Geothermal Disruption of Summit Glaciers at Mount Spurr Volcano, 2004–6: An Unusual Manifestation of Volcanic Unrest

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Abstract

Mount Spurr, a 3,374-m-high stratovolcano in the Cook Inlet region of Alaska, showed signs of volcanic unrest beginning in 2004 and lasting through 2006. These signs included increases in heat flow, seismicity, and gas flux, which we interpret as the results of a magmatic intrusion in mid-2004. In response, debris-laden meltwater beneath the glacier in Mount Spurr's geothermally active summit basin accumulated as the overlying snow and ice melted. As heat output increased, the icecap subsided into a growing cavity over a meltwater lake, similar to that observed during subglacial volcanic activity in Iceland. An ice plug collapsed into the lake sometime between June 20 and July 8, 2004, forming an ice cauldron that continued to grow in diameter during 2004 and 2005. A freefall of ice and snow into the lake likely caused a mixture of water and debris to be displaced rapidly upward and outward along preexisting englacial and, possibly, subglacial pathways leading away and downslope from the summit basin. Where these pathways intersected crevasses or other weak points in the sloping icefield, the mixture debouched onto the surface, producing dark, fluid debris flows. In summer 2004, the occurrence of two sets of debris flows separated in time by as long as a week suggests two pulses of summit ice collapse, each producing a surge of water and debris from the lake. A single debris flow was also emplaced on May 2, 2005. This event, which was captured by a Web camera, occurred simultaneously with a lake-level drop of ~15 m. To the east of the ice cauldron, a spillway that fed the debris flows has apparently maintained a relatively constant lake level for months at a time. Aerial photographs show that the spillway is in the direction of a breach in the summit crater. Melting of snow and ice at the summit has continued through 2006, with a total meltwater volume of ~5.4 million m^3 as of March 2006.

Introduction

Mount Spurr is a 3,374-m-high ice- and snow-covered stratovolcano situated in rugged wilderness 125 km west of Anchorage (fig. 1). Explosive eruptions from Crater Peak, a satellite vent 3.5 km south of the summit (fig. 2), occurred in 1953 (Juehle and Coulter, 1955) and 1992 (see Keith, 1995, and references therein), producing ash falls on populated areas of south-central Alaska and small-volume pyroclastic flows and lahars at the volcano. The summit of Mount Spurr, which is largely ice covered, has been interpreted as a lava-dome complex, on the basis of limited sampling (Nye and Turner, 1990). This feature lies within a 5.5-km-wide, largely ice filled collapse caldera that formed in late Pleistocene or early Holocene time (fig. 2; Nye and Turner, 1990). On the basis of studies of tephra deposits, the latest eruption at the summit is believed to have occurred ~5.2 ka (Riehle, 1985).

In summer 2004, increases in seismicity, heat flux, and gas flux and resulting drastic morphologic changes at the summit of long-dormant Mount Spurr heightened concern about a possible eruption. In response, the Alaska Volcano Observatory (AVO) enhanced its geophysical monitoring, mounted a series of observation flights and airborne gas and thermal measurements, increased acquisition of remotely sensed data, and examined historical imagery of the volcano in an effort to understand the significance of the observed changes. As of early 2006, seismicity remains above background level, but no eruption has occurred. Regardless, the ongoing volcanic unrest has been interpreted as an injection of magma beneath the summit, producing a prolonged increase in magmatic-gas output and heat flux (Power, 2004; Power and others, 2004; Cervelli and others, 2005; De Angelis and McNutt, 2005). This chapter describes and interprets the morphologic changes in glaciers at the summit of Mount Spurr in response to this magmatic intrusion.

Geology of the Summit

The Spurr volcanic complex, characterized by Nye and Turner (1990), is a long-lived stratovolcano that is the easternmost active volcanic center in the Aleutian Arc. The complex consists of ancestral Mount Spurr, which is as old as middle Pleistocene, on the basis of K-Ar dating of stratigraphically low lavas (>250 k.y.; Nye and Turner, 1990) and two Holocene vents. A much older volcanic center may have existed in the same place, on the basis of isolated exposures of Pliocene lavas (Nye and Turner, 1990; M.L. Coombs and A.T. Calvert, unpub. data, 2005). Ancestral Mount Spurr was eviscerated by a catastrophic landslide that formed a large debris-avalanche deposit to the south and southeast and an avalanche caldera, ~5 km in diameter. The date of this event is unknown but is probably early Holocene because the debris-avalanche deposit was not affected by late Pleistocene glaciation (Nye and Turner, 1990; Waythomas and Nye, 2002).

Since caldera formation, eruptive activity at Mount Spurr has focused at two vents: the summit and Crater Peak (fig. 2). Over the past several thousand years, most eruptions of the Spurr volcanic complex have been from Crater Peak, a satellite vent at the southern caldera margin. These eruptions produced basaltic andesite tephra falls and local flow deposits (Riehle, 1985; Nye and Turner, 1990). All historical eruptions of the complex have been from the Crater Peak vent, including the most recent in 1992 (see Keith, 1995, and references therein).

Less is known about the eruptive history of the summit. The mostly snow and ice covered summit dome complex rises 460 m above the icefield that fills the caldera. Several samples collected from the summit in the 1980s are dacitic (Nye and Turner, 1990). On the basis of chemical correlation, a single tephra fall dated at 5.2 k.y. is attributed to the summit vent (Riehle, 1985). Other relatively silicic, Holocene deposits may also have their origins at the summit, including a pyroclastic-flow deposit along the Chakachatna River (C.J. Nye, written commun., 2004).

Despite the relative scarcity of evidence for summit eruptions, the morphology of the summit dome complex suggests that this feature has not been extensively eroded by glaciers. Since the 1970s, the amount of snow and ice at the summit has fluctuated, at times allowing views of the crater that sits at its top. More discussion of historical observations follows in a later section.

The Spurr volcanic complex has been seismically monitored by AVO with a network of at least six stations since 1989 (Jolly and others, 1994). During the 1992 eruptions of Crater Peak, seismicity was at times focused beneath the summit and not at Crater Peak (Power and others, 1995); and since 1993, most earthquakes have occurred beneath the summit. Volcanic-gas measurements at the complex have focused on Crater Peak, the historically active vent. Airborne gas measurements

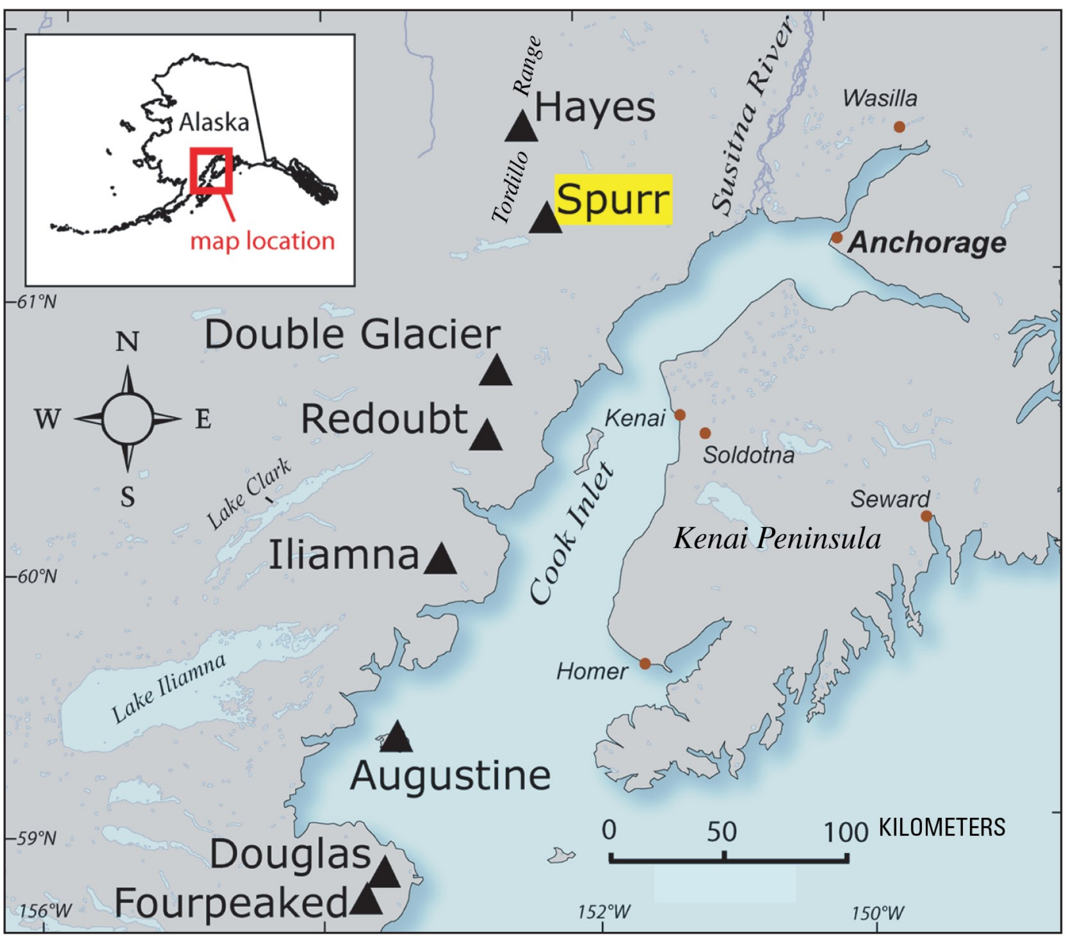


Figure 1. Cook Inlet region, southern Alaska, showing locations of Mount Spurr and other volcanoes (triangles). Dots, towns and villages. Map courtesy of Janet Schaefer, Alaska Division of Geological and Geophysical Surveys.

at Crater Peak indicate a background, noneruptive rate of SO_2 degassing of no more than a few tens of tonnes per day; Crater Peak also has consistently degassed a small amount of CO_2 (typically <200 t/d) since 1994 (Doukas, 1995; M.P. Doukas, written commun., 2004). Before the 2004–6 volcanic unrest, no airborne gas measurements had been made at the summit of Mount Spurr.

Onset of Unrest, Generation of Summit Ice Cauldron, and Debris Flows

In early July 2004, AVO seismologists noted an increase in the rate of volcanotectonic and long-period earthquakes occurring beneath the summit of Mount Spurr (Power, 2004; Power and others, 2004; De Angelis and McNutt, 2005). AVO was also contacted by a long-time Alaskan pilot who flew near the volcano on July 11 and reported a small steam plume from the ~1,675-m level of the east side of Crater Peak, as well as an odor of SO_2. Both observations were slightly unusual for the Crater Peak area. On the basis of this report and the increase in seismicity, AVO launched a fixed-wing observation flight to the volcano on July 15 (table 1). Although clouds obscured the summit, the east flank was visible and streaked with nearly a dozen dark debris-flow deposits (fig. 3; McGimsey and others, 2004)—to our knowledge, the first observation of debris flows from the summit of Mount Spurr. On August 2, an AVO overflight also confirmed the presence of a steep-walled collapse pit in the summit basin. We describe these features in sequence below and discuss their relation and significance to the volcanic unrest at Mount Spurr.

Summer 2004 Debris Flows

The summer 2004 debris flows produced sheets and elongate lobes of dark material that cascaded down the steep glacier surface, draping and flowing into and across crevasses (fig. 4). The flows emerged primarily from crevasses in the glacier on the precipitous (20–45°) east flank of the summit. Several flows appeared to have cascaded down the steep,

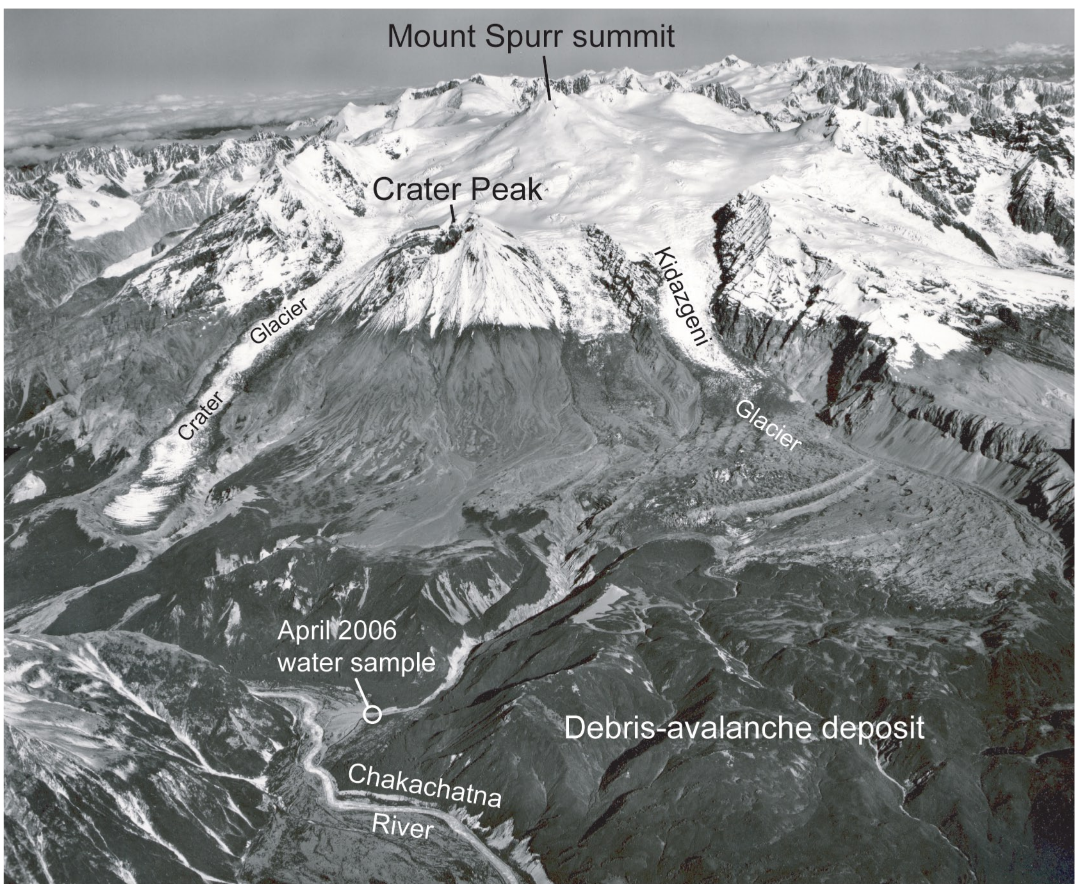


Figure 2. Spurr volcanic complex (see fig. 1 for location). Summit of Mount Spurr sits in an ice-filled collapse caldera, breached to the south; Crater Peak, a historically active satellite vent, sits in breach. Debris-avalanche deposit in foreground, which was formed during caldera formation, is dated at early Holocene (Waythomas and Nye, 2002). View northward; photograph 666–6 by Austin Post, taken September 4, 1964.

Table 1. Chronology of events and observations relating to volcanic unrest at Mount Spurr, Alaska, 2004–6

[ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; AVO, Alaska Volcano Observatory; FLIR, Forward-Looking Infrared; NASA, National Aeronautics and Space Administration; USGS, U.S. Geological Survey]

Date	Observation	Source	Area of ice cauldron (m^2)
1954	Crater, breached to the east, partly filled with snow and ice.	USGS aerial photograph ----------	---
August 7, 1957	Breached crater easily visible through the ice; steep perforation in the ice against north inner wall of crater.	do ------------------------------------	---
1964	Crater filled with snow and ice; crevassed perforation or subsidence pit in the northern portion of crater against high rock wall.	do ------------------------------------	---
1978	Summit crater with less bare ground visible (March and others, 1996, p. 25).	NASA high-altitude false-color infrared aerial photograph.	---
June 18, 2002	Undisturbed ice field mantling summit: subtle depression only.	Ikonos image------------------------	---
March 19, 2004	Climbers traverse area of future ice cauldron; no surface disturbance noted, steaming rock below the summit, audible gas emission, and strong H_2S reported.	Photograph by C. Arnold----------	---
May 3, 2004	Oblique aerial photograph of summit shows no deformation.	Photograph by S. Parks------------	---
June 20, 2004	Oblique aerial photograph shows development of subsidence in summit glacier.	Photograph by B. Hooper ---------	---
July 8, 2004	Ice cauldron first visible; no open water.	ASTER image ----------------------	4,250
July 10, 2004	Debris flows on the ESE flank of summit.	Landsat image ----------------------	---
July 15, 2004	Overflight confirms debris-flow deposits on the ESE flank of Spurr summit. More flows visible than in July 10 satellite image suggesting at least two generations of debris flows.	AVO observation flight------------	---
August 2, 2004	~50-m-diameter ice cauldron with open water	do ------------------------------------	---
August 4, 2004	Rock exposed in cauldron wall; dark sediment (tephra?) sloughing out of ice in walls; lake mostly covered by ice except for north edge.	do ------------------------------------	---
August 10, 2004	Size of cauldron, 65 by 95 m---	QuickBird image -------------------	5,270
August 12, 2004	Warm rock visible along shoreline of ice-cauldron lake.	AVO FLIR flight -------------------	---
September 4, 2004	Steaming from long-lived hole in glacier downslope and to the SSE of ice cauldron.	AVO observation flight------------	---
September 5, 2004	Size of cauldron, 150 by 170 m--	Satellite image ----------------------	---
September 23, 2004	Size of cauldron, 95 by 120 m; south half of lake ice-covered, north half partly open.	Aeromap orthorectified vertical aerial photographs.	10,770
October 29, 2004	Interior cauldron-wall retreat exposes horizon of 1992 tephra.	do ------------------------------------	---
October 30, 2004	Size of cauldron, 130 by 130 m-------------------------------------	do ------------------------------------	15,850
December 4, 2004	Lake surface partly covered with ice; little exposed rock visible.	do ------------------------------------	19,900

Table 1. Chronology of events and observations relating to volcanic unrest at Mount Spurr, Alaska, 2004–6—Continued

[ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer; AVO, Alaska Volcano Observatory; FLIR, Forward-Looking Infrared; NASA, National Aeronautics and Space Administration; USGS, U.S. Geological Survey]

Date	Observation	Source	Area of ice cauldron (m^2)
January 11, 2005	do--	do-------------------------------------	22,970
February 28, 2005	Lake surface almost entirely covered with ice debris except for three circles of roiling; steaming warm rock visible along lakeshore.	AVO gas and observation flight --	---
March 2, 2005	Ice covered south side of lake, north half ice free, steaming warm rock exposed along north lakeshore.	AVO observation flight	27,400
March 26, 2006	Steam in cauldron, ice covered south side of lake, north half ice free.	do	---
April 25, 2005	Ice covered south side of lake, north half ice free; large expanse of exposed rock on north and northwest walls of cauldron.	AVO FLIR and observation flight.	40,800
May 2, 2005	At ~11:00 a.m. A.s.t., debris flow observed ---------------	AVO Web camera; pilot report on May 3.	---
May 3, 2005	Observation that lake level had dropped from April 25, likely coincident with debris flow on May 2. Fumaroles in crater are stranded above waterline.	AVO observation flight------------	40,800
May 10, 2005	Detailed observations made of new debris-flow deposits. Steaming fumaroles above new, lower shoreline; thin fragmental ice cover on south side of lake, north half ice-free.	do-------------------------------------	40,800
June 21, 2005	Lake level similar to that seen in May; strong roiling observed in ice-free lake.	AVO FLIR and observation flight.	48,950
July 7, 2005	Another section of cauldron wall starts to founder.	AVO observation flight------------	59,380
August 1, 2005	Cauldron reaches its present size------------------------------------	do-------------------------------------	68,900
September 8, 2005	Lake free of ice, no upwelling noted, yellow precipitate visible along lake shore.	Photographs by D. Schwartz------	68,900
October 9, 2005	Lake surface partly covered with dirty ice, fumaroles active along lake shore.	Photographs by D. Dewhurst -----	---
November 3, 2005	Lake free of ice, no upwelling noted, lake partially obscured by steam.	AVO observation flight------------	69,250
March 22, 2006	Large roiling upwelling and S(?)-precipitate cloud in lake	do-------------------------------------	69,730
March 22, 2006	do--	Private climbing party -------------	---
April 14, 2006	Several areas of steaming on flanks of summit, highest temperature, 45°C; average lake temperature, 11°C; vigorous roiling in lake.	AVO FLIR and observation flight.	---
April 23, 2006	Previously steaming areas on flanks covered in snow; yellow precipitate observed along lakeshore.	AVO gas and observation flight --	---

exposed bedrock cliff on the northeast summit flank (hereinafter referred to as the northeast face, the site of scattered boiling-point fumaroles; Turner and Wescott, 1986).

The debris-flow deposits ranged from about 50 to 1,000 m in length and from 20 to 100 m in width. Dark brown to black, they appeared to be uniform in texture from the air. No large clasts were visible in magnified aerial photographs, suggesting that the debris flows were devoid of boulder-size material. The deposits also appeared to be fairly thin, as indicated by their diffuse appearance along flow margins where the underlying snow and ice were varyingly visible. Lateral levees were visible on some deposits. Several flows were marked by central rills, meters deep, indicating downcutting during or after emplacement. Some of the rills were washed clean, whereas others were mantled with sediment. Rills extended beyond the debris-flow deposits in a few places, indicating that water or watery debris flows traveled beyond the lobate deposit termini and caused simultaneous erosion of the ice surface. Flowing material may have been warm enough to melt surface snow and ice after coming to rest because several termini were incised below the level of the surrounding glacier. Alternatively, solar heating of the dark debris during the days after emplacement may have been sufficient to cause differential melting and relative subsidence of the deposit areas.

Comparison of satellite images indicates that the debris flows occurred in at least two pulses separated by several days to several weeks. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data from July 8 and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data on July 10 show some, but not all, of the deposits observed on July 15. Thus, some debris flows occurred between June 20 and July 8, and the rest between July 10 and 15.

Using the July 15 aerial photographs in combination with ASTER and QuickBird satellite imagery from August 10, we created a map of the distribution of debris flows (fig. 5). The debris flows were confined to the northeast and east. The June 20–July 8 debris flows emerged from the glacier in two areas: adjacent to a bedrock ridge that trends southeast from the summit (deposit a, figs. 3–5), and above the northeast face (deposits b, c). The July 10–15 debris flows were smaller and emerged primarily from lower-elevation points directly east of the summit (deposits d–h). Flows in the first set were larger in volume and traveled a greater distance. July 15 Forward Looking Infrared (FLIR) images show that the earlier flows were slightly warmer than the later flows, suggesting that the earlier flows were thicker and retained heat more efficiently.

The total area of the deposits observed in summer 2004 is 132,000 m^2; their thickness was not measured. A lahar deposit

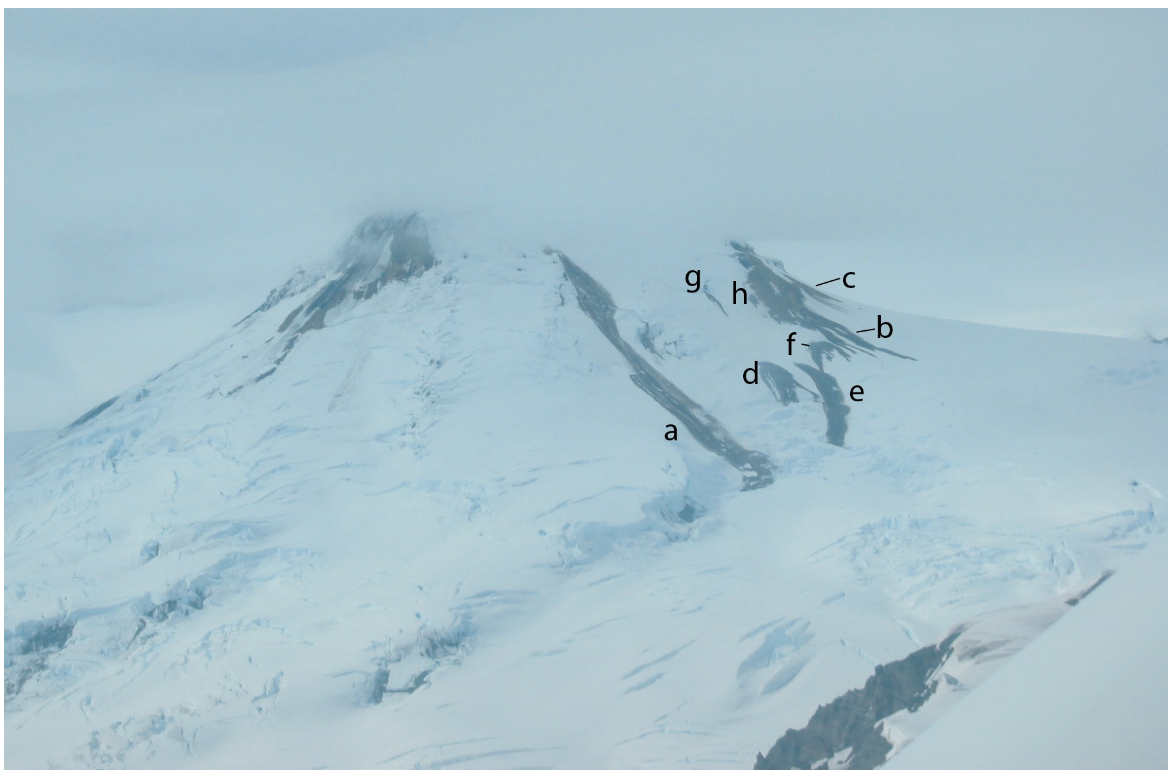


Figure 3. East face of summit cone of Mount Spurr (fig. 1), showing debris-flow deposits, lettered in order of deposition (see figs. 4, 5): a–c, June 20 to July 8, 2004; d–h, July 10–15, 2004. True summit is obscured by clouds. Area of dark bare ground and debris on south face (upper left) is a long-lived zone of frequent avalanches of mixed rock, ice, and snow. View northwestward; photograph by C.A. Neal, taken July 15, 2004.

that formed from a crater-lake outbreak at Chiginagak Volcano on the Alaska Peninsula in 2005 averaged 15 cm in thickness (Schaefer and others, 2005); using this thickness as a proxy suggests a combined volume of ~20,000 m^3, excluding any water that must have been present.

Another debris flow that formed in May 2005 is described in detail below.

Summit Ice Cauldron and Lake

AVO overflights on August 2 and 4, 2004, revealed a circular collapse pit, ~50 m in diameter, in the eastward-sloping summit icecap (fig. 6*D*). The pit was at approximately the north edge of a broad depression in the summit icefield, encircled by nested arcuate crevasses that indicated a much larger area of active subsidence. The crevasses mimicked the overall open-to-the-east shape of the summit basin. The pit walls were vertical to overhanging and exposed cavernous tunnels in the ice, as well as one conspicuous area of steeply sloping, gray bedrock that formed the lower northeast wall (fig. 6*E*). The bottom of the pit was an ice-choked lake with small areas of blue-gray open water.

The collapse pit and surrounding depression became known as the ice cauldron, following usage of the term at ice-covered Icelandic volcanoes that have had subglacial eruptions or transient subglacial geothermal events (for example, Björnsson, 1988; Gudmundsson and others, 2004). Unsafe landing conditions throughout the period of volcanic unrest prevented any ground-based observations of the summit ice cauldron, and so the record of its formation is reconstructed here on the basis of helicopter and fixed-wing overflights, aerial photographs and video, and satellite-image analysis. A review of pre-August 2, 2004, aerial photographs and mountaineering accounts provides some constraints on the timing of formation of the ice cauldron (table 1). Climbers in mid-March 2004 who traversed the slope that would later collapse noted no disturbance or evidence of incipient subsidence (fig. 6*A*). The first clear indication of summit deformation is in aerial photographs taken on June 20 (fig. 6*C*). Here, an east-facing, arcuate scarp across the summit basin displays subsidence of several meters. The position of the escarpment coincides with the well-developed outer set of nested crevasses visible on August 2 and 4 when AVO first observed the fully formed ice cauldron. An ASTER satellite image taken on July 8 shows a nearly circular depression with sharply defined walls enclosing a partially darkened area, suggesting ice-choked water (fig. 7*B*). Thus, collapse of 4,200 m^2 of the summit icefield likely occurred sometime between June 20 and July 8, 2004.

Growth of the Ice Cauldron

Overflights throughout late 2004 and 2005 documented the growth of the ice cauldron, continuing deformation and collapse of the surrounding icewalls, and variation in the area of open water on the surface of the crater lake. From early August through early December 2004, the ice cauldron enlarged gradually as blocks of ice ringing the depression toppled into the lake. The collapse pit, which was mapped in a geographic information system (GIS), using a combination of vertical and oblique imagery (fig. 8; table 1), increased systematically in area over time until August 2005 (fig. 9). At first, in midsummer 2004 through March 2005, its area increased fairly linearly. The growth rate increased somewhat from March to midsummer 2005, to an area of 68,900 m^2 by August 1. This increase in area was accomplished by expansion southward as large seracs became unstable, pulled away from the south wall of the summit crater, and toppled into the lake. From August 2005 to spring 2006, the area of the ice cauldron remained relatively constant, likely owing to a combination of decreasing heat flux, as evidenced by lower SO_2 emissions (M.P. Doukas and K.A. McGee, unpub. data, 2006) and lower seismicity rates (fig. 9*B*), and walling in of the collapse pit by rock on its north, west, and south sides.

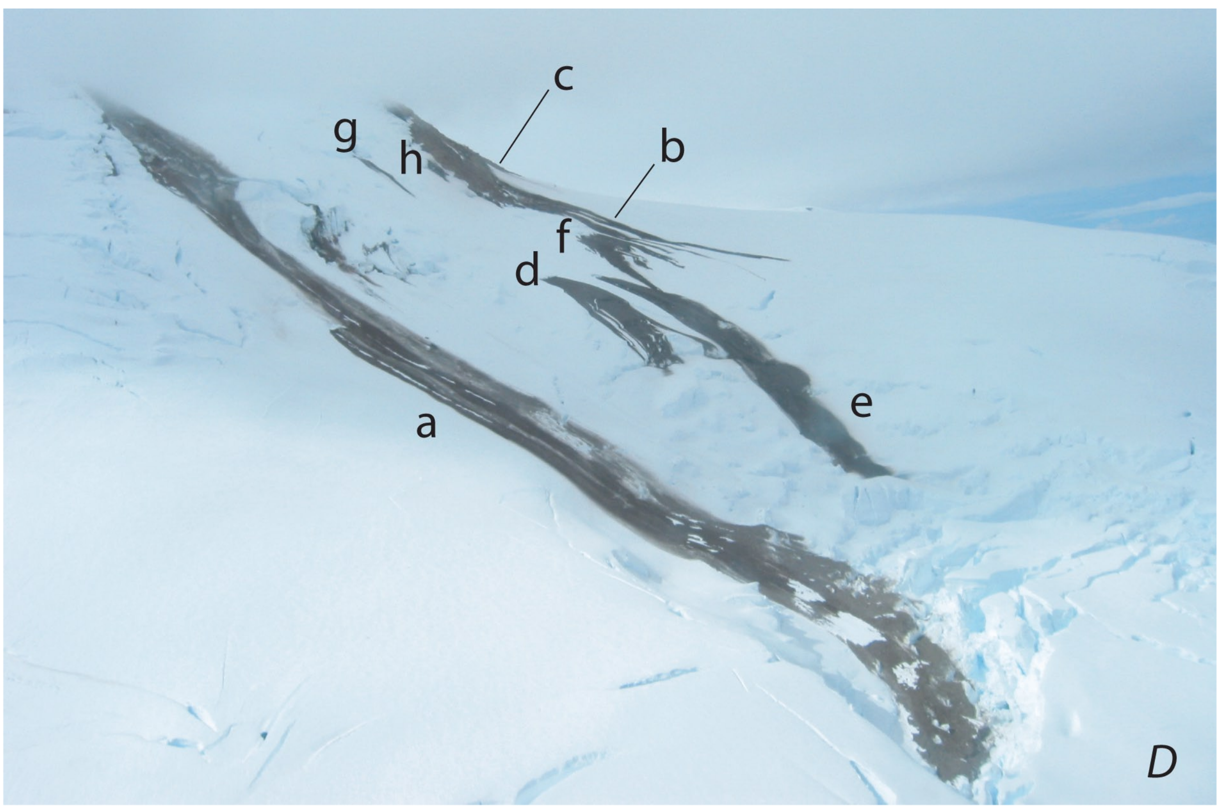
The height of the ice cauldron walls likely remained relatively constant. Before a sudden drop in lake level in May 2005 (discussed below), the water level also appeared to remain constant, as tracked by features in the pit walls. A high-resolution digital elevation model (DEM) of the summit area, generated from vertical aerial photographs taken on September 23, 2004, indicates that the elevation of the lake was 10,605 ft. Along the southwest rim, closest to the summit, the snow elevation was ~10,900 ft, and along the northeast rim it ranged from 10,810 to 10,830 ft. Thus, the average depth of the ice cauldron from snow surface to lake level was ~255 ft (78 m). The depth of the lake is unknown. Assuming an average elevation difference of 78 m throughout the period of volcanic unrest and assuming vertical walls, the total volume of melted snow and ice (as of Mar. 22, 2006) was 5.4 million m^3.

Lake, Fumaroles, and Rockwalls

Throughout much of the observation period, the color of the ice-cauldron lake remained dark gray as circular, ice-free zones, tens of meters across, appeared near the northeast bedrock shoreline and at several points farther from the lakeshore (fig. 10). In late February 2005, AVO noted roiling of the water surface within these circular zones for the first time, although previous aerial photographs show circular ice-free patches within the lake in early August 2004. These patches most likely represent upwelling of warm, gas-rich water from deeper within the lake, similar to the upwelling zones observed in the Crater Peak lake before the 1992 eruption (Keith and others, 1995). During observation flights through fall 2004 into early 2005, the area of open water persisted near the northeast shoreline.

Five FLIR surveys documented gradually increasing temperatures of the crater lake, fumaroles, and exposed bedrock outcrops between July 15, 2004, and April 16, 2006. The thermal surveys indicated that the lake-water temperature gradually increased from about 1°C (when the lake was mostly

Figure 4. Closeups of debris-flow deposits on summit cone of Mount Spurr. Same labels as in figures 3 and 5. Photographs by C.A. Neal, taken July 15, 2004. *A*, Main debris-flow lobes drape east sector of summit cone. Dark areas in upper left are outcrops and not flowage features. True summit is obscured by clouds. View north-northwestward. *B*, Reddish-brown outcrop of volcanic bedrock in upper right is northeast face, a longstanding feature that hosts diffuse boiling-point fumaroles and remains snow free much of the year. Several debris-flow deposits emerge from cracks and holes in glacier and cascade over crevasses; additional flows course over northeast face and extend outward onto glacial ice. Note central rill visible in deposit and narrow incised channel that extends from toe of debris flow at right (d).



Deposits at middle right (b) appear to have melted surface snow, resulting in negative topography. *C*, East-southeast face, showing nearly all of longest debris-flow deposit (a) that emerged from a point just obscured by clouds at top of photograph. Note diffuse debris cover along margins and clean ice along central part of flow, suggesting waterflow late in emplacement. Ice cliff at center, partly covered by a short debris-flow lobe to right of flow a, marks source of May 2005 debris flow. *D*, Main debris-flow field on east flank. Terminus of longest flow (a), visible in lower right, is where material flowed over and around crevassed ice. Note large patches apparently washed clean of debris. View northward.

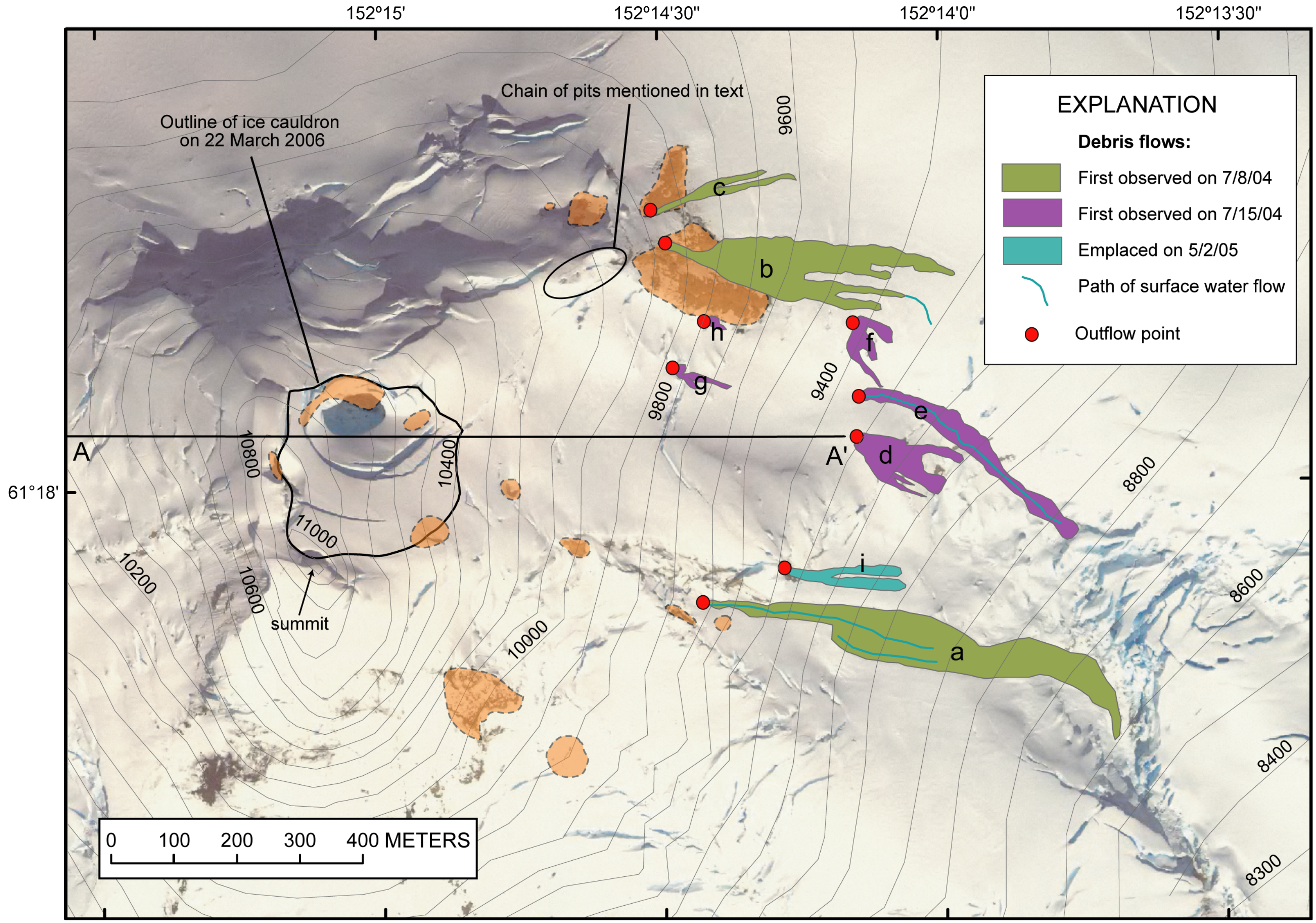
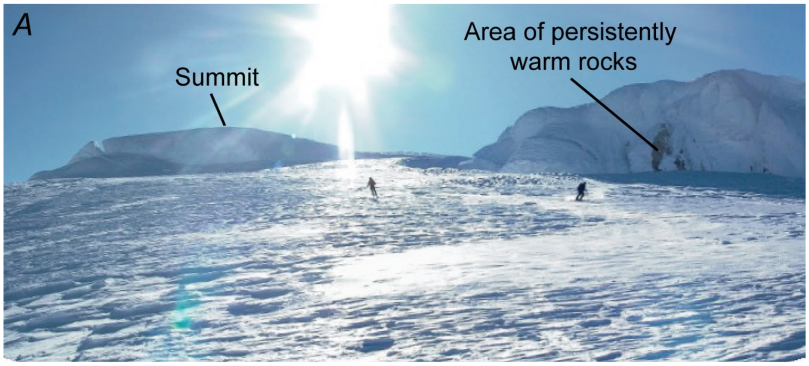
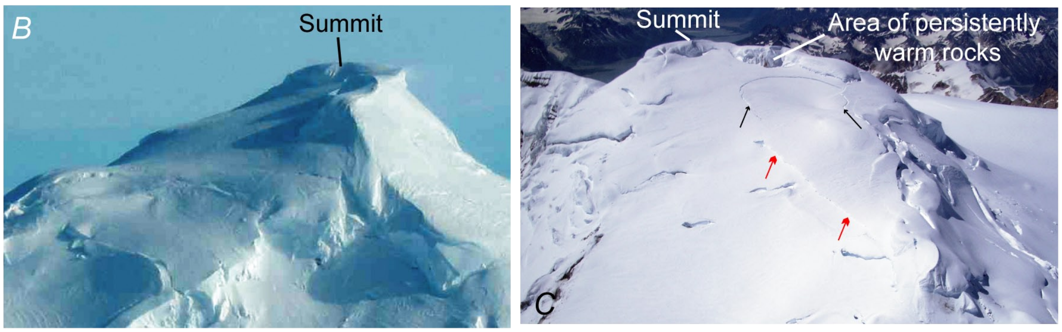
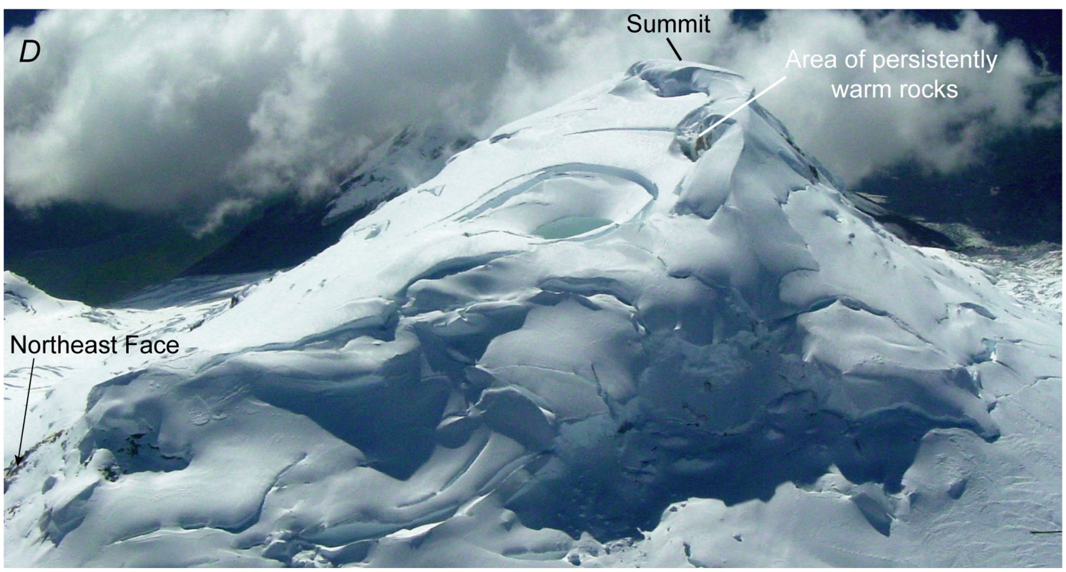


Figure 5. Mount Spurr area, showing locations of 2004–5 debris-flow deposits and other near-summit features. Same labels as in figures 3 and 4. Orange areas with dashed outlines are approximate zones or point sources of documented thermal activity, including areas of warm rock, anomalous-temperature zones defined by forward-looking-infrared imagery, and aerial photographs of steaming ground or crevasses. See figure 14 for cross section *A–A′*. Base from pan-sharpened, visible- and near-infrared-band 4, 0.62-m-resolution QuickBird satellite image, acquired August 10, 2004 (catalog ID 1010010003295802, copyright © Digital Globe). Contour interval, 100 ft; contours from U.S. Geological Survey topographic map.







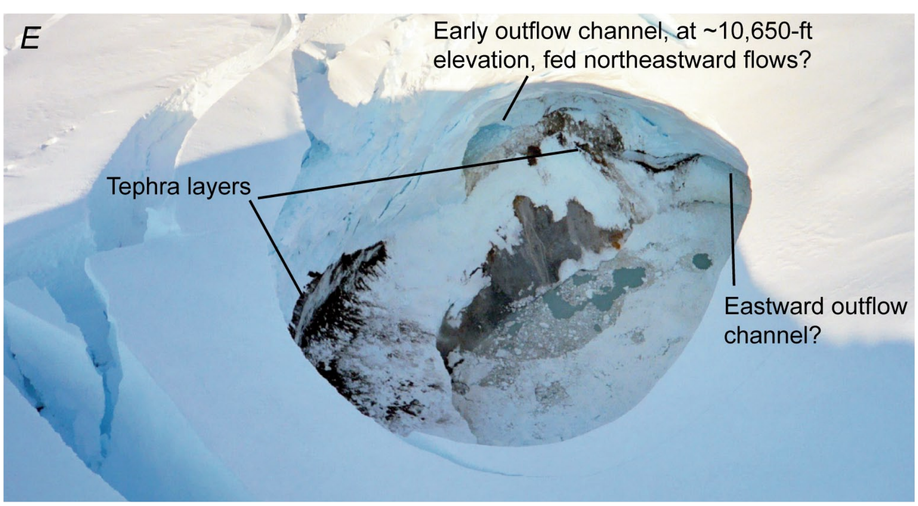


Figure 6. Stages in formation of ice cauldron at summit of Mount Spurr. *A*, Summit icefield on March 19, 2004, from atop a place that would later become ice cauldron. View south-southwestward; photograph by Cody Arnold. *B*, Summit on May 5, 2004. At this time, no deformation or subsidence is visible on summit plateau. View southward; photograph by Stuart Parks. *C*, Summit on June 20, 2004. By this time, ice cauldron had begun to subside, as shown by arcuate scarp (ends denoted by black arrows) marking edge of eventual pit. Note linear escarpment (south side down, denoted by red arrows) to east of protocauldron; this structure may mark boundary of bedrock ridge with a subsiding ice sheet to south. View westward; photograph by Bruce Hopper. *D*, Summit on August 2, 2004. First clear view of ice cauldron. View southward; photograph by Kristi Wallace. *E*, Ice-filled lake at summit, exposed rockwalls on north margin, dark debris (tephra?) sloughing out of ice, and crescentic ice tunnels providing potential spillways eroded into ice. View northeastward; photograph by Donna Eberhart-Phillips.

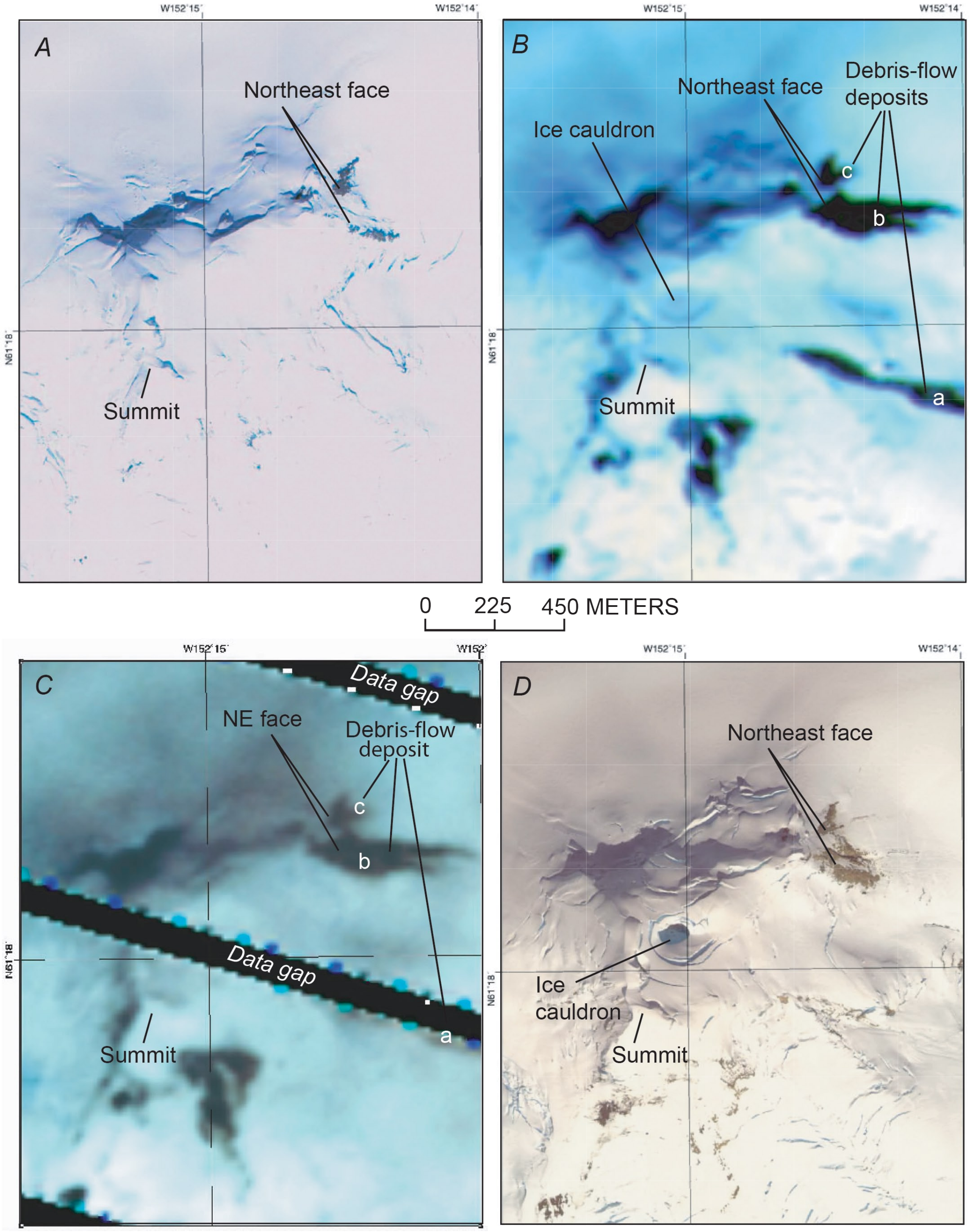


Figure 7. Satellite images of summit of Mount Spurr, cropped and scaled to same footprint. *A*, View from Ikonos, taken 21:34:42 u.t.c. June 15, 2002 (image ID 2002061521344230000010079111, copyright © Space Imaging), showing no obvious pit or subsidence at summit. *B*, View from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), taken 21:49:42 u.t.c. July 8, 2004 (granule ID AST_L1A_00307082004214924_073020044131349), showing beginning of ice cauldron and first set of debris-flow deposits. *C*, View from Landsat 7 Enhanced Thermal Mapper Plus (ETM+), taken 21:09 u.t.c. July 10, 2004 (scene ID 7070017000419251), showing same debris-flow deposits as in figure 7*C* but not all flows observed on July 15, 2004, overflight. *D*, View from QuickBird, taken August 10, 2004 (catalog ID 1010010003295802, copyright © Digital Globe). Same base as in figure 5.

filled with ice) to over 11°C in April 2006. The rise in lake temperature likely is partly controlled by a decrease in the volume of water over time, coupled with a decrease in the volume of snow and ice falling into the lake. The temperatures of the circular upwelling areas were not significantly higher than the average lake temperatures during a June 21, 2005, survey; however, an April 2006 survey indicated that the temperature of the upwelling area in a slightly shallower lake was at least 25°C, while the average lake temperature was 11°C.

The area of exposed bedrock near the bottom of the ice cauldron also increased and occasionally produced a visible vapor plume. By August 2005, bedrock was visible around the lakeshore in all quadrants except the south-southeast (fig. 10). Yellow-tinted snow, ice, and rock in the vicinity of the lake indicated sulfur deposition near the lake margin. Ongoing release of volcanic gases, including SO_2 and CO_2, was confirmed by periodic airborne gas measurements (Neal and others, 2005; K.A. McGee and M.P. Doukas, unpub. data, 2005). The FLIR-measured temperature of fumaroles in the bedrock outcrop on the northwest shore of the lake increased from 60°C in June 2005 to over 150°C in April 2006.

May 2005 Debris Flow

From August 2004 through late 2004, the lake level remained fairly constant. In early May 2005, however, another debris-flow event occurred in conjunction with a rapid drop in lake level. After a pilot reported of a dark flow on the flank of Mount Spurr, an AVO overflight on May 3 revealed that the lake level was ~15 m lower since a flight on April 25—the first decrease of this magnitude noted since the lake had become exposed (fig. 11). Newly exposed rock was steaming

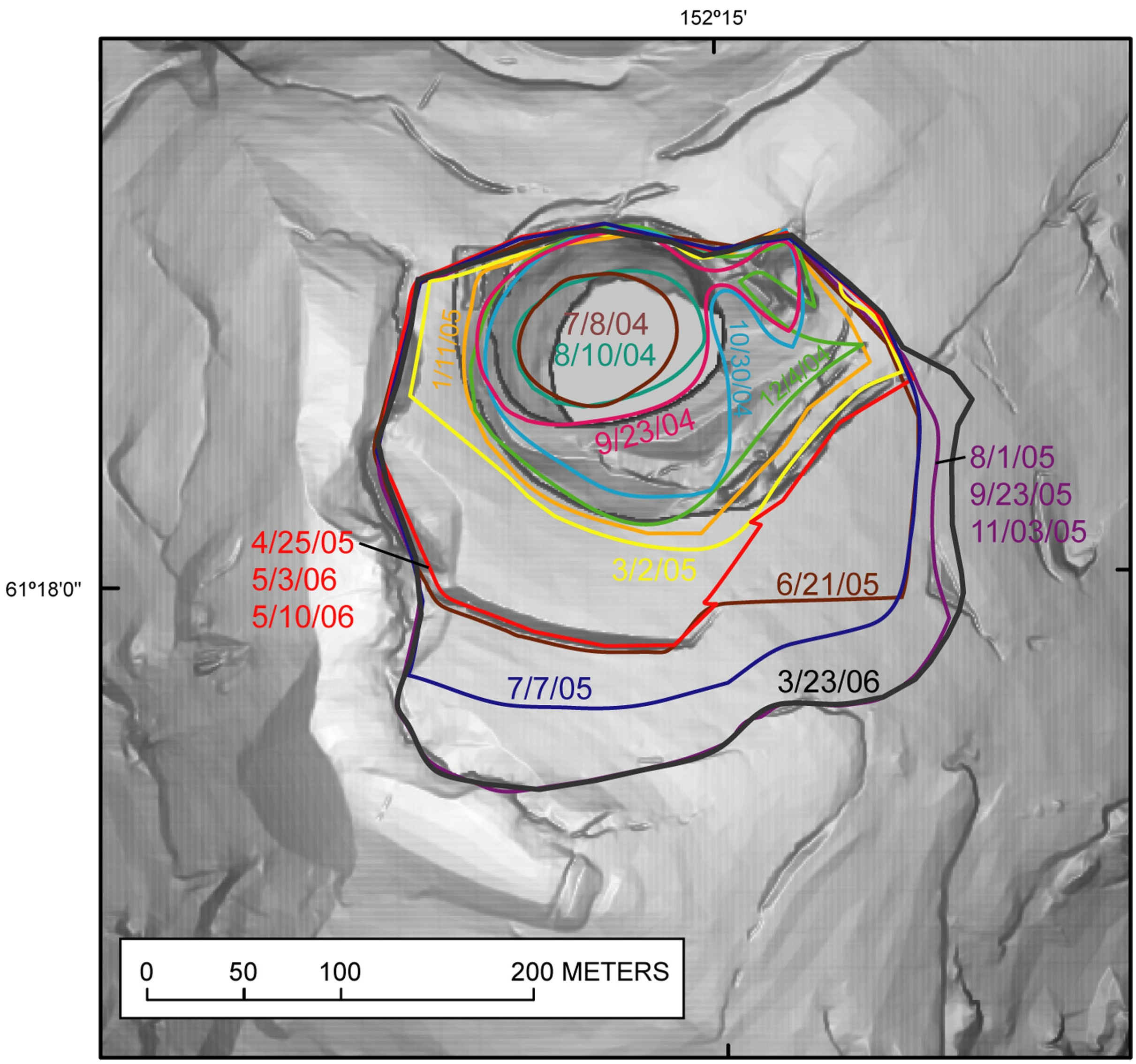


Figure 8. Summit of Mount Spurr, showing outlines of growing ice cauldron between July 8, 2004, and March 23, 2006. Digital elevation model from vertical aerial orthophotograph, taken September 23, 2004.

vigorously. About 600 m southeast of the lake at ~2,865-m elevation, a new debris-flow deposit (i, fig. 5) was observed in the same area as the 2004 flows. This 190-m-long, 30-m-wide deposit was also dark, composed of fine material, and apparently emplaced with abundant water, as evidenced by erosion of snow and ice. Using the area of the ice cauldron mapped from April 25, 2005, images and a decrease in depth of 15 m, we calculate that ~600,000 m^3 of water drained from the lake during this event.

Emplacement of the May 2 debris-flow deposit was recorded by a Web camera installed for monitoring purposes by AVO in September 2004. Images show that the flow reached its full length in 12 minutes or less (fig. 12). Web camera images from the morning of May 3 show a steam plume rising several hundred meters above the summit. Because such a strong steam plume had not been observed previously, we conclude that the onset of steaming reflected a drop in lake level. Although the debris flow was emplaced at ~11:00 a.m. A.d.t. May 2, clear Web camera views from that afternoon show no steam; this delay may have been caused by changing meteorologic conditions.

To our knowledge, the May 2005 debris-flow event was the only such incident after July 2004. In November 2005, however, AVO received photographs from a pilot that showed rilling of the snow and ice cover along the same swath affected by the May 2005 debris flows (fig. 13). The timing of this event is uncertain. Although any dark, solid component involved in outflow may have been covered by new snow, the

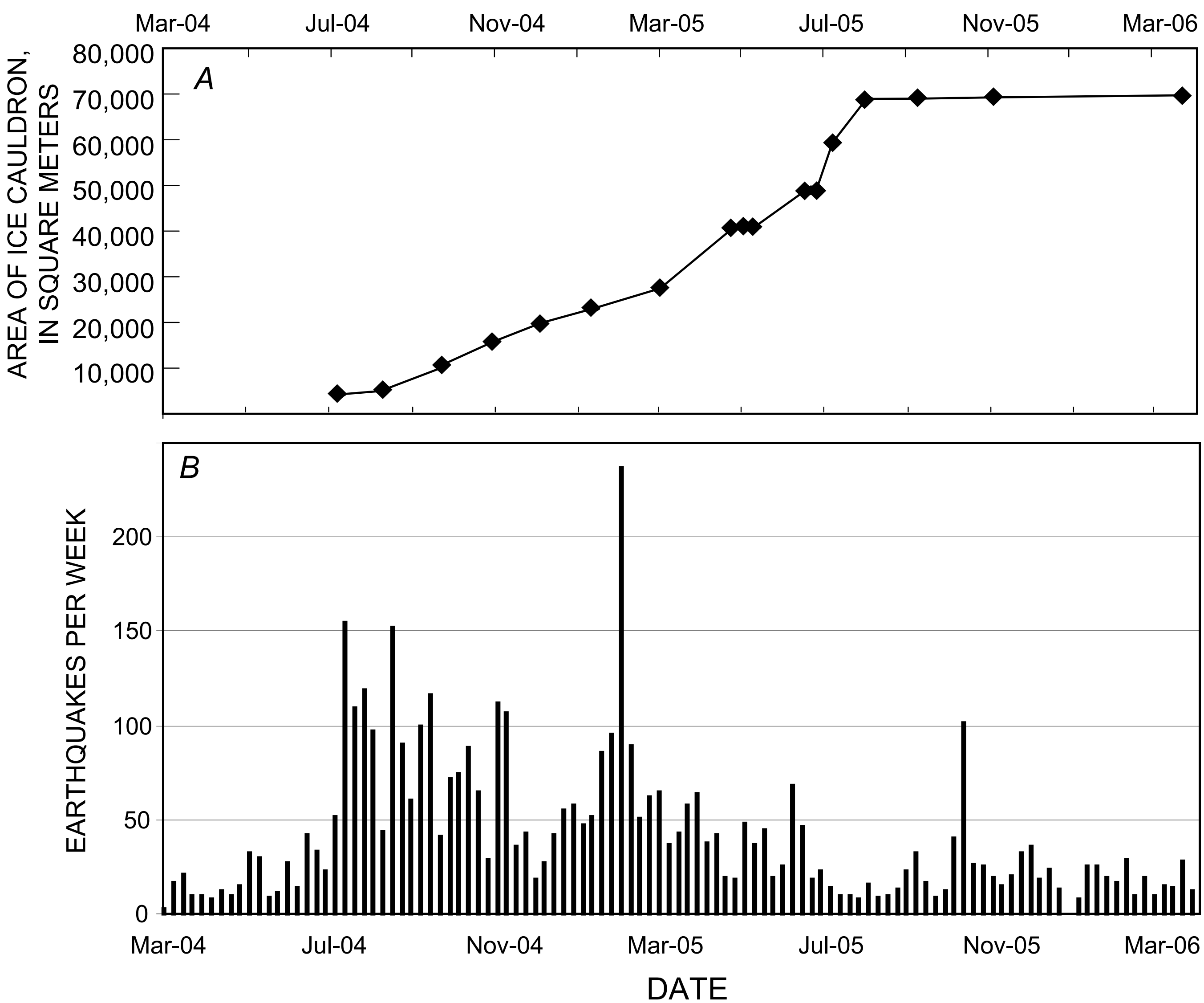


Figure 9. Correlation between growth of ice cauldron at summit (*A*) and weekly frequency of earthquakes in Mount Spurr area from March 2004 through March 2006 (*B*). Earthquake data from Dixon and others (2005) and Alaska Volcano Observatory (unpub. data, 2006).

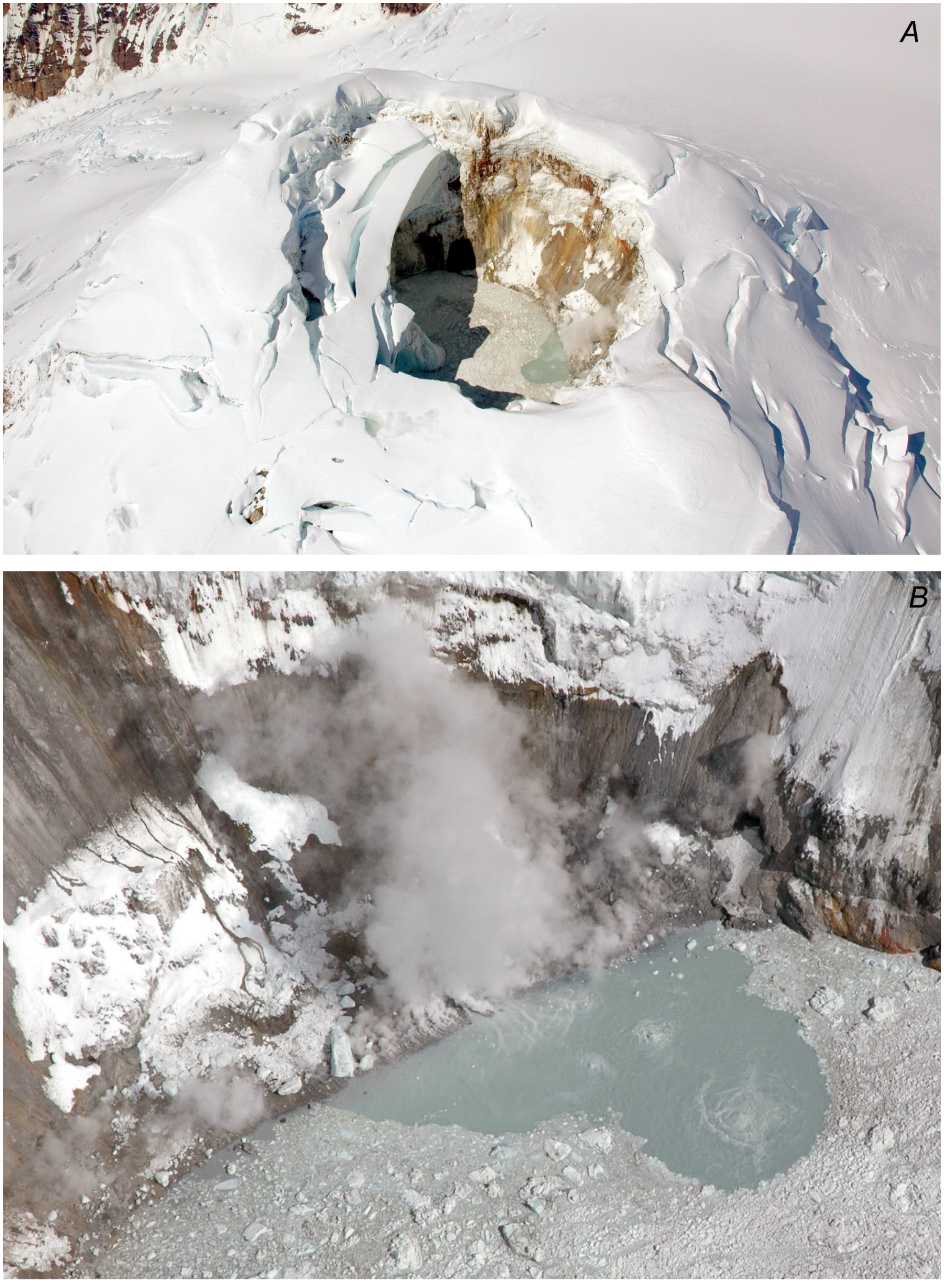


Figure 10. Summit of Mount Spurr, showing fully developed ice cauldron, approximately 200 m across north-south. *A*, Area of consistent upwelling and roiling in lake is visible along north shore (to right). View westward. *B*, Closeup of upwelling area and shoreline fumaroles. Photographs by Dave Schneider, taken June 21, 2005.

event may also have involved simply water and remobilized snow and ice with no suspended sediment.

Discussion

Source of Sediment and Water in Debris Flows

We were unable to directly sample the 2004 debris-flow deposits, which rapidly became covered with snow in steep terrain. A likely source of the sediment fraction is lapilli- and ash-size tephra-fall deposits from the 1992 eruptions of Crater Peak (Neal and others, 1995; McGimsey and others, 2001). These deposits are visible as conspicuous dark-gray bands in seracs and in the walls of the ice cauldron (fig. 6*E*). The June 1992 eruption cloud traveled northward from the vent, depositing as much as 50 cm of tephra on the summit of Mount Spurr (McGimsey and others, 2001). The August 1992 eruption of Crater Peak may have just dusted the summit, and the September 1992 eruption deposited <1 cm of material in the vicinity of the summit. Two fine ash falls from the 1989–90 eruptions of Mount Redoubt (fig. 1; Scott and McGimsey, 1994) would also have left measurable, fine-ash tephra layers on the summit of Mount Spurr. Subsequently, these lapilli and ash deposits were progressively buried in the glacier. Gradual melting and collapse of the glacier to form a meltwater lake would have incorporated this material; additional sediment for entrainment in the debris flows may have come from the crater floor and wallrock.

The generation of debris flows requires a heat source to create and maintain liquid water at the 3,374-m-high summit of Mount Spurr. Long-term observations suggest that transient geothermal heating has occurred in the summit area for decades, including reports from climbers of bare and warm rock along the summit ridge and diffuse, boiling-point fumaroles on the northeast face of the summit and in selected areas around the summit ridge, as described by Turner and Westcott (1986) and Nye (1987). A more recent increase in geothermal output is indicated by exposures of snow-free bedrock along the lakeshore, adjacent areas of (sometimes roiling) open water, and hand-held and helicopter-mounted FLIR measurements of the inner collapse pit that showed areas as hot as 39ºC (D.J. Schneider and R. Wessels, unpub. data, 2005). De Angelis and McNutt (2005) suggested that long-period earthquakes in the recent swarm are caused by the flux of hot gases through fluid-filled cracks, a likely mechanism for the current heat transfer to the summit.

Debris-Flow Formation and Summit Hydrology

Draining of geothermally heated subglacial or ice-cauldron lakes is a common occurrence in Iceland, where much of the active neovolcanic zone is buried by glaciers. The volumes of documented glacial-outburst floods, or jökulhlaups (0.05–5 km^3; Björnsson, 1992), are typically much greater than those of the debris flows observed at Mount Spurr, and occur at the toe of the glacier, although the discharge and flow mechanisms for such jökulhlaups may be similar. Like many of the ice-cauldron lakes in Iceland, the summit lake at Mount Spurr is in a preexisting crater of volcanic origin and formed in response to geothermal heating. This crater became exposed as more and more snow and ice has melted, revealing that much of the lake is walled by rock, not ice.

What triggers a sudden outflow from such subglacial reservoirs? A subglacial or ice-cauldron lake with a perfect ice-rock seal would drain only when the hydrostatic pressure, which is a function of water depth, exceeds the ice-overburden pressure (Nye, 1976). Most of the ice-cauldron lakes that have been studied in Iceland, however, appear to drain at water levels below this critical depth (Björnsson, 1992). In such lakes, cracks in the glacier, or basal channels or permeable layers in the ice or in underlying sediment or bedrock, facilitate the release of water at hydrostatic pressures less than those required to “float” the surrounding ice (Nye, 1976; Fisher, 1973). This is likely true at Mount Spurr as well, although the water depth of the ice-cauldron lake there is unknown.

Because water release typically occurs below this critical depth, other mechanisms must be responsible, such as (1) sudden changes in the discharge or drainage system beneath the ice dam, leading to enlargement of subglacial conduits (Röthlisberger and Lang, 1987); (2) an increase in lake temperature, leading to accelerated growth of conduits (Björnsson, 1992); or (3) a rock-slide displacing water within the lake (Kjartansson, 1967).

The coincidence in time and space of debris flows and formation of an ice cauldron at the summit of Mount Spurr suggests a causal relation. Melting-induced collapse of an ice plug into the lake occurred sometime between June 20 and July 8, 2004, and the first debris flows were emplaced in two pulses sometime between June 20 and July 15. The May 2005 lake-level drop and debris flow have an even more constrained temporal relation, occurring on the same day, probably simultaneously.

One possible mechanism for sudden water release (and resulting debris flows) may have been the collapse of ice and snow into the lake. Such collapse could have caused the water-debris mixture to be displaced rapidly upward and outward along preexisting englacial and, possibly, subglacial pathways leading away and downslope from the summit basin. Where these pathways intersected crevasses or other weak points in the sloping icefield, the mixture debouched onto the surface, producing debris flows. In 2004, the occurrence of two sets of debris flows separated in time by as long as a week suggests two pulses of collapse, each producing a surge of debris and water from the lake (fig. 14). In May 2005, observations indicate that lake-level drop and debris-flow formation were not accompanied by significant ice collapse. This drainage could have instead occurred in response to sudden enlargement of an englacial or subglacial conduit by erosion, heating, or glacier flow.

The ice-cauldron lake at Mount Spurr maintained a fairly constant level—as determined by comparing features on consecutive photographs—during the first 9 months of its

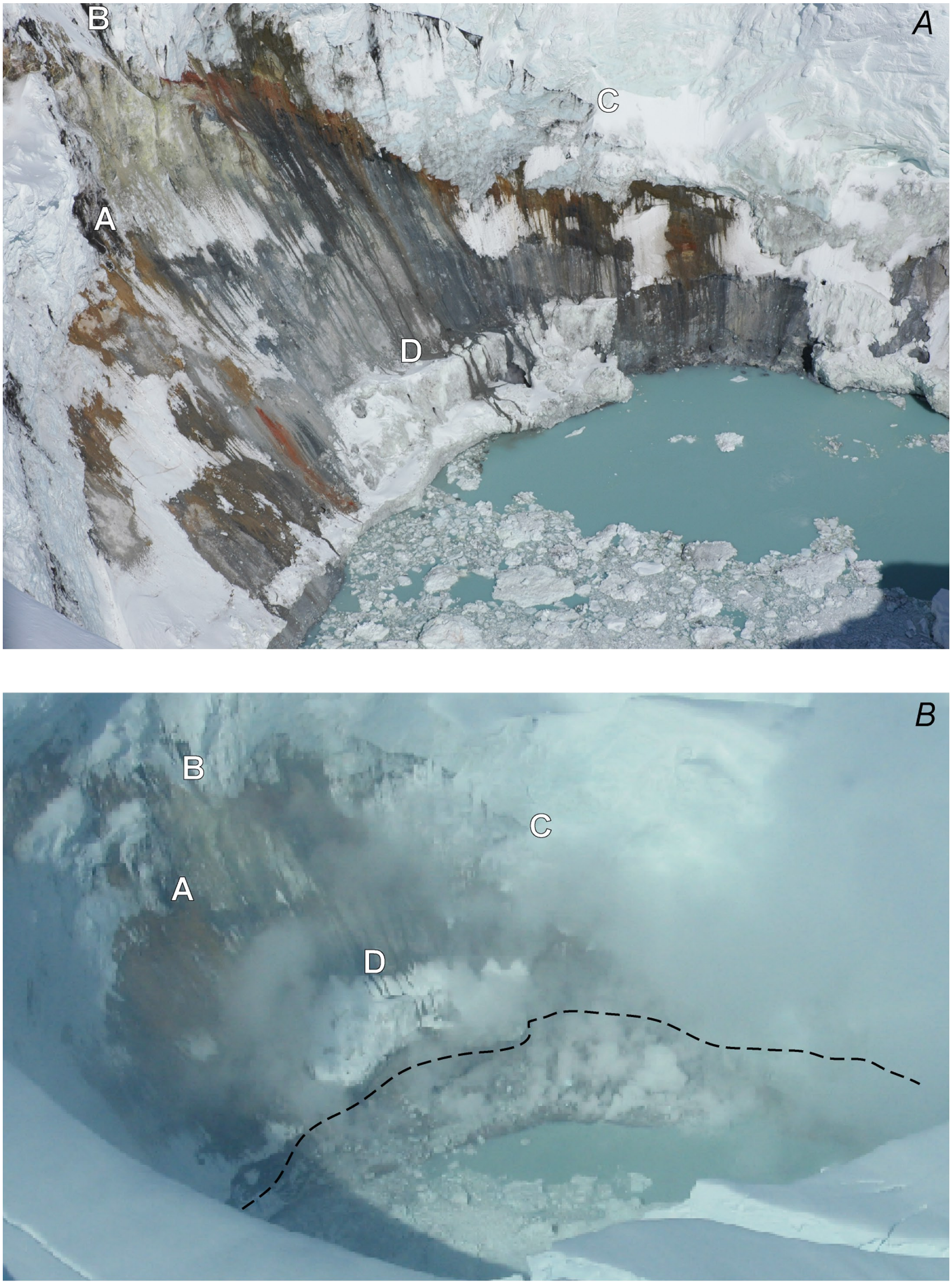


Figure 11. Summit of Mount Spurr, showing ice cauldron before (*A*) and after (*B*) lake-level drop that occurred in early May 2005. A–D, features common to both views. *A*, April 25, 2005. Photograph by Dave Schneider. *B*, May 3, 2005, showing lake-level drop of approximately 15 m, estimated from 90-m overall height of predrainage west wall calculated in September 23, 2004, digital elevation model. Photograph by M.L. Coombs.

most rapid growth. The first major drop in lake level occurred in early May 2005 (discussed above), and a second, smaller drop between January and March 2006. For the period of constant lake level, water must have been exiting at a rate approximately equal to the input by melting collapsed blocks of snow and ice and precipitation. Either water was percolating through a porous crater floor into the edifice, or water was draining over a low point(s) in the enclosing rim and flowing beneath or within the glacier. Constancy of lake level even during times when the influx of snow and ice was reduced, including late 2006 when the cauldron reached its apparent maximum size, argues against steady loss of water through the crater floor. Furthermore, high-temperature alteration of volcanic rock produces clay minerals that are likely to create a relatively impermeable lake floor.

Our preferred interpretation is that lake water exits the crater through a spillway (or multiple spillways) at approximately the same rate as it is being generated. No such spillway is clearly visible despite many good views and aerial photographs of all sections of the lake margin. As the ice cauldron grew to its present and apparently stable size (figs. 8, 9), sheer rockwalls became exposed around much of the lake. As of this writing (April 2006), ice remains in contact with the lake surface in the east quadrant. This quadrant, which coincides with the distribution of debris flows in 2004–5 (fig. 5), is the best candidate for a spillway; it is also the “breached” part of the crater structure that exists at the summit of Mount Spurr (see next section; Turner and Westcott, 1986).

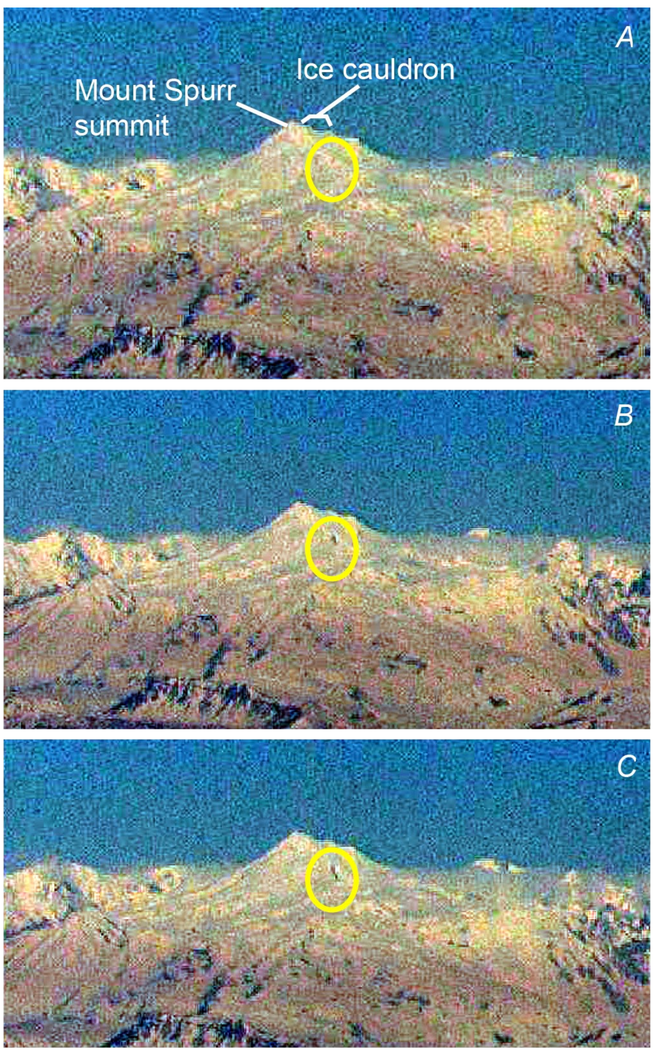


Figure 12. Series of Web camera photographs of Mount Spurr taken May 2, 2005, showing emplacement of new debris-flow deposit (yellow circle) on east flank. Debris flow occurred sometime after 10:57 A.d.t. (*A*) and came to rest by 11:09 A.d.t. *(C)*.

Although AVO aerial observations and photographs have not unequivocally shown that such a spillway exists in the east quadrant, stranded cavernous openings on the east and southeast sides of the growing lake, visible early in ice-cauldron formation, may have reflected drainage pathways during debris-flow emplacement (fig. 6*E*). Photographs taken by climbers on the summit of Mount Spurr on March 22, 2006, show a surface sag in the snow and ice wall over the southeastern part of the lake (fig. 15). A similar sag in a thin tephra layer tens of meters below the lake surface demonstrates that the sagging is not a surface feature but involves a thick layer of the glacier. The sagging may reflect the presence of an outflow channel or englacial tunnel carrying water from the lake out of the summit crater and down the east-southeast flank. Outside the ice cauldron in this quadrant are several long-lived steaming holes in the ice (fig. 5); it is unknown whether these holes reflect buried fumarolic sources or, possibly, trace the path of warm water exiting the lake. The glacier that covers the east side of the summit cone plunges steeply (20–45°) and is heavily crevassed.

An ice-mantled bedrock ridge extends about 750 m northeastward from the summit and terminates in several exposures of permanently warm and largely snow free bedrock, the largest of which, the northeast face, has long been described as an area of diffuse boiling-point fumaroles (Turner and Wescott, 1986). During the initial formation of the ice cauldron, the ice mantling this ridge became bounded on its southern margin by a linear crevasse that formed as ice draining the southeast sector of the summit crater subsided (figs. 5, 6*C*). At least temporary englacial tunnels or pathways must have existed atop this ridge in 2004, on the basis of the appearance of debris flows lower on the northeast face. A line of pits and openings in the ice may trace the path of such a drainage pathway to the upslope edge of the northeast face (fig. 5). A second broad bedrock ridge with scattered thermal features extends about 700 m east-southeastward from the summit of the volcano; vapor plumes, never more than a few tens of meters high, emanate from areas of bare ground and crevasses. A steep rockface on the south-southeast flank of the summit area was determined by FLIR images on April 14, 2006, to be warmer than expected from solar heating alone, suggesting some geothermal component. Still other areas of steaming ground and warm rock occur along an escarpment that separates the broad bedrock ridge from glacial ice draining the east flank of the summit cone.

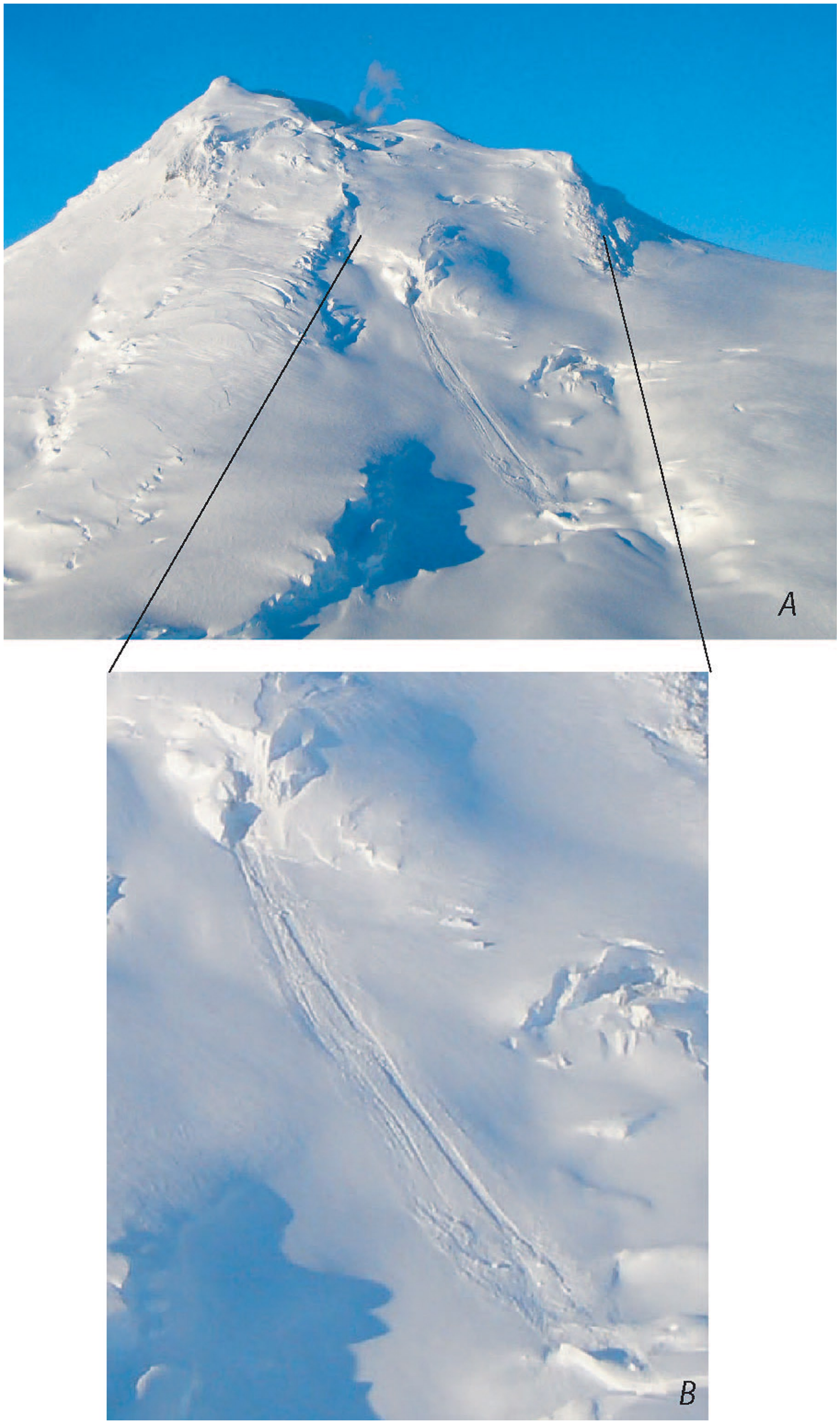


Figure 13. Southeast face of summit cone on Mount Spurr in November 2005. *A*, Rilling and avalanching of snow from ice cliff at approximately 9,300-ft elevation that was outlet point for May 2005 debris flow. *B*, Closeup of area of rilling and avalanching. Photographs by Diana Maroney.

Other Examples of Geothermal Heating, Glacial Response, and Release of Crater-Lake Water

Other examples of sudden release of a large volume of crater-lake water are not limited to Iceland. Sudden breaches of volcanic lakes, not associated with eruptions, have led to the formation of lahars at Mount Ruapehu, New Zealand, in 1953 and at Agua Volcano, Guatemala, in 1541 (Delmelle and Bernard, 2000).

Recurring debris avalanches and manifestations of increasing geothermal activity at Mount Baker in Washington provide a particularly good analogy for several aspects of the 2004–6 volcanic unrest at Mount Spurr (Frank and others, 1975; Frank and others, 1977). Ice-filled Sherman Crater near the summit of Mount Baker is similar in size to the summit crater of Mount Spurr and has also been the site of long-term fumarolic activity. In March 1975, an increase in thermal output produced a series of new and enlarged depressions and other disruption of the ice, including a 50- by 70-m collapse pit enclosing a small lake (Frank and others, 1977, fig. 10). Fumaroles were active on the lakeshore, and as many as five circular zones of upwelling, similar to those at Mount Spurr, were observed.

No debris-flow outbursts were recorded during the ~1-year-long episode of increased heating and melting of the summit ice at Mount Baker; however, unlike at Mount Spurr, a well-formed spillway of meltwater beneath Boulder Glacier was able to accommodate the increased melting and discharge freely. Interestingly, a distinctive water-chemistry anomaly was detectable in Boulder Creek several kilometers downstream from Sherman Crater (Frank and others, 1977), suggesting that if the summit lake at Mount Spurr is, indeed, losing water to a specific drainage, it might be documentable through systematic water sampling.

A prolonged period of increasing volcanic heat flux resulted in ice-cauldron formation, the loss of >40 million m^3 of ice, and ephemeral bodies of standing water in the summit caldera of Mount Wrangell, Alaska, in the 1960s and 1970s (Benson and Motyka, 1978; Motyka, 1983). Also interpreted as the result of degassing of a shallow magma body, the Mount Wrangell geothermal event was not associated with any known outbursts of water or debris.

An additional analog appeared in Alaska less than a year after the onset of volcanic unrest at Mount Spurr. In early summer 2005, a much larger (400-m diam) ice cauldron formed at Chiginagak Volcano on the Alaska Peninsula. Ice-cauldron formation was accompanied by rapid release of an acidic sediment-water mixture that exited beneath and within the glacier, partially draining the summit crater, although the relative timing of events is poorly constrained (fig. 16; Schaefer and others, 2005). The formation of a temporary, steaming circular depression in the icefield on Snowy Volcano, Alaska (Neal and others, 2004), without subsequent collapse and exposure of standing water may represent a less well developed, geothermally induced subsidence feature.

Farfield Effects of Lake Drainage

The effect of the 2004–5 debris flows on the icefield of Mount Spurr remains uncertain but likely was minor. Some sediment and much of the water must have eventually drained into openings in the glacial ice and the englacial plumbing

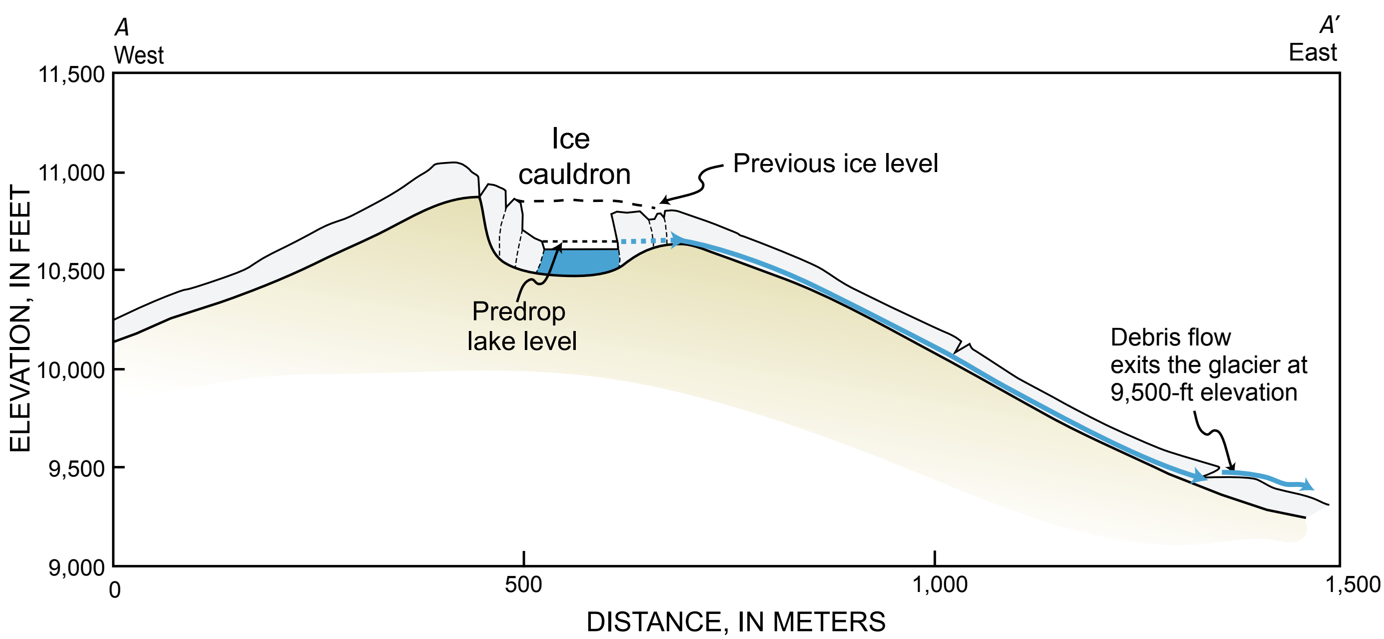


Figure 14. Cross section *A–A′* (fig. 5) of summit of Mount Spurr. Surface elevation of ice (snow) and lake level are calculated from digital elevation model of September 23, 2004; bedrock surfaces are inferred from estimated thickness of ice.

system. Glacial-drainage maps by March and others (1997) indicate that Kidazgeni Glacier (fig. 2) is the most likely part of the Mount Spurr icefield to have absorbed runoff from the 2004–5 debris flows. Aerial observations and photographs of the glacier in summer 2004, however, revealed no obvious surface effects, such as sagging over tunnels or point sources of clearly anomalous water discharge. The limited extent of individual debris flows suggests that the volume of liquid water was quite small and may have been accommodated without significant modification of the icemass. March and others (1997) reported a 1981 ice thickness of >150 m near the toe of Kidazgeni Glacier; small, deeply buried tunnels may not be sufficiently voluminous to perturb the surface.

In addition, we have no direct evidence of abnormal outflow at the snout of Kidazgeni Glacier (fig. 2). Aerial photographs taken in early March 2005 and again in early April 2006, however, showed water exiting the front of the glacier at a much higher rate than at adjacent glaciers draining the Tordrillo Range (fig. 17). The outflow stream was open bank to bank, unlike other glacial outlets nearby, with the single exception of the Crater Creek drainage, which is partly fed by warm springs on the slope of Crater Peak. Because we have no data on glacial stream discharge or composition at Mount Spurr, we cannot state with certainty whether these observations are significant. In April 2006, a single water sample collected from the outflow stream of Kidazgeni Glacier just above the confluence with the Chakachatna River (fig. 2) showed high conductivity and anion concentrations suggestive of geothermal input (W.C. Evans, written commun., 2006). Frank and others (1977) documented a clear change in downstream water chemistry after the increase in subglacial fumarolic activity at Mount Baker in 1975 (Bortleson and others, 1976). By analogy, further sampling of water discharging from glaciers draining the summit of Mount Spurr is warranted.

New Insights into the Geology of the Summit Revealed by Ice-Cauldron Formation

The 2004–5 events at Mount Spurr more clearly exposed the structure of the summit. Though briefly noted by previous workers (Turner and Wescott, 1986; March and others, 1997) and retrospectively quite clear in mid-20th-century aerial photographs, the size and significance of this feature was not well known before the present volcanic unrest.

Aerial photographs of gradually increasing exposure of the crater walls show multicolored, altered rockfaces with steep, gray talus ramps descending to the lake edge on the south, west, and north. Conspicuous, steeply dipping, red oxidized horizons are complexly interbedded with pale-yellow-gray, hydrothermally altered zones (fig. 10). Cavernous, steaming openings in gray, clastic-appearing material on the northeast lakeshore suggest sites of long-term fumarolic discharge. Without the benefit of samples or closer examination, we cannot say with certainty much about the details of exposed outcrops; however, their overall appearance suggests that the walls are largely composed of volcanic breccia and lava-flow or dome rock that has been pervasively altered. The steep, fairly regular north, west, and south crater walls are reminiscent of Crater Peak, and so we suggest that the summit of Mount Spurr most likely represents a young, explosively reamed vent structure, little modified by ice.

Over the course of the current volcanic unrest, new thermal features—defined as zones of visible vapor production, anomalous bare ground, and, in some places, visible sulfur precipitate—have appeared in the summit area of Mount Spurr. The approximate distribution of these newly recognized thermal areas, added to those known from previous decades of observation but never mapped, defines several structures (fig. 5) of potential significance to our understanding of the summit area.

Exposed fumaroles and steaming bedrock at the summit partly outline the 200- by 300-m-diameter crater now well exposed by the ice cauldron. This crater is at least 160 m deep as measured from the true summit to the surface of the lake. As described by earlier workers, the crater rim appears to be much lower on the east and may be poorly defined or absent in the east-southeast sector. A glacier filling the crater flows eastward into the icefield filling the caldera of the Spurr volcanic complex, feeding the east branch of Kidazgeni Glacier (fig. 2).

Earlier Geothermal-Heating Events and Fumarolic Activity at Mount Spurr

How unusual is the formation of an ice cauldron at the summit of Mount Spurr? To our knowledge, this is the first ice cauldron containing open water at the summit, at least since written records of volcanic activity in Alaska (mid-1700s) and certainly since regular overflights began in the mid-1900s, as well as the first known occurrence of debris flows from the summit. Historical reports and photographs, however, document significant variation in the snow and ice cover at the summit that at times has been low enough to expose a basin or breached-crater structure (Turner and Westcott, 1986; Nye, 1987) in the same area as the current ice cauldron. When snow and ice volume is low, such as in aerial photographs taken in 1954, 1957, and 1964, a distinct arcuate wall enclosing an ice-filled basin becomes visible (fig. 18), which was described by March and others (1997) as an ~200- to 300-m-diameter feature open to the east-northeast. Aerial photographs show a hole in the icecap near the base of the north crater wall. The crater wall itself is devoid of snow and ice, suggesting warmth. Although no open water is visible, the 1957 aerial photograph shows several dark patches that could represent warm or exposed bedrock. Photographs from the USGS High Altitude False Infrared Series, taken throughout the 1980s and 1990s and as recently as spring 2004 (figs. 6*A*, 6*B*), show a summit crater that is more subdued and difficult to discern, but no hole or perforation in the ice, possibly owing to greater net ice and snow accumulation during this period.

Summit ice thickness can be influenced by several factors, including variations in heat flux, ice mobility, snowfall,

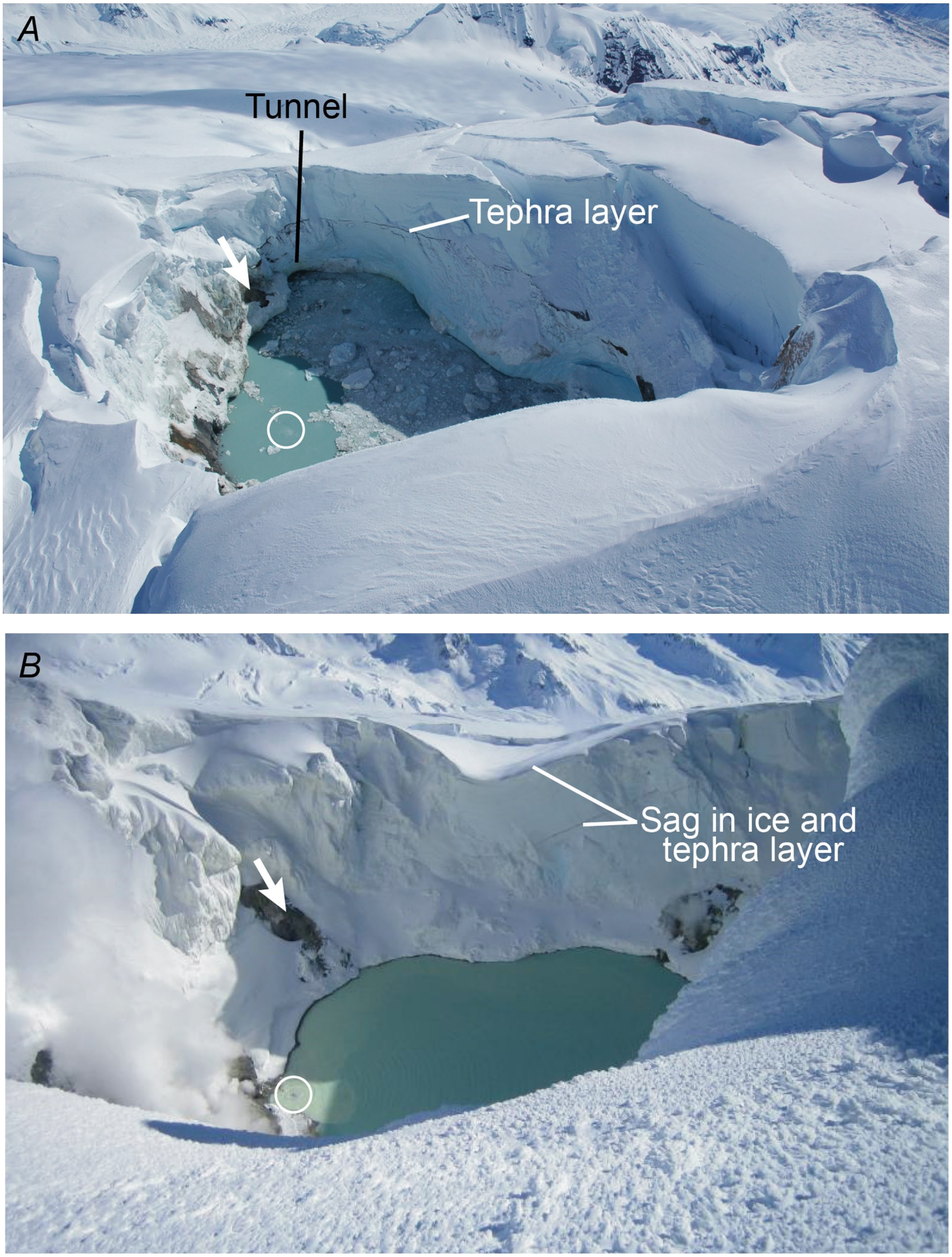


Figure 15. Formation of ice cauldron at summit of Mount Spurr between 2005 and 2006. Arrows denote bare, warm rockface; circles identify area of active upwelling in lake. *A*, April 25, 2005. Note tunnel that may lead to drainage along rock-ice interface, as well as near-horizontal tephra layer within ice. View southeastward; photograph by Dave Schneider. *B*, March 22, 2006. Note faint, deformed tephra horizon in icewall across lake; sag may reflect subsidence of surface ice over a drainage pathway beneath ice. Lower lake level is shown by position of upwelling zone relative to lakeshore. View southeastward; photograph by Nathan Bluett.

Figure 16. Summit of Chiginagak Volcano on the Alaska Peninsula. Sometime between two photographs, increased geothermal heating led to formation of a crater lake that drained and sent acidic lahars and floods downstream (Schaefer and others, 2005). *A*, August 24, 2004. *B*, August 20, 2005. Photographs by Janet Schaefer, Alaska Division of Geological and Geophysical Surveys.

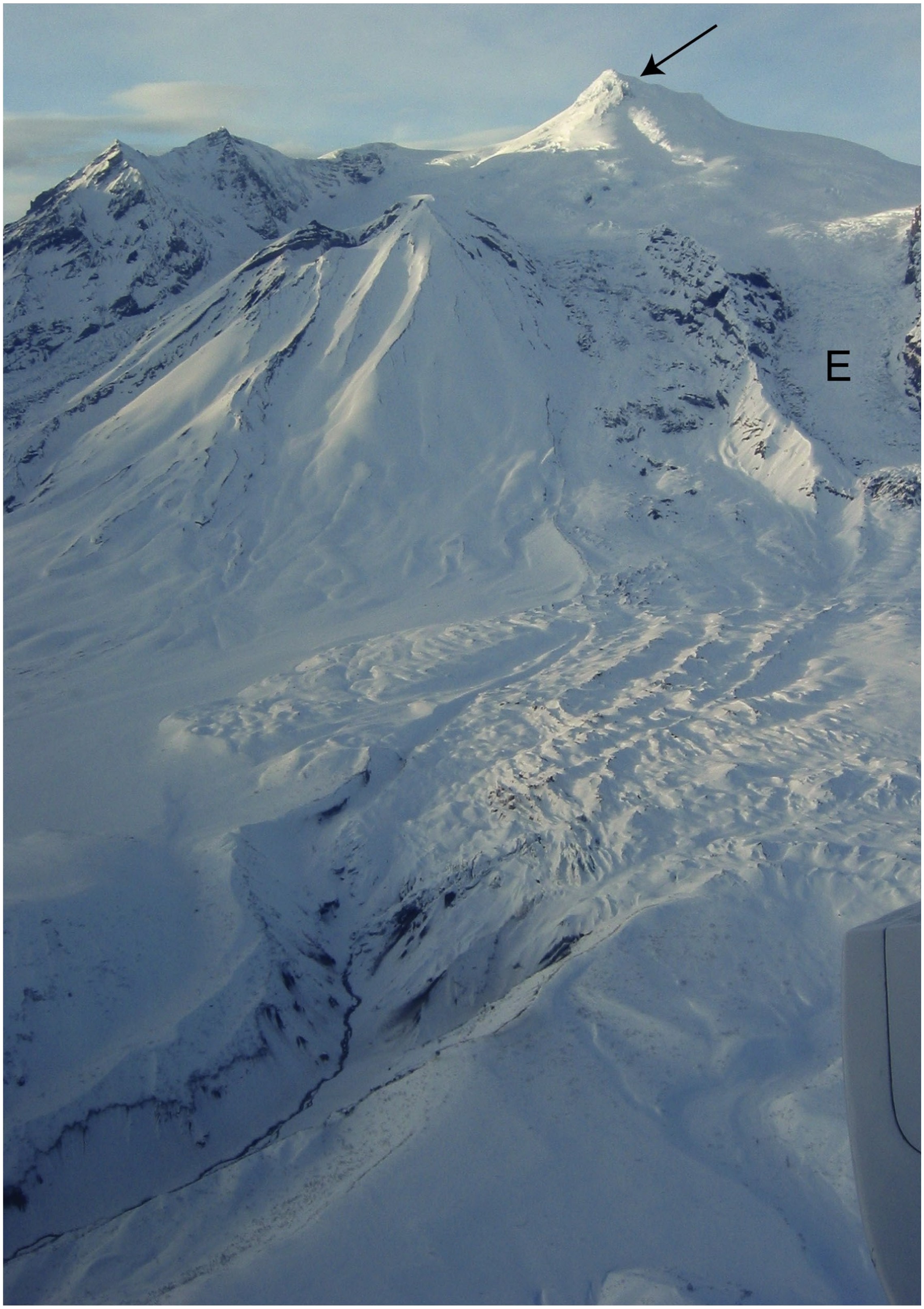


Figure 17. Termini of Kidazgeni Glacier, which descends in two arms from ice field of the Spurr volcanic complex. East arm (E) drains east flank of summit of Mount Spurr (arrow; March and others, 1997). Discharge from glacial outlet (lower left) at time of photograph (March 2005) appeared to be more vigorous and open than that from other glacial-outlet streams then and again in April 2006. Photograph by C. A. Neal, taken March 2, 2005.

snowdrift, and ice accumulation as a function of climatic conditions. Few long-term measurements of glacial mass balance in south-central Alaska are available to evaluate climatic control on ice volume. Data from Wolverine Glacier, 200 km southeast of Mount Spurr on the Kenai Peninsula (Mayo and others, 2004), suggest a decline in glacial mass in 1965–76 (a period of distinct summit-crater morphology at Mount Spurr) that may be a reasonable analog to the Spurr glacial system. This decline was followed by a net ice accumulation through 1988 (see URL http://ak.water.usgs.gov/glaciology/all_bmg/3glacier_balance.htm). After 1988, data for Wolverine Glacier suggest a net mass loss that continues to the present, consistent with glacial wastage throughout Alaska (Arendt and others, 2002). These trends are largely consistent with climatic shifts documented for the North Pacific Ocean in 1977 and 1989 (Hare and others, 2000), suggesting that these trends may be widespread across southern Alaska. Such shifts may have influenced the "disappearance and reappearance" of the summit crater at Mount Spurr during the late 20th century and into the current cycle of ice-cauldron formation. Further analysis of meteorologic and hydrologic records is required to fully evaluate climatic effects on the Mount Spurr icefield. Nonetheless, the 2004–5 events demonstrate that heat (and gas) flux can play a role in snow and ice thickness at the summit of Mount Spurr and lead to the formation of transient melt and collapse features.

Geothermal activity at Mount Spurr has been intermittently robust enough to produce visible steam plumes since at least the early 20th century. Capps (1935) noted "* * * the highest peak of the mountain, from vents near the top of which

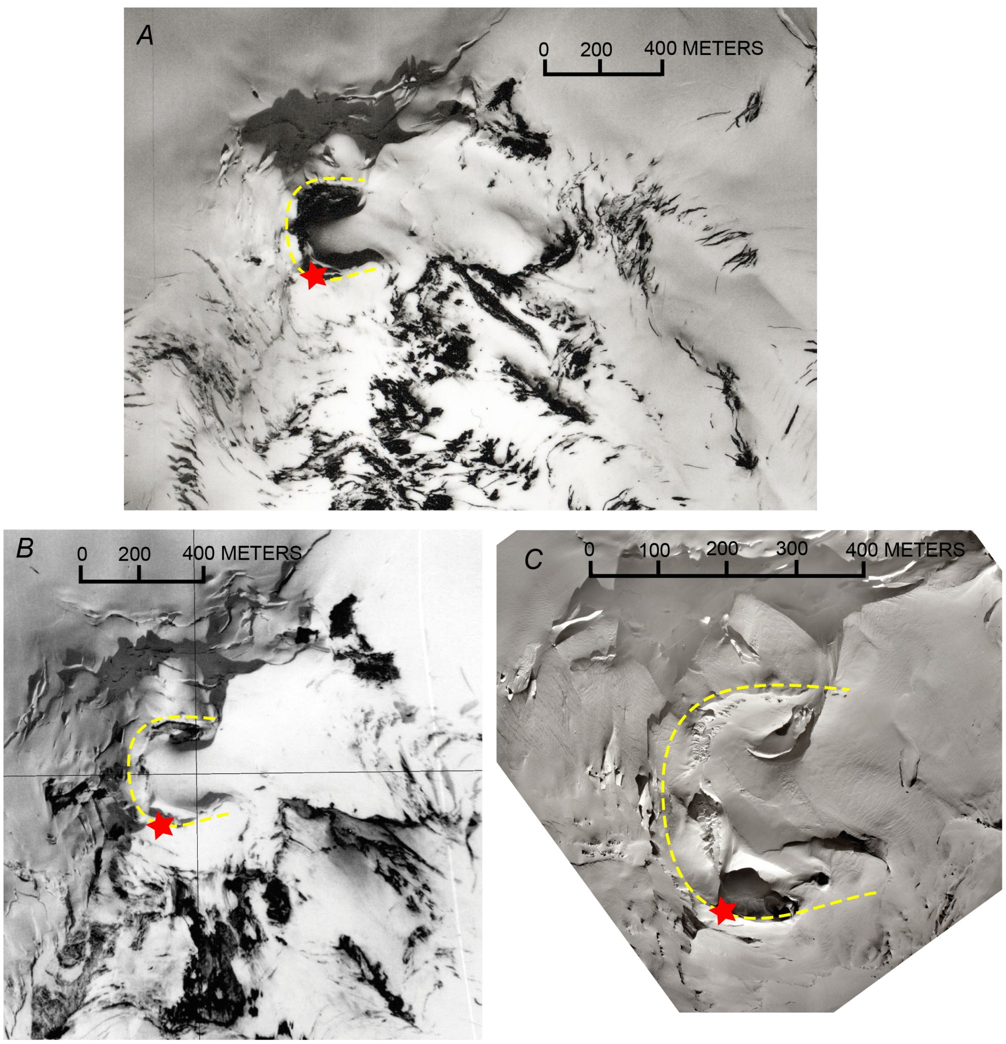


Figure 18. Pre-2004 summit of Mount Spurr. Yellow dashed lines mark approximate position of summit-crater rim; star marks topographic summit. North is at top in all photographs. *A*, August 29, 1954. U.S. Geological Survey EROS Data Center's Mission M4H55, frame 104, roll 1. *B*, August 7, 1957. U.S. Geological Survey EROS Data Center's Mission M–237, frame 10115, roll 76. *C*, August 25, 1964. University of Alaska, Fairbanks, Geophysical Institute, Geodata Center's North American Glacier Photography, Ice, and Climate Project, roll V644, exposure 199, altitude 13,000 ft. Aerial photograph by Austin Post.

steam sometimes still issues." Juehle and Coulter (1955) stated, "During the past three decades, a vapor plume has issued from the summit of Mt. Spurr at irregular intervals."

Pilots reported an increasing discharge of steam from the summit of Mount Spurr during late spring 1953, just weeks before the July 1953 eruption of Crater Peak. The original report, which appeared in the Fairbanks *News-Miner* (May 21, 1953, p. 9), further describes steam emerging from a "fissure 300 ft beneath the peak on the northeast, or Anchorage, side." The pilot described the steaming source as "a big chimney" with "smoke [sic] coming out under pressure," and mentioned that he had been smelling sulfur for the past week. In 1960, climbers on the first successful ascent of Mount Spurr reported "interesting crystal formations" that they surmised to have resulted from sulfurous ("lemon-yellow") steam escaping from numerous vents (Wilson and others, 1999).

Two newspaper articles (Anchorage *Daily Times*, Feb. 2, 1965, p. 1, 9; Fairbanks *Daily News-Miner*, 1965, v. 43, no. 28, p. 9) describe steam discharge from Mount Spurr; however, it is unclear whether the source was Mount Spurr or Crater Peak. The second ascent party of Mount Spurr in June 1969 again described fumaroles on the summit cone, but subsequent accounts by climbers through 1978 reported no fumarolic activity. Climbers in 1983 reported several crevasses near the summit venting sulfurous gases (Wilson and others, 1999).

A photograph of the summit of Mount Spurr by Tom Miller of AVO in fall 1972 shows a small vapor plume above the summit basin. Boiling-point fumaroles that occasionally produce vapor plumes were reported on exposed bedrock (the northeast face) at the 2,925- to 3,050-m level on the east face of the summit peak (Turner and Westcott, 1986). Nye (1987) observed, but did not visit, fumaroles on the south and southwest flanks of the summit. AVO field crews conducting a gas-measurement flight in 1993 spotted a possible vapor source on a rib of exposed rock on the south flank of the summit. Climbers in 1997 reported no fumarolic activity or sulfur smell near the summit (Dale Letourneay, written commun., 2004). We note that the local Dena'ina Indian name for Mount Spurr, *K'idazq'eni*, means "one that is burning inside," suggesting that plumes related to thermal output at the summit had been visible for some time before the mid-1700s and the onset of written documentation in Alaska (Wilson and others, 1999, p. 28).

Systematic gas-measurement flights and aerial observations of the summit were not conducted before 2004, largely owing to its assumed level of inactivity and absence of geologic evidence for late Holocene eruptions. March and others (1997) mentioned the summit crater and possible outburst floods from water impounded in this crater and their potential impact on Kidazgeni Glacier and, ultimately, the Chakachatna River (fig. 2).

Conclusions

The 2004–present ice cauldron at the summit of Mount Spurr reflects a prolonged period of increased magmatic-gas and heat flux from an intracaldera vent that is believed not to have erupted during the past ~5 k.y. Melting and collapse of snow and ice has exposed a breached crater open to the east. Exposed bedrock appears to be a combination of hydrothermally altered rock and bedded pyroclastic deposits, suggesting that the summit of the volcano is an explosive vent feature atop a glaciated dome complex. Should elevated geothermal activity continue in the summit area, increasing exposure of the summit bedrock will allow a more complete interpretation of the characteristics and origin of this structure.

Formation of an ice cauldron in response to increasing volcanic heat flux at Mount Spurr, though not unique, is the first such feature of which we are aware in Alaska to be associated with debris flows. The formation of a similar feature at Chiginagak Volcano in summer 2005 (Schaefer and others, 2005), with an outburst of acidic waters, underscores this process as a potentially hazardous consequence of any volcano capable of sustaining a lake over an active geothermal area. Numerous other iceclad volcanoes in Alaska retain the potential for geothermal melting of significant volumes of ice, formation of meltwater lakes, and periodic debris flows.

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Appendix: Volcano Monitoring

Increasing seismicity, in combination with observations of debris flows from the summit, prompted concern about accelerating volcanic unrest at Mount Spurr. On July 26, 2004, AVO elevated the Level of Concern color code to yellow (the first degree of elevated concern above green, or background), and maintained it through the end of 2005. Nearly all weekly summaries and daily status reports emphasized that despite the departure from background activity at Mount Spurr, there were no signs of imminent eruptive activity. On October 8, 2004, AVO announced the public availability of Web camera images of Mount Spurr on the AVO Web site (URL http://www.avo.alaska.edu/). The Web camera rapidly became a popular public page and an important monitoring tool for AVO.

AVO issued three Information Releases on Mount Spurr activity in 2004 and 2005, in addition to summarizing the situation there in standard weekly updates on all Alaskan volcanoes. In March 2005, as the Alaska Range climbing season began, AVO distributed a special information release discussing specific hazards in the immediate vicinity of the summit, a popular climbing target for mountaineers. Several articles appeared in the Anchorage *Daily News* (July 28, 2004, p. A1; Aug. 8, 2004, p. B3). In response to the yellow Level of Concern color-code declaration, the National Weather Service issued a one-time Volcanic Ash Advisory (VAA), and the Federal Aviation Administration (FAA) issued a Notice to Airmen (NOTAM) on July 26, 2004, that was canceled on November 9, 2004 (NOTAM 4/2284; B. Brown, FAA, written commun., 2005). After more than a year of slowly declining seismicity and gas emissions, AVO downgraded the Level of Concern color code for Mount Spurr to green on February 21, 2006.

AVO Information Releases

Monday, July 26, 2004 12:05 PM ADT (2005 UTC)
MOUNT SPURR VOLCANO (CAVW#1103–04)
61°18′ N 152°15′ W, Summit Elevation 11,070 ft (3,374 m)
Previous Level of Concern Color Code: Green
Current Level of Concern Color Code: YELLOW

AVO has identified an increase in earthquake activity beneath the summit of Mount Spurr volcano located about 130 km (80 mi) west of Anchorage. Some of these earthquakes can be interpreted to reflect the beginning stages of volcanic unrest. Because this is a notable departure from the normal background seismicity of the volcano, AVO is raising the level of concern color code to YELLOW. However, there are no indications that an eruption is imminent. Often this type of seismicity will decline without producing an eruption.

Retrospective analysis suggests that the current increase began slowly, perhaps as early as February 2004. At present, AVO is locating 15–20 earthquakes below the volcano each day. This is a rate greater than any observed since the last eruptive period in 1992. All earthquakes are less than magnitude 1.5 and range in depth between 1 and 6 km (0.6 and 4 miles) below sea level. To date, relatively few earthquakes have been located beneath the Crater Peak vent, the site of the 1953 and 1992 eruptions. The current earthquake activity differs markedly from that seen prior to the1992 eruption, which started with a small cluster of earthquakes directly beneath Crater Peak nearly a year before the eruption began.

AVO geologists visited Spurr by fixed-wing aircraft on July 15 and observed no indications of recent volcanic activity. On July 11, a pilot flying by the volcano reported a sulfur smell and new area of steaming, but neither was noted during the AVO flight, although a significant portion of the Crater Peak area was obscured by low clouds. AVO geologists did document several fresh-looking, dark debris flow/avalanche deposits on the southeast and south face of the summit dome complex suggesting water flow at the surface, but this may simply reflect recent unseasonably warm and sunny conditions.

AVO will continue to monitor activity at Mount Spurr closely using seismic data, satellite images, and overflights, and will issue further information releases as appropriate.

Spurr volcano is an ice- and snow-covered stratovolcano located on the west side of Cook Inlet. The only historical eruptions in 1953 and 1992 occurred at the Crater Peak flank vent located 3.5 km (2 mi) south of the Spurr summit. These eruptions were explosive, brief in duration, and produced towering columns of ash that rose up to 20 km (65,000 ft) above sea level and deposited several mm of ash on populated areas of south-central Alaska, including approximately 6 mm of ash in Anchorage in 1953. The summit dome complex of Mount Spurr is largely covered in ice; its last known eruption was approximately 5,000 years ago. Primary hazards from future eruptions at Mount Spurr and Crater Peak include far-traveled ash clouds, ash fall, pyroclastic flows, and lahars or mudflows that could impact drainages primarily on the south and east sides of the volcano.

Tuesday, August 3, 2004 2:00 PM ADT (2200 UTC)
MOUNT SPURR VOLCANO (CAVW#1103–04)
61°18′ N 152°15′ W, Summit Elevation 11,070 ft (3,374 m)
Current Level of Concern Color Code: YELLOW

An overflight of Mount Spurr by AVO scientists yesterday afternoon revealed a circular depression in the icecap just northeast of the summit. The depression is approximately 50 meters (165 feet) in diameter and about 25 meters (82 feet) deep. The floor of the depression contains an icy pond, with small areas of open water. No steam or volcanic emissions were observed. Depressions of this sort may have existed on Spurr before, but AVO is not aware of any in recent decades. The depression may have formed by heat from the volcano melting the ice, or, the release of stored water which might account for the minor mudflows observed several weeks ago on the upper flanks. If due to heat, it is not known if the flow of heat to the surface has increased and is related to the recent increase in earthquake activity.

There is no evidence or suggestion of any explosive activity; no fresh ash was observed anywhere on the mountain. Crater Peak, the vent responsible for the eruptions in 1953 and in the early 1990s, showed no sign of any unusual activity.

Earthquake activity continues beneath Mt. Spurr with no significant change over the past week.

Based on these observations and our continuing seismic monitoring of the volcano, there are no signs that an eruption is imminent or even certain. Ephemeral summit craters have been described before at Mt. Spurr and temporary increases in earthquake activity below a volcano often decline without producing an eruption. AVO will continue to monitor activity at Mount Spurr closely using seismic data, satellite images, and overflights, and will issue further information releases as appropriate.

Spurr volcano is an ice- and snow-covered stratovolcano located on the west side of Cook Inlet. The only historical eruptions in 1953 and 1992 occurred at the Crater Peak flank vent located 3.5 km (2 mi) south of the Spurr summit. These eruptions were explosive, brief in duration, and produced towering columns of ash that rose up to 20 km (65,000 ft) above sea level and deposited several mm of ash on populated areas of south-central Alaska, including approximately 6 mm of ash in Anchorage in 1953. The summit dome complex of Mount Spurr is largely covered in ice; its last known eruption was approximately 5,000 years ago. Primary hazards from future eruptions at Mount Spurr and Crater Peak include far-traveled ash clouds, ash fall, pyroclastic flows, and lahars or mudflows that could impact drainages primarily on the south and east sides of the volcano.

Thursday, August 12, 2004 11:40 AM ADT (1940 UTC)
MOUNT SPURR VOLCANO (CAVW#1103–04)
61°18′ N 152°15′ W, Summit Elevation 11,070 ft (3,374 m)
Current Level of Concern Color Code: YELLOW

AVO received a pilot report at approximately 8:15 AM ADT, today, August 12, 2004, of possible emission of ash from Mt. Spurr volcano. At this time we have no evidence that an eruption has occurred or is in progress. Crater Peak, the vent responsible for the eruptions in 1953 and in the early 1990s, also shows no sign of any unusual activity.

Earthquake activity continues beneath Mt. Spurr with no significant change over the past several weeks.

Based on these observations and our continuing seismic monitoring of the volcano, there are no signs that an eruption is imminent or even certain. Ephemeral summit craters have been described before at Mt. Spurr and temporary increases in earthquake activity below a volcano often decline without producing an eruption. AVO will continue to monitor activity at Mount Spurr closely using seismic data, satellite images, and overflights, and will issue further information releases as appropriate.

Tuesday, February 21, 2006 3:15 PM AKST (015 UTC)
SPURR VOLCANO (CAVW#1103–04)
61°17′58″ N 152°15′4″ W, Summit Elevation 11070 ft (3374 m)
Current Level of Concern Color Code: GREEN
Previous Level of Concern Color Code: YELLOW

The purpose of this Information Release is to summarize the recent period of volcanic unrest at Mt. Spurr Volcano and present AVO's rationale for downgrading the Level of Concern Color Code from Yellow to GREEN.

Summary

AVO identified an increase in earthquake activity beneath the summit of Mount Spurr Volcano beginning in February 2004. The increase marked a notable departure from the normal background seismicity of the volcano, and AVO raised the level of concern color code to YELLOW on July 26, 2004. By this time, the seismicity had increased to a rate greater than that observed since the last eruptive period in 1992. Seismicity remained elevated until about April 5, 2005, declined gradually since about June 25, 2005, and has remained relatively stable since then. The majority of located earthquakes have been smaller than magnitude 1.5 and range in depth between 1 km above and 6 km (0.6 and 4 miles) below sea level. Relatively few earthquakes have been located beneath the Crater Peak vent, the site of the 1953 and 1992 eruptions. In response to the elevated seismicity, AVO geologists first observed Mt. Spurr Volcano by fixed-wing aircraft on July 15, 2004, and observed no indications of obvious volcanic activity, but did observe several fresh-looking, dark debris-flow deposits on the southeast and south face of the summit edifice suggesting water flow at the surface. On August 3, 2004, AVO scientists observed a circular melt depression; about 50 meters (165 feet) in diameter and about 25 meters (82 feet) deep in the snow and ice cover just northeast of the summit of Mt. Spurr. A small ice-rich pond on the floor of the depression also was observed. Since then, the melt depression and pond have increased in size although the volume of water in the depression has fluctuated somewhat. Occasionally a small steam plume has been visible above the depression from Anchorage and by passing pilots. Intermittent observations made from August 2004 through September 2005 chronicled the enlargement of the melt depression, documented areas of warm rock on the floor of the depression and in other areas on the edifice with an infrared camera, and noted at least two additional debris flows. Localized but vigorous roiling within the medium-grey colored lake was observed on numerous occasions and is consistent with emission of hot volcanic gases, whereas the persistent grey color usually indicates high acidity. Intermittent airborne measurements of volcanic gases (CO_2, H_2S, and SO_2) from August 2004 to September 2005 indicated small but distinctly measurable quantities, although by September 2005 gas emissions had declined to low levels. As of the last AVO over flight of Mt. Spurr in January, 2006, the melt depression persists, the lake remains open, but had a distinctly greenish cast.

The declining seismicity, the reduced gas emissions, and the changing summit lake color, all suggest a reduced level of activity at the volcano. Although the overall level of seismicity has remained higher than it was prior to the recent period of unrest, it now appears that this level denotes a new background condition for Mt. Spurr Volcano. Thus, based on available information and an increased level of monitoring of Mt. Spurr, AVO concludes that the current episode of unrest at Mt. Spurr has ended and the likelihood of eruption in the near term has diminished significantly. Thus the level of concern color code for Mt. Spurr is returning to GREEN.

Present Hazards

Although the overall level of unrest at Mt. Spurr Volcano has declined to a new background level, conditions on the mountain could remain hazardous to skiers, snowboarders, mountaineers, pilots (especially those landing near the summit area) and other visitors for some time. It is possible for unstable snow and ice conditions to persist in and around the summit area, especially the steep and unstable walls of the melt pit, and for low-level gas emissions to continue. Thus, visitors to the area may encounter foul-smelling and possibly dangerous levels of volcanic gas that might be impossible to detect from a distance. Occasional felt earthquakes may occur and these could be large enough to disturb steep or unstable areas of ice and snow. Water still impounded in the summit melt depression could be released quickly and without warning and this could lead to hazardous fast-moving floods of debris or water on the upper flanks of the summit.

Additional information about Mt. Spurr hazards can be found on the AVO Web site at http://www.avo.alaska.edu/activity/Spurr.php.

Special Information Release for Climbers and Other Backcountry Users

March 5, 2005
MOUNT SPURR VOLCANO (CAVW#1103–04)
61°18′ N 152°15′ W, Summit Elevation 11,070 ft (3,374 m)
Current Level of Concern Color Code: YELLOW

Continued volcanic unrest at Mount Spurr has led to several conditions on the mountain that could be hazardous to skiers, snowboarders, mountaineers, pilots (especially those landing near the summit area) and other visitors. This information release is intended to provide the public with an inventory of the main volcanic hazards that may exist on Mount Spurr. It should not be taken as an exhaustive list, since some volcanic hazards are inherently unpredictable.

(1) Unstable snow and ice conditions near the summit of Mount Spurr. Higher than normal heat flow at Mt. Spurr's summit has created a large (>100 meters across) melt pit, just below the topographic summit of the mountain. The rim of this melt pit is extremely unstable—we have direct evidence that large pieces of the rim fail and slide into the pit regularly, perhaps several times per day. The high heat flow has also created several additional melt holes and may have increased steam and gas output from pre-existing fumaroles near Spurr's summit. Other melt holes, some likely covered by a thin crust of snow or ice, likely exist.

(2) High concentrations of volcanic gases near the summit of Mt. Spurr and Crater Peak. Both Spurr and the Crater Peak cone, 3 km south of Spurr, are emitting volcanic gases, including carbon dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S). In high concentrations, all of these gases can be lethal. Carbon dioxide is of particular concern since it is heavier than air and ponds in low-lying areas or depressions. Carbon dioxide can also accumulate in the snow pack; snow caves built in CO_2-saturated snow pack can be extremely dangerous, with the gas causing dizziness, headaches, muscular weakness, respiratory distress, and, in high enough concentrations, death (see http://seis.bris.ac.uk/~glcjh/ivhhn/guidelines/gas/co2.html and http://pubs.usgs.gov/fs/fs172-96/).

(3) Potentially unstable snow and ice conditions down slope from Mount Spurr. Because hotter than normal water may be flowing from the summit melt pit, unusual or unseasonable snow and ice conditions may exist within the drainages flowing from the summit. A sudden release of water impounded in the summit melt pit is also possible.

(4) Acidic water. Because of dissolved volcanic gasses, the lake in the summit melt pit is likely acidic, possibly with sufficient strength to burn skin. It is also possible that this acidic water is emerging from as of yet unknown points on the volcano.

(5) Earthquake-caused rock or ice fall. Mt. Spurr is currently experiencing seismicity rates that are much higher than normal. So far, these earthquakes have been too small to cause rock or ice fall, but the potential for larger earthquakes cannot be ruled out. Such earthquakes could add to the background avalanche hazard.

(6) Higher than normal probability of volcanic eruption. Although there are no signs that an eruption is imminent, the current unrest at Mt. Spurr may result in an eruption either from the summit itself or from Crater Peak. Earthquake swarms will almost certainly precede an eruption, but the earthquakes may be too small for people to feel. Even a relatively minor eruption could be extremely dangerous to anyone within several kilometers of the vent. For information about hazards and a description of recent activity, refer to http://www.avo.alaska.edu/avo4/atlas/volc/spurr/spurr2004/index.html or call the Alaska Volcano Observatory.

NOTAM and VAA Texts

Volcanic Ash Advisory issued by the Anchorage VAAC and NOTAM issued by the FAA when AVO declared Level of Concern color code yellow. These formal warning notices to aviation are required as part of the Interagency Operating Plan for Volcanic Ash Episodes in Alaska (National Oceanic and Atmospheric Administration, Federal Aviation Administration, and U.S. Geological Survey, 2004).

VAA Issued by the Anchorage VAAC

Subject: FVAK20 PANC 262116
FVAK20 PANC 262116
VAAAK0
VOLCANIC ASH ADVISORY-WATCH
ISSUED 2004JUL26/2115Z VAAC: ANCHORAGE
VOLCANO: SPURR 1103–04
LOCATION: N6118W15215
AREA: ALASKA
SUMMIT ELEVATION: 11,070 FT (3,374 M)
ADVISORY NUMBER: 2004/01
INFORMATION SOURCE: ALASKA VOLCANO OBSERVATORY
AVIATION COLOR CODE: UPGRADED FROM GREEN TO YELLOW

REMARKS:
AVO HAS IDENTIFIED AN INCREASE IN EARTHQUAKE ACTIVITY BENEATH THE SUMMIT OF MOUNT SPURR VOLCANO LOCATED ABOUT 130 KM (80 MILES) WEST OF ANCHORAGE. THERE ARE NO INDICATIONS THAT AN ERUPTION IS IMMINENT. OFTEN THIS TYPE OF SEISMICITY WILL DECLINE WITHOUT PRODUCING AN ERUPTION. HOWEVER, AN ERUPTION IS STILL POSSIBLE IN THE NEXT FEW WEEKS AND MAY OCCUR WITH LITTLE OR NO WARNING.

NEXT ADVISORY:
NO ADDITIONAL WATCHES WILL BE ISSUED AT THIS TIME.

ERW JUL 04

NOTAM issued by the FAA

FDC 4/7470
A) ZAN
B) WIE
C) UFN

E) AK. SEISMIC ACTIVITY ADVISORY FOR MOUNT SPURR VOLCANO AK. /6118N15215W/. ALASKA VOLCANO OBSERVATORY HAS REPORTED INCREASED SEISMIC ACTIVITY IN THE VICINITY OF MOUNT SPURR VOLCANO, WHICH INDICATES THE POSSIBILITY OF A VOLCANIC ERUPTION. AIRCRAFT SHOULD REMAIN ALERT FOR POSSIBLE ERUPTIONS, STEAM OR ASH CLOUDS AND REPORT ANY SIGHTINGS TO ATC IMMEDIATELY. CONTACT ANCHORAGE ARTCC 907–269–1103 FOR ADDITIONAL INFORMATION.