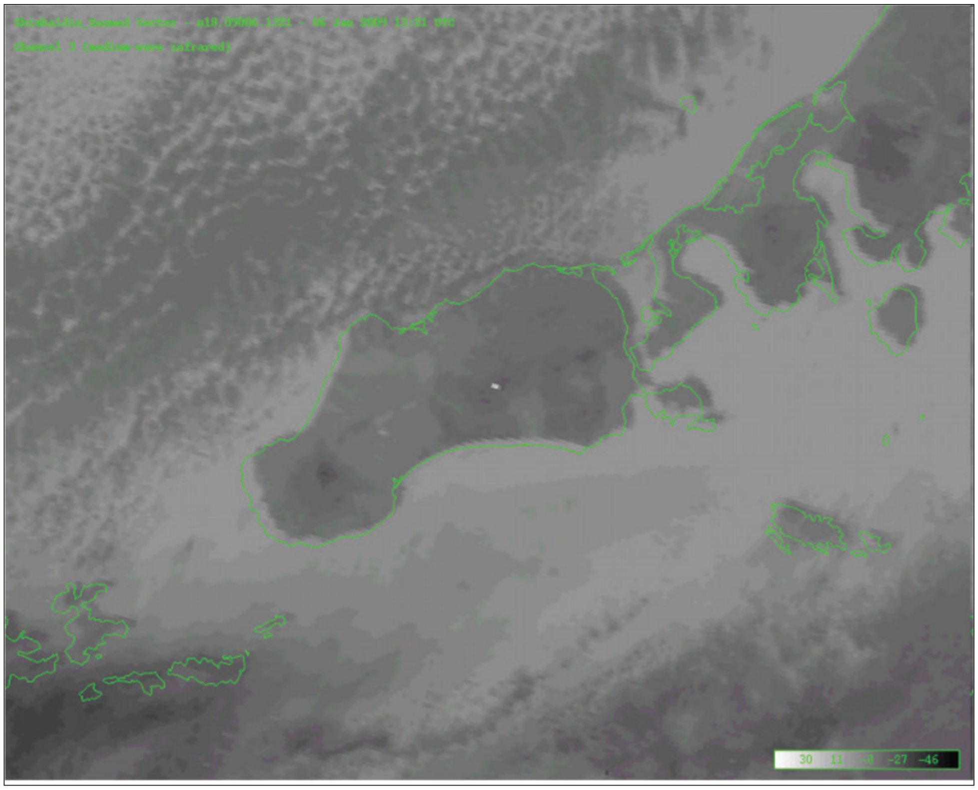


Figure 58. AVHRR satellite image of Unimak Island showing a 2-pixel thermal anomaly centered on the summit crater of Shishaldin Volcano, January 6, 2009, NOAA 18. The anomaly was first observed the previous day, January 5. The low zenith angle of view provided imaging down into the deeper portion of the crater. Unimak Island is about 112 km (70 mi) long.

Figure 59. Shishaldin Volcano, surrounded by low-altitude clouds, producing a pulsing steam plume on January 11, 2009. Photograph by Greg Johnson. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=16232.

Figure 60. AVO Web camera image on February 28, 2009, showing a modest steam plume rising from the summit of Shishaldin Volcano.

Figure 61. Shishaldin Volcano steaming on May 14, 2009. View is from the northwest. Photograph by Michael Levine, NOAA Ship *Oscar Dyson*. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=18710. Inset: Steaming and minor streams of dirty water on the upper flanks of Shishaldin Volcano on May 14, 2009. Photograph by Michael Levine, NOAA Ship *Oscar Dyson*. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=18713.

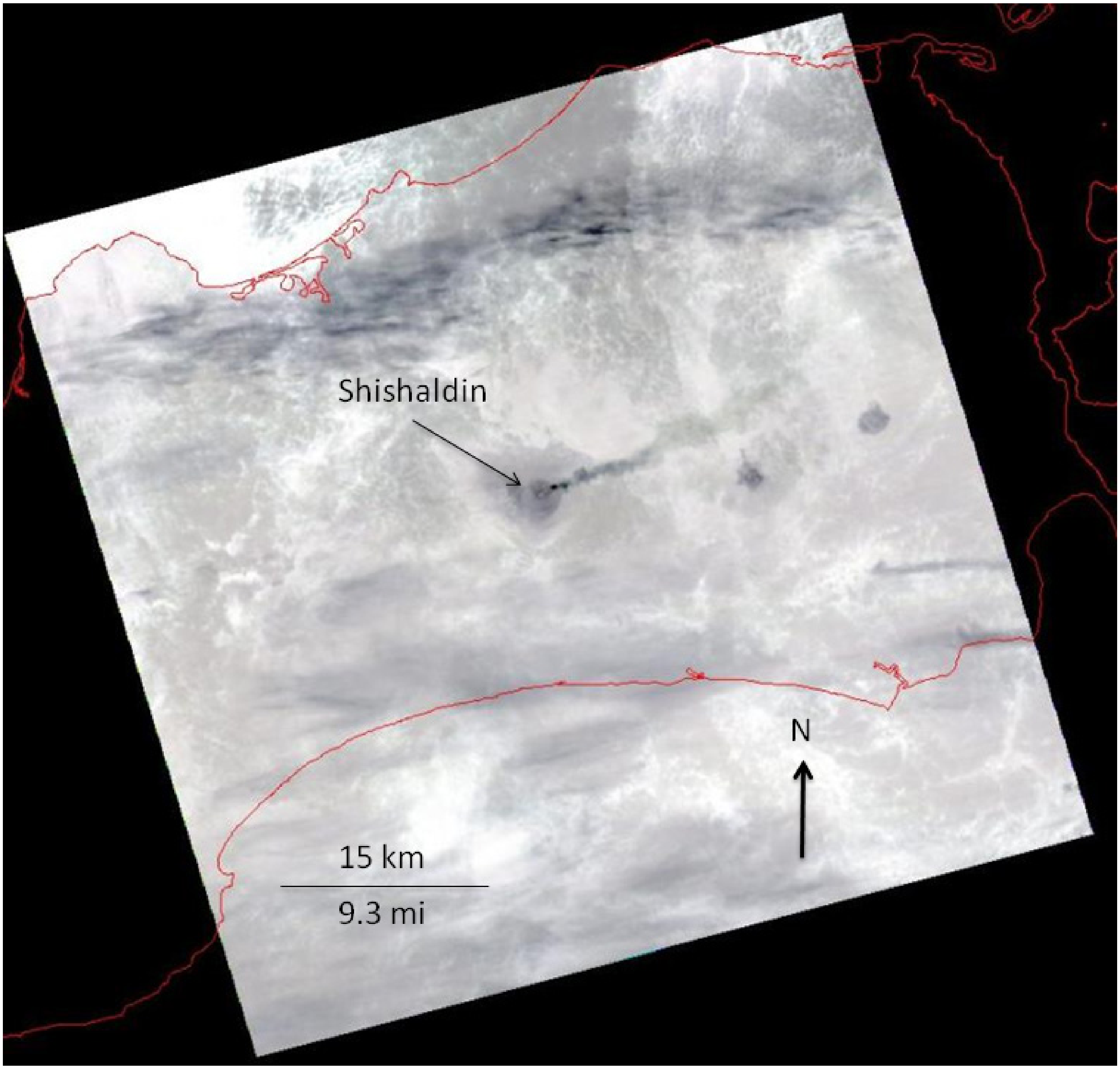


Figure 62. ASTER nighttime thermal infrared image of the eastern part of Unimak Island, Alaska, June 25, 2009. The island is mostly covered by clouds, but the summit of Shishaldin is visible above the cloud deck. This image also shows a weak thermal anomaly and a 22-km-long (14 mi) steam plume at Shishaldin Volcano. Image processed by Rick Wessels, AVO/USGS. Image data courtesy of NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team. AVO database image at URL: http://www.avo.alaska.edu/images/image.php?id=18882.

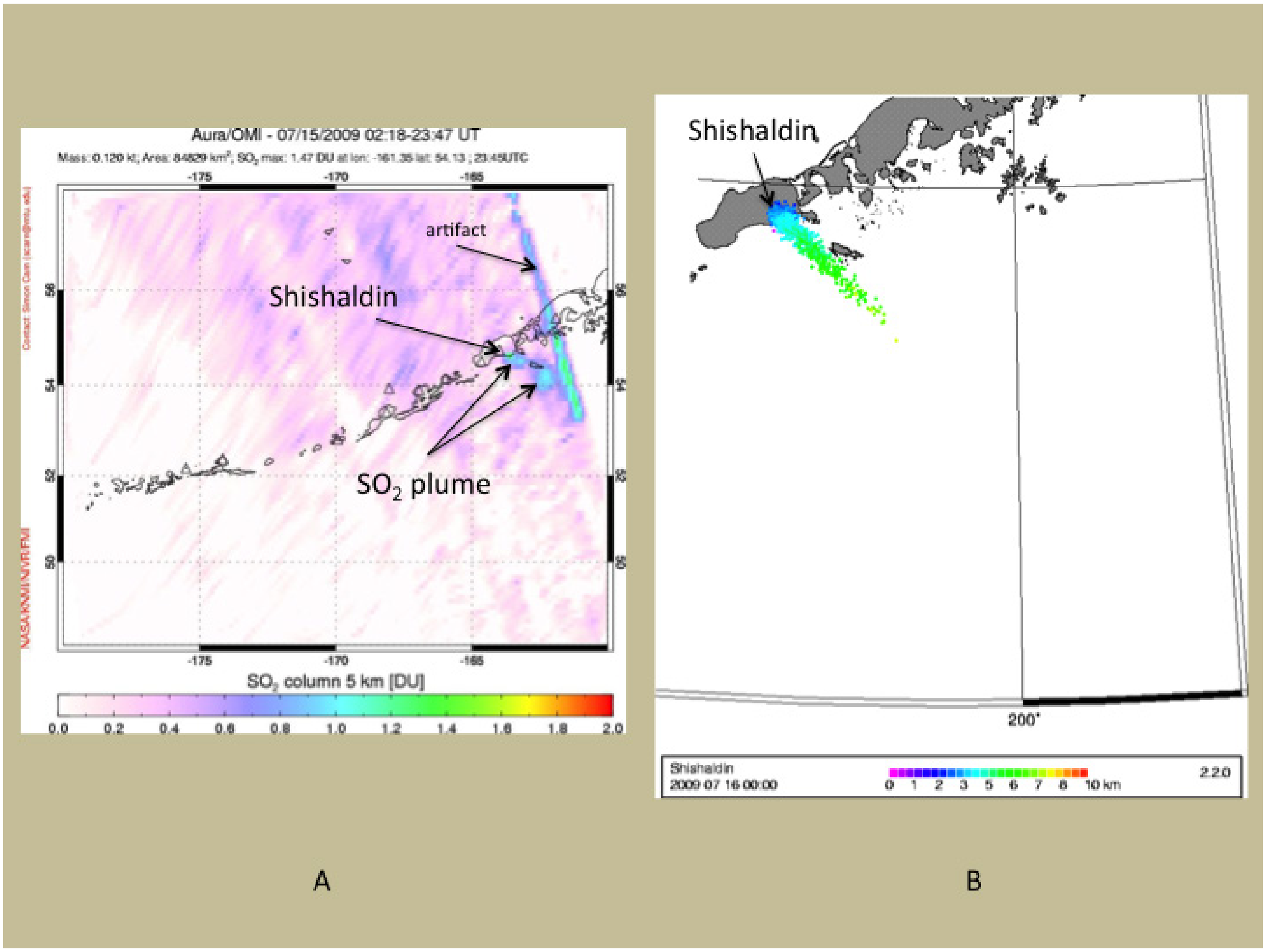


Figure 63. (A) OMI satellite image showing a SO_2-rich plume emanating from Shishaldin. The long band to the right is an “artifact” and not a cloud. (B) PUFF simulation using measured regional winds showing the path of a hypothetical plume originating at Shishaldin, which corresponds with the SO_2-rich cloud shown on the OMI image in (A).

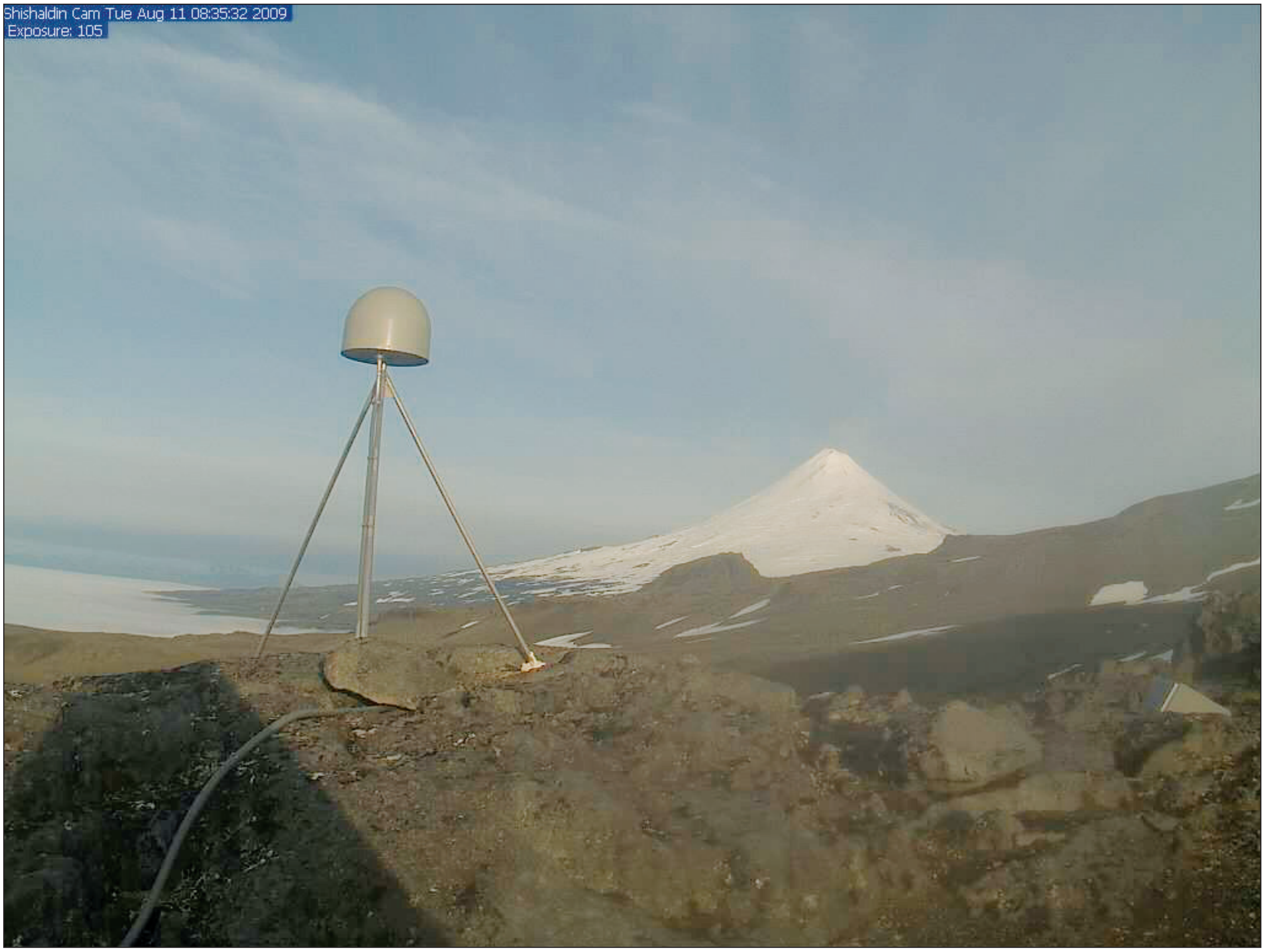


Figure 64. Photograph from the AVO Web camera of Shishaldin Volcano on August 11, 2009. A PBO crew working on Unimak Island replaced the camera on August 10. The previous camera had been off-line since April 30, 2009. This new camera would operate until October 11, 2009. The tripod-mounted instrument in the foreground is a GPS receiver.

Following the report of a thermal anomaly on August 16, no more anomalies were detected through the remainder of 2009 except for a weak thermal anomaly on November 2. In mid-September, seemingly anomalous air waves were detected on pressure-sensors located on Shishaldin (station SSLN_BDF), which could be indicative of minor explosions. Retrospective analysis of pressure-sensor data for the previous 2 months revealed that these air waves are common phenomenon and correlated to episodic gas bursts, as documented in 2003–04 (Petersen and McNutt, 2007).

The persistent absence of thermal anomalies, decrease in steam emissions, and seismicity considered to be within background levels, prompted AVO to downgrade the Aviation Color Code/Volcano Alert Level for Shishaldin to **GREEN/NORMAL** on October 19, 2009. The volcano remained quiet for the remainder of 2009.

Shishaldin Volcano is centrally located on Unimak Island, easternmost of the Aleutian Islands. This large, symmetrical stratocone is about 16 km (10 mi) in diameter at the base; summit elevation is 2,857 m (9,373 ft) making it the highest peak in the Aleutians. The upper 2,000 m (6,500 ft) is almost entirely covered with perennial snow and ice. With more than 28 eruptions reported since 1775, Shishaldin is one of the most active volcanoes in the Aleutian volcanic arc (Miller and others, 1998). The most recent significant eruption was in 1999 (Nye and others, 2002; McGimsey and others, 2004); however, occasional dustings of windblown or possibly phreatic ash on the upper flanks attest to a hot and active shallow hydrothermal system. Monitored by a 5-station seismic network, Shishaldin maintains a high level of normal background seismicity. In addition to satellite surveillance, activity at the volcano also is monitored by 13 GPS stations and 6 borehole tiltmeters installed by the Plate Boundary Observatory, as well as an AVO pressure sensor and Web camera.

The summit is capped by a steep-walled crater—about 200 m (656 ft) in diameter narrowing to a 100-m-wide (328 ft) vertical-walled throat—that produces a constant, and frequently visible, vapor plume. Satellite imagery having a high zenith angle will often capture a striking thermal anomaly in the summit crater. AVO recurrently receives calls from airlines and mariners about plumes and possible ash deposits on the upper slopes of Shishaldin.

Okmok Volcano

CAVW# 1101-29-
53°25'N 168°08'W
1,073 m (3,520 ft)

Umnak Island, eastern Aleutian Islands

CALDERA FLOOR UPLIFT, TREMOR BURSTS

Okmok Volcano produced a 5-week-long phreatomagmatic eruption from multiple vents on the caldera floor during the summer of 2008 (Larsen and others, 2009; Neal and others, 2011). The eruption ended in August 2008, and the Aviation Color Code/Volcano Alert Level were downgraded to **GREEN/NORMAL** on November 19, 2008. No further anomalous seismic or eruptive activity occurred in 2008.

Activity at Okmok remained at background levels until the morning of March 2, 2009, when a series of relatively strong, tremor-like events were recorded on the local seismic network (fig. 65). The largest tremor burst occurred at about 21:11–21:18 UTC (*B* on fig. 65). These events were recorded on average about once per hour during a 24-hour period, but were not detected on adjacent networks. A clear satellite view on February 28 revealed a 1-pixel thermal anomaly in the caldera near the location of Cone D, on the northeastern floor of the caldera. Clouds obscured satellite views of the area on March 2, and any surface manifestation accompanying the seismic activity went unobserved. In response to this abrupt, anomalous seismicity, AVO upgraded the Aviation Color Code/Volcano Alert Level to **YELLOW/ADVISORY** on the evening of March 2, 2009. A pilot flying low over the caldera on March 3 made observations and took several photographs. Several of the photographs appear to show an indistinct flowage deposit down the flank of New Cone, a 400-m (1,300-ft) high tephra cone (Schaefer and others, 2012) developed inside the caldera at the primary eruption site (see fig. 25 of Neal and others, 2011 for location). A clear satellite view on March 9 revealed an area of broad, but apparently shallow, slope failure on the west-northwest side of New Cone, which partly filled the pair of shallow pits located between the cone and the new lake west of Cone D. Material—likely pumice—also spread out into the lake but had been windblown to the eastern shore.

Deformation (uplift) of the caldera floor began in August 2008 following cessation of the eruption. The GPS data from September 1, 2008 to March 1, 2009, show a linear progression of 9 cm of uplift in the center of the caldera (J. Freymueller and T. Fournier, UAFGI, written commun., May 3, 2009, AVO internal log entry 29436) (fig. 66). Although seemingly rapid, the uplift was not considered unusual compared to the considerably more rapid inflation pulse that occurred in 2002–03 during a non-eruptive episode (J. Freymueller, UAFGI, written commun., May 3, 2009, AVO internal log 29436).

Seismicity remained at low, to near background levels for the next several weeks, and satellite views showed no activity, thus prompting AVO to lower the Aviation Color Code/ Volcano Alert Level to **GREEN/NORMAL** on March 20, 2009. No significant changes or activity occurred for the next 2 months. Then, on May 24–25, 2009, a series of tremor bursts were recorded, including a 15-minute-long high amplitude signal that registered across the entire Okmok network (fig. 67). The activity ceased almost as quickly as it began, and the network returned to near background seismic levels.

Activity at Okmok remained at background levels through the remainder of 2009. The only point of interest was that satellite imagery in June compared with earlier imagery revealed extensive erosion of the 2008 eruption features within the caldera (J. Larsen, UAFGI, written commun., 2009, AVO internal log entry 32872). Many of the collapse pits had been filled with erosional debris, the flanks of New Cone became heavily rilled, and the crater floor enlarged as sediment began filling and raising the bottom. The two lakes adjacent to New Cone also increased significantly in size (see fig. 24, Neal and others, 2011 for location).

Although not directly related to Okmok, on Monday, October 12, 2009, at 9:37 p.m. AKDT (October 13, 05:37 a.m. UTC), a magnitude 6.5 regional earthquake struck in the Fox Islands area of Alaska near Okmok (fig. 68). Another strong earthquake of magnitude 6.4 occurred on Tuesday, October 13 at 12:21 p.m. AKDT (20:21 UTC) in the same area. The Alaska Earthquake Information Center (AEIC) located 440 aftershocks over the next couple of weeks, the largest of which was a magnitude 5.6 on Wednesday, October 15 at 4:13 p.m. AKDT (October 16, 00:13 UTC) (AEIC: http://www.aeic.alaska.edu/quakes/fox_islands_20091013.html).

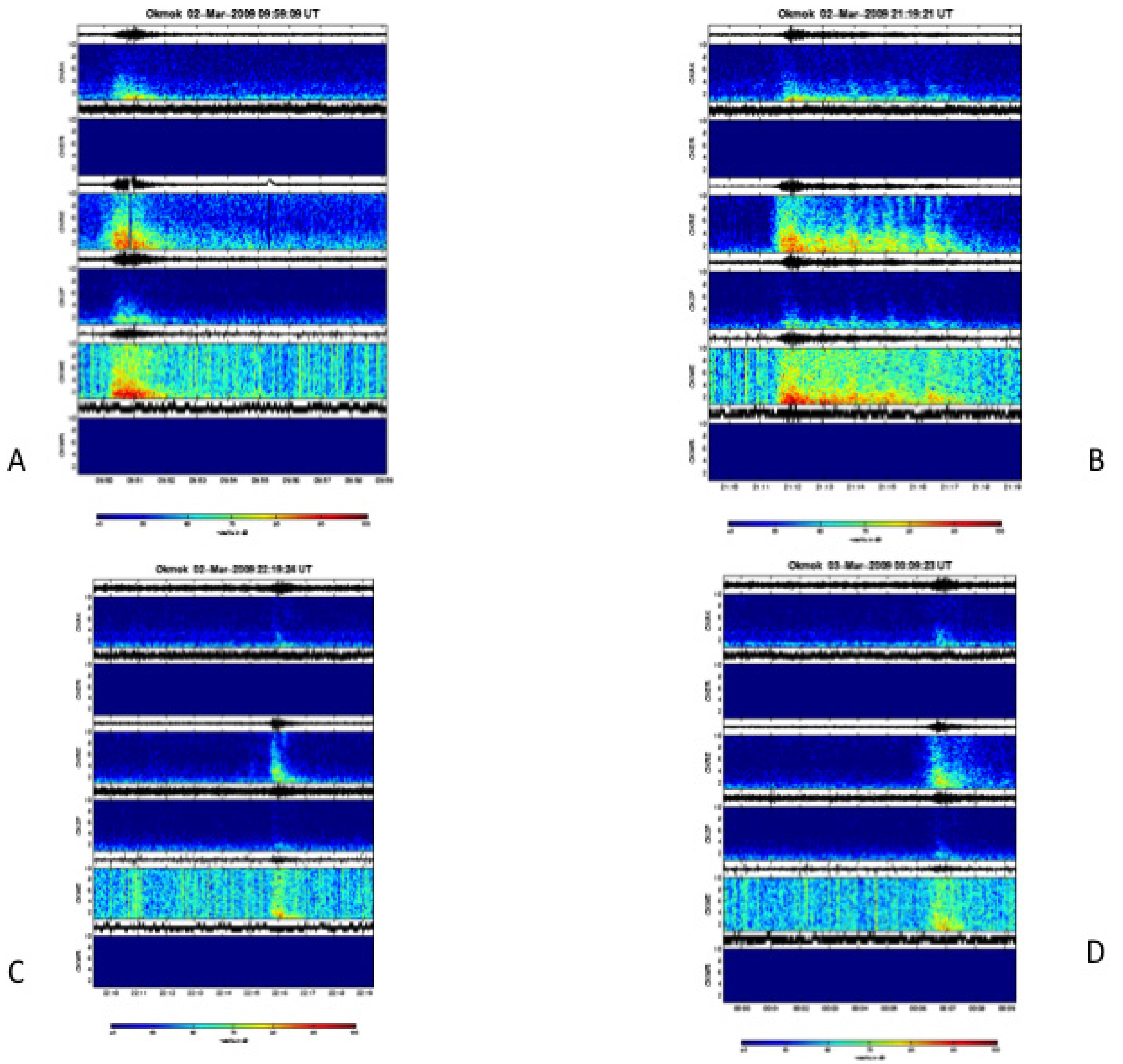


Figure 65. Spectrograms of tremor bursts at Okmok on March 2 and 3, 2009. (A) March 2, 2009, 09:59:09 UTC; (B) March 2, 2009, 21:19:21 UTC; (C) March 2, 2009, 22:19:24 UTC; (D). March 3, 2009, 00:09:23 UTC. The burst in *B*, between 21:11 and 21:18 UTC, was the strongest of the series. Produced by Scott Stihler, AVO internal log entry 29429.

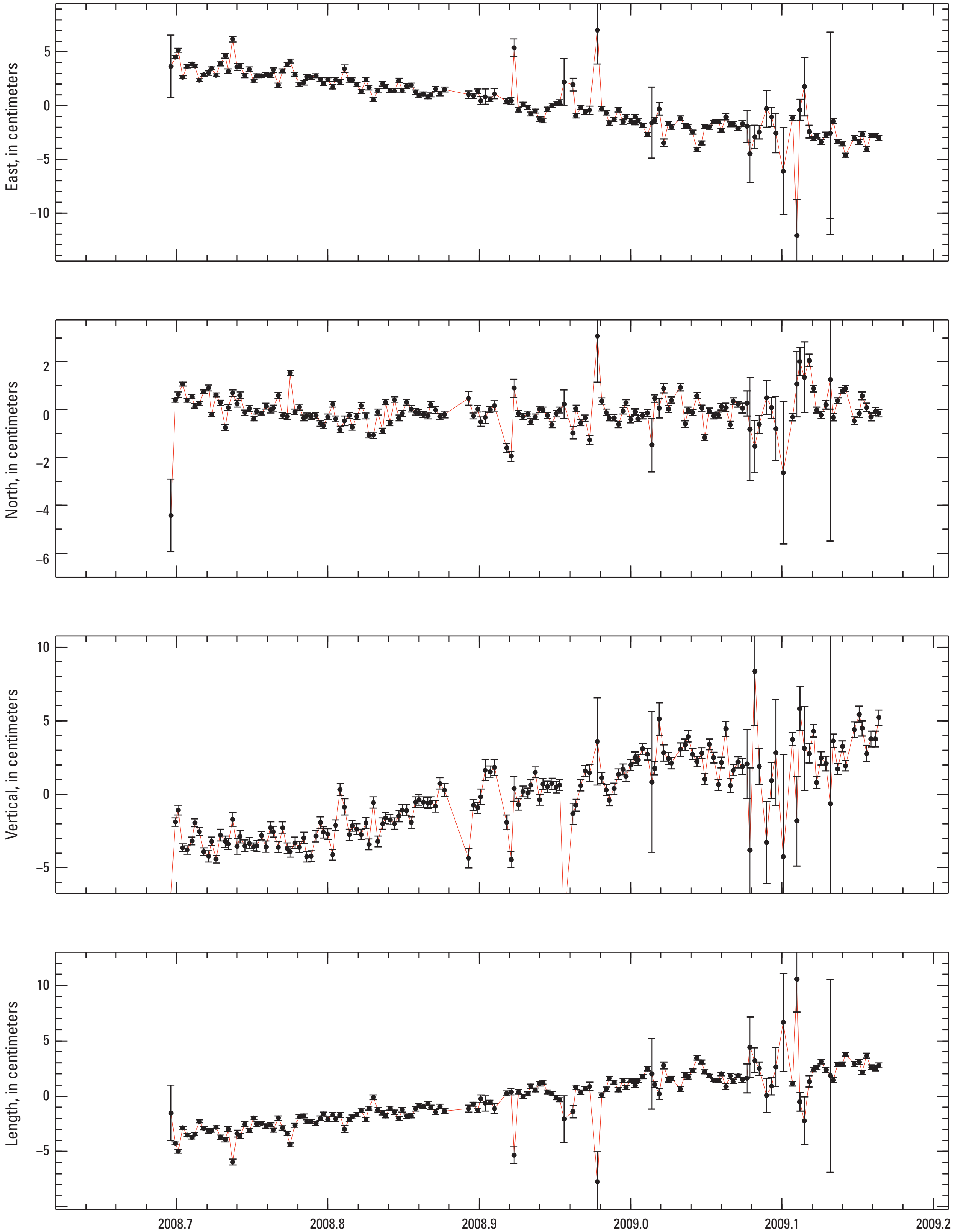


Figure 66. Position of GPS station OKCE within the caldera at Okmok volcano, relative to station AV09 in Dutch Harbor. The plot shows four panels, which are from top to bottom, east, north, up, and length between OKCE and AV09. Deformation appears to be linear with time from September 1, 2008 to March 1, 2009. The westward and upward motion of OKCE is consistent with inflation, which had been occurring since the eruption ended in August 2008. Previous inflation events at Okmok have had associated tremor. Tom Fournier, UAFGI, written commun., 2009, AVO internal log entry 29436.

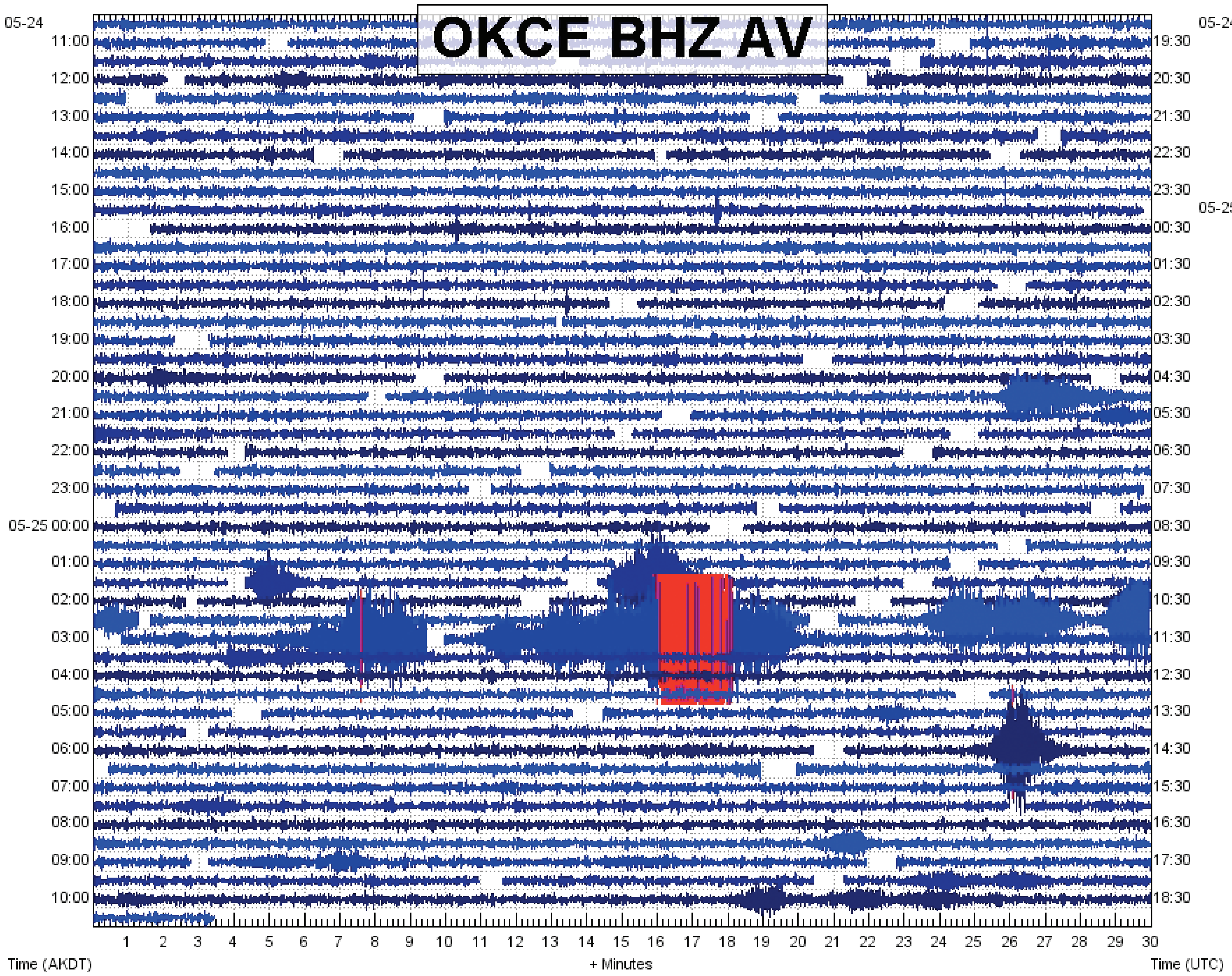


Figure 67. Plot of earthquakes and tremor on seismic station OKCE at Okmok for a 24-hour period spanning May 24–25. The red zone is where the signal amplitude was large enough to "clip", or reach instrument saturation level. This seismicity appears to correspond with a persistent steam plume visible in satellite imagery on May 24 and extending as far as 186 km (115 mi) south of the volcano. John Bailey, UAFGI, written commun., 2009, AVO internal log entry 32379.

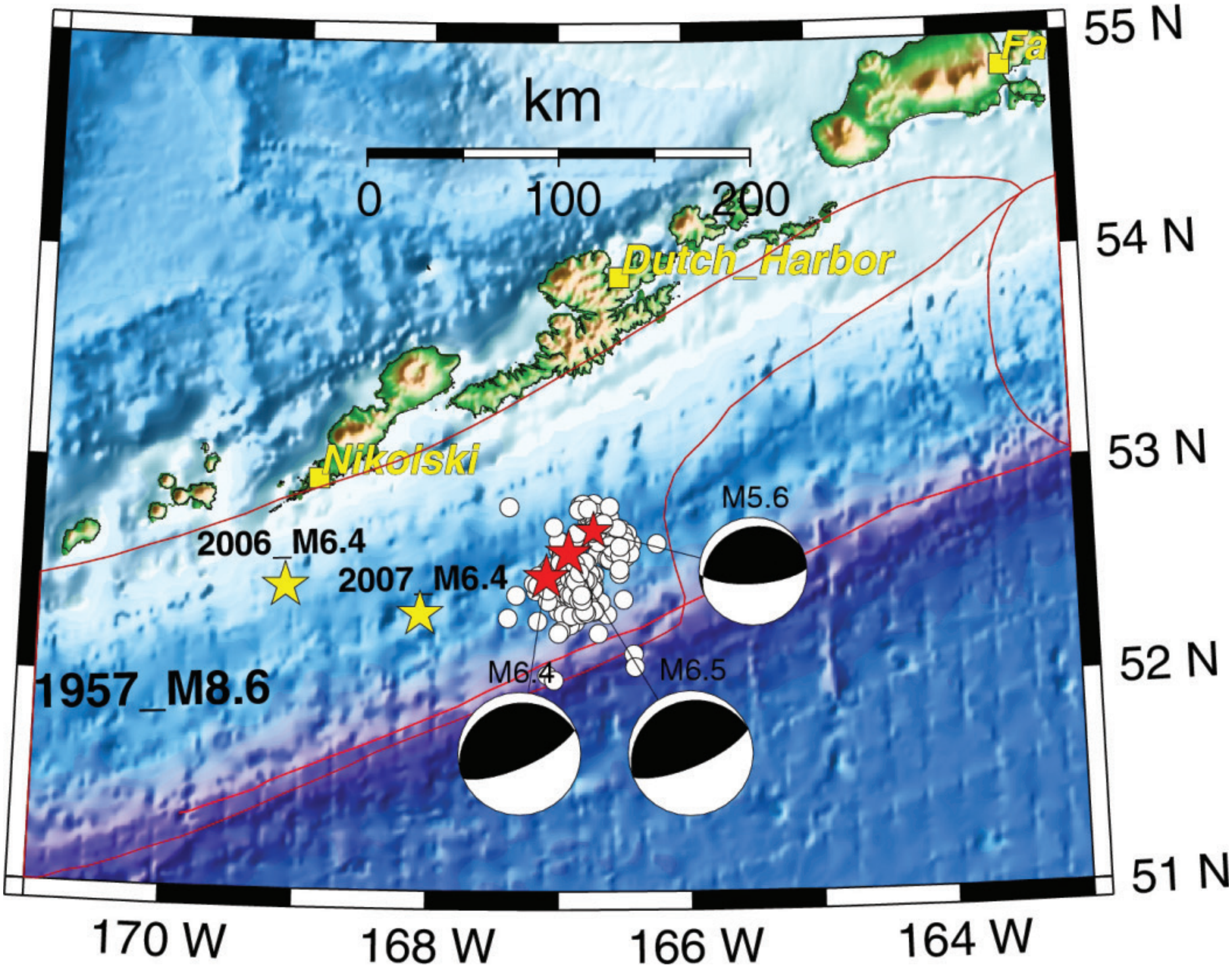


Figure 68. Plot of the M6.5 and M6.4 earthquakes (large red stars) that struck the Fox Islands region on October 13, 2009. A larger aftershock M5.6 earthquake (small red star) occurred on October 15, 2009. The white circles represent the 440 aftershocks recorded through the end of October, 13 of which had magnitudes 4 or greater. The M6.5 earthquake was reported felt in Nikolski and Unalaska. The large black and white circles indicate thrust-type faulting. Alaska Earthquake Information Center: http://www.aeic.alaska.edu/quakes/fox_islands_20091013.html.

Okmok Volcano is a 10-km-wide (6.2-mi) caldera that occupies most of the eastern end of Umnak Island, located 120 km (75 mi) southwest of the important fishing and transportation hub of Unalaska/Dutch Harbor in the eastern Aleutian Islands. Okmok has had several historic eruptions typically consisting of ash emissions occasionally more than 9 km (30,000 ft) ASL, but generally much lower; lava flows crossed the caldera floor in 1945, 1958, and 1997 (Begét and others, 2005). The nearest settlement is Nikolski, population 27 (Alaska Community Database, Community Information Summaries: http://www.commerce.state.ak.us/dca/commdb/CIS.cfm; accessed November 14, 2012), 72 km (45 mi) west of the volcano. A ranch caretaker family lives at Fort Glenn on the flank of the volcano about 10 km (6.2 mi) east of the caldera rim. Prior to 2008, AVO had installed an extensive real-time seismic and deformation monitoring network at Okmok. Eight short period and four broadband seismometers and four continuous GPS stations were distributed about the caldera; at the time of the 2008 eruption, only three GPS stations were operational (Larsen and others, 2009). The eruption destroyed one permanent broadband seismometer and GPS station and damaged at least three other instrument sites; several were resurrected during the September 2008 field campaign (M. Kaufman, UAFGI, written commun., November 2009). During 2009, the Okmok network comprised 12 stations. By December, six had become non-functional. On December 14, three more stations failed leaving only two stations fully functioning and a third operating less than 80 percent of the time (C. Read, AVO/USGS, written commun., 2009, AVO internal log entry 34551).

Cleveland Volcano

CAVW# 1101-24

52°49'N 169°57'W
1,730 m (5,676 ft)

Chuginadak Island, east-central Aleutian Islands

INTERMITTENT EXPLOSIONS
Thermal anomalies, minor ash and gas emissions, flowage and ballistic deposits

Cleveland volcano on Chuginadak Island in the central Aleutians (fig. 1) is unmonitored by ground-based instrumentation. Thick cloud cover frequently limits even satellite remote sensing abilities to reliably detect thermal anomalies and ash clouds resulting from explosions. Cleveland is frequently active and typically produces intermittent explosions with small to moderate ash plumes, ballistics, and Strombolian activity that generates water and debris flows down the flanks. Most unrest is accompanied by thermal anomalies detected in satellite images. Activity at Mount Cleveland in 2009 generally was a continuation of that which occurred intermittently in previous years since 2001 when the last episode of significant eruptions occurred (table 4; Dean and others, 2004; Neal and others, 2009a).

Cleveland experienced eight Aviation Color Code/Volcano Alert Level changes in 2009 (table 3), and began the year in **YELLOW/ADVISORY** status, having been upgraded from **UNASSIGNED** on December 24, 2008, following satellite observations on December 23 of a persistent thermal anomaly near the summit. Similar anomalies at Cleveland often precede eruptive activity. Following that pattern, on January 2, 2009, a brief but explosive ash emission was detected in satellite images. The plume was visible in satellite images for several hours, rose to about 20,000 ft (6 km), and drifted east-southeast up to 240 km (150 mi) downwind dispersing harmlessly over the North Pacific. Flowage deposits draped the flanks with the two largest flows (about 100 m wide; 328 ft) extending down the northeastern and northwestern flanks for at least 2 km (1.2 mi). The eruption produced airwaves that registered on seismometers on adjacent Umnak and Unalaska Islands, as well as on a pressure sensor at Shishaldin Volcano on Unimak Island. Similar airwaves were observed from the November 3, 2008, eruption of Cleveland (M. Haney, AVO/USGS, written commun., 2009, AVO internal log entry 28398).

No further activity was noted until the end of January when satellite images showed evidence of recent eruptive activity visible around the summit of Cleveland. Retrospective analysis on January 23 of prior satellite data indicated that a short-lived, low-level ash emission may have occurred early on the morning of January 21.

For the next 3 months, no significant activity was reported or observed at Cleveland, and on May 1, 2009, AVO downgraded the Aviation Color Code and Volcano Alert Level to **UNASSIGNED**. Then, on the morning of June 25, 2009, satellite imagery caught a small eruption occurring that sent an ash plume up to about 15,000 ft (about 4,600 m) and ballistics onto the upper flank snowfields. As with several previous eruptions, air waves generated by the event were registered on seismometers at nearby volcanoes (M. Haney, AVO/USGS written commun., 2009, AVO internal log entry 32929). AVO promptly elevated the Color Code/Alert Level from **UNASSIGNED** to **ORANGE**. When observed, the plume was already detached and moving south over the North Pacific. Based on no further reports or evidence of activity over the next several days, AVO lowered the Color Code/Alert Level to **YELLOW/ADVISORY** on June 27. The volcano remained quiet for next couple of weeks, and on July 15, the Color Code/Alert Level was downgraded to **UNASSIGNED**. No activity was observed or reported during the subsequent 2.5 months. Then, on October 2, 2009, another small eruption occurred at Cleveland.

Satellite images from 08:11 and 08:25 UTC (00:11 and 00:25 a.m. AKDT) on October 3, 2009, showed a detached ash cloud moving to the northeast away from the volcano. The HYSPLIT particle trajectory model calculated a 6-km-high (20,000 ft) plume originating at about 07:15–07:30 UTC on October 2 (11:15–11:30 p.m. AKDT). A strong ash signal was indicated from analysis of the satellite data. The cloud was 40 km long (25 mi), 12 km wide (7.5 mi), and 122 km (76 mi) from the volcano at 08:25 UTC (October 3) (fig. 69). By 10:00 UTC (02:00 a.m. AKDT on October 3), the cloud was 231 km (144 mi) from the volcano. In response to this activity, AVO upgraded the Aviation Color Code/Volcano Alert Level to **ORANGE/WARNING** at 02:29 a.m. AKDT (10:29 UTC) on the morning of October 3, 2009.

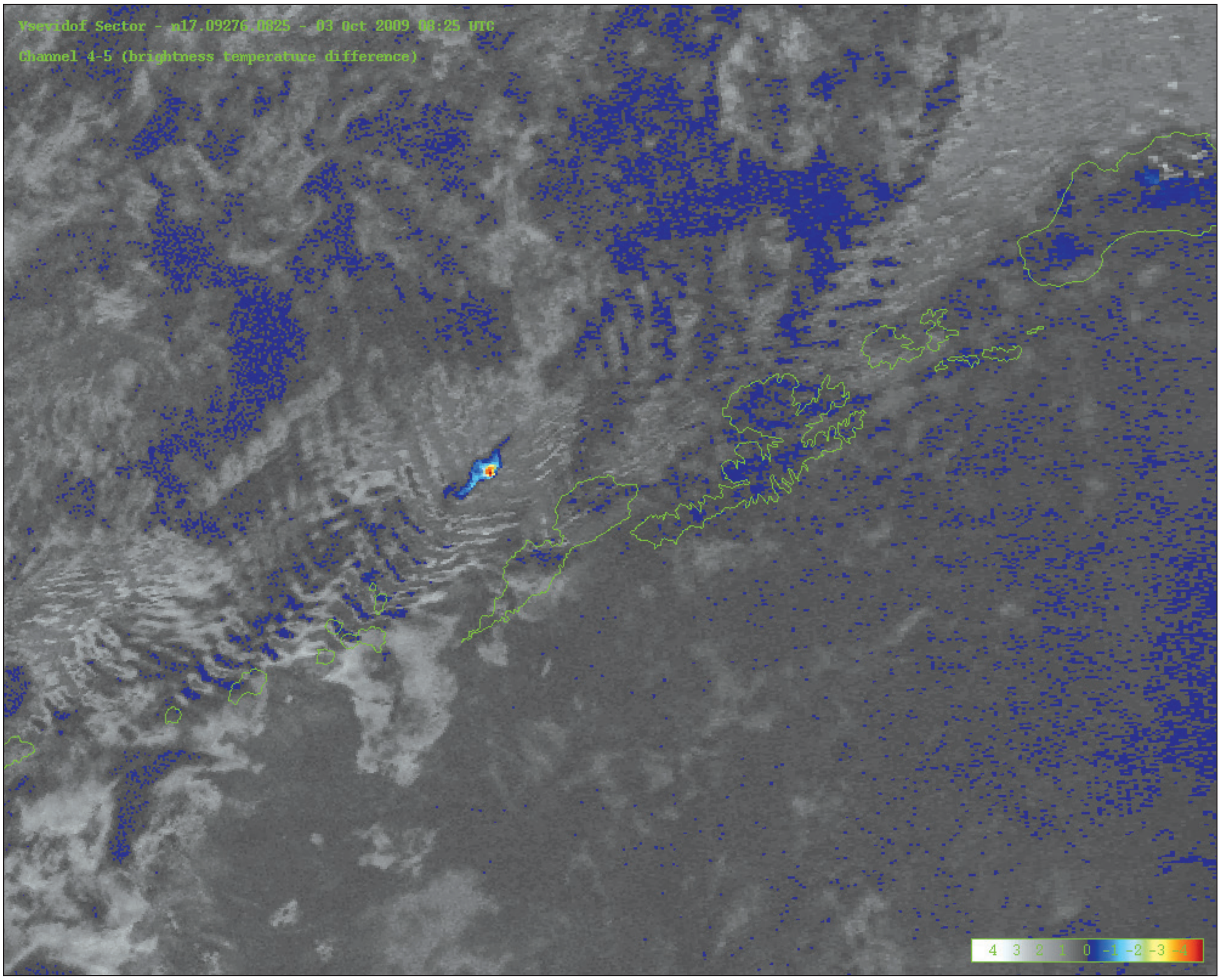


Figure 69. AVHRR satellite image showing a 40-km-long (25-mi-long), 12-km-wide (7.5-mi-wide) detached ash cloud 122 km (76 mi) northeast of Cleveland Volcano, the likely source, October 3, 2009. The colors are indicative of potential ash content and relate to the subtraction of thermal band 5 from 4; the more negative the value, the greater potential ash content. HYSPLIT particle trajectory model tracked the plume back to Cleveland with a start time between 07:15 and 07:30 UTC October 3, 2009 (11:15–11:30 p.m. AKDT, October 2).

Activity decreased as abruptly as it had started, and on the afternoon of October 5, 2009, the Color Code/Alert Level was downgraded to **YELLOW/WATCH**. Clear satellite views, particularly on October 15 and 19, showed no further signs of activity, and on October 19, 2009, status of the volcano was downgraded to **UNASSIGNED**. Cleveland remained quiet almost to the end of 2009. A small, low-level ash plume was emitted on December 12, 2009, but there were no changes to the status for the remainder of 2009.

Cleveland volcano forms the western portion of Chuginadak Island, an uninhabited island in the Islands of Four Mountains group in the east-central Aleutians. Cleveland is located about 75 km (45 mi) west of the community of Nikolski, on neighboring Umnak Island, and 1,500 km (940 mi) southwest of Anchorage. Historical eruptions have been characterized by short-lived ash explosions, lava fountaining, lava flows, and pyroclastic avalanches down the flanks. In February 2001, after 6 years of quiescence, Cleveland had three explosive events that produced ash clouds as high as 12 km (39,000 ft) ASL (Dean and others, 2004), a rubbly lava flow, and a hot avalanche that reached the sea. Intermittent explosive eruptions have occurred in every year since 2001. In fact, the current activity may be considered a continuation of the 2001 unrest.

AVO has no seismic instruments located on Chuginadak Island, and therefore monitoring of Cleveland volcano is accomplished by analyzing daily satellite images, occasional pilot and mariner reports, and on rare clear days, a Web camera located in Nikolski (http://www.avo.alaska.edu/webcam/Cleveland.php).

Volcanic Activity, Kamchatka Peninsula, and the Northern Kurile Islands, Russia

More than 60 potentially active volcanoes on Russia's Kamchatka Peninsula and Kurile Islands pose a serious threat to aircraft in the North Pacific, especially for planes on the North Pacific, Russian Trans-East, and Cross-Polar air routes (Neal and others, 2009b). The primary responsibility for monitoring and alerting the aviation community to activity in Russia lies with the Kamchatka Volcanic Eruptions Response Team (KVERT) for Kamchatka and the northern Kuriles, and the Sakhalin Volcanic Eruption Response Team (SVERT) for the remaining Kuriles (see section, "Volcanic Activity, Central and Southern Kurile Islands").

KVERT is a cooperative program consisting of scientists from the Institute of Volcanology and Seismology (IVS), the Kamchatka Branch of Geophysical Surveys (KBGS), and AVO. The KBGS component of KVERT monitors 11 of the most frequently active volcanoes in Kamchatka with one or more seismometers (fig. 70**;** table 7). The IVS component of KVERT also evaluates AVHRR and MODIS and MTSAT satellite data daily and all KVERT scientists examine real-time, web-camera images of Sheveluch, Klyuchevskoy, Bezymianny, and Koryaksky. In addition, KVERT receives occasional reports of volcanic activity from scientific observers in the communities of Severo–Kurilsk on Paramushir, Klyuchi, and Kozyrevsk. KVERT also receives reports from scientific field parties working in the vicinity of Karymsky Volcano, and pilot reports of volcanic activity are relayed to KVERT from the local Civil Aviation Meteorological Center at Yelizovo Airport. AVO conducts satellite monitoring of portions of the Russian volcanic arc and shares twice-daily satellite monitoring reports with KVERT staff via email. By formal agreement, AVO also assists with dissemination of hazard information for eruptions from the Kuriles and Kamchatka.

A total of eight volcanoes in Kamchatka and on the northern Kurile Island of Paramushir were active requiring some level of AVO response in 2009. Summaries of this activity and related color code changes for Russian volcanoes are listed in tables 8 and 9.

Figure 70. Kamchatka Peninsula and the northern Kurile Islands of Alaid and Paramushir. Volcanoes discussed in this report are labeled with bold red type.

Table 7. Seismically monitored volcanoes of Kamchatka as of December 2009.

[Compiled by S. Senyukov, Kamchatka Branch of Geophysical Surveys (KBGS RAS), and C.A. Neal, Alaska Volcano Observatory. Prior to 1979, other Russian scientific institutes maintained programs of volcano monitoring in Kamchatka (a partial listing includes: 1946–61, F. Yu. Levinson-Lessing Kamchatkan Volcanological Station; 1961–71, Pacific Seismological Department of Institute of Earth Physics; 1972–78—Institute of Volcanology FED RAS). PK—Petropavlovsk, Kamchatska; S-K—Severo-Kurilsk, Paramushir Island, Northern Kuriles]

Volcano	Approximate start date of continuous seismic monitoring by KEMSD (now KBGS)	Other monitoring techniques used routinely
Sheveluch	Seismic station – February 1987 Telemetered data – 1980 Digital format – September 1996 Near-real time processing – 1999	Seismic station—1946; near real-time video system (2002); direct observation from nearby Klyuchi; satellite imagery; field observation.
Klyuchevskoy	Seismic station – 1961 Telemetered data – 1987 Digital format – September 1996 Near-real time processing – 1999	Seismic station—1946; near real-time video system (2000); direct observation from nearby Klyuchi and Kozyrevsk; satellite imagery; field observation.
Bezymianny	Seismic station – 1961 Telemetered data – October 1988 Digital format – September 1996 Near-real time processing – 1999	Seismic station—1958; near real-time video system (2003); direct observation from nearby Kozyrevsk; satellite imagery; field observation.
Ushkovsky	Seismic station — 1961 Telemetered data — 1987 Digital format — September 1996 Near-real time processing — 1999	Direct observation from nearby Klyuchi and Kozyrevsk; satellite imagery; field observation.
Plosky Tolbachik	Seismic station – January 1977 Telemetered data – November 1990 Digital format – September 1996 Near-real time processing – 1999	Seismic station—1958; direct observation from nearby Kozyrevsk; satellite imagery; field observation.
Kizimen	Seismic station – July 2003 Telemetered data – July 2003 Digital format – July 2003 Near-real time processing – July 2003	Near real-time video system (2010); satellite imagery; field observation.
Karymsky	Telemetered data – September 1989 Digital format – January 1996 Near-real time processing – 1996	Satellite imagery; field observation.
Koryaksky	Seismic station – April 1963 Telemetered data – 1975 Digital format – January 1996 Near-real time processing – 1996	Near real-time video system (2009); direct observation from PK; satellite imagery; field observation.
Avachinsky	Seismic station – April 1963 Telemetered data – July 1976 Digital format – January 1996 Near-real time processing – 1997	Near real-time video system (2009); direct observation from PK; satellite imagery; field observation.
Gorely	Telemetered data – July 1980 Digital format – January 1996 Near-real time processing – 1996	Near real-time video system (2010); direct observation from PK; satellite imagery; field observation.
Mutnovsky	Telemetered data – July 1980 Digital format – January 1996 Near-real time processing – 1996	Direct observation from PK; satellite imagery; field observation.
Alaid	Telemetered data – August 2001 to January 15, 2009 Digital format – August 2001 to January 15, 2009 Near-real time processing – August 2001 to January 15, 2009	Satellite imagery.

Table 8. Summary of VOLCANIC ACTIVITY on Kamchatka Peninsula and in the Kurile Islands, Russia, 2009.

[Location of volcanoes shown in figures 70 and 93]

Volcano	Date of activity	Type of activity
Sheveluch	Intermittently active throughout 2009	Lava dome growth, short-lived, explosive episodes, hot avalanches, pyroclastic flows, ash plumes and clouds, local ash falls.
Klyuchevskoy	Intermittently active throughout 2009	Strombolian lava fountaining, lava flows, Vulcanian explosions, ash plumes and clouds, local ash falls.
Bezymianny	Intermittently throughout 2009; significant explosion mid-December	Short-lived explosions, hot avalanches, pyroclastic flows, lava flow, ash plumes and clouds, ash falls.
Kizimen	July–December November 2009	Increase in seismicity and fumarolic activity.
Karymsky	Intermittently throughout 2009	Periods of increased seismicity, explosions, ash plumes and clouds, ash falls, lava flow.
Koryaksky	Intermittently active throughout 2009	Increased fumarolic output, phreatic ash plumes and clouds, sulfur dioxide emission, local ash falls.
Gorely	March–May 2009	Increased heat flux, fumarolic activity and an increase in seismicity.
Ebeko	April–July 2009	Low-level phreatic explosions, local ash falls.
Raikoke	June 12–13, 2009	Fumarolic emission and possible phreatic(?) ash.
Sarychev	June 2009	Sub-plininan (?) eruption, ash clouds, ash falls, pyroclastic flows, lahars, lava flows.

Table 9. Kamchatkan volcanoes with Color Code changes in 2009.

[Beginning August 27, 2009, KVERT adopted the ICAO Aviation Color Code also used by AVO (appendix 2). Times are only shown where Color Code changes were short-lived during rapidly evolving events. Dates are from the KVERT Information Releases and reflect UTC date]

Aviation Color Code	Date of change
SHEVELUCH	
ORANGE	January 1 – April 26
RED	April 26 – April 28
ORANGE	April 28 – September 10
RED	September 10 – September 11
ORANGE	September 11 – December 31
KLYUCHEVSKOY	
ORANGE	January 1 – January 22
YELLOW	January 22 – January 27
ORANGE	January 27 – January 29
YELLOW	January 29 – June 11
GREEN	June 11 – August 1
YELLOW	August 1 – September 10
GREEN	September 10 – September 17
YELLOW	September 17 – October 8
ORANGE	October 8 – December 31
BEZYMIANNY	
YELLOW	January 1 – December 16
RED	December 16 – December 17
ORANGE	December 17 – December 21
YELLOW	December 21 – December 31
KIZIMEN	
GREEN	January 1 – July 30
YELLOW	July 30 – August 31
GREEN	August 31 – October 10
YELLOW	October 10 – November 12
GREEN	November 12 – December 31

Aviation Color Code	Date of change
KARYMSKY	
ORANGE	January 1– April 24
YELLOW	April 24 – August 31
GREEN	August 31 – September 22
YELLOW	September 22 – September 24
ORANGE	September 24 – December 31
KORYAKSKY	
ORANGE	January 1 – January 7
YELLOW	January 7 – March 4
ORANGE	March 4 – April 29
YELLOW	April 29 – August 17
ORANGE	August 17 – August 27
YELLOW	August 27 – November 4
GREEN	November 4 – December 31
GORELY	
GREEN	January 01 – March 26
YELLOW	March 26 – May 21
GREEN	May 21 – December 31
EBEKO	
GREEN	January 1 – April 2
YELLOW	April 2 – July 30
GREEN	July 30 – December 31

Sheveluch Volcano

CAVW# 1100-27=

56°38'N 161°21'W

3,283 m (10,771 ft) 2,500 m (8,200 ft) – approximate elevation of the active lava dome

Kamchatka Peninsula

LAVA DOME GROWTH CONTINUES

Explosive episodes, hot avalanches, pyroclastic flows, ash plumes and clouds, local ash falls

Sheveluch Volcano continued its long-lived eruption throughout 2009. A persistent thermal anomaly coincided with the region of the growing lava dome. Ash explosions and hot avalanches occurred intermittently accompanying extrusion of viscous lava. The volcano was at Level of Concern Color Code **ORANGE** from January until April.

According to seismic data, strong ash explosions may have occurred on January 7 [estimated to be up to 8.8 km (29,000 ft) ASL based on the amplitude of seismicity] and on January 9 and 14 [to 7.3 km (24,000 ft) ASL]. On January 7, minor ash deposits were noted as far as 20 km (65,600 ft) northeast from Klyuchi, 45 km (28 mi) southwest of the volcano. In February and March, hot pyroclastic avalanches with accompanying ash clouds as high as 6 km (20,000 ft) were noted on several occasions. Beginning in February, a significant increase in the number of volcanic earthquakes and magnitude of volcanic tremor was noted, changes usually indicative of an approaching large explosive event. Strong explosive episodes occurred on March 24 and April 9 sending ash to 8 and 7.5 km (26,000 and 24,600 ft) ASL, respectively.

At 06:43 UTC on April 25, another strong explosion sent ash to 7.5 km (25,000 ft) ASL; the cloud drifted south-southwest from the volcano about 140 km (87 mi). Observers noted that following this explosive event, an apparent “fissure” had formed across the southern flank of the dome and a new debris chute began to form (fig. 71). The Level of Concern Color Code was changed to **RED** on April 26 (05:25 UTC) in anticipation of additional strong ash emissions. From April 25–28, ash emission from the fissure atop the dome was essentially continuous. Ash rose up to 5–6 km (16,400–19,700 ft) ASL but extended downwind more than 500 km (311 mi) from the volcano. Small pyroclastic flows were produced during strong pulses of emission (fig. 72). After 09:40 UTC on April 28, satellite imagery indicated no further ash production and the Level of Concern Color Code was changed to **ORANGE**.

The volcano remained relatively quiet until a seismically detected strong explosive event on September 10 from 14:19 until 14:50 UTC and again at 15:57 UTC. Based on the amplitude of seismicity, ash clouds may have reached up to 15 km (49,000 ft) and 10 km (32,800 ft) ASL, respectively. The Aviation Color Code was changed to **RED** following these events. The volcano was obscured by dense weather clouds and no visual or satellite confirmation was possible. On September 13, however, pyroclastic flow deposits were observed at the foot of the lava dome extending downslope about 5 km (about 3 mi). Explosive activity of the volcano decreased in intensity and the Aviation Color Code was changed to **ORANGE** on September 11 (21:50 UTC). Nearly continuous extrusion of lava occurred in late September and into the fall. At night, hot avalanches were frequently observed (fig. 73).

Beginning in mid-October, the number of volcanic earthquakes and the magnitude of volcanic tremor increased markedly, indicating an increased likelihood of a strong explosive event. At 07:30 UTC on October 30, an explosion sent ash possibly as high as 17 km (55,800 ft) ASL. The resulting ash plume was visible on satellite images extending about 255 km (158 mi) towards the east-northeast from the volcano. Images from the newly installed infrared Web-camera (fig. 74), captured explosions triggering collapse of blocks from the lava dome and the resulting hot avalanche. Pyroclastic flow deposits were of minor volume extending only about 4 km (2.5 mi). In November and December, the level of activity decreased [ash clouds accompanying hot avalanches rose to 5–6 km (16,400–19,700 ft) ASL] but the lava dome continued to grow. A thermal anomaly was consistently observed over the lava dome as well as over the accumulating fan of hot pyroclastic deposits to the south of the dome. Ash plumes produced in 2009 were distributed primarily in eastern and southern sectors of the volcano.

Sheveluch Volcano is one of the largest and most active of Kamchatkan volcanoes with at least 60 large eruptions during the Holocene (Bogoyavlenskaya and others, 1985; Ponomareva and others, 1998, 2008). Historical eruptive activity has been characterized by lava-dome growth and explosive collapse, often accompanied by large pyroclastic flows. A catastrophic flank collapse event in 1964 formed the modern amphitheater within which the active lava dome is now growing (Gorshkov and Dubik, 1969; Melekestsev and others, 1991; Zharinov and others, 1995). The current phase of lava-dome growth and explosive activity began in late September 1980 and has continued intermittently into 2013.

Figure 71. Sheveluch Volcano and the active lava dome in low-level eruption. A new debris chute on southern flank of the dome became a prominent pathway for hot avalanches from the dome in 2009. Photograph by Yuri Demyanchuk, IVS, April 26, 2009.

Figure 72. Pyroclastic flow in progress produced by an avalanche of hot debris from the active lava dome at Sheveluch Volcano. Photograph by Yuri Demyanchuk, IVS, April 26, 2009.

Figure 73. Incandescent rubble draping the southern flank of the active lava dome at Sheveluch Volcano. Photograph by Yuri Demyanchuk, IVS, November 2, 2009.

Figure 74. Ash emission and hot avalanche activity at Sheveluch Volcano taken by the infrared Web-camera installed in 2009 at the F.Yu.Levinson-Lessing Kamchatkan Volcanological Station. Image date is October 30, 2009.

Klyuchevskoy Volcano

CAVW# 1000-26=

56°03'N 160°38'E
4,750 m (15,585 ft)

Kamchatka Peninsula

STROMBOIAN, VULCANIAN ACTIVITY, LAVA FLOW PRODUCTION
Ash plumes, ash falls, lava flows, phreatic explosions as lava flow interacts with glacial ice

In January 2009, activity at Klyuchevskoy continued the intermittent effusive-explosive eruption that began in October 2008. Continuous Strombolian activity and gas-steam plumes containing small amount of ash up to 5.6 km (18,400 ft) ASL were noted (Girina and others, 2011). A lava flow continued to overflow the summit crater and descend into Krestovsky chute. A thermal anomaly was constantly observed over the summit in satellite imagery. On January 12, a gas-steam plume containing minor amounts of ash rose up to 6.8 km (22,300 ft) ASL. The Level of Concern Color Code was **ORANGE** from January 1 through 22. As activity of the volcano began to decrease, the Level of Concern Color Code was downgraded to **YELLOW** on January 22 (22:35 UTC).

On January 26–27, while the level of overall activity was decreasing, ash plumes rose to 5.3 km (17,400 ft) ASL and extended about 80 km (50 mi) to the east-northeast from the volcano; a small ash fall was noted in the nearby settlement of Klyuchi, 30 km (19 mi) north of the volcano. The Level of Concern Color Code was changed to **ORANGE** for January 27–29. According to satellite monitoring, ash plumes extended about 40–230 km (25–143 mi) primarily to the northwest, east, and northeast from the volcano during January. Seismicity of the volcano at this time was high and volcanic tremor measured 14–15 μ/s. By the end of January, explosive-effusive activity in the summit crater had ended.

From February 1 until July 31, the volcano was relatively quiet—only weak fumarolic activity producing a gas-steam column to 50–300 m (164–984 ft) above the crater was noted. The Level of Concern Color Code was **YELLOW** from January 29 until June 11, and **GREEN** from June 11 until August 1.

In early August, increased seismicity indicated the onset of a new eruptive phase. In late August into early September, intermittent ash explosions occurred from the summit crater, and on September 16, continuous Strombolian activity began anew. Lava fountains sent glowing fragments of lava 70–100 m (230–328 ft) above the crater rim. The Aviation Color Code was changed to **YELLOW** on September 17 (22:50 UTC).

Beginning October 8, the activity of the volcano began to intensify slowly and the Aviation Color Code was changed to **ORANGE** where it remained through the end of 2009 and into 2010. On occasion in October and November, observers noted incandescent bombs hurled 200–500 m (656–1,640 ft) above the crater (fig. 75). On November 13, lava overflowed the summit crater and moved down the southeastern flank (into Apahonchich chute; fig. 76). Strombolian activity continued into December. Gas-steam plumes with small amounts of ash rose to 5.2–6.2 km (17,000–20,300 ft) ASL and extended more than 90 km (56 mi) primarily northwest from the volcano.

From September 16 through the end of 2009, a thermal anomaly was recorded over the volcano continuously in satellite imagery as Strombolian and related lava flow activity increased in intensity.

Klyuchevskoy, the highest active volcano in Eurasia, is frequently active with Strombolian to Vulcanian explosions and occasional lava-flow production from the main vent in the steep-walled summit crater or from flank vents (Khrenov and others, 1991). Explosive eruptions have been recorded in nearly every decade and at multiple times during most years since the early 1700s (Siebert and others, 2011).

Figure 75. Klyuchevskoy Volcano in Strombolian eruption. Photograph by Yuri Demyanchuk, IVS, November 5, 2009.

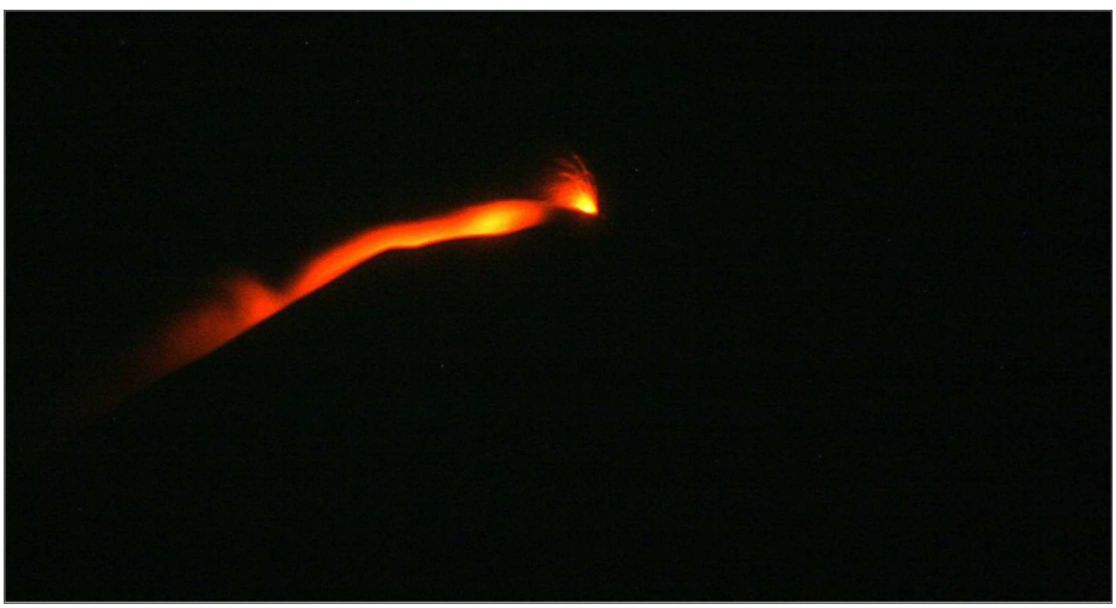


Figure 76. Klyuchevskoy Volcano in Strombolian eruption. Elongate pattern of glow is from lava flowing out of the summit crater and down the southeastern flank of the volcano. Photograph by Yuri Demyanchuk, IVS, November 14, 2009.

Bezymianny Volcano

CAVW# 1000-25=

55°58'N 160°36'W
2,882 m (9,456 ft)

Kamchatka Peninsula, Russia

INTERMITTENT LAVA DOME GROWTH AND EXPLOSION

Intermittent growth of the lava dome at Bezymianny Volcano continued in 2009 (Girina and others, 2011). The volcano began the year quietly at Aviation Color Code **YELLOW** and displayed little change for much of the year. Typically, a fumarolic plume rose above the active dome (fig. 77) and seismicity was at or slightly above background.

A thermal anomaly at the approximate position of the lava dome was common in clear satellite images. The temperature of the Bezymianny thermal anomaly began to increase on December 6, 2009, followed by an increase in the number of volcanic earthquakes on December 8. Details of seismicity were difficult to discern clearly due to the high rates of activity at nearby Klyuchevskoy volcano. In anticipation of an explosive event, the Aviation Color Code was changed to **RED** on December 16 (21:30 UTC). The expected event occurred, according to seismic data, between 21:45 UTC on December 16 and 04:00 UTC December 17, when an ash plume from a series of explosions rose to a seismically estimated 10 km (32,800 ft) ASL. Due to bad weather in the region, the eruption was not observed visually. Strong winds moved the ash plume to the west and northwest. On December 16–17, the ash plume was more than 25 km (16 mi) wide as seen from Kozyrevsk. A detached ash cloud 75 × 42 km (47 × 26 mi) was observed greater than 370 km (230 mi) from the volcano on December 17. A 2–3 mm ashfall occurred in Kozyrevsk Village from 22:20 until 23:30 UTC on December 16 (fig. 78); small amounts of ash fall continued intermittently for the next few hours. The main road “Petropavlovsk-Kamchatsky - Ust-Kamchatsk” near Kozyrevsk Village was covered with ash deposits for more than 35 km (22 mi).

As a result of the December explosion, it is inferred that a part of the southern flank of the dome was destroyed. During the event, pyroclastic flows and associated pyroclastic surges traveled down the southern slope of the volcano. Deposits were noted on the southeastern flank of the volcano; run-out distance for the December 16 pyroclastic flow deposits was about 5 km (3 mi) and pyroclastic surges traveled about 15 km (9.3 mi).

When activity at the volcano decreased significantly, the Aviation Color Code was changed at first to **ORANGE** on December 17 (06:55 UTC) and to **YELLOW** on December 21 (00:15 UTC). After the December 16 eruptive event, a large thermal anomaly was noted over the lava dome and on the southeastern flank of the volcano, now mantled by hot pyroclastic flow deposits. The high temperature of anomalies over the dome (66–530 ^{o}C) on December 17–26, were consistent with effusion of a new lava flow down the flank of the pre-existing active dome.

On March 30, 1956, Bezymianny’s first historic eruption began with a catastrophic flank failure, directed blast, pyroclastic flows and mud flows (Gorshkov, 1959; Bogoyavlenskaya and others, 1985); the eruption was quite similar to that which occurred at Mt. St. Helens on May 18, 1980 (Lipman and Mullineaux, 1981). Since then, lava extrusion has produced a dome that periodically produces powerful vertical or inclined ash emission events, pyroclastic flows and short-lived but far-traveled ash clouds (Girina and others, 1993; Carter and others, 2007).

Figure 77. Oblique aerial photograph of the summit and active lava dome complex of Bezymianny Volcano on September 5, 2009. Photograph by S. Ushakov, KVERT/IVS.

Figure 78. Minor ash deposits 2–3 mm thick at Kozyrevsk village by the Bezymianny eruption of December 16–17, 2009. Photograph by Yuri Demyanchuk, IVS.

Kizimen Volcano

CAVW# 1000-23=

55°08'N 160°19'E
2,485 m (8,153 ft)

Kamchatka Peninsula, Russia

INCREASED SEISMICITY AND FUMAROLIC ACTIVITY; NO ERUPTION

Kizimen Volcano in central Kamchatka had been monitored by a single telemetered seismometer by KBGS since 2003 (table 7). On July 11, 2009, seismicity at Kizmen increased abruptly (fig. 79). For the period July 11–23, 13 to 120 volcano tectonic earthquakes per day were detected. Because of the possibility of an explosive eruption, KVERT changed the Aviation Color Code for Kizimen from **GREEN** to **YELLOW** on July 30. Weak volcanic tremor commenced on August 20, and seismicity remained above background through the end of 2009.

Volcanologists visited the volcano from August 15 through 31, 2009. A temperature of 340 °C was measured at the fumarolic site “Revuschaya” and was about 100 °C above that measured in 1979–80 (fig. 80) (Kirsanova and others, 1983). No other changes were noted around the volcano. Seismic activity decreased with time and KVERT changed the Aviation Color Code from **YELLOW** to **GREEN** on August 31.

In response to the unrest, a new seismic station (KZV) was installed by the KBGS RAS on the southwestern slope of Kizimen [2.5 km (8,200 ft) from the summit] in September 2009. A weak thermal anomaly over the volcano was noted between August 21 and October 16, 2009, and a persistent plume emanated from the fumarole on the flank of the volcano (fig. 81). Based on the recurrence of elevated seismicity and possibility that a sudden explosive eruption would threaten aviation, KVERT changed the Aviation Color Code for the volcano from **GREEN** to **YELLOW** on October 10, 2009. Although seismicity remained somewhat above background, no explosions occurred and on November 12, 2009, KVERT changed the Aviation Color Code from **YELLOW** to **GREEN** where it remained through the year’s end.

Kizimen is a young, conical stratovolcano located about 250 km (155 mi) northwest of Petropavlovsk-Kamchatsky (fig. 70). A large explosion about 1,100 years ago created an amphitheater in the summit region; subsequent dome-building eruptions built a small dome complex within the structure (Meleketsev and others, 1995). The only documented historic eruption was a small explosive event that occurred in December 1927–January 1928 (Siebert and others, 2011).

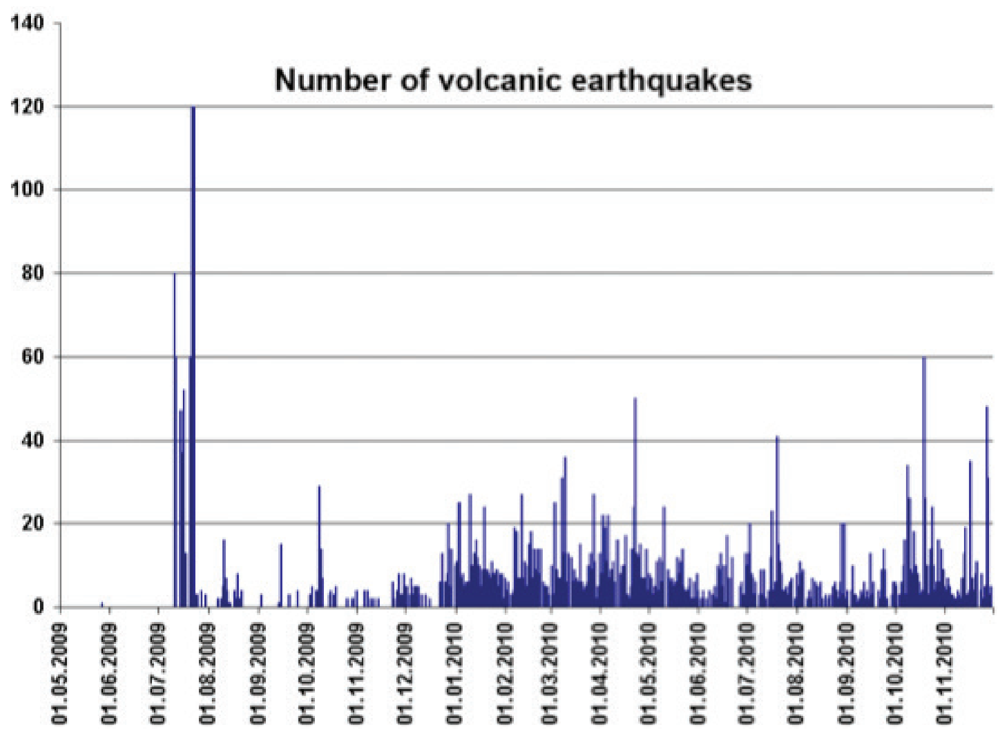


Figure 79. Plot of the number of volcanic earthquakes per day in the area of Kizimen Volcano in 2009 and into 2010. Data courtesy KBGS RAS.

Figure 80. Vigorous fumarolic activity at Kizimen Volcano on August 22, 2009. Photograph by A. Ovsyannikov. Note scientist in red jacket sampling fumarole called "Revuschaya."

Figure 81. Distant view of Kizimen Volcano on October 23, 2009. A vapor and gas plume emanates from Revuschaya fumarole area. Photograph by T. Kozhevnikova.

Karymsky Volcano

CAVW# 1000-13

54°03'N 159°27'E
1,486 m (4,876 ft)

Kamchatka Peninsula, Russia

STROMBOLIAN / VULCANIAN ERUPTION CONTINUES INTERMITTENTLY
Vulcanian explosions, ash cloud, local ash fall, lava flow

Karymsky Volcano continued its now 13-year-long eruption throughout 2009. Typical activity consisted of intermittent Vulcanian explosions producing short-lived ash plumes rising as high as 5 km (16,400 ft) ASL. Satellite images often recorded a thermal anomaly coincident with strong ash explosions and intermittent effusion of lava inside the Karymsky summit crater.

From January through May 2009, seismic activity of the volcano became irregular and unstable. At times, seismometers recorded spasmodic volcanic tremor, which likely reflected strong gas release events. The volcano began the year at Aviation Color Code **ORANGE**. According to KVERT field observations, on January 30 and April 14, a gas-steam plume of varying intensity rose up to 3 km (9,800 ft) ASL. According to AMC Yelizovo, pilots observed ash plumes up to 4 km (13,100 ft) ASL that extended to the east from the volcano on February 24 and March 3 and 12.

In April, seismicity decreased and the Aviation Color Code was changed to **YELLOW** on April 24 (00:00 UTC) and later to **GREEN** on August 31 (02:15 UTC). However, beginning in mid-September, eruptive activity resumed. The Aviation Color Code was changed to **YELLOW** on September 22 (06:35 UTC) and to **ORANGE** on September 24 (21:50 UTC) and remained such for the remainder of 2009. IVS scientists observed the volcano in August and into October and noted small ash plumes rising from the summit crater up to 3.5 km (11,500 ft) ASL (fig. 82).

Figure 82. Karymsky Volcano in eruption. Photograph by Alexander Manevich, KVERT/IVS, October 26, 2009.

Based on analysis of satellite and seismic data for the entire year, the majority of explosions and ash plumes occurred in March, June, November, and December. Their typical length as seen in satellite images was greater than 200 km (125 mi) primarily eastward from the volcano. Ash fall as seen from space (fig. 83) showed the extent of downwind impact of Karymsky ash.

In December, scientists of KBGS RAS flew over the volcano and discovered a small lava flow within the summit crater (fig. 84). The lava flow eventually overtopped the summit crater rim and descended the southern flank. The increasing size and brightness temperature of satellite-detected thermal anomalies during November and December were likely due to the lava-filled volcanic crater and the lava flow.

Karymsky is the most active volcano on the Kamchatkan Peninsula and explosive and effusive-explosive eruptions of andesitic tephra and lava flows alternating with periods of repose are typical of Karymsky (Ivanov and others, 1991). The current phase of unrest began in mid-April 1995 with increasing seismicity and culminated in an explosive eruption that began on January 1, 1996. Initial eruptive activity occurred simultaneously at Karymsky Volcano and from a vent at the northern part of Karymsky Lake, a distance of about 10 km (32,800 ft); (Fedotov, 1998; Belousov and Belousova, 2001). Since then, periods of explosive eruptions of ash and blocks have alternated with periods of lava-flow production.

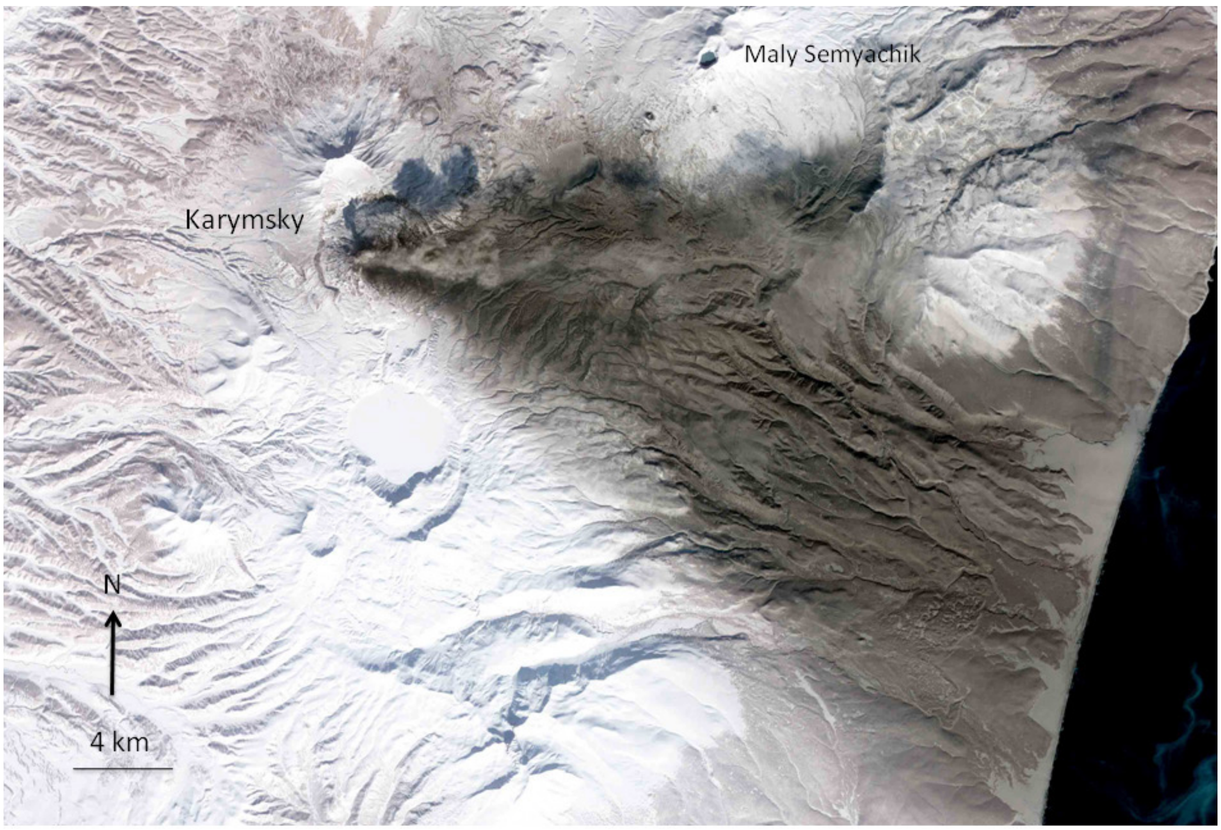


Figure 83. ASTER image showing Karymsky Volcano in low level eruption, March 7, 2009. Dark region east of the volcano shows area affected by recent Karymsky ash fall. Image courtesy of NASA.

Figure 84. Oblique aerial photograph of the summit crater of Karymsky Volcano. A viscous lava flow has erupted from the central vent and ponded in the summit crater. Photograph by Vasily Yaschuk, December 8, 2009.

Koryaksky Volcano

CAVW# 1000-09=

53°19'N 158°43'E
3,456 m (11,339 ft)

Kamchatka Peninsula, Russia

INCREASED FUMAROLIC OUTPUT, PHREATIC EXPLOSIONS
Minor ash fall, ash plumes on satellite imagery

On December 24, 2008, about 1 month after a slight increase in background seismicity and visible fumarolic output, KVERT reported a moderate phreatic eruption from an area of active fumaroles on the northwestern flank of Koryaksky Volcano (Girina and others, 2010; Neal and others, 2011). The Aviation Color Code for the volcano was **ORANGE** at the start of 2009.

Between January 1 and 5, 2009, the volcano was obscured by dense clouds. On January 6–7, only moderate fumarolic activity was observed from Petropavlovsk-Kamchatsky, and the Aviation Color Code was changed to **YELLOW** on January 7. From January 11 through July 20, a weak thermal anomaly occasionally was detected on satellite images, likely produced by vigorous fumaroles high on the volcano's flank (fig. 85). At times, the strong fumarolic activity produced distinct columns of steam and volcanic gas up to about 4.5 km (about 14,800 ft) ASL (for example, January10–14). On January 15–22, aerosol plumes extended tens kilometers to the east and west from the volcano.

Several periods of intense emission of phreatic ash from the highest elevation fumarole occurred in 2009 (fig. 86). On February 23 and 25, an ash and gas plume extended 200 km (125 mi) to the north and the east-northeast from the volcano, respectively. From March 3 to 14, the amount of ash contained in the plumes rose sharply. The Aviation Color Code was changed to **ORANGE** on March 4 and remained there until April 29. From March 3 to April 18 ash plumes were detected on satellite images every day. They stretched up to 680 km

Figure 85. Oblique aerial view of Koryaksky Volcano and vigorous fumarolic emission, January 8, 2009. Photograph by Alexander Sokorenko, IVS, used with permission.

Figure 86. Ash column at Koryaksky volcano on April 9, 2009. Photograph by Sergey Ushakov, KVERT/IVS.

(420 mi) in various directions from the volcano. Thickness of ash on the pass between Avachinsky and Koryaksky volcanoes was 0.1–0.2 cm on March 4; at an elevation of about 1 km (0.6 mi) on the northern slope of Koryaksky, ash fall was 4 cm thick; at the top of the volcano on March 7, up to 5 cm of ash was recorded. In Petropavlovsk-Kamchatsky, the ash deposit thickness did not exceed 0.1–0.2 cm. The most energetic activity of 2009 was observed on April 9 [when the height of the gas-steam column containing ash was 5.5 km (18,000 ft) ASL] and again on May 10 and 22 [when the column reached 4.5 km (14,800 ft) ASL]. Although from April 18 on, ash plumes from Koryaksky volcano were not seen in satellite

images; from the ground, gas-steam plumes containing ash remained visible until April 22. Between April 24 and 25, the lower fumarole ceased emitting. The Aviation Color Code was changed to **YELLOW** on April 29 and only moderate fumarolic activity prevailed into early August.

The next increase of activity at Koryaksky volcano was observed on August 12 when both visual and satellite data began to record ash plumes reaching heights of up to 5 km (16,400 ft) ASL. The Aviation Color Code was changed to **ORANGE** on August 17. From August 16 to 27, ash plumes were observed regularly, and their length ranged from 20 to 385 km (12 to 240 mi) (fig. 87). On August 17–18, trace amounts (< 1 mm) of ash was reported at many summer cottages (Dachas) situated on the slopes of Koryaksky volcano. From August 26 through December 31, no ash plumes were observed. The Aviation Color Code was changed to **YELLOW** on August 27 (21:50 UTC), and to **GREEN** on November 04 (22:30 UTC).

Analysis of tephra deposits indicates no involvement of juvenile magma in ash emission. Anikin and others (2011) divide crystal fragments in the ash into groups: (1) the rock-forming minerals (plagioclase, ortho- and clinopyroxenes, olivine, magnetite and also volcanic glass), (2) accessory minerals (sphene, rutile, zircon, corrundum, garnet, pyrite, ilmenite, spinel, muscovite, apatite, pyrrhotite), and (3) minerals that may have hydrothermal genesis (gypsum, barite, pyrite, sulfur, quartz, cristobalite, and amorphous silica). Overall, the mineralogical characteristics of ash indicate a hydrothermal and phreatic origin.

Activity from Koryaksky in 2009 was a significant source of volcanic SO_2. On March 18 in clear weather over southern Kamchatka, the volcanic aerosol plume from Koryaksy volcano contained about 0.48 kilotons SO_2 (fig. 88) (Girina and others, 2010).

The large eroded, rugged Koryaksky stratovolcano looms about 25 km (15.5 mi) outside Kamchatka's largest city, Petropavlovsk-Kamchatsky and the International Airport at Yelizovo (fig. 70). There is no historical record of significant explosive eruptions. In 1956–57, a VEI 2 event produced small explosions containing small amount of ash. A vigorous permanent fumarole—the area active during 2008 and 2009—exists high on the northwestern flank of the volcano. Holocene lavas are present on the western and southwestern flanks; lahars associated with a period of lava effusion from south- and southwest-flank vents about 3,900–3,500 years ago reached Avacha Bay (Siebert and Simkin, 2002).

Figure 87. Koryaksky volcano on August 20, 2009. Photograph by Alexander Sokorenko, IVS, used with permission.

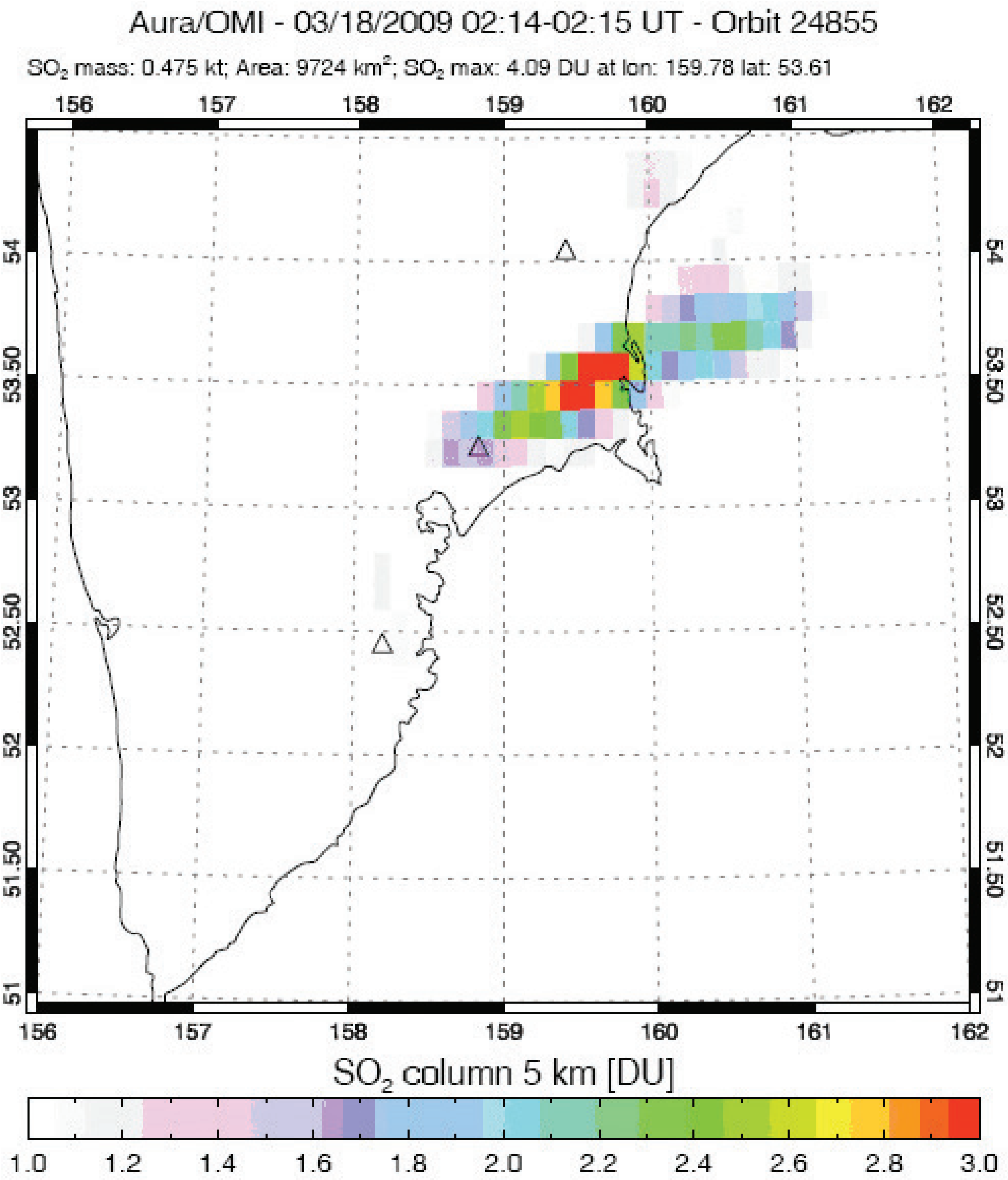


Figure 88. OMI image showing a sulfur dioxide cloud from the Koryaksky Volcano phreatic eruption, March 18, 2009. Location of Koryaksky Volcano shown by red triangle. Concentrations are in Dobson Units (DU). Figure courtesy of NASA and Simon Cairn.

Gorley Volcano

CAVW# 1000-07

52°33'N 158°02'E
1,829 m (6,001 ft)

Kamchatka Peninsula, Russia

INCREASED FUMAROLIC ACTIVITY AND AN INCREASE IN SEISMICITY; NO ERUPTION

According to KBGS RAS, about 1,000 volcanic earthquakes occurred within a radius of 7 km (4.3 mi) of the Gorely summit from January 23 until March 13. All events were of M<1.9 and they were located at depths of 0–10 km (0–6.2 mi) below sea level. This frequency of volcanic earthquakes under the volcano Gorely was unprecedented since the installation of seismic stations at the volcano in 1996. Based on this uptick in seismicity, the Aviation Color Code was changed to **YELLOW** on March 26.

Volcanologist A. Ovsyannikov visited the summit crater lake of Gorely on June 23, 2009 (figs. 89–90). The water level in the lake had risen compared to that observed in 2008. Fumaroles in the western and northwestern parts of the crater were completely flooded. On the turquoise surface of the lake, upwellings of hot water and gas produced circular patches surrounded by floating sulfur. In the southeastern part of the lake, an active boiling mud pot persisted while in the northeastern sector of the crater, two new fumarole areas had developed. The eastern sector of the crater showed evidence of continued subsidence (constant collapse of the crater walls and disappearance of one of the colluvial fans.)

Figure 89. Gorely summit crater and acidic lake. Mutnovsky Volcano in the distance on the skyline at right. Photograph by Denis Bud'kov, used with permission. www.photokamchatka.ru.

Figure 90. Acidic crater lake of Gorely volcano on June 23, 2009. Areas of thermal upwelling are accentuated by floating tendrils of sulfur precipitate. Photograph by A. Ovsyannikov, used with permission.

A small thermal anomaly was detected at Gorely on satellite images from time to time in 2009.

Seismic activity of the volcano remained stable with no acceleration of seismic or thermal activity and the Aviation Color Code was changed to **GREEN** on May 21 through the year's end.

Gorely Volcano consists of a complex set of five overlapping stratovolcanoes within a late Pleistocene caldera (Siebert and others, 2011). Many of the several dozen flank craters contain lakes. Historical eruptions have been dominated by Vulcanian and Phreatic explosions; Siebert and Simkin (2002-) list 13 possible eruptions since about 1700, the most recent in 1986.

Ebeko Volcano

CAVW# 0900-38=

50°41'N 156°01'E
1,156 m (3,792 ft)

Northern Kuriles, Paramushir Island, Russia

INCREASED FUMAROLIC OUTPUT, SMALL PHREATIC EXPLOSIONS
Gas-steam plumes containing small amount of ash, ash falls

According to observations from Severo-Kurilsk (Paramushir Island), a weak phreatic eruption of Ebeko occurred intermittently from January 29 through June 18, 2009. On January 31, observers noted gas-steam plumes containing ash that rose up to 250–300 m (820–984 ft) above the crater and extended about 20 km (12.4 mi) to the east-northeast. Beginning February 1, nearly constant emission of gas and steam produced a weak column containing ash up to 0.3–1.0 km (984–3,281 ft) above the crater (fig. 91). Slightly more energetic ash bursts up to 1.6–4.5 km (5,200–15,000) ASL were observed 3–6 times per day. Resulting clouds from these bursts extended 6–10 km (19,700–32,800 ft) and sometimes 40 km (25 mi) downwind. The source of these bursts was a vent located on the northeastern wall (up to 26 m [85 ft] from the bottom) of the northern crater. Ash plumes were not detected in satellite images.

Figure 91. Plume containing minor ash from Ebeko Volcano on February 11, 2009. Photograph by T. Kotenko, IVS.

Towards the end of March, the level of activity at the volcano increased. Gas-steam plumes containing small amounts of non-juvenile ash rose up to 3.2 km (10,500 ft) ASL and extended about 20 km (12.4 mi) primarily to the northwest and east from the volcano (fig. 92). Minor ash falls occurred in Severo-Kurilsk on March 13, 29, and 31. The thickness of ash at the town was about 0.1–0.2 cm. The Aviation Color Code for the volcano was changed to **YELLOW** on April 2, and remained so until July 30 when it was downgraded to **GREEN**. Gas-steam plumes containing small amounts of ash rose to a maximum up to 3.5 km (11,500 ft) ASL and extended to a maximum of 30 km (18.6 mi) from the volcano on April–June. Throughout this period, KVERT did not detect a thermal anomaly or expression of the gas and ash clouds in satellite imagery.

Ebeko is a 1,156 m (3,793 ft) high composite stratovolcano with a central cone and three summit craters on the northern end of Paramushir Island in the North Kuriles (Gorshkov, 1970). The northernmost of the Ebeko craters has at times contained a small, cold lake (Gorshkov, 1970) and the middle crater contains a lake as well as numerous solfataras that occur along the lakeshore and the floor of the lake. The central Ebeko cone is at the northern end of a complex of five volcanic cones. Lava flows and pyroclastic material range in composition from basaltic to andesitic (Gorshkov, 1970). Historic eruptive characteristics include central-vent eruptions, explosive eruptions, phreatic explosions (often involving the crater lakes), lahars, fumarolic activity, and radial-fissure eruptions. The northern crater has been the focus of activity since at least the 1987–89 eruption (Siebert and Simkin, 2002-). The most recent eruption, in 2006, was characterized by gas, steam, and some ash emissions. No seismometers are installed on or near Ebeko; KVERT uses satellite imagery and occasional ground-based observations to monitor activity at the volcano.

Figure 92. Gas-steam burst containing small amount of ash from Ebeko Volcano, March 18, 2009. Photograph by L. Kotenko, IVS.

Volcanic Activity, Central and Southern Kurile Islands

The Institute of Marine Geology and Geophysics (IMGG), the host institute for the Sakhalin Volcanic Eruption Response Team (SVERT; Rybin and others, 2004; Neal and others, 2008, 2009b), reports on activity at Kurile Island volcanoes (fig. 93). SVERT uses twice-daily MODIS and other satellite imagery of the Kurile Islands, periodic (every 10 days) reports of seismic data from Kunashir and Iturup Islands, and visual observations from several southern Kurile Islands. By agreement between SVERT and KVERT, the northernmost Kurile Islands of Paramushir and Alaid are under the reporting jurisdiction of KVERT.

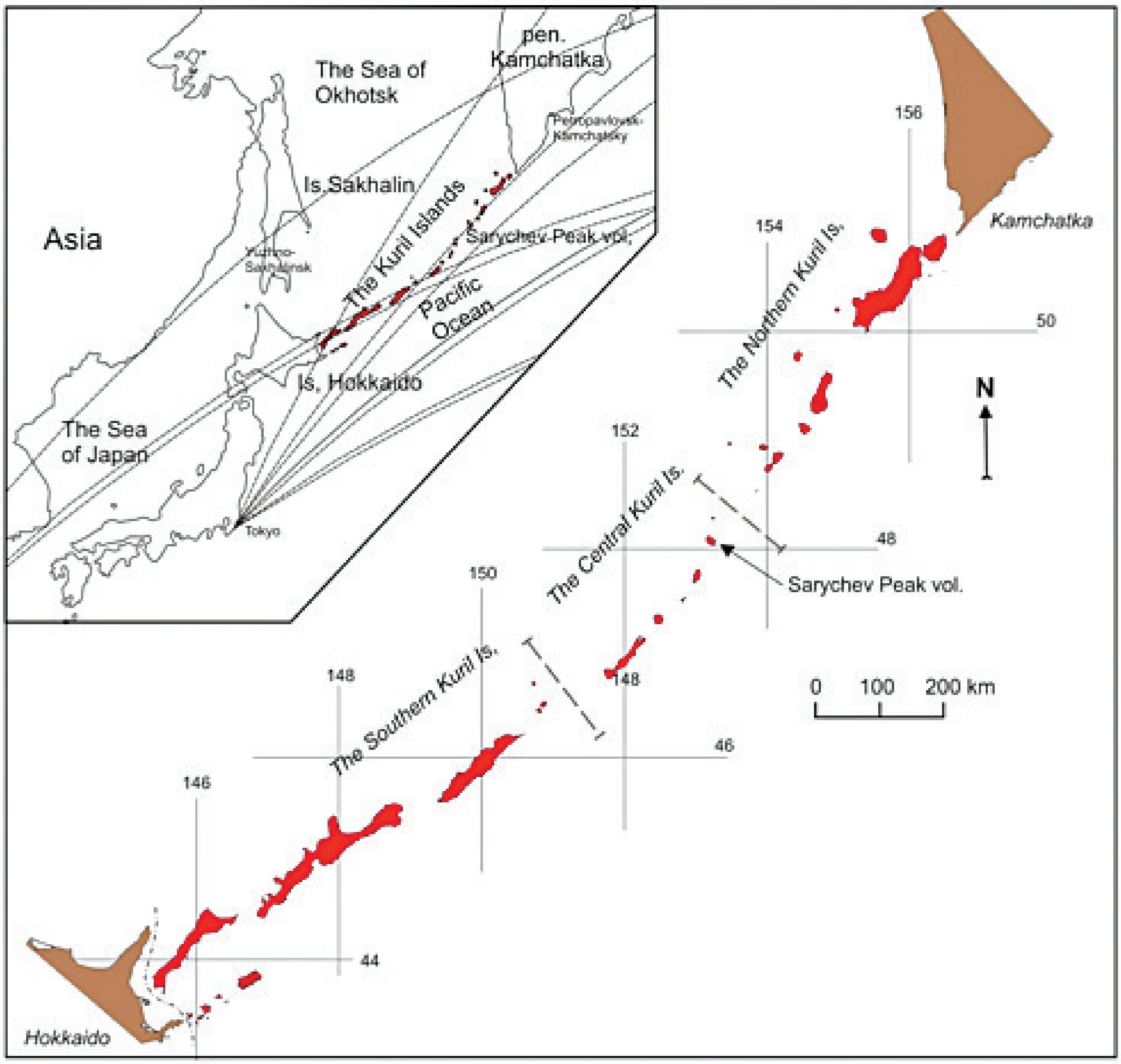


Figure 93. Map of the Kurile Islands showing location of Sarychev and Raikoke Volcanoes. Inset shows generalized air routes over parts of the western North Pacific. Map courtesy of SVERT.

Sarychev Volcano

CAVW# 0900-24=

48°06'N 153°12'E
1,446 m (4,744 ft)

Central Kuriles, Matua Island, Russia

SIGNIFICANT EXPLOSIVE ERUPTION
Ash clouds, ash fall, pyroclastic flows, lava flows

SVERT responded to the first significant eruption on its watch when, after many years of relative quiet, Sarychev Volcano became active in June 2009. The following summary is taken largely from Rybin and others (2011).

Sarychev Volcano on Matua Island in the central Kuriles (figs. 93, 94) is remote and little visited; a true understanding of background behavior was not well known. Scientific visitors to Sarychev on June 6, 2009, only 5 days before the onset of eruption, noted strong output of gas from the summit crater. The first sign of volcanic activity at Sarychev volcano was noted during its routine daily analysis of National Aeronautical and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) on June 11.

Figure 94. Sarychev Peak Volcano in 2008. Photograph by M.V. Chibisova, SVERT/IMGG.

Subsequently, SVERT alerted the AVO, the Tokyo, Anchorage, and Washington Volcanic Ash Advisory Centers (VAACs), and a variety of other agencies noting a thermal anomaly and a possible weak ash plume in a MODIS image from 0031 UTC. Subsequently, two discrete explosions of ash estimated to rise only to 4 km (13,100 ft) ASL occurred at 0200 and 0700 UTC on June 11.

On June 12, activity intensified about 0200 UTC and over the next 24 hours, eight explosive events sent ash plumes to altitudes of 5–12 km (16,400–39,400 ft) ASL. Analysis of satellite imagery suggested that the first composite ash cloud from this sequence of explosions extended to the southeast as far as 350 km (217 mi) from the volcano. SVERT declared Aviation Color Code **RED** for the volcano and remained at that level until June 19. Another large explosion occurred at 0757 UTC June 12 and formed a voluminous ash column with a diameter of 35 km (21.8 mi) and a maximum vertical reach of about 12 km (39,400 ft) determined using the altitude-temperature method (Kienle and Shaw, 1979; Sparks and others, 1997). Wind shear sent ash clouds in multiple directions from the east to southeast and southwest. Beginning at 1457 UTC, another series of explosions sent an ash cloud to the southeast more than 500 km (311 mi) and to the southwest more than 150 km (93 mi). Pyroclastic flows inundated the northern and northwestern flanks of the volcanic cone (fig. 95). Emplacement of these pyroclastic density currents was captured in a series of spectacular photographs from the International Space Station (fig. 96).

A number of additional explosions occurred on June 13 producing ash clouds that extended up to 500 km (311 mi) to the east and southeast. The largest explosion of the entire eruptive sequence occurred following about 11 hours of continuous low-level ash emission at 2130 UTC. The estimated height of the resulting ash column was 21 km (68,900 ft) ASL and the ash cloud spread southeast and northwest.

Ash emission appeared to cease for about 14 hours before explosions resumed at 1850 UTC on June 14. The eruption

Figure 95. Pyroclastic flow deposit at the shoreline on the northwestern part of Matua Island. Ash-covered Sarychev Peak is in the background. Photograph courtesy SVERT.

Figure 96. Photograph from the International Space Station of Sarychev in eruption on June 12, 2009. North is to upper right. Note pyroclastic avalanches descending the northern, western, and southeastern flanks of the volcano. Airborne ash from an earlier explosive event is visible at the left margin of the image. Image courtesy of NASA.

cloud from this event reached an estimated 15 km (49,200 ft) ASL in altitude and rapidly spread both east and west. Over the next 26 hours, an additional seven explosions occurred; lesser events sent ash to 5 km (16,400 ft) ASL and the larger explosions sent ash to 10–16 km (32,800–52,500 ft) ASL. The resulting ash clouds drifted primarily northwest and southeast more than 800 km (500 mi).

In between explosive episodes, continuous lower-level emission of ash occurred. Explosive activity on June 15 produced the largest ash cloud in terms of aerial extent as prevailing winds sent ash over the Sea of Okhotsk, eventually Sakhalin Island, and the Khabarovsky District west of Sakhalin Island on the Asian mainland, where a dusting of ash occurred. In a single satellite image, the visual length of ash plume was more than 800 km (500 mi) and its width up to 150 km (93 mi).

The final significant explosion was on June 16 and was followed by continuous low-level ash emission. Minor activity—ash and gas emission punctuated by very weak explosions—continued through June 19 when activity became dominated by emission of voluminous gas plumes with occasional small amount of ash. Strong volcanic gas clouds with occasional minor amounts of ash continued to be detected in satellite images and by ground-based observers into October 2009. During this period, SVERT also reported thermal anomalies related to the strong fumarolic sources and the hot pyroclastic debris. The northwestern half of the island was completely blanketed with thick tephra deposits; however, some bird life was able to return to nest soon after the eruption (figs. 97–98).

The 2009 Sarychev eruption had significant impacts on regional aviation. The Federal Aviation Administration (FAA) estimates that between June 12 and 15, 65 re-routes, 6 diversions, 12 unplanned fuel stops, and 2 aircraft turned around in flight resulted from Sarychev ash clouds, costing air carriers approximately $1.8M (International Airways Volcano Watch Operations Group, 2010). FAA sources commented that aircraft avoiding ash-contaminated air space added between 90 and 120 minutes of flight time over optimum routings, a significant increase in fuel consumption and associated costs.

Warnings regarding ash clouds from this eruption required coordination of messages from multiple Volcanic Ash Advisory Centers (VAACs), Air Route Traffic Control Centers (ARTCCs), and Meteorological Watch Offices (MWOs). Formal warnings to aviation were the immediate responsibility of the Tokyo VAAC and the Aviation Meteorology Center (AMC) in Petropavlovsk, when ash was in Russian air space in the immediate vicinity of Matua Island. For the period of eruption, Tokyo VAAC issued 78 Volcanic Ash Advisories through July 27, 2009. As the ash clouds traveled across VAAC and Flight Information Region boundaries, formal messages from both the Anchorage VAAC (4) and the Washington VAAC (38) were issued. The Yelizovo AMC in Petropavlovsk produced 68 Significant Metrological Information (SIGMETs) during the eruption and an unknown number of additional SIGMETs were issued by Tokyo and the U.S. Aviation Weather Center.

As the eruption unfolded, SVERT assigned an aviation level of concern color code and provided updates on the ongoing activity via email messages to international aviation and meteorological agencies and local authorities. SVERT declared Aviation Color Code **RED** for the volcano on June 12 and remained at that level until June 19 when the volcano was downgraded to **ORANGE** following cessation of major explosive activity. SVERT downgraded the Aviation Color Code to **YELLOW** on July 8 and finally to **GREEN** on October 6. SVERT Information Releases were posted on the IMGG web site and mirrored at the AVO web site.

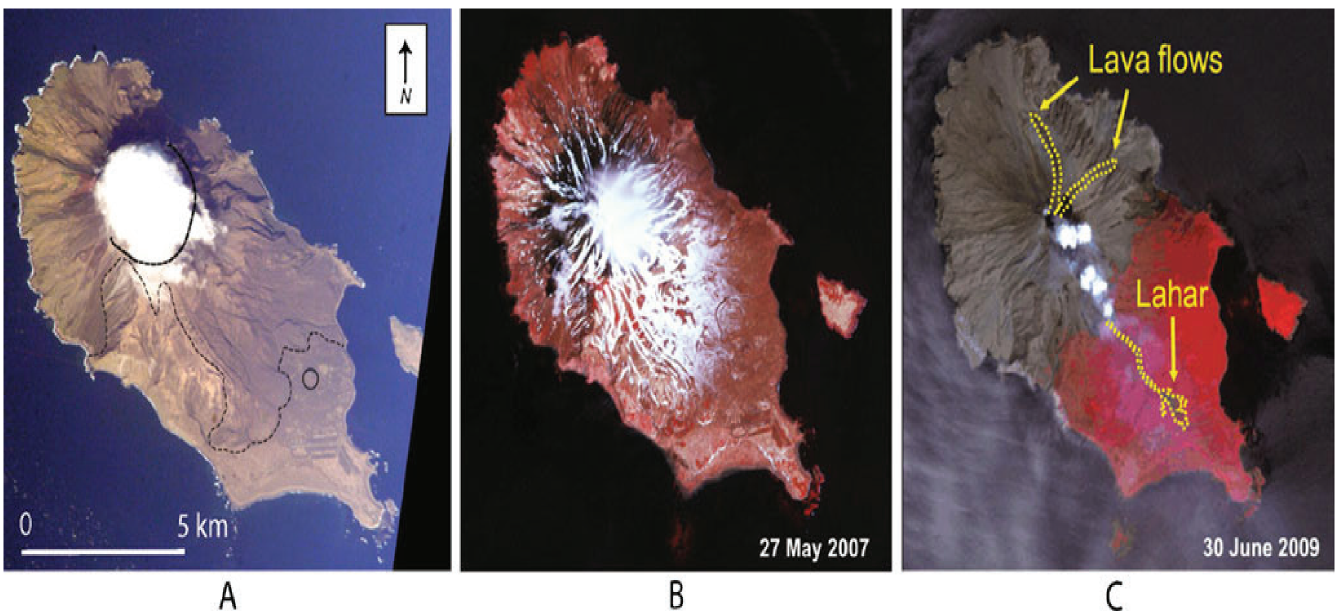


Figure 97. Successive space-based view of Sarychev Peak Volcano, Matua Island. North is towards the top. A. International Space Station image from 2002. The thin dashed line approximates the extent of modern Sarychev lavas and pyroclastic deposits; the thick dashed line represents the inferred caldera rim that existed prior to growth of the modern Sarychev cone. Circled feature in the southeast is a young monogenetic cone (geology modified from Gorshkov, 1970). The remains of a World War II Japanese military airfield and base are visible at the lower right. Cropped from image ISS005, Roll E, Frame 17795 taken October 18, 2002. Courtesy of the Image Science and Analysis Laboratory, NASA, Johnson Space Center, http://eol.jsc.nasa.gov. B. ASTER daytime thermal infrared (TIR) imagery of Matua Islsand (12×6 km) on May 27, 2007, before the eruption, C. ASTER daytime TIR image on June 20, 2009, after the eruption. The elongated dark feature extending from the summit to the southeast at *C* corresponds to a lahar and two lava flows produced during the 2009 eruption. The southeast portion of the island was essentially untouched by pyroclastic flows and surges. Image data courtesy of NASA/GSFC/METI/ERSDAC/JAROS and US/Japan ASTER Science Team.

Figure 98. Seacliffs exposing old lavas and heavily draped by ash from the 2009 eruption of Sarychev. Some bird nests remained viable even in the severely impacted northwestern part of Matua Island. Photograph courtesy SVERT.

AVO conducted telephone call-downs to U.S. aviation and meteorological authorities to communicate key information about the eruption and the path of the ash cloud. AVO staff also looked at satellite imagery of the region frequently and shared observations with SVERT via email.

Sarychev Peak, historically one of the most active of Kurile volcanoes, is located on remote and currently uninhabited Matua Island in the Central Kuriles (fig. 93). Modern Sarychev cone has grown within an older caldera. Sarychev lavas and pumice primarily are basaltic andesite and rarely andesites (Gorshkov, 1967; Andreev and others, 1984). Prior to the 2009 eruption, the conical stratocone's summit was marked by a steep-walled crater containing a vigorous solfatara field.

Sarychev has been very active in the historic period (here defined as approximately the last 250 years) with at least 10 eruptions dating back to 1760. SVERT considers Sarychev to be the most historically active volcano in the Kurile chain. The 1946 eruption remains one of the strongest Kurile events in the last century producing both lava flows and pyroclastic flows from Sarychev Peak. Prior to 2009, the most recent activity recorded for Sarychev Peak occurred in the 1980s but details are scant. According to the Smithsonian Institution (1987; 1989), a fresh lava flow was observed in 1986 and small amounts of ash were observed on the flanks of the volcano in 1989; however, it is likely that the lava flow was in fact the still-warm 1976 flow rather than a new eruptive product.

Raikoke Volcano

CAVW# 0900-25=

48°17'N 153°15'E
551 m (1,808 ft)

Central Kuriles, Raikoke Island, Russia

FUMAROLIC EMISSION AND POSSIBLE PHREATIC (?) ASH

On June 12–13, 2009, SVERT reported satellite evidence of possible weak activity of Raikoke volcano. On MODIS images (fig. 99), a plume inferred to contain gas, water vapor, and possibly some ash, extended southeast from the volcano a distance of 180 km (112 mi). No further observations of the volcano were possible due to poor weather conditions over the next few days and no additional indications of activity were noted.

Raikoke volcano is a small, steep-sided stratovolcano 551 m (1,808 ft) in elevation and 2.45 km (1.52 mi) across, located in the central part of the Kurile Islands (figs. 93, 100). A 700-m-diameter (2,297 ft) summit crater up to 200 m (656 ft) deep has sheer inner walls. The southern slope of the volcanic island is covered with pyroclastic material and the eastern side is covered with lava flows. The island is currently uninhabited. Significant eruptions are known in 1760 and 1778; during the 1778 event, the upper one-third of the volcanic cone was destroyed, the shoreline completely changed, and 15 fatalities are recorded. In 1924, another significant explosive event changed the physical structure of the cone.

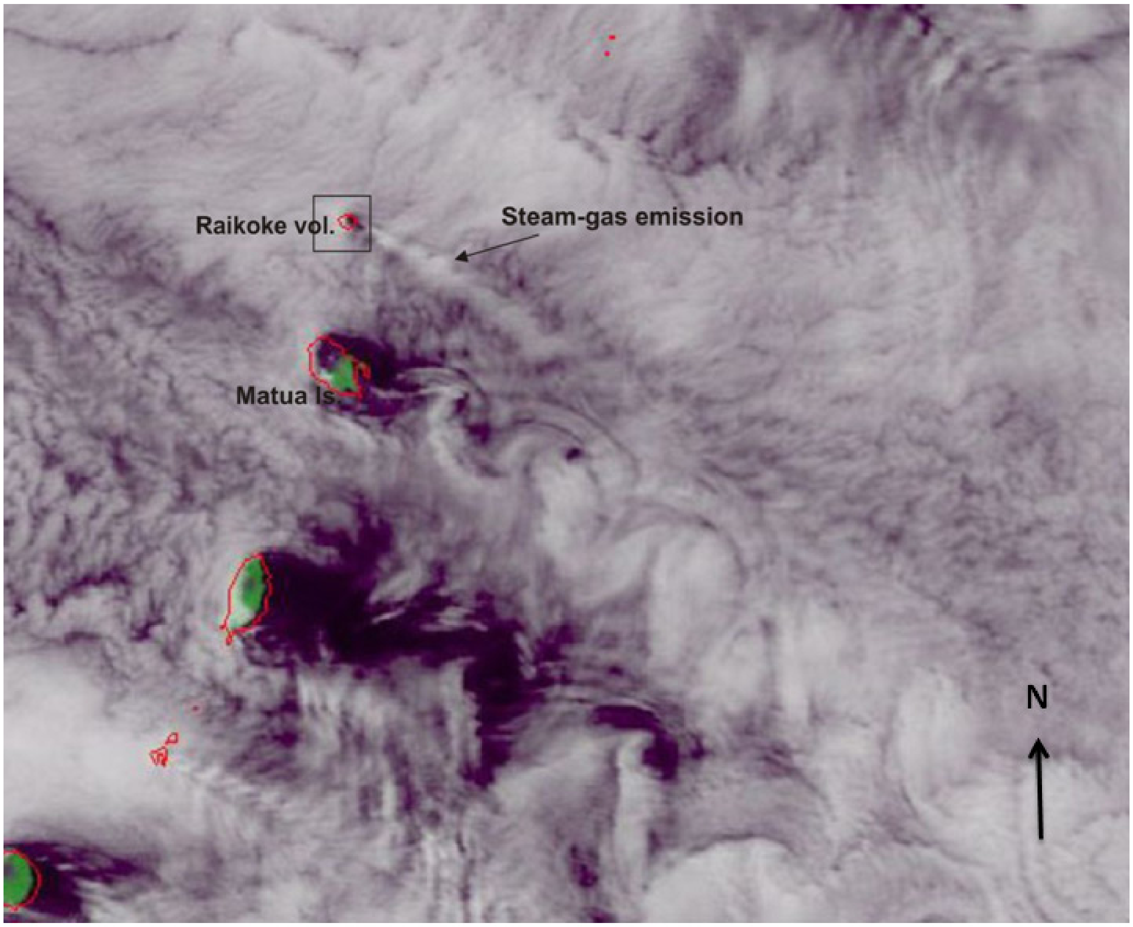


Figure 99. MODIS image showing steam-gas emission at Raikoke Volcano (Raikoke Island). MODIS image courtesy of NASA.

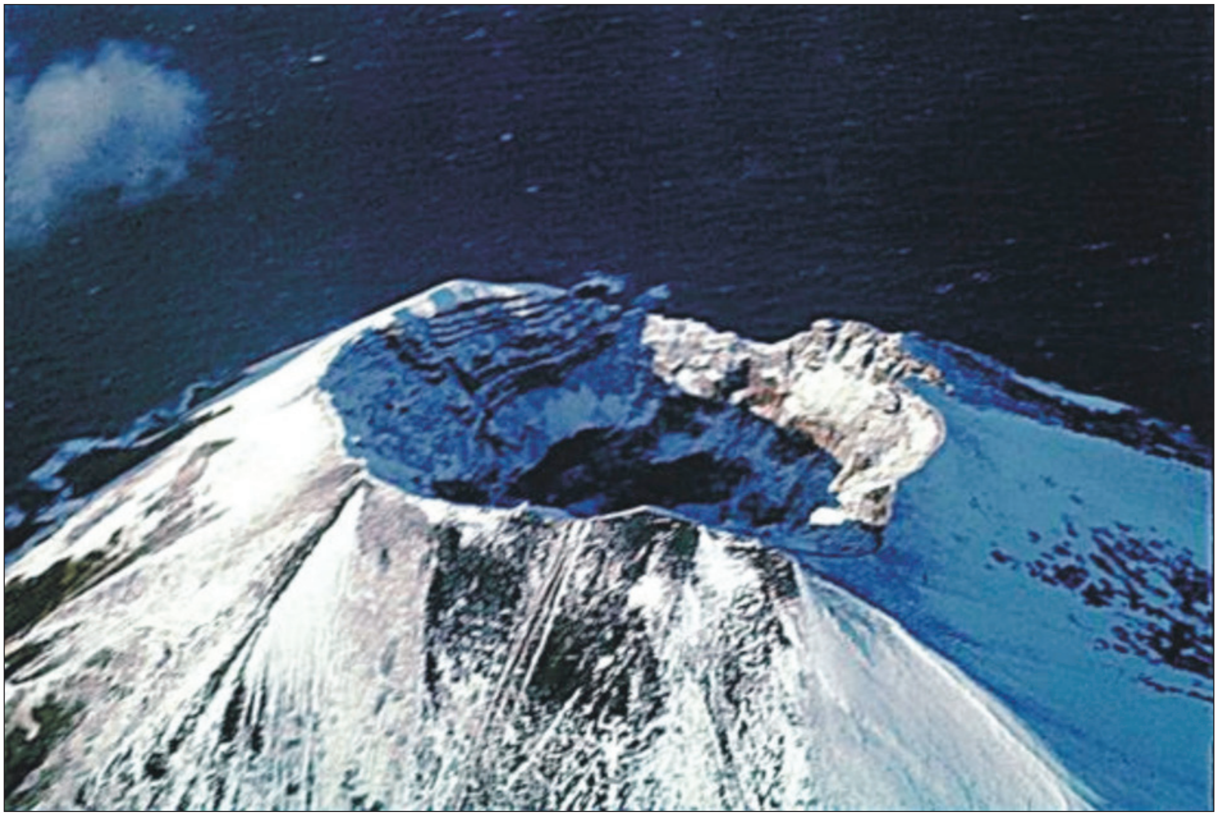


Figure 100. Raikoke Volcano. Photograph by R. Bulgakov.

Summary

The Alaska Volcano Observatory responded to volcanic unrest or reports of unusual activity at, or near, 8 separate volcanic centers in Alaska, and 10 Russian volcanoes. A significant eruption from Redoubt, one of the Cook Inlet volcanoes located near Anchorage, disrupted air traffic, oil production, and commerce. Multiple explosive episodes from ongoing eruptions at several Kamchatkan volcanoes repeatedly sent ash across the heavily traveled North Pacific and Russian Trans-East air routes, however, no aircraft encounters with ash occurred.

Acknowledgments

This report represents the work of the entire Alaska Volcano Observatory, colleagues from other USGS Volcano Observatories, staff at cooperating agencies, and the public. Russian activity documented here reflects tenacious monitoring, documentation, and analysis by scientists at the Institute of Volcanology and Seismology, the Kamchatkan Branch of Geophysical Surveys, and the Institute of Marine Geology and Geophysics. In particular, we thank Sergey Senyukov of KBGS for his generous sharing of information and insights. We also acknowledge the significant contributions of our colleagues at the Alaska Division of Geological and Geophysical Surveys for design and maintenance of the Alaska Volcano Observatory image database, a powerful tool for review of activity through the year. Technical reviews by Janet Schaefer and Tom Miller improved the content and presentation. All images and photographs from our colleagues and the public in this report are appreciated and used with permission.

Sources of Photographs in this Report and Other Images of Alaska and Russia

Online sources of digital images from this report:
http://libraryphoto.cr.usgs.gov/
http://www.avo.alaska.edu/images/
http://pubs.usgs.gov/dds/dds-39/
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Glossary of Selected Terms and Acronyms

AAWU “Alaska Aviation Weather Unit” of the National Weather Service.

\`a\`a Hawaiian term for lava flows characterized by a rough, jagged, blocky surface.

AEIC Alaska Earthquake Information Center.

AFTN Aeronautical Fixed Telecommunications Network.

AKDGGS Alaska Division of Geological & Geophysical Surveys.

AKDT “Alaska Daylight Time”; UTC -8 hours AKDT.

AKST “Alaska Standard Time”; UTC -9 hours AKST.

AMC Aviation Meteorology Center.

andesite volcanic rock composed of about 53–63 percent silica (SiO^2, an essential constituent of most minerals found in rocks).

ARTCC Air Route Traffic Control Centers.

ash fine fragments (less than 2 millimeters across) of lava or rock formed in an explosive volcanic eruption.

AS above sea level.

ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer.

Aura a multi-national NASA scientific research satellite in orbit around the Earth, studying the Earth’s ozone layer, air quality and climate.

AVHRR “Advanced Very High Resolution Radiometer”; AVHRR provides one form of satellite imagery.

AVO Alaska Volcano Observatory.

basalt general term for dark-colored igneous rock, usually extrusive, containing about 45–52 weight percent silica (SiO^2, an essential constituent of most minerals found in rocks).

bomb boulder-size chunk of partly solidified lava explosively ejected from a volcano.

caldera a large, roughly circular depression usually caused by volcanic collapse or explosion.

CAVW Smithsonian Institute’s “Catalog of Active Volcanoes of the World” (Simkin and Siebert, 1994).

cinder cone small, steep-sided conical hill built mainly of cinder, spatter, and volcanic bombs.

COSPEC “Correlation Spectrometer,” a device for measuring sulfur-dioxide emissions.

CWSU “Center Weather Service Unit” of the National Oceanic and Atmospheric Administration, stationed at the Air Route Traffic Control Center.

CVO Cascade Volcano Observatory.

EarthScope A program of the National Science Foundation that deploys thousands of seismic, GPS, and other geophysical instruments to study the structure and evolution of the North American continent and the processes that cause earthquakes and volcanic eruptions.

ERSDAC Earth Remote Sensing Data Analysis Center.

DRE Dense rock equivalent; used to compare volumes of erupted material, the volume is calculated as if it were free of the spaces created by gas bubbles and loose packing of particles

FAA Federal Aviation Administration.

fallout a general term for debris which falls to the Earth from an eruption cloud.

fault A fracture along which the blocks of the Earth’s crust on either side have moved relative to one another parallel to the fracture.

FIR Flight Information Region.

fissure a roughly linear or sinuous crack or opening on a volcano; a type of vent which commonly produces lava fountains and flows.

FLIR “Forward Looking Infrared Radiometer,” used to delineate objects of different temperature.

fumarole a small opening or vent from which hot gases are emitted.

GSFC Goddard Space Flight Center.

glaciolacustrine pertaining to sediments deposited in glacial lakes, and resulting landforms.

GMS Geostationary Meteorological Satellite.

GOES Geostationary Operational Environmental Satellite.

GPS Global Positioning System.

GVN "Global Volcanism Network" of the Smithsonian Institution.

Holocene geologic epoch extending from the present to 10,000 years ago.

HYSPLIT Hybrid Single Particle Lagrangian Integrated Trajectory Model. A NOAA program for tracking and back-tracking particles in the atmosphere (e.g. ash).

IMGG Russian "Institute of Marine Geology and Geophysics."

incandescent glowing red or orange due to high temperature.

InSAR Interferometric Synthetic Aperture Radar.

interferogram a pattern formed by wave interference, especially one represented in a photograph or diagram

intracaldera refers to something within the caldera.

ISS International Space Station.

IVS Russian "Institute of Volcanology and Seismology."

JAROS Japan ASTER Science Team.

JMA Japanese Meteorological Agency.

JPEG "Joint Photographic Experts Group," type of digital photographic file.

Ka thousands of years before the present.

KDT "Kamchatkan Daylight Time" equals AKDT + 21 hours.

KBGS Kamchatka Branch of Geophysical Surveys.

KEMSD Russian "Kamchatka Experimental and Methodical Seismological Department."

KST "Kamchatka Standard Time" equals AKST + 21 hours.

KVERT Kamchatkan Volcanic Eruption Response Team.

lapilli pyroclasts or volcanic fragments that are between 2 and 64 mm in diameter.

lava molten material at the Earth's surface.

magma molten material below the surface of the Earth.

METI Ministry of Economy, Trade, and Industry.

MODIS Satellite-based "Moderate-resolution Imaging Spectroradiometer."

MWO Meteorological Watch Office.

NASA National Aeronautics and Space Administration.

NOAA National Oceanic and Atmospheric Administration.

NOGAPS Navy Operational Global Atmospheric Prediction System.

NOPAC North Pacific air route corridors.

NOTAM "Notice to Airmen," a notice containing information [not known sufficiently in advance to publicize by other means] concerning the establishment, condition, or change in any component [facility, service, or procedure of, or hazard in the National Airspace System] the timely knowledge of which is essential to personnel concerned with flight operations.

NPS National Park Service.

NWS National Weather Service.

OMI Ozone Mapping Instrument.

PBO Plate Boundary Observatory. The PBO is the geodetic component of EarthScope, operated by UNAVCO, and funded by the National Science Foundation, to precisely measure Earth deformation resulting from the constant motion of the Pacific and North American tectonic plates in the western United States.

phreatic activity an explosive eruption caused by the sudden heating of ground water as it comes in contact with hot volcanic rock or magma.

phreatic ash fine fragments of volcanic rock expelled during phreatic activity; this ash usually is derived from existing rock and not from new magma.

PIREP "Pilot Weather Report"; a report of meteorological phenomena encountered by aircraft in flight.

pixel contraction of "picture element." A pixel is one of the many discrete rectangular elements that form a digital image or picture on a computer monitor or stored in memory. In a satellite image, resolution describes the size of a pixel in relation to area covered on the ground. More pixels per unit area on the ground means a higher resolution.

PK "Petropavlovsk"; capital city of Kamchatka, Russia.

Pleistocene geologic epoch extending from 2–3 million years ago to approximately 10,000 years before present.

PUFF a volcanic ash-tracking model (see URL: http://volcview.wr.usgs.gov/puff/main.pl).

pyroclast an individual particle ejected during a volcanic eruption; usually classified by size, for example, ash, lapilli.

RSAM Real-time Seismic-Amplitude Measurement.

regional earthquake earthquake generated by fracture or slippage along a fault; not caused by volcanic activity.

RFE Russian Far East.

SAB "Synoptic Analysis Branch" of NOAA.

SAR Synthetic Aperture Radar.

satellite cone a subsidiary volcanic vent located on the flank of a larger volcano.

seismic swarm a flurry of closely spaced earthquakes or other ground shaking activity; often precedes an eruption.

shield volcano a broad, gently sloping volcano usually composed of fluid lava flows of basalt composition (for example, Mauna Loa, Hawaii).

SI Internation System of Units.

SIGMET SIGnificant METeorological information statement, issued by NWS.

SRTM Shuttle Radar Topography Mission.

Stratovolcano Also called a stratocone or composite cone, a steep-sided volcano, usually conical in shape, built of interbedded lava flows and fragmental deposits from explosive eruptions.

Strombolian type of volcanic eruption characterized by intermittent bursts of fluid lava, usually basalt, from a vent or crater as gas bubbles rise through a conduit and burst at the surface.

sub-plinian style of explosive eruptions characterized by vertical eruption columns and widespread dispersal of tephra.

SVA Suspect Volcanic Activity.

SVERT "Sakhalin Volcanic Eruption Response Team" monitors and reports on Kurile Island volcanoes.

SWIR Short Wave Infrared.

tephra a general term covering all fragmental material expelled from a volcano (ash, bombs, cinders, etc.).

TA thermal anomaly.

TFR "Temporary Flight Restriction," issued by FAA.

TIR Thermal Infrared.

UAFGI University of Alaska Fairbanks Geophysical Institute.

UNAVCO A consortium of research institutions that supports and promotes a better understanding of Earth by using high-precision techniques to measure crustal deformation.

USCG U.S. Coast Guard.

USFWS U.S. Fish and Wildlife Service.

USGS U.S. Geological Survey.

UTC "Coordinated Universal Time"; same as Greenwich Mean Time (GMT).

UUA Urgent pilot report.

VAAC Volcanic Ash Advisory Center.

VAA Volcanic Ash Advisory.

VAN Volcanic Activity Notice. A VAN is issued by AVO for any change in Aviation Color Code and Volcano Alert Level, as well as for any significant change in volcanic activity. VANs are a standardized communication tool used by all U.S. volcano observatories.

vent an opening in the earth's surface through which magma erupts or volcanic gasses are emitted.

VNIR Very Near Infrared.

volcano-tectonic earthquakes earthquakes generated within or near a volcano from brittle rock failure resulting from strain induced by volcanic processes.

Vulcanian type of explosive eruption consisting of repeated, violent ejection of incandescent fragments of viscous lava, usually in the form of blocks, along with volcanic ash. Sometimes, Vulcanian eruptions involve water mixing with erupting magma.

Appendix 1. Volcano Alert Levels and Revised Aviation Color Codes Used by United States Volcano Observatories

Alert levels address the overall activity at the volcano, not just the hazard to aviation. There may be situations where a volcano is producing lava flows that are dangerous on the ground and merit a WATCH or WARNING, however, the hazard to aviation is minimal. Alert level announcements contain additional explanation of volcanic activity and expected hazards where possible (Gardner and Guffanti, 2006).

Alert Levels	
NORMAL	Typical background activity of a volcano in a non-eruptive state. *Or, after a change from a higher level:* Volcanic activity considered to have ceased and volcano reverted to its normal, non-eruptive state
ADVISORY	Elevated unrest above known background activity. *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 for eruptive activity. *Or:* A minor eruption is underway that poses limited hazards.
WARNING	Highly hazardous eruption underway or imminent.

Level of Concern Codes for Aviation	
AVO will continue to use the color-coded level of concern designation that has been in place since 1990. Colors will now reflect only the hazards posed to the aviation community. Definitions of each color have changed slightly. Typically, this means that color codes indicate the likelihood or presence of airborne ash and ash clouds that threaten aircraft.	
GREEN	Volcano is in a normal, non-eruptive state. *Or, after a change from a higher level:* Volcanic activity considered to have ceased and volcano reverted to its normal, non-eruptive state
YELLOW	Volcano is exhibiting signs of elevated unrest above known background levels. *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 unrest with increased likelihood of eruption. *Or:* Volcanic eruption underway with no or minor ash emission.
RED	Eruption is forecast to be imminent with significant emission of ash into the atmosphere likely. *Or:* Eruption is underway with significant emission of ash into the atmosphere.

Appendix 2. Level of Concern Color Code for Volcanic Activity Used in Kamchatka and the Kurile Islands in January–August 2009

Level of Concern Color Code: Generic	
GREEN	**No eruption anticipated.** Volcano is in quiet “dormant” state.
YELLOW	**An eruption is possible in the next few weeks and may occur with little or no additional warning.** Small earthquakes detected locally and (or) increased levels of volcanic gas emissions.
ORANGE	**Explosive eruption is possible within a few days and may occur with little or no warning. Ash plume(s) not expected to reach 25,000 feet above sea level.** Increase numbers of local earthquakes. Extrusion of a lava dome or lava flows (non-explosive eruption) may be occurring.
RED	**Major explosive eruption expected within 24 hours. Large ash plume(s) expected to reach at least 25,000 feet above sea level.** Strong earthquake activity detected even at distant monitoring stations. Explosive eruption may be in progress.

Aviation Color Code for Volcanic Activity used in Kamchatka and the Kurile Islands from August 2009.

AVIATION COLOR CODES RECOMMENDED BY THE INTERNATIONAL CIVIL AVIATION ORGANIZATION	
GREEN	Volcano is in normal, non-eruptive state, ***or, after a change from a higher level***: Volcanic activity considered to have ceased, and volcano reverted to its normal, non-eruptive state.
YELLOW	Volcano is experiencing signs of elevated unrest above known background levels, ***or, after a change from higher level:*** Volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE	Volcano is exhibiting heightened unrest with increased likelihood of eruption, ***or,*** Volcanic eruption is underway with no or minor ash emission. ***[specify ash-plume height if possible]***
RED	Eruption is forecast to be imminent with significant emission of ash into the atmosphere likely, ***or,*** Eruption is underway with significant emission of ash into the atmosphere. ***[specify ash-plume height if possible]***

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