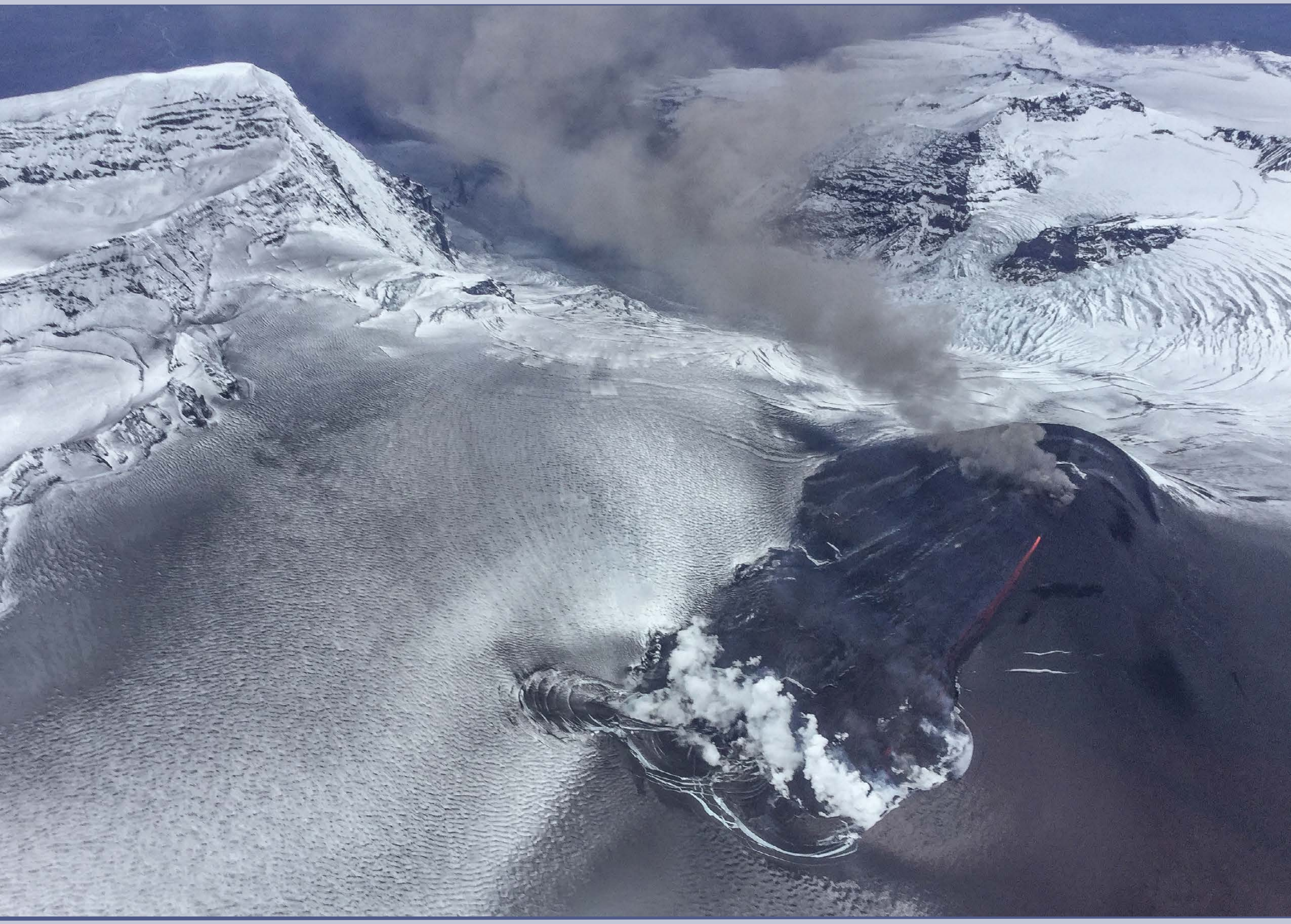
The 2018 Eruption of Mount Veniaminof, Alaska



Scientific Investigations Report 2022–5075

U.S. Department of the Interior
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Cover: Oblique aerial photograph looking north toward cone A at Mount Veniaminof showing small lava flow on southwest flank of cone and minor ash emissions occurring from cone summit. Note ice-melt depressions at base of cone caused by subaerial lava effusion. Composite width of the melt depressions is about 700 meters. Photograph by M. Laker, U.S. Fish and Wildlife Service, September 26, 2018.

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By Christopher F. Waythomas, Hannah R. Dietterich, Gabrielle M. Tepp, Taryn M. Lopez, and Matthew W. Loewen

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
kilogram per second (kg/s)	2.205	pound avoirdupois per second (lb/s)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1929 (NAVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

AIRS	Atmospheric Infrared Sounder
AKDT	Alaska daylight time
AKST	Alaska standard time
AVHRR	Advanced Very High Resolution Radiometer
AVO	Alaska Volcano Observatory
IASI	Infrared Atmospheric Sounding Interferometer
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
RSAM	real-time seismic amplitude
TROPOMI	TROPOspheric Monitoring Instrument
UTC	coordinated universal time
VEI	Volcanic Explosivity Index
VIIRS	Visible Infrared Imaging Radiometer Suite

The 2018 Eruption of Mount Veniaminof, Alaska

By Christopher F. Waythomas,[1] Hannah R. Dietterich,[1] Gabrielle M. Tepp,[1] Taryn M. Lopez,[2] and Matthew Loewen[1]

Abstract

The 2018 eruption of Mount Veniaminof occurred from September 3–4 to December 27, lasting about 114 days. This report summarizes the types of volcanic unrest that accompanied the eruption and provides a chronology of events and observations. Information about the 2018 eruption was derived from geophysical instrumentation on or near the volcano that included an eight-station seismic network and regional infrasound sensors. Other observations came from frequent satellite images of the eruption, occasional aerial photographs and videos contributed by passing pilots, and web-camera views of the volcano from Perryville, Alaska, about 35 kilometers (km) south of the volcano. Eruptive activity involved small vents on the upper south flank of a cinder cone (cone A) within the ice-filled caldera that characterizes Mount Veniaminof. The 2018 eruption consisted of occasional explosive emissions of ash and gas (reaching up to 6,000 meters above sea level), episodes of low-level lava fountaining, Strombolian explosive activity, and effusion of lava flows. By the end of the eruption, lava covered an area of about 600,000 square meters (m^2) on the lower south flank of cone A. The lava flows melted into ice and snow, slowly creating melt depressions around the flow margins. No unusual outflows of water were observed exiting the caldera through the main drainage northwest of the cone. Minor ash emissions were generated throughout the eruptive period, and trace amounts of ash fell on Perryville on October 25 and November 21–22. There were no reports of aircraft encounters with ash clouds. The amount of lava and ash erupted from early September to late December 2018 resulted in the generation of about 1,200,000 cubic meters (m^3) of lava and 20,000–30,000 m^3 of ash, which would characterize the 2018 activity as having an eruption magnitude of 1–2 on the Volcanic Explosivity Index (VEI) scale.

Introduction

The purpose of this report is to describe and synthesize the volcanic activity that occurred during the 2018 eruption of Mount Veniaminof, Alaska. The eruption source was a cinder cone (informally named cone A) within the ice-filled caldera that characterizes the volcano (fig. 1). The 2018 eruption lasted about 114 days from September 3–4 to December 27, when observations and seismic data indicated the eruption had ended. The eruption resulted in the generation of about 1,200,000 cubic meters (m^3) of lava and 20,000–30,000 m^3 of ash.

Mount Veniaminof is a dacite to basaltic-andesite stratovolcano about 350 cubic kilometers (km^3) in volume, located on the Alaska Peninsula (56.2° N., 159.4° W.) (fig. 1). The volcano is characterized by an 8-by-10-km diameter ice-filled summit caldera (highest point on caldera rim is 2,507 meters [m] above sea level) that formed and was subsequently enlarged during three significant eruptions in the late Pleistocene to Holocene (Miller and others, 2002). Because of its breadth and summit height, Mount Veniaminof supports an extensive cover of glacier ice, about 273 square kilometers (km^2), and an even greater amount of ice covered the volcano during times of Pleistocene glacial maxima (Detterman and others, 1981). The flanks of the volcano are deeply incised by glacial erosion and numerous glaciated valleys with nearly vertical walls, except for parts of the south flank where a broad lobe of ice drapes over a morphologically subdued caldera rim (fig. 1).

Mount Veniaminof is one of the largest and most active volcanoes in the Aleutian Arc and has erupted at least 18 times since 1830 (Miller and others, 1998; see also www.avo.alaska.edu). All known historical eruptions have occurred from vents located on cone A, one of two cinder cones within the caldera (fig. 1). Historical eruptions have been mostly small to moderate Strombolian explosive events (Volcanic Explosivity Index [VEI] 1–3) characterized by burst-like emissions of ash and gas (Miller and others, 1998; www.avo.alaska.edu). Intermittent periods of lava fountaining and occasional effusion of lava also have occurred (Miller and others, 1998; www.avo.alaska.edu). Ash plumes associated with historical eruptions have been relatively small in volume and typically do not reach more than about 4,500–6,200 m above sea level. Occasional stronger bursts of activity have generated slightly higher rising plumes, such as during the 1939 and 1956 eruptions, when ash plumes rose to at least 6,200 m above sea level (Miller and others, 1998), and during the 1983–84 eruption when the largest ash plume reached a height of 8,000 m above sea level (Yount and others, 1985). During the 2018 eruption, an ash cloud reached a height of about 4,500 m above sea level on November 21, 2018.

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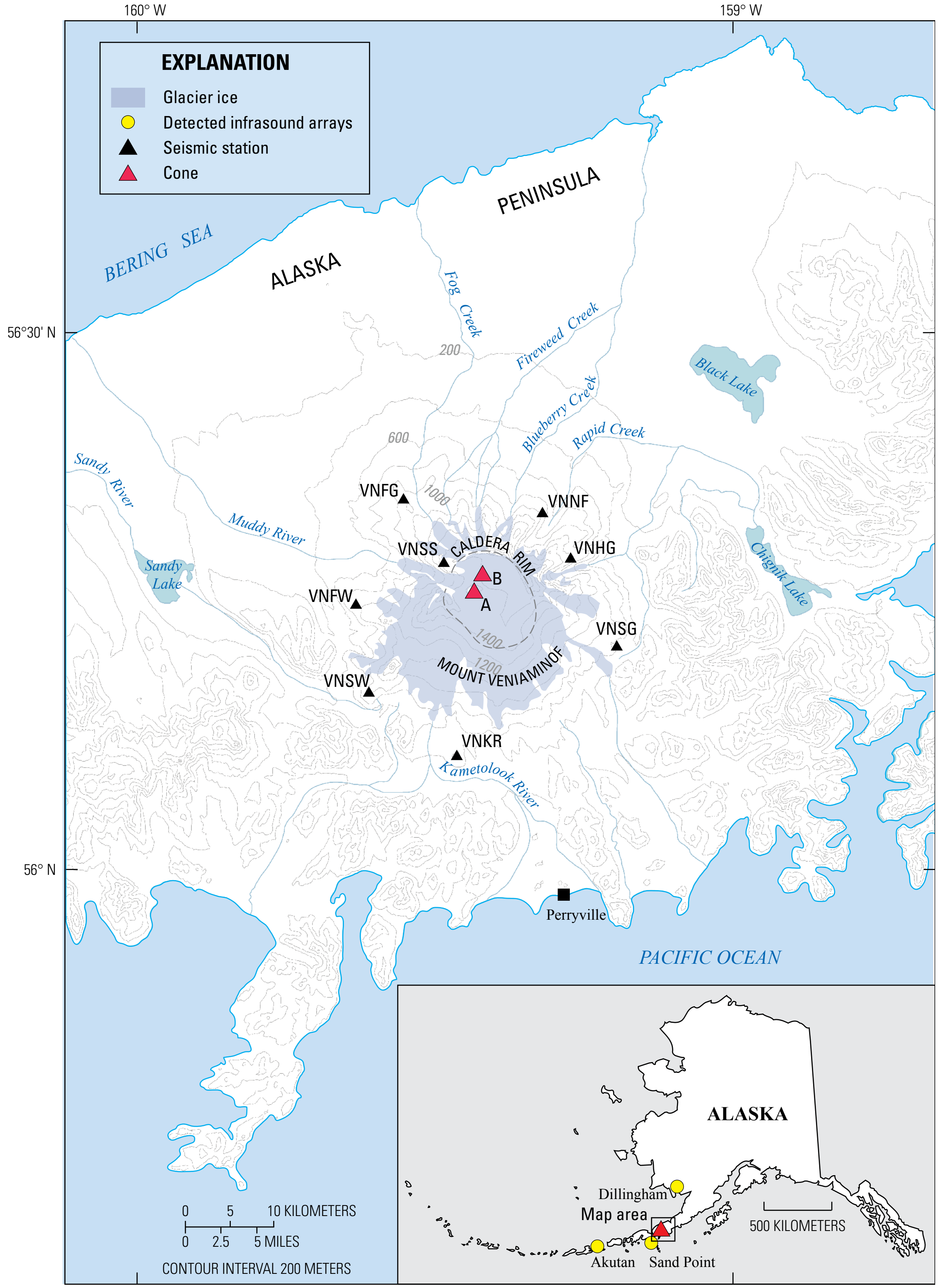


Base from U.S. Geological Survey, Chignik and Stepovak Bay maps, 1:250,000, 1963

Figure 1. Map of Mount Veniaminof on the Alaska Peninsula. The red triangle labeled A locates cone A that has been the site of all known historical eruptive activity. The red triangle labeled B locates an older intracaldera cone that is mostly covered by ice and snow and has had no known historical eruptions. Light blue area over the volcano shows the modern extent of glacier ice. Black triangles locate seismic stations. *Inset*, Map of Alaska showing location of Mount Veniaminof and location of Dillingham, Akutan, and Sand Point infrasound arrays.

Holocene pyroclastic flow, lahar, and tephra deposits mantle the flanks of the volcano beyond the caldera rim and record multiple caldera-forming eruptions and several smaller explosive events (Miller and Smith, 1987; Miller and others, 2002; Waythomas and others, 2015). The pre-Holocene eruptive history of the volcano is constrained by $^{40}Ar/^{39}Ar$ and K-Ar dating of basalt, andesite, and dacite lavas and indicates an approximately 340,000-year-long record of eruptive activity punctuated by the caldera-forming eruptions during the late Quaternary (Calvert and others, 2005; Bacon and others, 2007).

The caldera icefield has a relatively flat surface at about 1,860 m above sea level and is interrupted by two constructional cones (A and B) that protrude above the ice surface (fig. 1). Cone B, the northernmost cone, is visible only during times of low snow cover but is clearly a positive topographic feature within the caldera icefield. The eruptive history of this cone is unknown, but one sample of lava collected from it in 1973 was basaltic in composition (Yount and others, 1985). Cone A is located near the head of Cone Glacier (fig. 1). This cone has 250–300 m of relief above the surrounding icefield and covers an area of about 3 km^2. Cone A has several active fumaroles and small explosion craters on its surface that change location with the passing of each episode of volcanic unrest. Persistent degassing keeps cone A snow free most winters. The cone itself is composed of rubbly ʻaʻā lava flows interbedded with near-vent spatter, bombs, lapilli, and ash typical of other cinder cones at Mount Veniaminof and elsewhere. Two lava samples collected in 1973–1974 contained 53.8 and 55.4 weight percent SiO_2 (Yount and others, 1985). Several samples of the lava flows erupted in 2018 contained 53.5–54.5 weight percent SiO_2 (Loewen and others, 2019), indicating that eruptive products produced by cone A are basaltic to basaltic andesite in composition.

There are at least three additional small (300–400 m diameter) cinder cones that extend above the ice surface along the southeastern margin of the caldera icefield. These cones appear young, and it is possible that one or more of them were active historically, but their eruptive history is unknown. Another field of cinder cones northwest of the main edifice (Nakamura and others, 1977) also record post-glacial eruptive activity, but the chronology of activity at these cones is also not known.

Eruption Chronology

A summary of the 2018 eruption based on variations in real-time seismic amplitude (RSAM) is shown on figure 2. This figure also provides a chronology of some of the main events that occurred during the eruption, including color-code changes, significant ash cloud heights, satellite detection of SO_2, and other pertinent observations throughout the eruption. Throughout the following discussion of the eruption chronology, dates and times given are in coordinated universal time (UTC) unless otherwise noted.

Pre-eruptive Unrest

Low-level, non-eruptive unrest is somewhat common at Mount Veniaminof. Occasional earthquakes, short bursts of tremor, and steaming from cone A are often observed during repose periods. Parts of cone A remain warm as a result of degassing and slightly elevated heat flux, and there is often a lack of snow cover on the cone during the winter months.

Mount Veniaminof's previous eruption in 2013 ended by about October 17, and its eruptive activity in 2018 was confirmed on September 4. This gives an approximate repose time of 1,782 days. During this period, there was an episode of slightly elevated unrest lasting about 2 months from late September to early November 2015 (Dixon and others, 2017). The seismicity at Mount Veniaminof increased above background levels during that interval and was characterized by episodic volcanic tremor and small low-frequency earthquakes. As a result of the higher levels of seismicity, the Alaska Volcano Observatory (AVO) raised the Aviation Color Code and Volcano Alert Level to YELLOW/ADVISORY on October 1, 2015. Occasional clear web-camera views of the volcano from Perryville (fig. 1) in October–November showed minor gas emissions from cone A but no ash was observed (Dixon and others, 2017). Intermittent, short bursts of seismic tremor continued into November, but by the end of November, the seismicity had decreased to near background levels. On December 11, 2015, the Aviation Color Code and Volcano Alert Level were lowered to GREEN/NORMAL.

During the months of July and August 2018, occasional clear satellite views of the volcano showed slightly elevated surface temperatures at cone A. This is not considered unusual and does not necessarily indicate a heightened level of unrest. Local data transmission problems interrupted the flow of seismic data during July 24–August 30. After August 30, some small long-period earthquakes were detected on September 2. By the next day, seismic activity at the volcano had increased above background levels and was characterized by steady, low-level volcanic tremor. As a result, AVO raised the Aviation Color Code to YELLOW and the Volcano Alert Level to ADVISORY on September 3. No signs of eruptive activity were apparent then, but minor ash emissions were observed the following day, signifying the start of the 2018 eruption.

Activity in September 2018

On September 3, the level of seismic activity began increasing at the volcano. This activity consisted of a few weak long-period earthquakes and two deep long-period earthquakes located northwest of cone A at 19 and 16 km depth. This unrest was followed by several hours of volcanic tremor, frequently with clearly defined harmonics, observed across the Mount Veniaminof seismic network. As a result of this increase in seismicity, the Aviation Color Code and the Volcano Alert Level were raised to YELLOW/ADVISORY. The tremor strength decreased, and the seismicity transitioned into frequent short tremor bursts and long-period earthquakes around midday on September 3, but overall, the seismicity grew stronger during the afternoon of September 3. Minor steam emissions were observed in web-camera images obtained from the Federal Aviation Administration Perryville northwest web camera during the day on September 3, but these were inconclusive in confirming that eruptive activity had commenced. A Sentinel-2 satellite image acquired on September 3 showed no obvious signs of activity, although what appeared to be a trace amount of ashfall mantled the icefield on the north side of cone A. It was not possible to determine if this was primary ash or material removed from cone A by wind.

The tremor continued into September 4, though mostly without the harmonic signal that was prevalent the previous day. Several Visible Imaging Infrared Radiometer Suite (VIIRS) mid-infrared satellite images showed slightly elevated surface temperatures at cone A on September 4. However, these signals were similar to non-eruptive temperatures detected at cone A that are commonly observed during periods of quiescence and were inconclusive evidence for eruptive activity. Web-camera images from Perryville during the morning of September 4 continued to show apparent light degassing from cone A. The strong long-period earthquakes of the previous day disappeared by this time, but weak tremor bursts and smaller long-period events continued. By early afternoon on September 4, low-level ash emissions were apparent in web-camera images and were also reported by observers in Perryville. This activity prompted AVO to raise the Aviation Color Code to ORANGE and the Volcano Alert Level to WATCH as an active eruption was now confirmed. Satellite observations on September 4 indicated a trace amount of ashfall on the southwest sector of the caldera icefield. Web-camera images obtained throughout the day on September

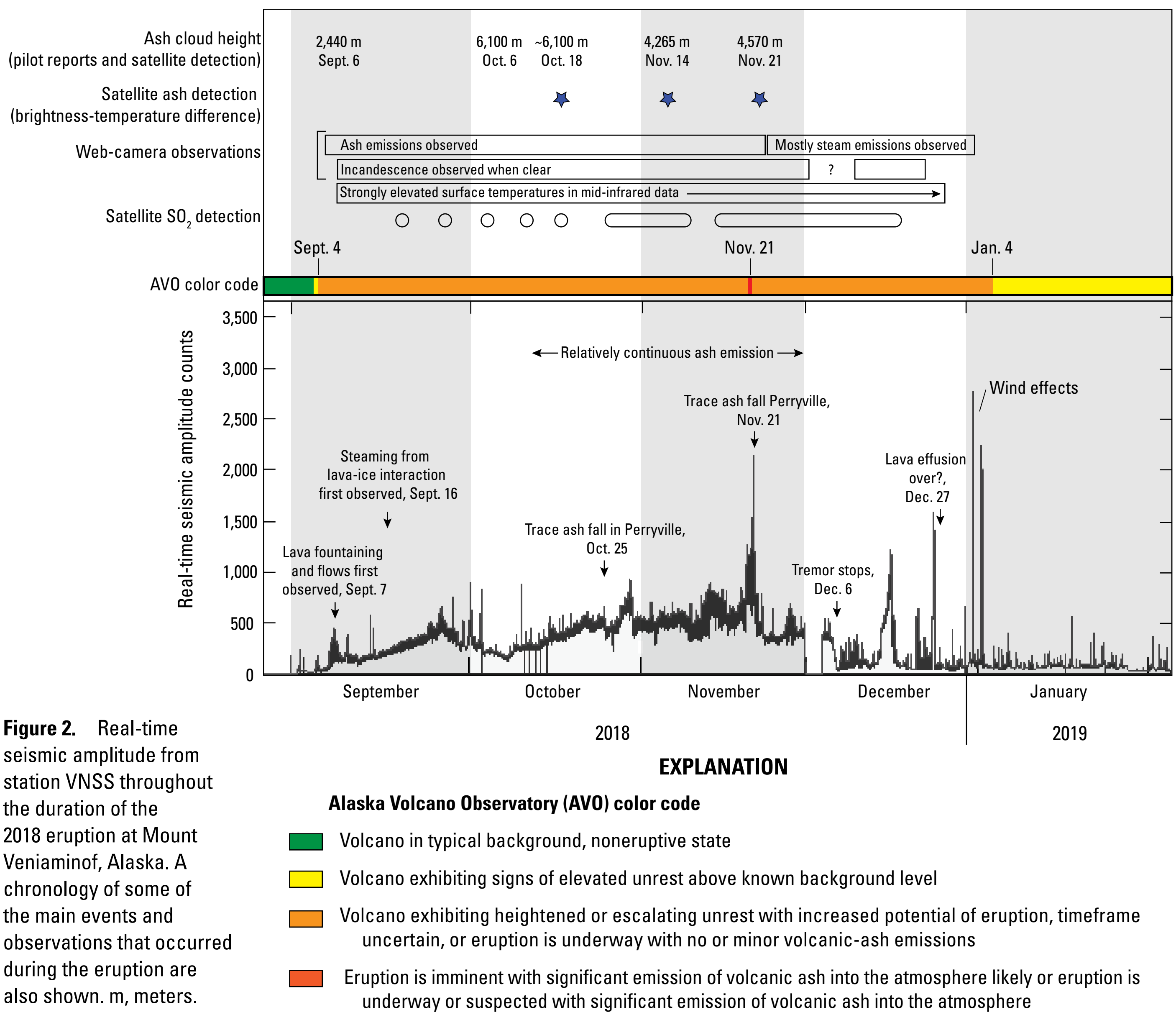


Figure 2. Real-time seismic amplitude from station VNSS throughout the duration of the 2018 eruption at Mount Veniaminof, Alaska. A chronology of some of the main events and observations that occurred during the eruption are also shown. m, meters.

4–5 indicated distinct pulsatory ash emissions, which likely resulted from small Strombolian explosions. Minor ash emissions were observed by passing pilots on September 5 (fig. 3), and diffuse ash clouds to about 3,048–4,572 m above sea level drifted hazily over the caldera. Weak tremor continued through September 5 with tremor bursts increasing in duration and occasionally having a harmonic character.

By September 6, mid-infrared satellite images showed increasingly persistent thermal signals indicative of possible lava at the surface of cone A. Two weak infrasound signals were recorded by a local station during the morning of September 6 when background noise was low. These signals also indicated that small Strombolian explosions were occurring. Incandescence was observed in morning web-camera images from Perryville on September 7 (fig. 4), and mid-infrared satellite images showed strongly elevated surface temperatures at cone A. These observations confirmed that active lava effusion was underway by September 7 but may have begun as early as September 6. During this time, and throughout the rest of the eruption, the seismicity was characterized by relatively continuous tremor and intermittent harmonic tremor punctuated by short bursts of slightly stronger tremor lasting for several tens of seconds.

On September 11, observations and video obtained by a passing pilot indicated that pulsatory low-level lava fountaining was feeding several thin, ribbon-like lava flows on the south flank of cone A from at least five small vents (fig. 5). Lava flows erupting from as many as four small vents on the south flank of cone A were observed in a satellite image acquired on September 11 (fig. 6). The extent of lava observed in this image indicated that by September 11, lava flows covered an area of about 50,600 square meters (m^2). On September 12, the first satellite detections of elevated SO_2 emissions from cone A were observed in TROPOMI (TROPOspheric Monitoring Instrument) data.

Figure 4. View of Mount Veniaminof, Alaska, from the Federal Aviation Administration Perryville northwest web camera at dawn, September 7, 2018. The white arrow locates an area of incandescence at cone A and likely represents low-level lava fountaining in progress. The distance from Perryville to cone A is about 35 kilometers.

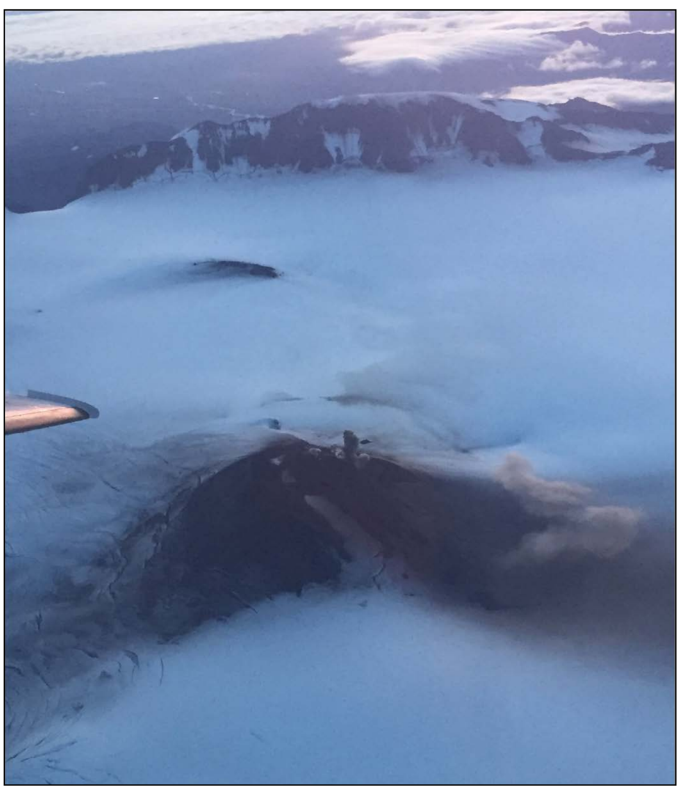


Figure 3. Aerial photograph of low-level ash emissions from cone A at Mount Veniaminof, Alaska, September 5, 2018. Photograph by Joe Timmreck, Alaska Central Express, used with permission.

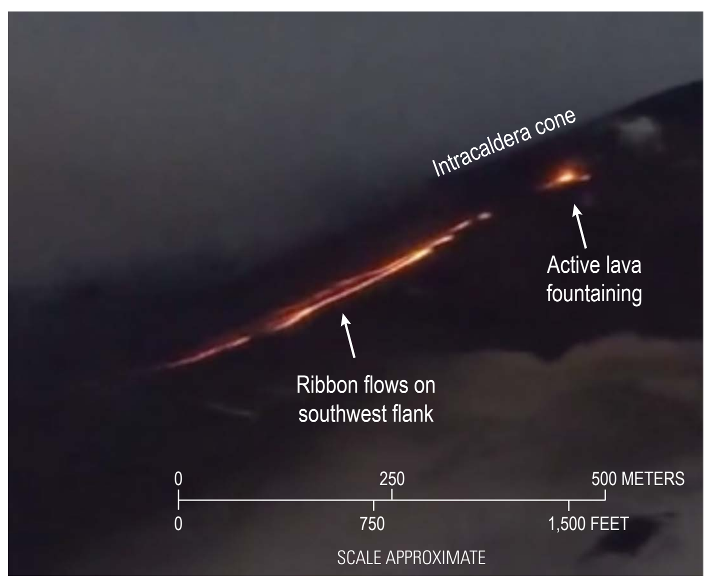
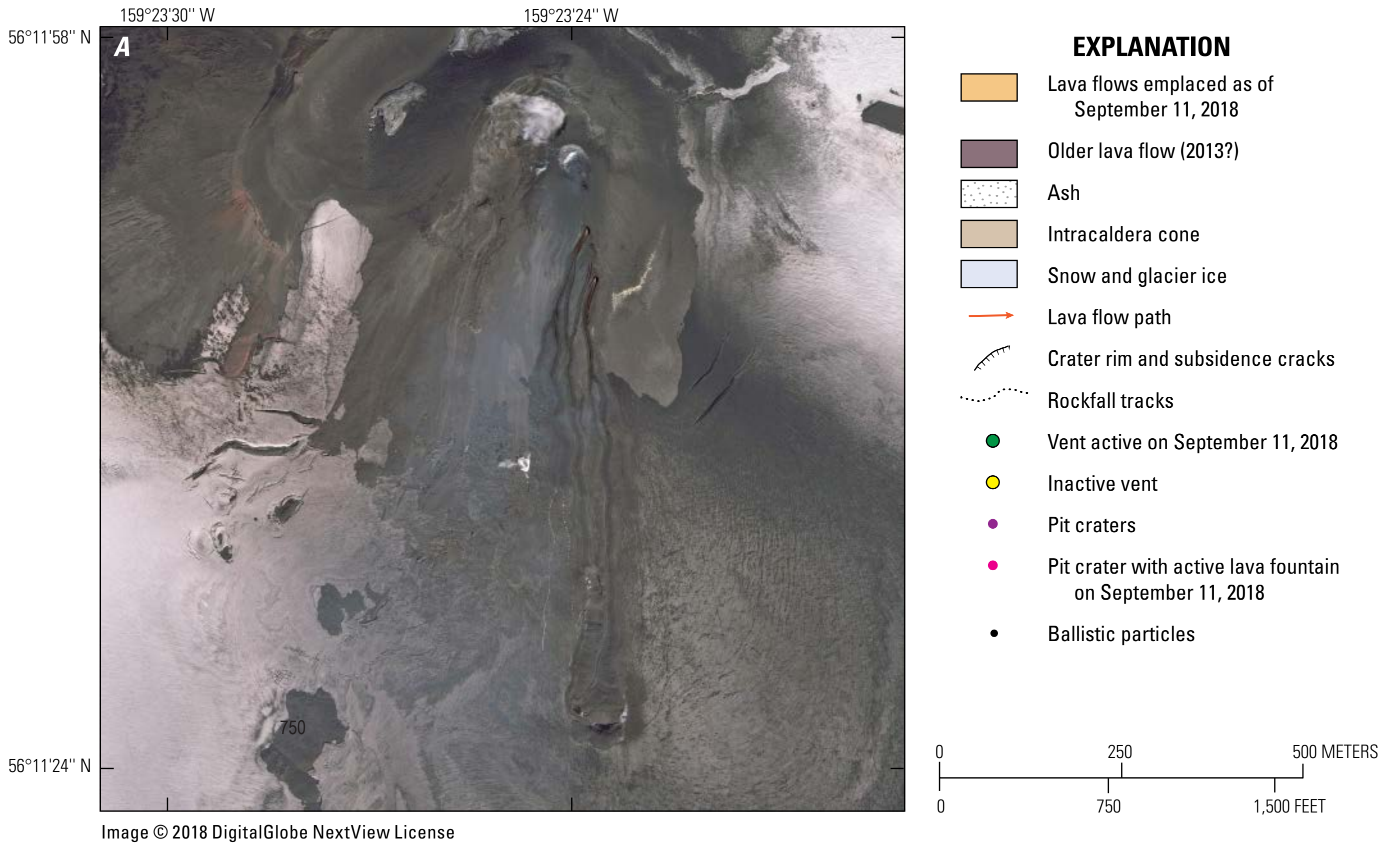


Figure 5. Image of active low-level lava fountaining and lava effusion at Mount Veniaminof, Alaska, September 11, 2018. Image is a still frame extracted from a video recorded by Joe Timmreck, Alaska Central Express, used with permission.



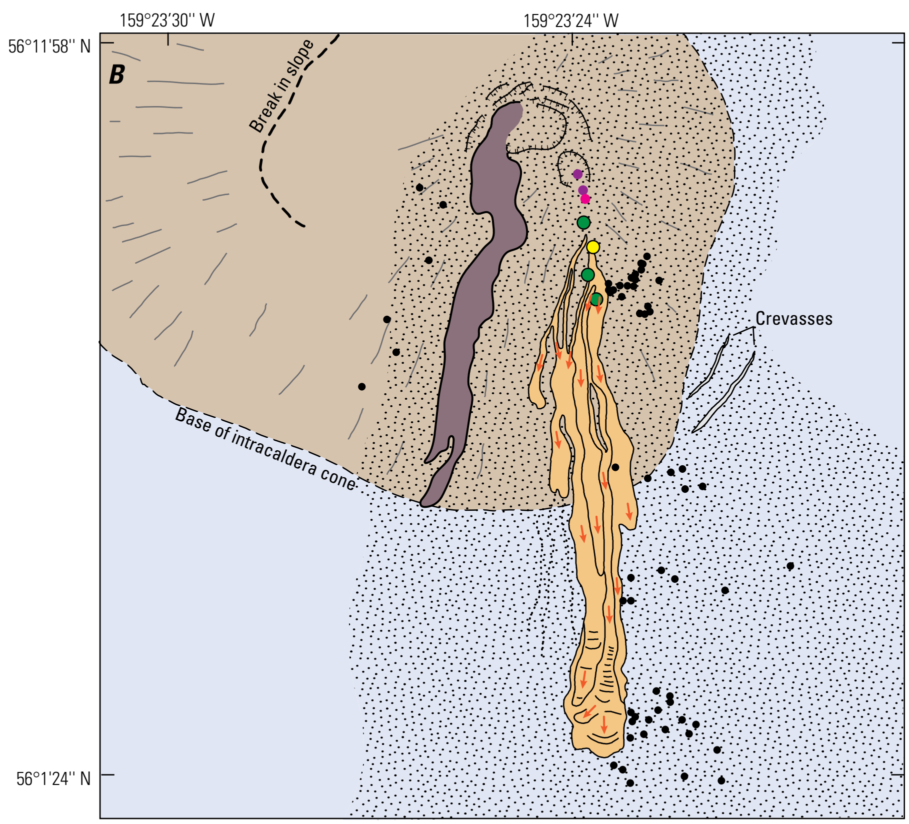


Figure 6. GeoEye-1 image (*A*) and map (*B*) of lava flows and features at Mount Veniaminof, Alaska, on September 11, 2018. The lava flows emplaced by September 11 cover an area of about 50,600 square meters. Note that poor terrain correction of this image results in slight wavy representation of the lava flows.

Pilot observations on September 14 indicated low-level ash emissions but no apparent lava-ice interaction as steam emissions around the lava flow were not evident (fig. 7). By September 16, however, a Sentinel-2 satellite image showed definitive steam emissions associated with lava-ice interaction at the terminus of the lava flow (fig. 8). On September 25, robust vertically rising steam emissions associated with lava-ice interaction were evident in web-camera images from Perryville (fig. 9) and in a Landsat 8 satellite image (fig. 10). The September 25 Landsat 8 image and aerial photographs taken on September 26 confirmed that the lava flows had begun to melt into the ice and snow on the south side of the intracaldera cone (fig. 11). Prominent, concentric, melt-related subsidence cracks around the periphery of the lava flow were evident in the images from September 25 and 26.

Additional satellite observations from September 26 indicated that activity was focused at a dominant vent, slightly south of the cone A summit. This vent exhibited low-level lava fountaining and associated deposits of spatter and scoria

Figure 7. Oblique aerial photograph of Mount Veniaminof, Alaska, showing crater-rim high point and minor ash emissions at cone A, September 14, 2018. View is toward the northwest. By this time, lava flows had developed on the south flank of cone A, but the absence of any white steam indicated that the flows had not begun to melt ice and snow at the base of the cone. Photograph by Zachary Finley, used with permission.

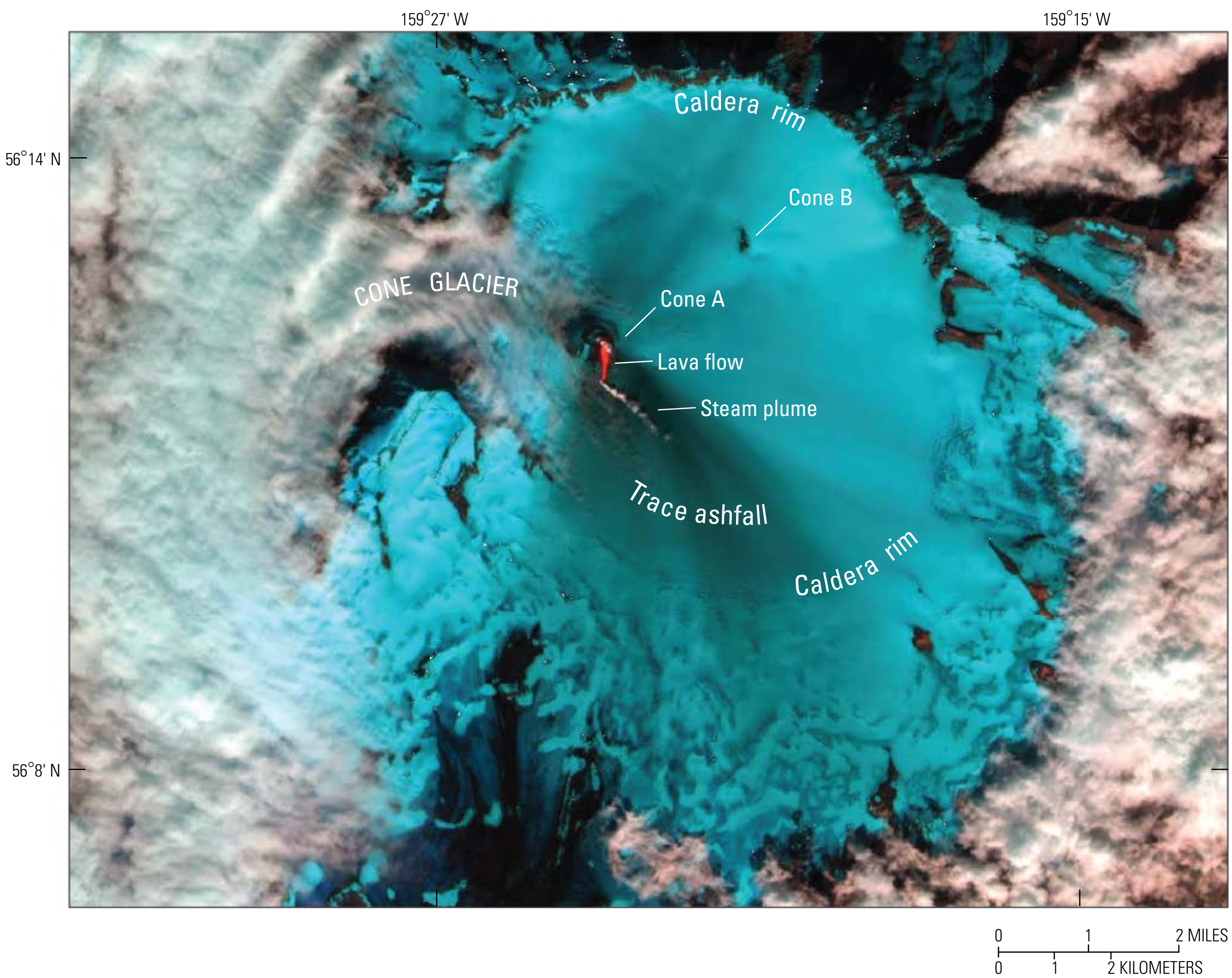


Figure 8. Sentinel-2 satellite image of lava flow on the south flank of cone A on Mount Veniaminof, Alaska, September 16, 2018. Note steam plume at terminus of lava flow and trace cover of ash south-southeast of cone A. The blue areas in the image show ice and snow.

completely buried a preexisting vent to the north of the cone A summit by late September. Only an eastern lobe of the lava flow was active after September 26, and by September 30 that lobe was about 1 km in length.

Slightly stronger seismicity was detected September 25–26 as the tremor amplitude increased, and ground-coupled airwaves were detected on distal seismic stations. This could have been a result of slightly greater effusion rates and stronger Strombolian explosions during this period.

Emissions of SO_2, which are indicative of magma degassing, were detected near the volcano on September 20, 24, and 25 by multiple satellite sensors, including Ozone Monitoring Instrument (OMI), Ozone Mapping and Profiler Suite (OMPS), and Infrared Atmospheric Sounding Interferometer (IASI). The emissions on September 25 had an estimated SO_2 mass of 0.46 thousand metric tons (kt), whereas the emissions detected on September 20 and 24 were just barely above detection limits.

Figure 9. Image of steam plume at cone A on Mount Veniaminof, Alaska, September 25, 2018. Plume height is about 4,572 meters above sea level. Image from Federal Aviation Administration Perryville northwest web camera.

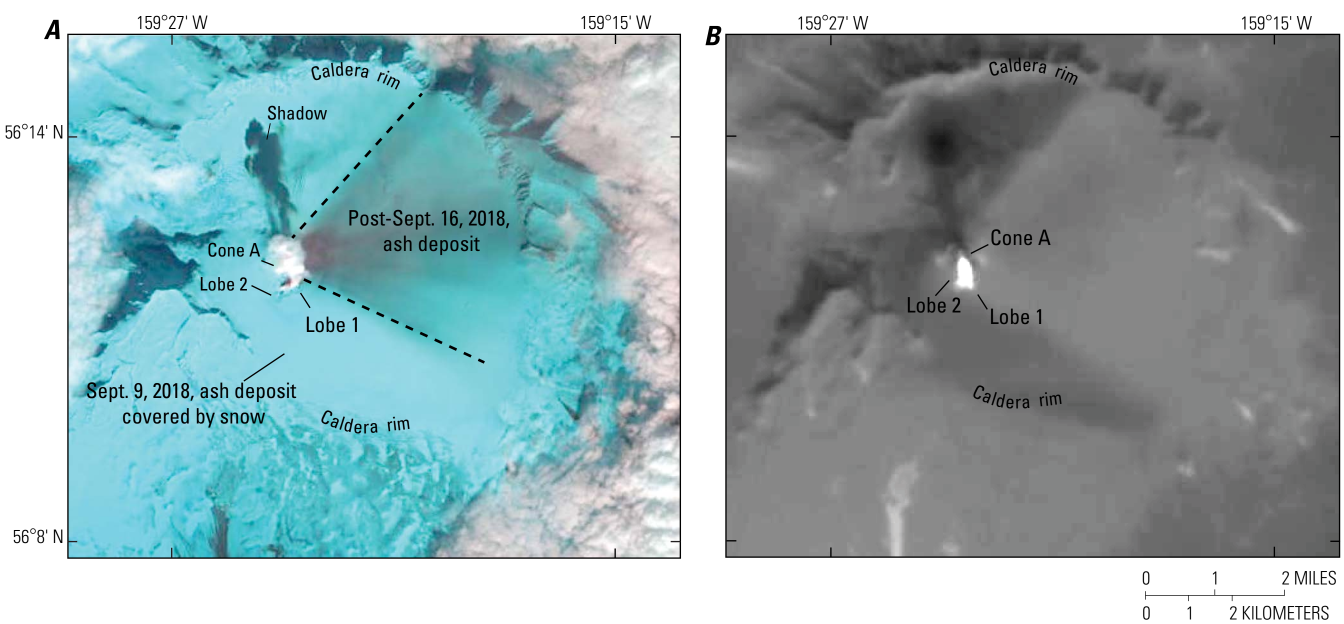
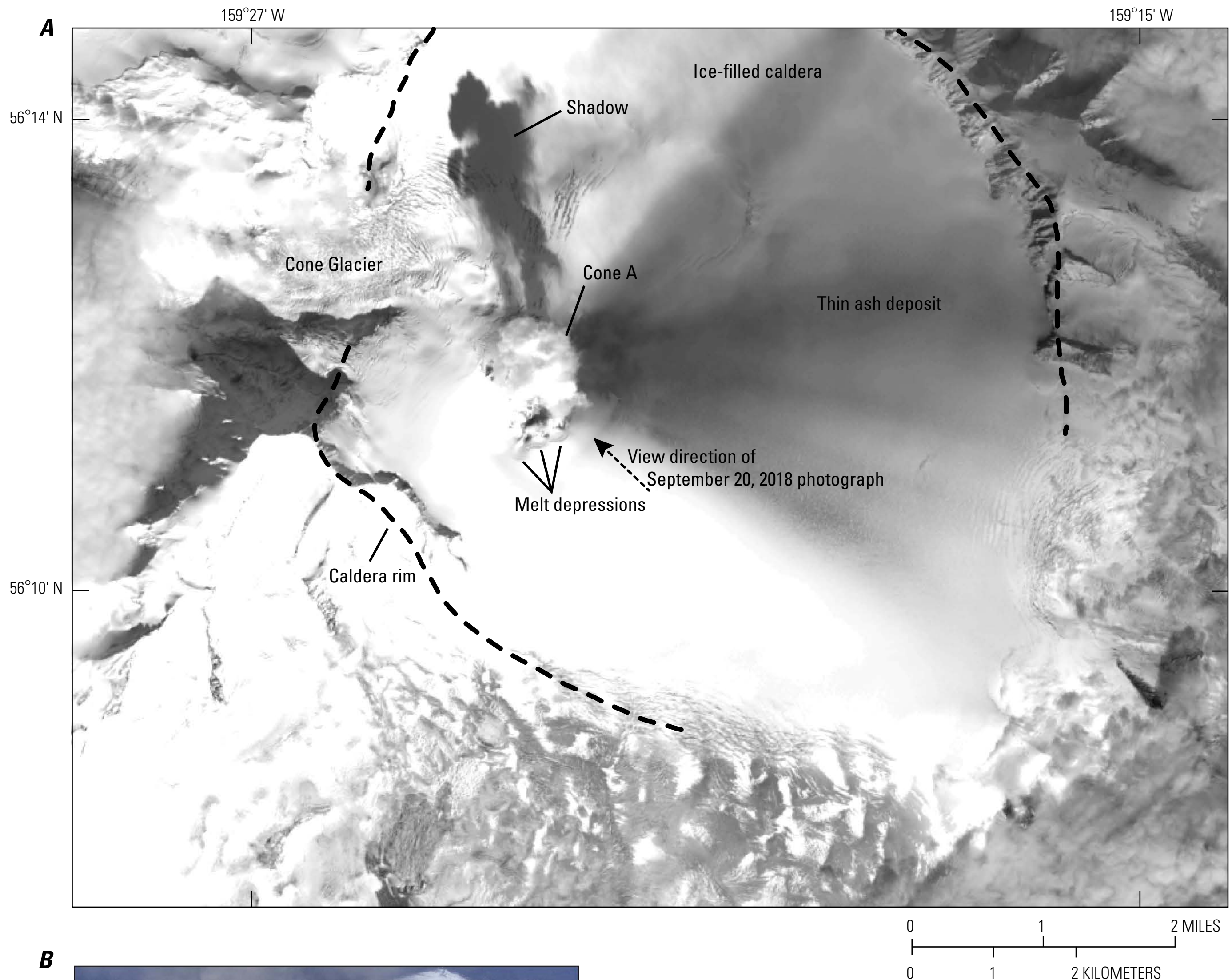


Figure 10. Images showing lava flows, ash, and surface temperature on September 25, 2018, at Mount Veniaminof, Alaska. *A*, Landsat 8 satellite image showing lava flows and a new ash deposit in the eastern part of the caldera. The image also shows two of three lobes of the lava flow melting into the snow and ice at the base of cone A. *B*, Thermal infrared image showing area of elevated surface temperatures. Lighter areas are warmer than darker areas.

A



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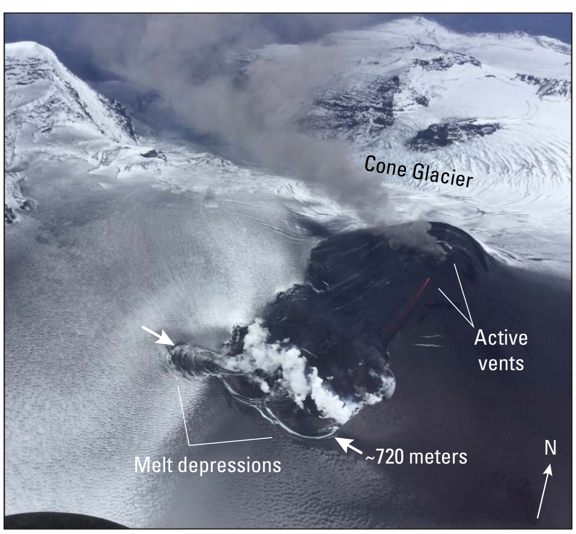

Figure 11. Images of lava flows and melt depressions on Mount Veniaminof, Alaska, on September 25–26, 2018. *A*, Landsat 8 satellite image of the lava flows and associated melt depressions at cone A. Image acquired on September 25, 2018. *B*, Inset oblique aerial photograph shows melt depressions and lava flows on the southwest flank of cone A. U.S. Fish and Wildlife Service photograph by Mark Laker, September 26, 2018.

Activity in October 2018

Continued lava effusion associated with low-level tremor, nighttime incandescence, and persistent strong thermal signals at cone A characterized activity in early October 2018. Emissions of SO_2 were again detected in satellite data on October 4 by multiple sensors including TROPOMI, OMI, and OMPS. A WorldView-3 satellite image from October 3 showed lava effusion from a single vent on the upper south flank of cone A, ash and gas emissions from the summit vent, and a series of nested concentric subsidence cracks peripheral to the lava flow field resulting from melting (fig. 12). The total surface area of lava erupted as determined from this image was 184,000 m^2. A Sentinel-2 satellite image obtained on October 6 indicated an active lava flow extending into in the southeastern sector of the flow field accompanied by robust steaming along the eastern flow margin and minor ash emission from the summit of the intracaldera cone (fig. 13). Hot spatter deposits, consistent with low-level lava fountaining are evident on the upper slopes of cone A in near infrared satellite data.

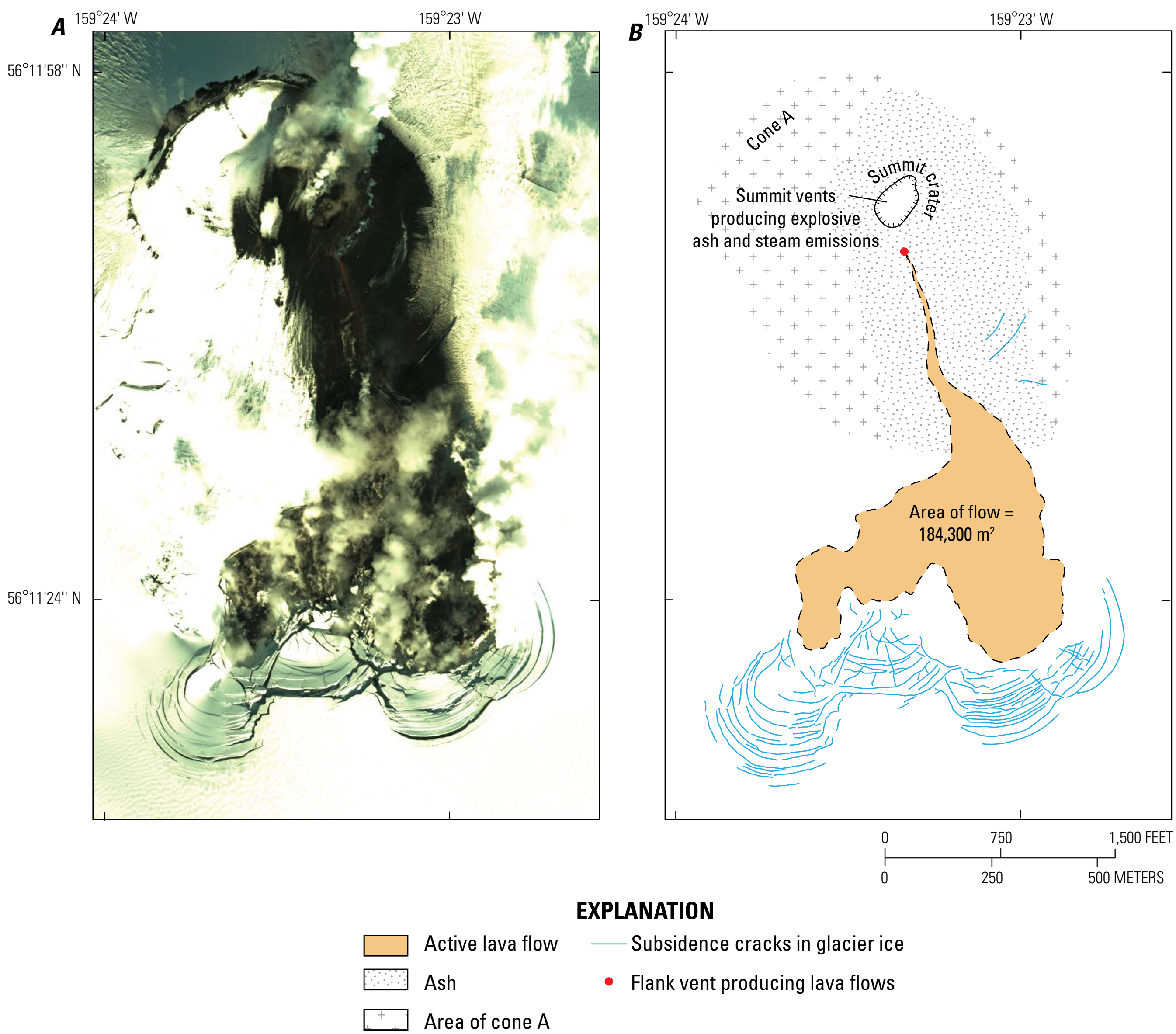

Figure 12. Image and map of lava flows from cone A of Mount Veniaminof, Alaska, on October 3, 2018. *A*, WorldView-3 satellite image of cone A and associated lava flows. *B*, Comparative sketch map of features as of October 3, 2018. Throughout the eruption, there were at least two active vents, one associated with explosive ash and steam emissions at the summit, and one or more flank vents associated with effusion of lava and occasional lava fountaining. m^2, square meter.

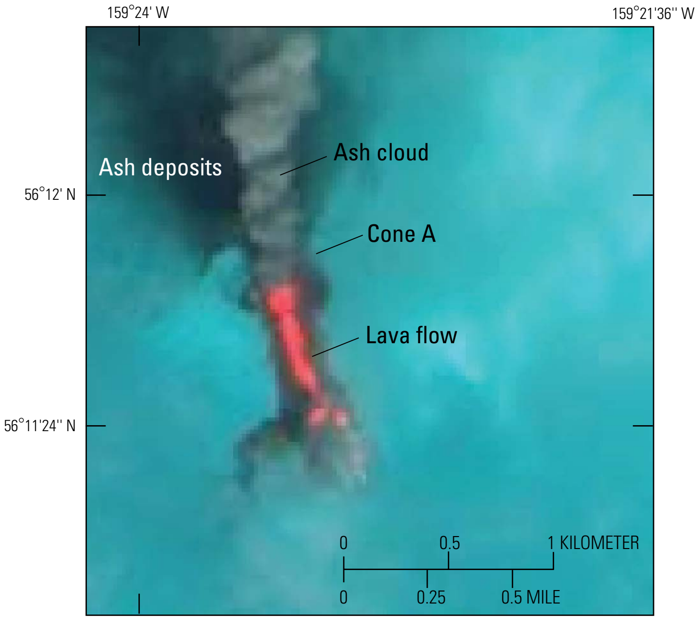

Figure 13. False color Sentinel-2 satellite image of lava flows on the south flank of cone A on Mount Veniaminof, Alaska, October 6, 2018. The image shows continued lava effusion and an ash plume with a thin tephra deposit beneath extending to the north. The active lava flow is about 1 kilometer in length with the most active front on the southeast side, which has a short-wave infrared (SWIR) anomaly extending to the flow front. A branch in the channel feeding the western lobes appears to be active as well, but without any SWIR anomaly near the flow front, this western branch is likely less active. The southeastern flow front is producing the strongest steam plume.

Emissions of SO_2 near Mount Veniaminof were detected in OMI satellite data on October 10. The amount was slightly above background levels, and it is uncertain if the SO_2 was entirely volcanic in origin.

From October 10 to 17, the volcano was mostly obscured by clouds. Elevated surface temperatures and SO_2 emissions were detected occasionally in satellite data during this period when cloud cover was thinner.

On October 18, viewing conditions improved considerably and web-camera views from Perryville showed a billowy, low-level ash cloud extending southeast from the intracaldera cone. Several satellites detected SO_2 on October 17 and 18 and about 0.27 kt of SO_2 was measured on October 18 from OMI data. A Landsat 8 satellite image from October 18 showed continued lava effusion and a steam and minor ash plume extending to the northeast (fig. 14). Strongly elevated surface temperatures and incandescence consistent with sustained lava effusion were detected on October 19–20 in satellite and web-camera data, and ash emissions on October 19 reached about 6,000 m above sea level. Minor ash deposits in the caldera were observed in visible satellite images on October 23.

From October 23 to 25, web-camera views of the volcano were obscured by clouds, but satellite observations continued to show strongly elevated surface temperatures and SO_2 was detected by multiple sensors. On October 25, trace ashfall was reported in the community of Perryville, 35 km south of the volcano, and the active lava flow was flowing predominantly west and was about 1.2 km in length (fig. 15). Satellite observations indicated that the total area covered by lava as of October 25 was 385,000 m^2.

Through the end of October, the volcano remained restless with lava effusion and intermittent low-level ash emissions continuing. Occasionally, slightly stronger bursts of ash occurred, and one of these was detected in a thermal infrared brightness-temperature difference satellite image (fig. 16). Emissions of SO_2 were detected in satellite data on October 28–31.

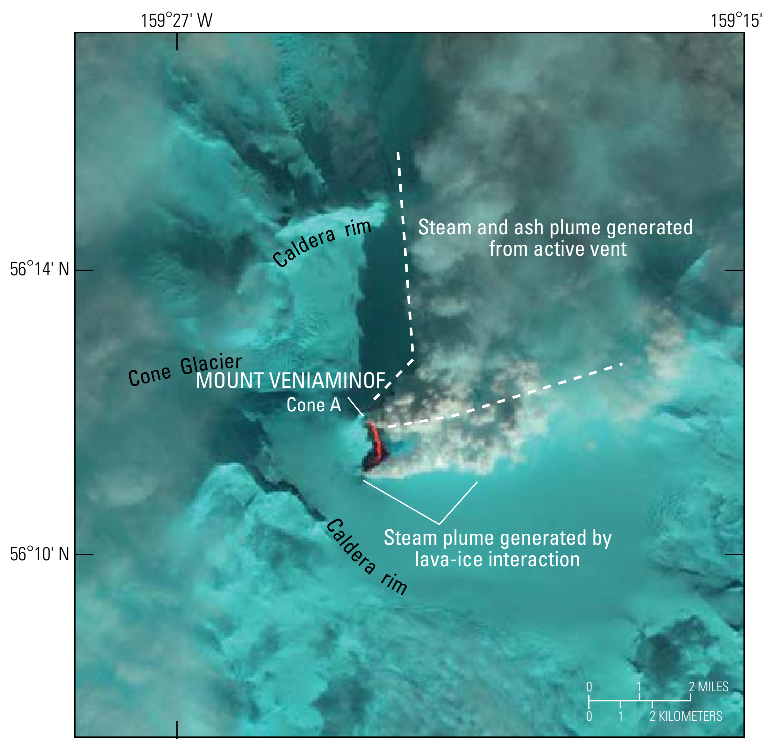

Figure 14. Landsat-8 satellite image of Mount Veniaminof, Alaska, on October 18, 2018, showing continued lava effusion and steam and a minor ash plume extending to the northeast. Note the robust steam plume at the distal end of the lava flow associated with lava-ice interaction. In this false-color image, short-wave infrared emissions display as red and show that the western flow front is the most active. The length of the active lava flow is about 1.2 kilometers.

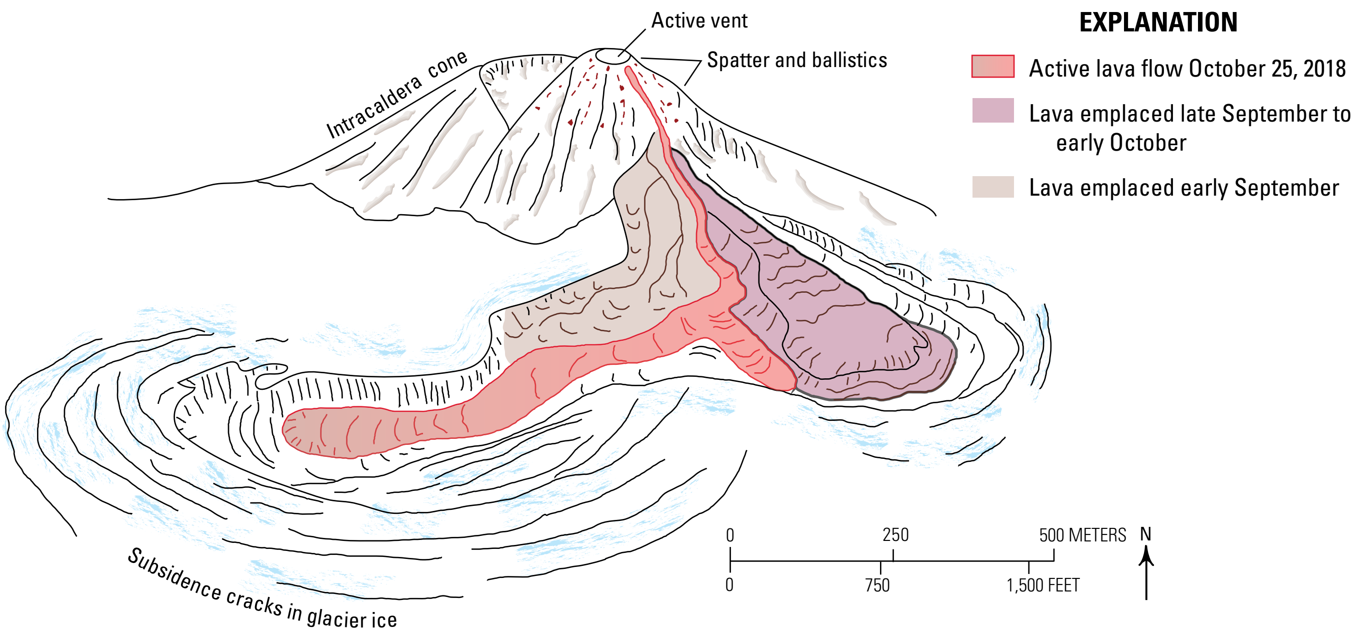

Figure 15. Sketch of cone A and active lava flow on Mount Veniaminof, Alaska, on October 25, 2018. The active lava channel is flowing toward the west-southwest and is about 1.2 kilometers in length. Modified from a sketch made by U.S. Geological Survey scientist Rick Wessels.

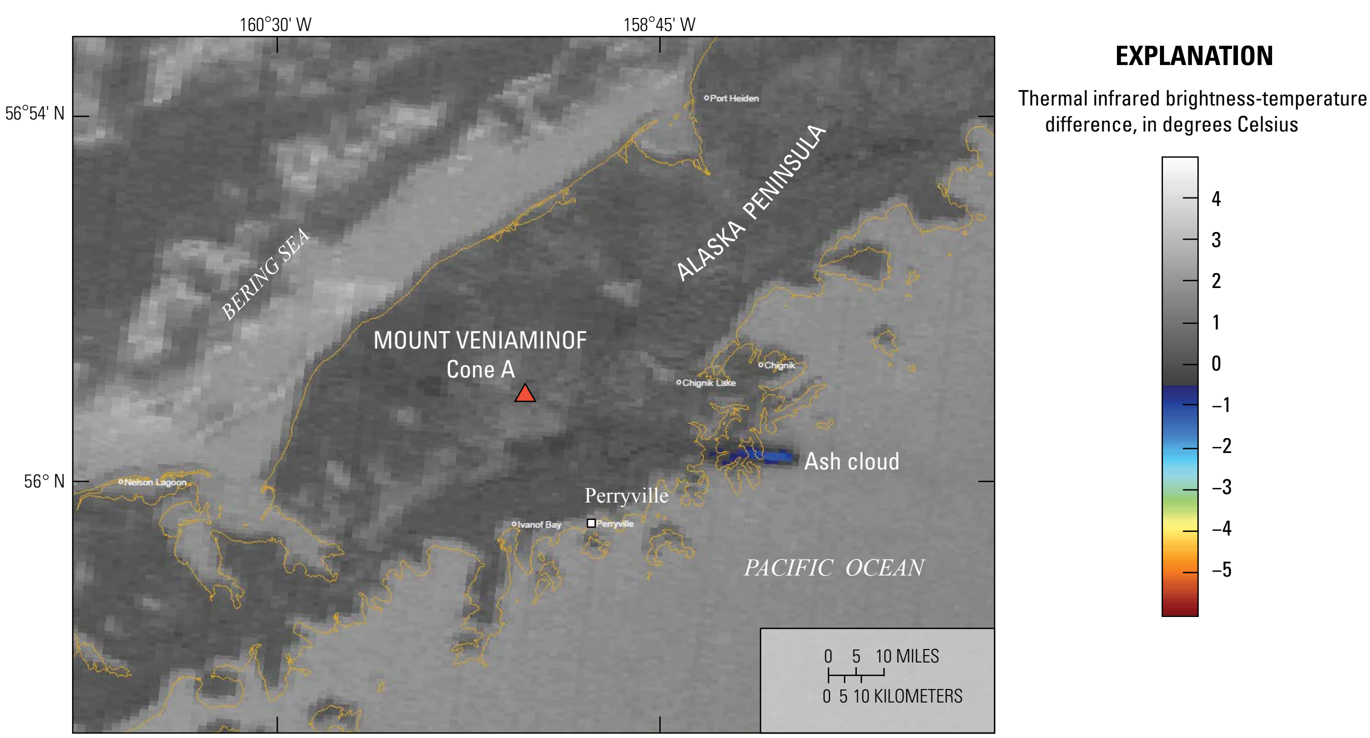

Figure 16. National Oceanic and Atmospheric Administration satellite NOAA-19 thermal infrared brightness-temperature difference (in degrees Celsius) image taken on October 30, 2018, showing a small ash cloud southeast of Mount Veniaminof, Alaska. The leading edge of the signal is about 80 kilometers southeast of cone A. The ash cloud reached a maximum height of 4,572 meters above sea level. Landmass is outlined in orange. The pixel resolution of the image is 1.1 kilometers and the somewhat blurry appearance is likely caused by motion artifacts.

Activity in November 2018

By November 3, activity at Mount Veniaminof began to transition slightly to episodic emission of more robust steam, gas, and ash clouds that were evident in satellite data. Emissions of SO_2 were detected by multiple sensors on November 3–5. On November 4–5, strongly elevated surface temperatures were detected in mid-infrared Advanced Very High Resolution Radiometer (AVHRR) satellite imagery (fig. 17), and nighttime web-camera images from Perryville showed apparent pulsatory incandescence that occasionally illuminated the eruption plume (fig. 18). An eastward-drifting plume was detected in satellite data during the early morning hours of November 5. The ash-bearing volcanic cloud was apparent in several satellite images, extending at least 60 km beyond the vent and reaching a maximum altitude of about 4,267 m above sea level, as confirmed by a pilot observation. A WorldView-2 panchromatic image of cone A obtained on November 5 (fig. 19) showed a fresh-appearing lava flow with an area of about 157,000 m^2 that had been emplaced on top of previous flows. The total lava-flow area in the

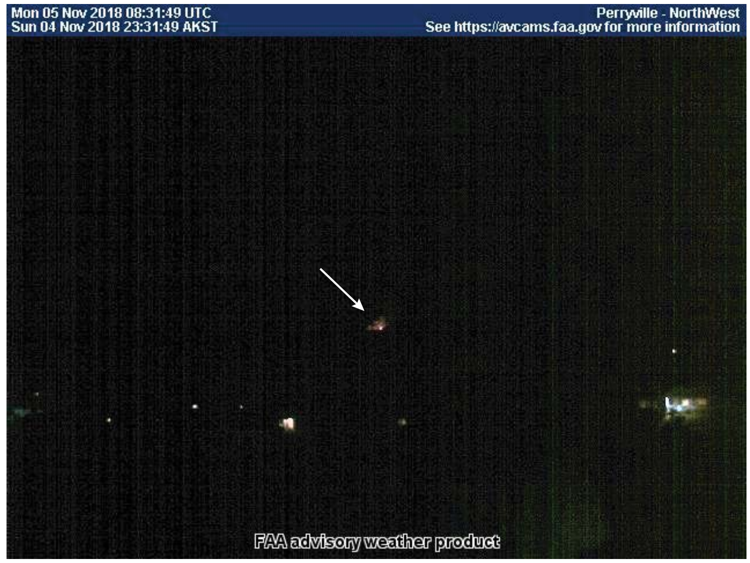

Figure 18. Nighttime view of active lava fountaining at cone A on Mount Veniaminof, Alaska, on November 4 (Alaska standard time), 2018 (white arrow). Strong incandescence illuminates the nearby eruption cloud. Image from Federal Aviation Administration Perryville northwest web camera, about 35 kilometers from the eruption site.

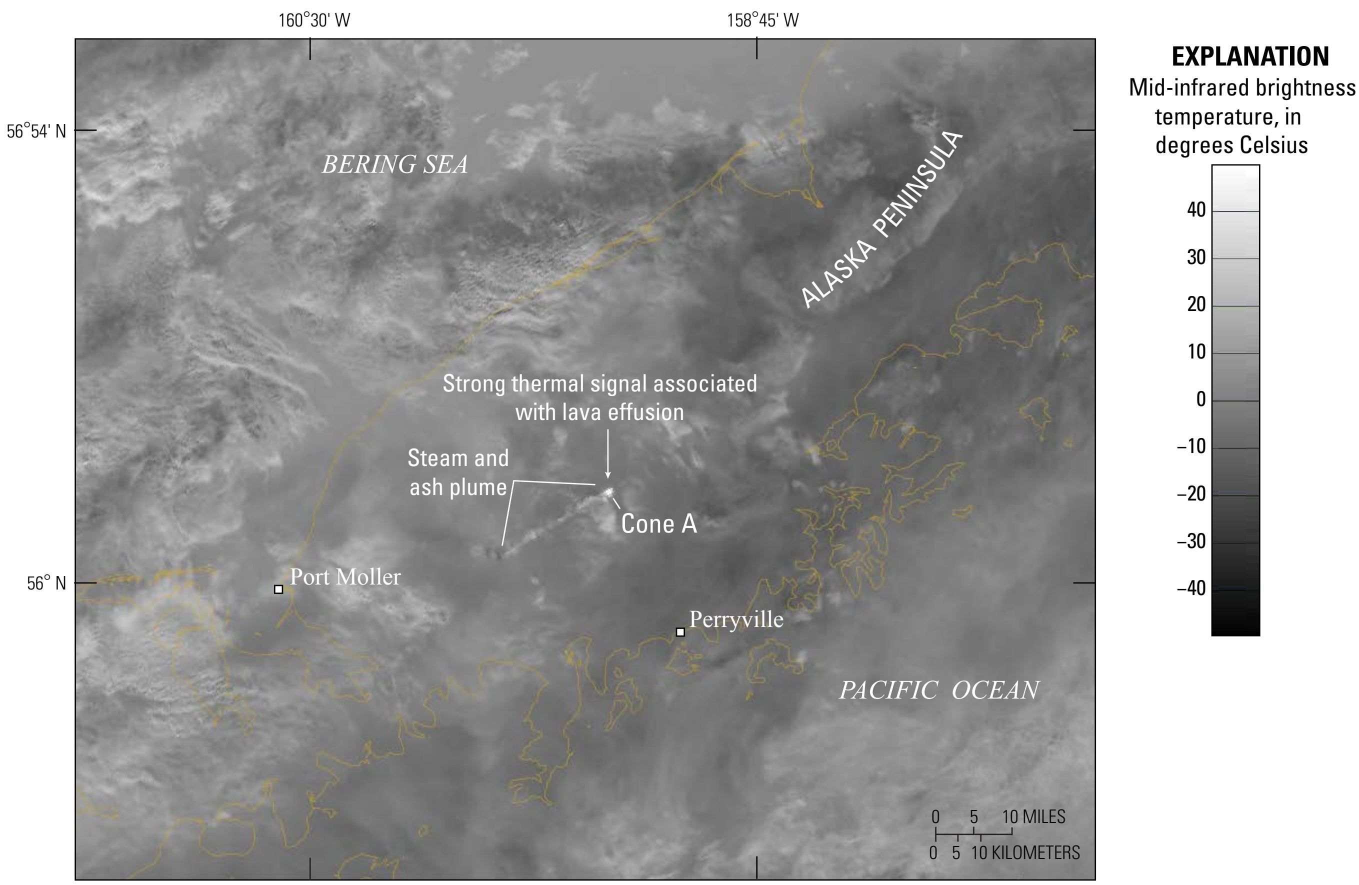

Figure 17. National Oceanic and Atmospheric Administration satellite NOAA-20 Visible Infrared Imaging Radiometer Suite (VIIRS) mid-infrared image showing a strong thermal signal at cone A on Mount Veniaminof, Alaska, and a linear steam and ash plume extending southwest from the volcano. Image taken on November 3, 2018. Landmass is outlined in orange. The pixel resolution of the image is about 370 meters.

November 5 image is about 374,000 m^2. From November 6 to 19, satellite data and occasional photographs (fig. 20) showed a persistent volcanic cloud consisting of steam and ash extending about 64 km beyond cone A in the range of 2,400–3,650 m above sea level.

Intermittent satellite detection of SO_2 near Mount Veniaminof occurred throughout early to middle November (fig. 2). Declining levels of ultraviolet light in November and December made detection and estimation of atmospheric SO_2 loadings by ultraviolet sensors less certain. Detections of SO_2 by infrared sensors, primarily Infrared Atmospheric Sounding Interferometer (IASI) and Atmospheric Infrared Sounder (AIRS), became the primary data sources for monitoring SO_2 emissions during the winter months.

On November 19, volcanic tremor increased in amplitude and reached the highest level of the eruption to date (about 1,200 counts on station VNSS; fig. 2). The increase in seismicity was associated with infrasound detections by instruments located in Dillingham, Alaska, 322 km northeast of the volcano (fig. 1). Satellite data indicated that by November 19 the total area of lava erupted was 540,000 m^2.

On November 21, conditions at the volcano escalated further, with ash emissions and tremor amplitudes increasing significantly (fig. 2). A prominent ash cloud was detected in satellite imagery at 11:43 UTC (2:43 Alaska standard time [AKST]) that extended more than 130 km southeast from cone A and reached an altitude of at least 4,572 m above sea level. The ash cloud was observed during the day from Perryville (fig. 20) and residents reported distinct "booming" sounds coming from the direction of the volcano that were likely Strombolian explosions. The level of seismicity and the extent of the ash cloud prompted AVO to raise the Aviation Color Code to RED and the Volcano Alert Level to WARNING. This was the first time that AVO elevated Mount Veniaminof to RED/WARNING.

Nearly continuous ash emission continued for much of November 21 and resulted in the ash cloud lengthening to the southeast, eventually reaching a distance of at least 400 km from the vent (figs. 21, 22). Activity began to decline by late afternoon on November 21 (AKST) and no further ash emissions were evident in satellite or web-camera data until the next day. As a result of the decline in ash emissions,

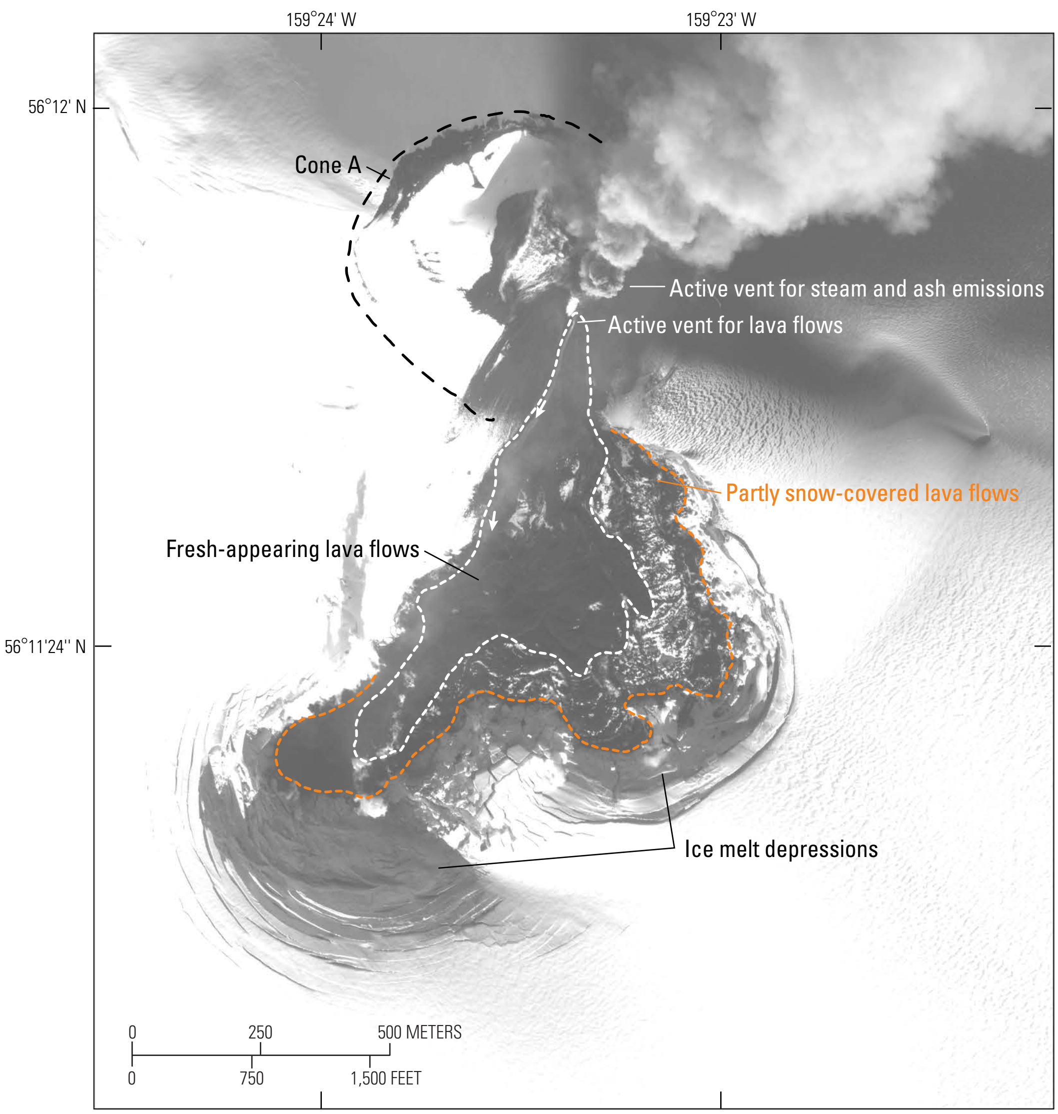

Figure 19. WorldView-2 panchromatic image of cone A on Mount Veniaminof, Alaska, on November 5, 2018. The fresh-appearing lava flow has an area of about 157,000 square meters (m^2) and a volume of 157,000 to 314,000 cubic meters, assuming an average flow thickness of 1–2 meters. The total lava-flow area in this image is about 374,000 m^2.

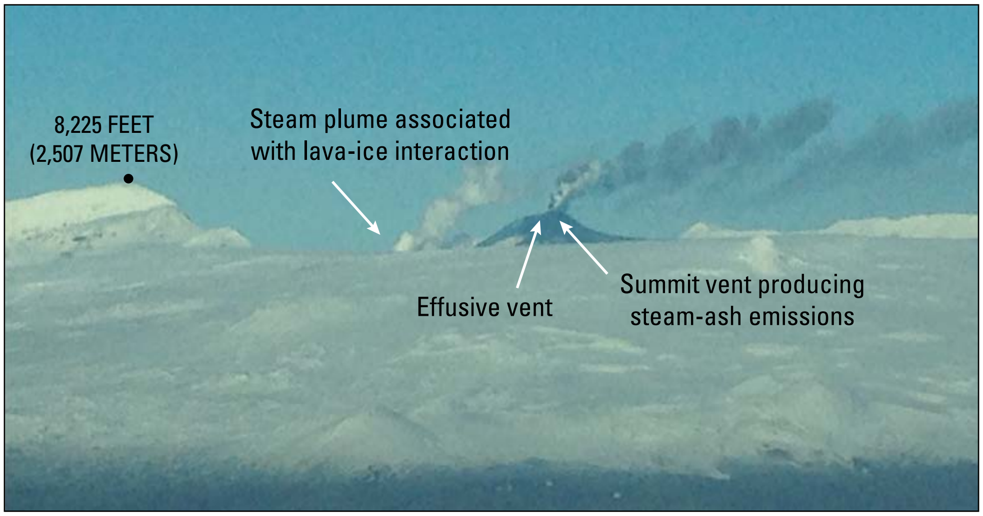

Figure 20. Aerial photograph of cone A on Mount Veniaminof, Alaska, on November 9, 2018, showing a steam plume generated by lava-ice interaction, the approximate location of effusive vent(s) associated with lava flows, and the summit vent associated with generation of steam and ash clouds. Photograph by Zachary Finley, used with permission.

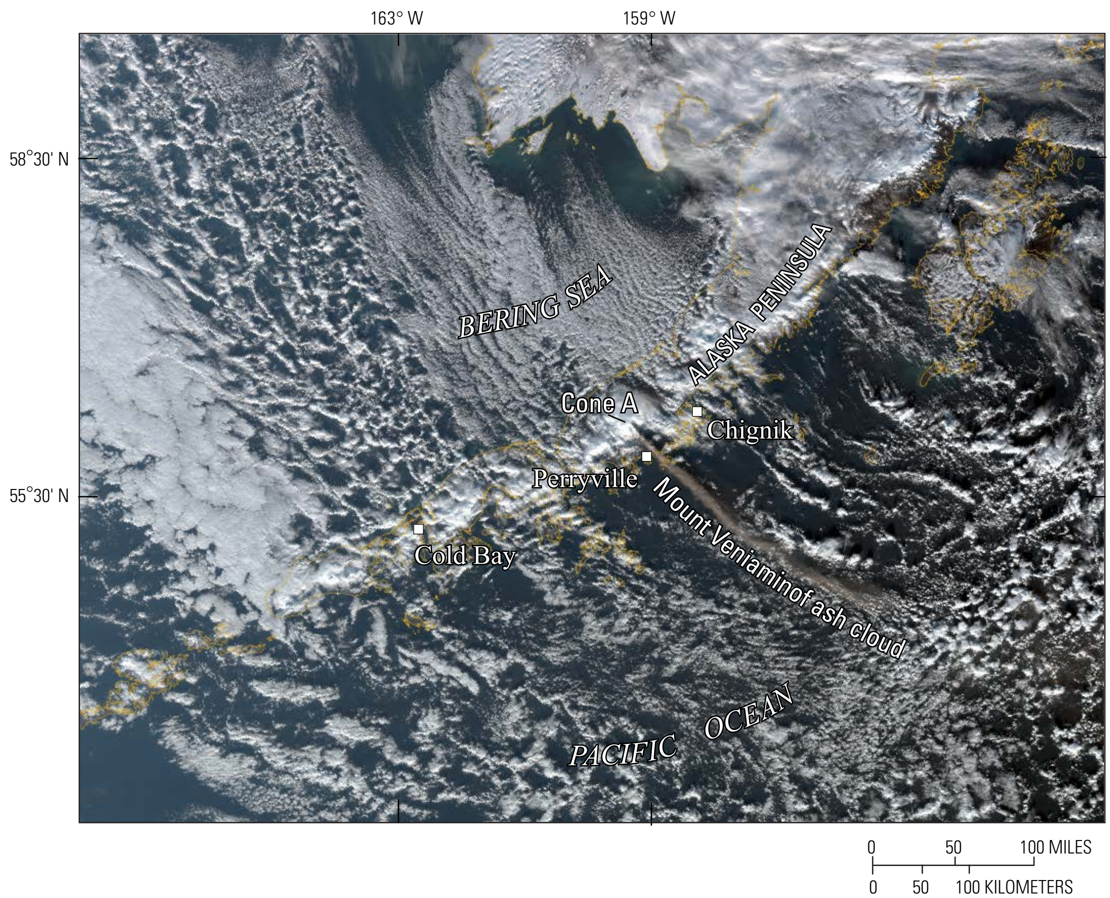

Figure 21. Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite true-color satellite image of the ash cloud extending southeast from cone A on Mount Veniaminof, Alaska, on November 21, 2018. The ash cloud extended at least 400 kilometers southeast from the cone and reached an altitude of about 4,500 meters above sea level. Landmass is outlined in orange.

AVO lowered the Aviation Color Code to ORANGE and the Volcano Alert Level to WATCH on November 22. Clear web-camera views from Perryville on November 22 showed nearly continuous low-level ash emissions (fig. 23) extending as far as 100 km beyond the vent and reaching an altitude of about 3,000 m above sea level. Web-camera views at night showed incandescence at cone A.

By November 25, ash emissions were no longer evident from the cone A, coincident with the gradual decline in tremor amplitude following the November 21–22 ash emissions. On November 28, the level of volcanic tremor increased slightly, and occasional pulses of infrasound were detected on infrasound arrays in Dillingham, Sand Point, and Akutan (fig. 1). This slight increase in activity was associated with minor ash emissions that were observed in satellite data.

From November 30 to December 3, data transmission from remote seismic stations on the volcano was interrupted and AVO relied entirely on satellite observations to maintain surveillance of the volcano. During this period, elevated surface temperatures and SO_2 emissions continued to be detected in satellite data, and small volcanic clouds (probably steam and minor ash) were apparent in some images.

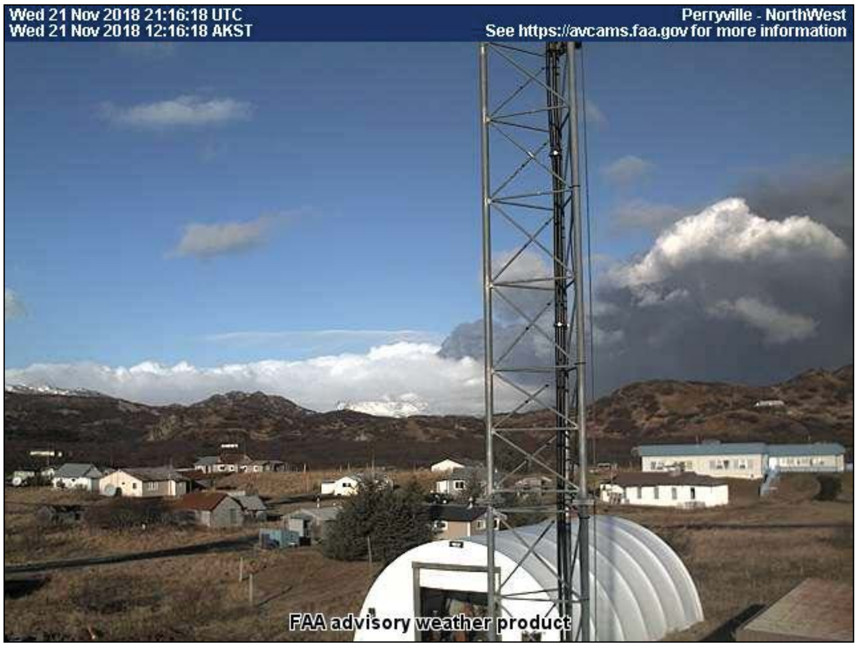

Figure 22. Image of robust ash emissions above Mount Veniaminof, Alaska, observed from Federal Aviation Administration Perryville northwest web camera on November 21, 2018.

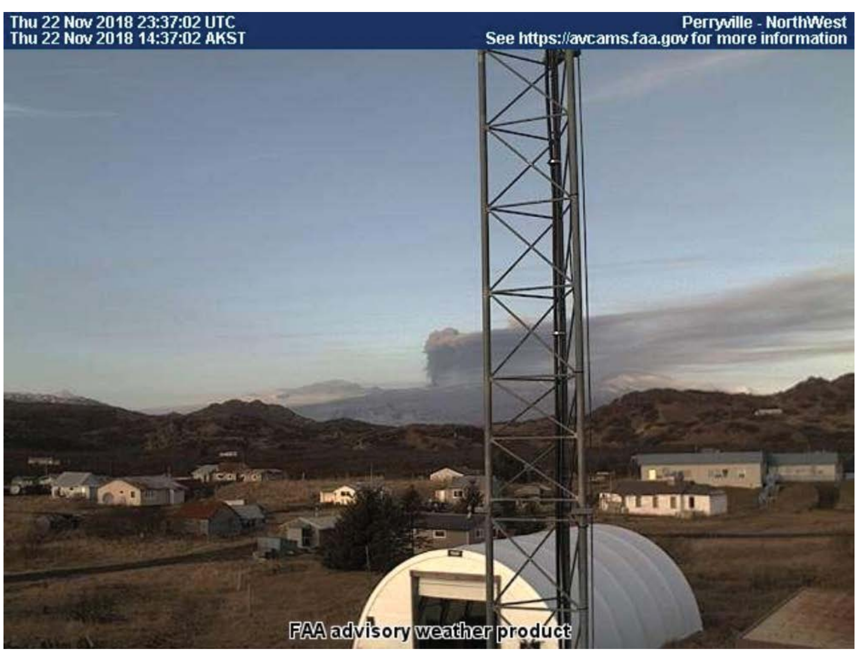

Figure 23. Image of ash emissions from cone A on Mount Veniaminof, Alaska, as viewed from the Federal Aviation Administration Perryville northwest web camera on November 22, 2018. Maximum ash cloud height was about 3,000 meters above sea level.

Activity in December 2018

A clear Sentinel-2 satellite image acquired on December 5 showed significant steaming from the interaction of lava with snow and ice (fig. 24). Prominent steam plumes also were visible in web-camera views from Perryville. By December 6, the continuous tremor signal that had been characteristic of the eruption transitioned to frequent long-period events. The change in seismicity was likely related to a pause or cessation of lava effusion. Emissions of SO_2 were detected in satellite data on December 5–7.

A partly cloudy Sentinel-2 satellite image obtained on December 10 showed a light dusting of snow on parts of the cone A lava flows and only minor steam emissions. The low level of seismic activity, absence of continuous tremor, and apparent cooling of the lava flows further indicated that the eruptive activity ongoing since early September had ceased.

Numerous ground-coupled airwaves associated with long-period events were detected in seismic data on December 11, but no other outward signs of unrest were observed in satellite or web-camera data. Ash emissions from cone A were again observed in web-camera views from Perryville on December 13 and 16, and, as cloud cover decreased over the volcano, satellite data again showed elevated surface temperatures, indicating that lava effusion had resumed. Small volcanic clouds of ash and gas extending from cone A were also observed in satellite data (fig. 25). This resumption in eruptive activity was accompanied by the return of low-level nearly continuous tremor that persisted until December 16, when the tremor signal ended and was replaced by numerous, discrete low-frequency events. Continuous and impulsive infrasound signals were detected in Dillingham from December 14 to 16, consistent with the observations of lava effusion and possible Strombolian explosions. Minor ash emissions were observed in web-camera data from Perryville through December 17, after which time the volcano was obscured by clouds. Satellite data also confirmed that SO_2 emissions occurred December 13–19 during this brief period of heightened unrest and SO_2, possibly from Mount Veniaminof, was detected over the Seward Peninsula, about 970 km north of the volcano.

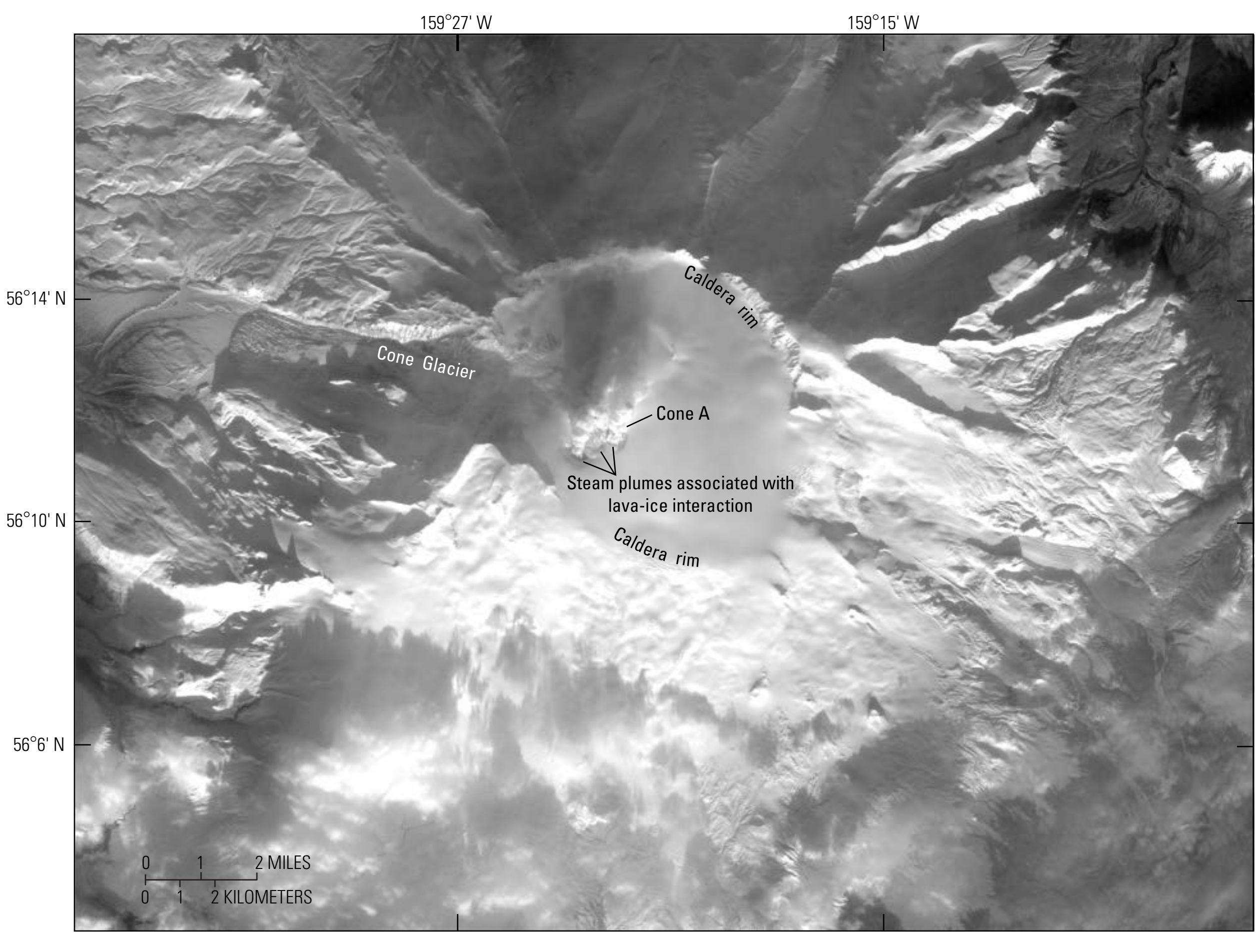

Figure 24. Sentinel-2 satellite image of Mount Veniaminof and cone A in Alaska, on December 5, 2018. Note the robust steam plumes associated with lava-ice interaction.

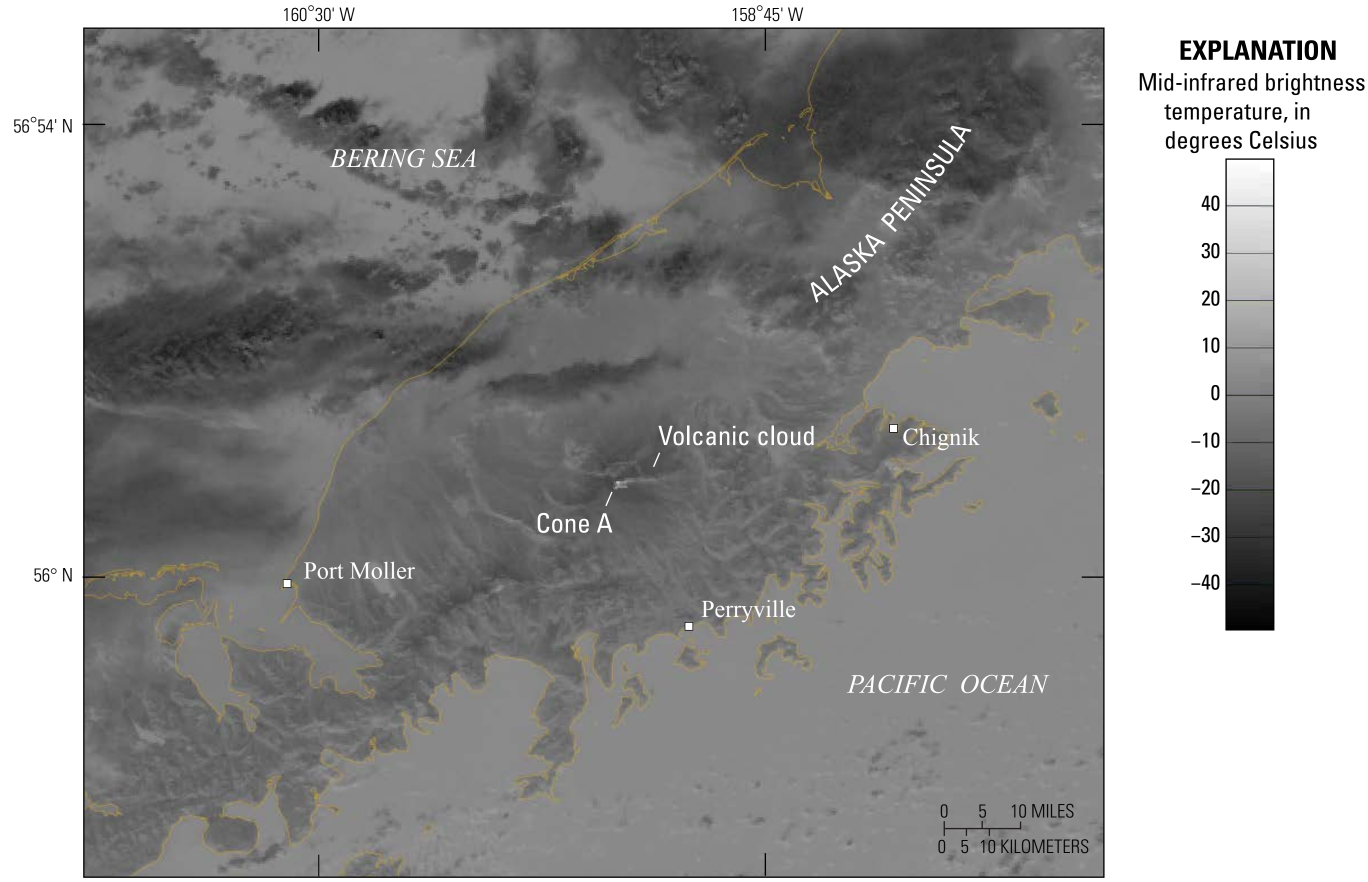

Figure 25. Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite mid-infrared satellite image from December 13, 2018, showing elevated surface temperatures at cone A on Mount Veniaminof, Alaska, and a small volcanic cloud extending east. Landmass is outlined in orange.

A Sentinel-2 satellite image acquired on December 20, 2018, indicated no evidence of active lava effusion, or additional advance of the active lava flows. Slight fluctuations in the amplitude of seismic tremor occurred December 21–28 and on December 23 (AKST) strong thermal signals were again evident in satellite data. Incandescence associated with possible lava fountaining was observed in web-camera images on December 23 (fig. 26) and elevated SO_2 emissions were detected December 23–24.

By December 27, satellite, seismic, and web-camera data all indicated that active lava effusion had slowed or perhaps stopped completely. After December 27, there were no further signs of unrest and from then into early January 2019 the level of unrest at Mount Veniaminof declined to background levels. On January 4, AVO lowered the Aviation Color Code to YELLOW and the Volcano Alert Level to ADVISORY.

Weak long-period earthquakes were regularly detected for several months following the end of observable eruptive activity. Weak tremor also occurred occasionally in the months following the eruption. No outward signs of unrest correlative with these periods of slightly elevated seismicity were observed.

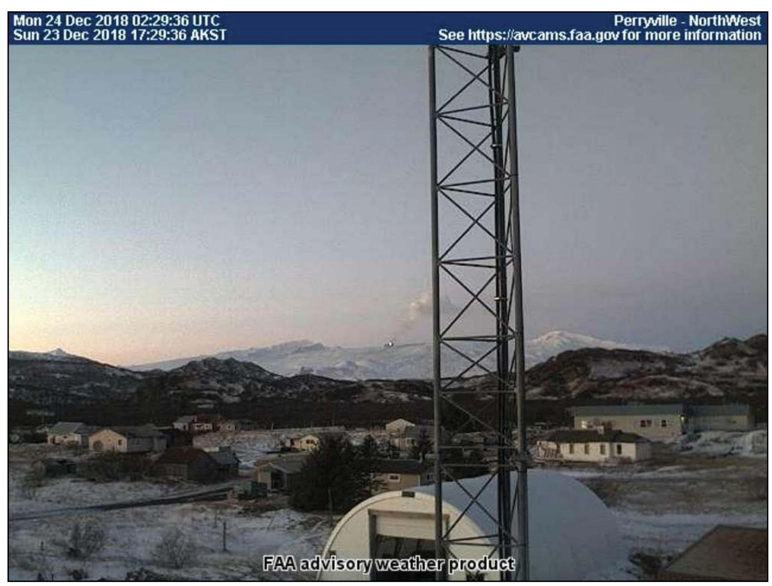

Figure 26. Image of incandescence and steam plume at cone A on Mount Veniaminof, Alaska, on December 23, 2018 (Alaska standard time). Image from the Federal Aviation Administration Perryville northwest web camera. Cone A is about 35 kilometers north of Perryville.

Eruptive Products and Processes

The primary eruptive products generated by the 2018 eruption were tephra (ash, bombs, spatter) and lava flows. Most of what is known about these products comes from remote observations obtained from satellite images, photographs, and video. A brief field visit to the volcano in July 2019 permitted some documentation and sampling of the lava flows and tephra deposits close to cone A (Loewen and others, 2019). Some preliminary observations from this work are reported below.

The 2018 Mount Veniaminof eruption had several noteworthy characteristics that were documented by seismic and infrasound data, augmented by observations obtained from satellite data, web-camera images, and occasional aerial photographs and video recordings. Among the main features of the eruption were: (1) continuous eruption tremor: (2) periods of sustained lava effusion, sometimes accompanied by lava fountaining; (3) burst-like ash emissions, typically lasting for tens of minutes; and (4) occasional explosions detected in seismic and infrasound data. Lava effusion and explosive ash emission occasionally occurred at the same time from separate but closely spaced vents (figs. 19, 20).

Tephra Fallout

The 2018 eruption was not a particularly explosive eruption and, although numerous ash clouds were generated, the extent of measurable tephra fallout was limited (fig. 27). Trace amounts of ash (<0.1 millimeter [mm]) fell on Perryville on October 25 and November 21–22 (AKST) during moderate

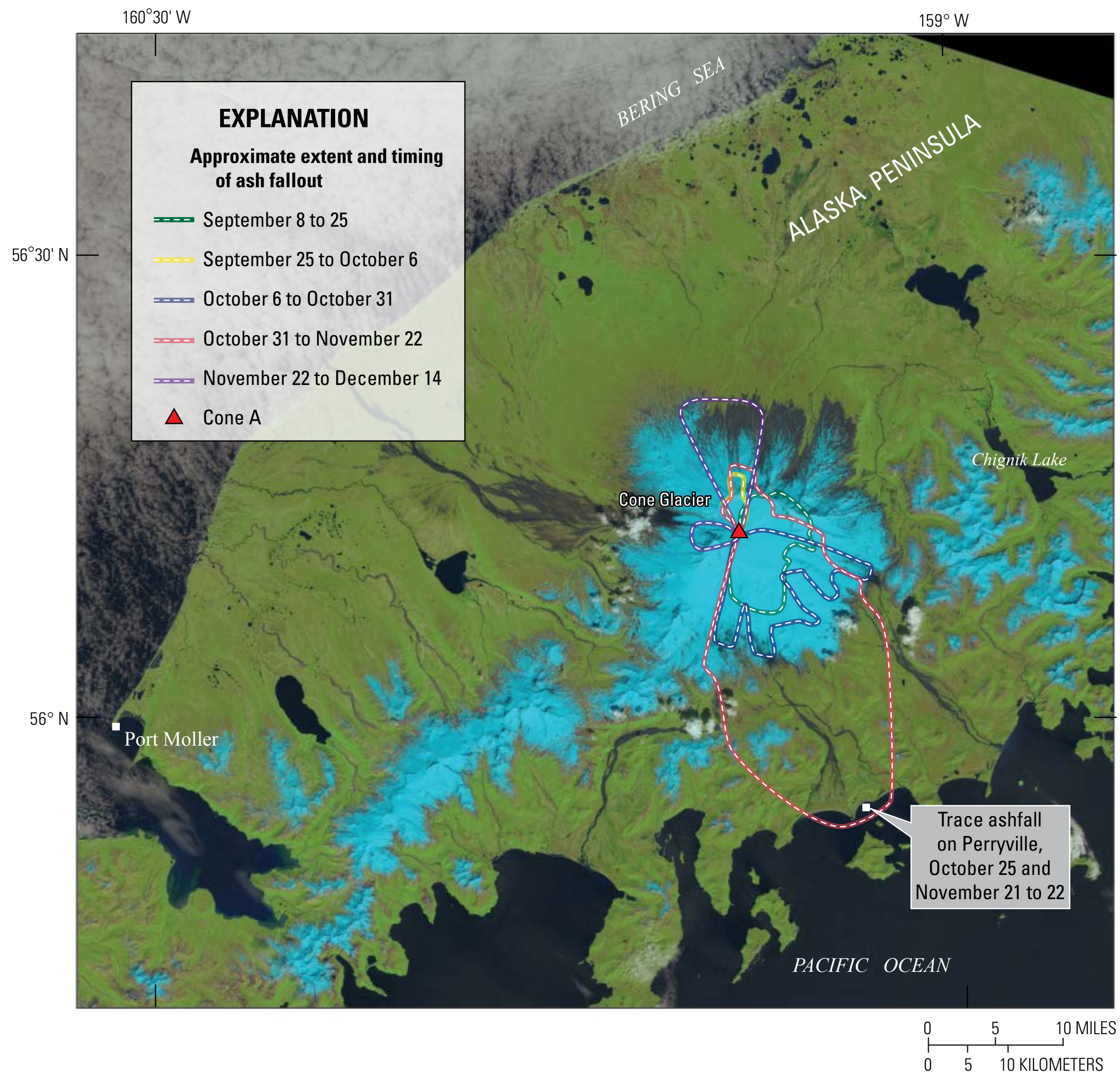

Figure 27. Map showing the approximate extent and timing of ash fallout during the main ash-producing phases of the 2018 eruption of Mount Veniaminof, Alaska. Base image is a Landsat-8 satellite image from June 12, 2018.

ash-producing events. Most of the fallout was confined to the Mount Veniaminof edifice itself and generally did not extend more than about 24 km beyond cone A (fig. 27). Determining the timing of ashfall was challenging because it required acquisition of a clear satellite image soon after an ashfall event, which was rarely possible. Thus, the extent of ashfall shown on figure 27 is approximate. Given the composite extent of ashfall and assuming an average ash thickness of 0.1 mm, a ballpark estimate of the amount of ashfall is on the order of 20,000–30,000 m^3 and an erupted mass of about 6×10^7 to 8×10^7 kilograms (kg), which is reasonable for low-level Strombolian activity of the type observed at Mount Veniaminof.

A record of 2018 ashfall deposits is preserved in the snow surrounding cone A, and at least seven distinct scoriaceous fall layers of basaltic andesite composition are present (fig. 28). However, it is uncertain how many of these layers might be composite, representing several ash-fall events during a period with no intervening snow falls. Analyses of these ash samples are ongoing (Loewen and others, 2019).

Eruption Magnitude

The explosive character of an eruption, and thus its general magnitude, is indicated by the Volcanic Explosivity Index (VEI; Newhall and Self, 1982). A VEI value is assigned to an eruption based on the following criteria, listed in order of importance: ejecta volume, column height, type of activity, and duration of explosive ash emission (Newhall and Self, 1982). The VEI value reported for an eruption should be determined from the largest single event of the eruptive period, if possible (Newhall and Self, 1982; Houghton and others, 2013). The criteria used to estimate the VEI of the 2018 eruption of Mount Veniaminof are given in table 1. The ejecta volume (tephra and ash) for individual explosive ash-producing events is not known. An order of magnitude estimate of the total ejecta volume for the 2018 eruptive period is 2×10^4 to 3×10^4 m^3; individual explosive events would have ejecta volumes less than this. Based on ejecta volume, the 2018 eruption would rank as having a VEI of 0–1. The maximum height reached by an ash cloud occurred on October

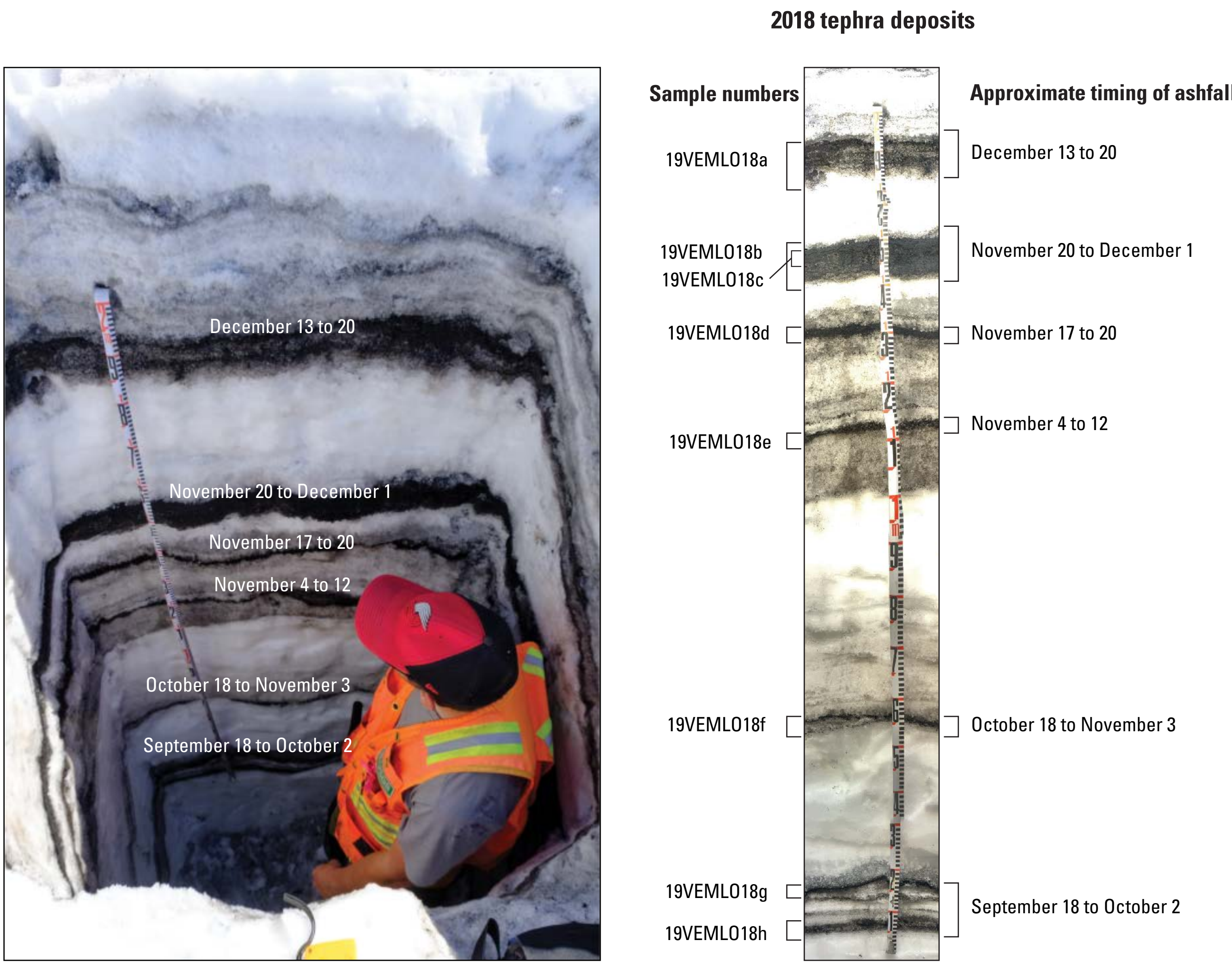

Figure 28. Photographs showing tephra-snow stratigraphy in a hand-dug pit near cone A on Mount Veniaminof, Alaska, on July 2, 2019. U.S. Geological Survey photographs by Hannah Dietterich and Matthew Loewen.

Table 1. Criteria used to estimate the Volcano Explosivity Index (VEI) of the 2018 Mount Veniaminof, Alaska, eruption.

[km, kilometer; m^3, cubic meters]

Criteria	Values	VEI estimate
Total ejecta volume, m^3	2×10^4 to 3×10^4	1
Single-event ejecta volume, m^3	Unknown	≤1?
Maximum column height, km	6.1	3
Qualitative description	Effusive to explosive	1–2
Classification	Low-level Hawaiian lava fountaining to minor Strombolian explosions	1–2
Duration of continuous ash emission, hours	<1	1–2

18 and was about 6,100 m above sea level. Based on ash column height alone, the 2018 eruption would rank as having a VEI of 2–3. By all other criteria, the 2018 eruption has a VEI of 1–2. Given the uncertainties in estimating the ejecta volume, it seems reasonable to conclude that a VEI of 1–2 best fits the observed eruption characteristics of the 2018 activity.

Seismicity During Lava Effusion and Ash Emission

Steady non-harmonic tremor with occasional bursts of stronger tremor (lasting tens of seconds to minutes) occurred throughout the approximately 114-day eruption. Non-harmonic tremor is a common eruptive seismic signal at many Aleutian Arc volcanoes, including Pavlof Volcano (McNutt, 1987), Shishaldin Volcano (Thompson and others, 2002), and Mount Veniaminof (De Angelis and McNutt, 2007). The tremor signal is related to continuous ground vibration caused by movement of fluids (magma and gas) within the volcanic edifice (McNutt and Nishimura, 2008; Chouet and Matoza, 2013). Commonly, strong continuous tremor is associated with lava effusion.

At times throughout the eruption, tremor transitioned into swarms of long-period earthquakes that were also related to the movement of fluids, often directly back to tremor (Chouet, 1988; Neuberg and others, 2000; McNutt, 2005). The tremor observed during the first several hours of the eruption was mostly harmonic. Short periods of harmonic tremor also were observed at other times during the early and late part of the eruption (fig. 29). Several processes in volcanic conduits can produce harmonic tremor; a common explanation is resonance or oscillation within fluid-filled cracks (Chouet 1988; Fujita and others, 1995; Schlindwein and others, 1995; Montegrossi and others, 2019). Harmonic tremor during the 2005 Mount Veniaminof eruption was explained as the result of a resonating gas-filled conduit (De Angelis and McNutt, 2007). The same mechanism likely produced the harmonic tremor observed during the 2018 eruption. Given that explosive activity was noted prior to the onset of lava effusion, it is plausible that conduit was initially plugged. As magma entered a plugged conduit and exsolved gas built up, pressure perturbations may have induced standing waves that resonated within the conduit system.

Bursts of tremor and low-frequency seismic events were common during the last two weeks of December 2018 as the eruption was coming to an end. This type of seismicity continued intermittently into 2019 but was not related to any known eruptive activity. Ground-coupled airwaves indicative of small discrete explosions were detected only on September 25–26 and December 11, and infrasound signals, both discrete and continuous, were detected on an array in Dillingham (fig. 1) on November 19–22 and 30 and December 14–16. However, the detection of infrasound and ground-coupled airwaves is strongly dependent on atmospheric conditions, and weaker signals could have been masked by wind and other noise sources.

The steady, non-harmonic tremor observed throughout the 2018 eruption is correlative with sustained lava effusion, whereas the burst-like seismicity and ground-coupled airwaves indicate explosive activity and tephra emission. Periods of moderate ash emission occurred on September 5, October 18, November 4–5, November 6–19, and November 21–22. During these times, ash clouds reached 2,000–6,000 m above sea level and extended as far as 400 km beyond the vent. The ash emissions on November 21–22 corresponded with an increase in eruption tremor amplitude. Infrasound signals were not clearly related to all of the ash emission events, but infrasound was detected at the Dillingham array several times during November 19–22.

Satellite Observations of Lava Effusion

The onset of lava effusion was confirmed with satellite data on September 6–7, when mid-infrared satellite images showed elevated surface temperatures indicative of lava at the surface of cone A. Incandescence associated with low-level lava fountaining was first observed in web-camera images from Perryville on September 7. By December 27, 2018, seismic and satellite data indicated that lava effusion had likely ceased. Thus, the period of lava effusion lasted approximately 111 days from September 7 to December 27 (table 2). It is possible that lava effusion ceased as early as December 15 based on satellite observations. However, minor ash emissions were observed in web-camera images from Perryville through December 17, and incandescence associated with possible lava effusion was observed in web-camera images on December 23–24, indicating that eruptive activity continued into late December.

During the period September 7–December 27, about 600,000 m^2 of lava was erupted, and the cumulative increase in area covered by lava was approximately linear (fig. 30). Assuming an average lava-flow thickness of 2–3 m, the total bulk volume of lava erupted was 1.2×10^6 to 1.8×10^6 m^3. Using these values, the average effusion rate was 10,800–16,200 cubic meters per day (m^3/d) or 0.1–0.2 cubic meters per second (m^3/s). The greatest rate of lava effusion estimated

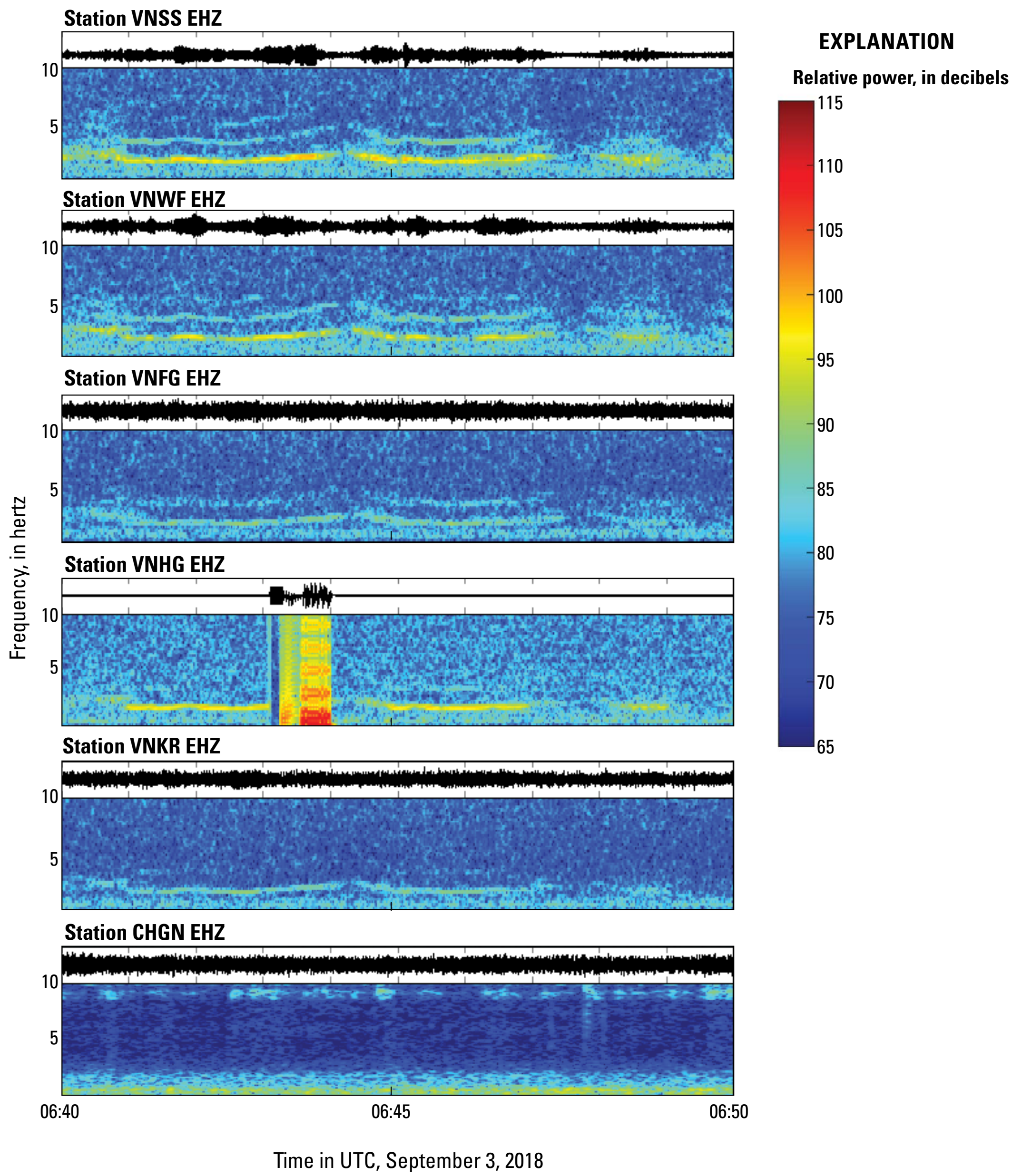

Figure 29. Plots showing examples of harmonic tremor detected by the Mount Veniaminof seismic network, September 3, 2018. See figure 1 for location of seismic stations. UTC, coordinated universal time. EHZ refers to a short-period seismometer with a single vertical component. All seismic data were downloaded from the Incorporated Research Institutions for Seismology (IRIS) Wilber 3 system (https://ds.iris.edu/wilber3).

from the mapped extent of lava flows was about 0.3 m^3/s over the period September 11–24 (fig. 31).

Lava discharge during the 2018 eruption also was analyzed using high-resolution VIIRS mid-infrared and thermal-infrared satellite data to detect thermal anomalies relative to ambient background temperatures. The VIIRS thermal time series indicates the first thermal anomaly at 11:50 UTC (3:50 Alaska daylight time [AKDT]) on September 2, prior

Table 2. Lava-flow characteristics and estimated lava-effusion rates determined from satellite observations of Mount Veniaminof, Alaska.

[m, meter; m^2, square meter; m^3, cubic meter; m^3/d, cubic meter per day; m^3/s, cubic meter per second]

Date	Area (m^2)	Average thickness (m)	Cumulative lava volume (m^3)	Lava volume added (m^3)	Period (days in 2018)	Effusion rate (m^3/d)	Effusion rate (m^3/s)
Sept. 11, 2018	50,600	1	50,600	50,600	Sept. 7–Sept. 11 (5 days)	10,120	0.12
Sept. 24, 2018	170,000	2	340,000	289,400	Sept. 11–Sept. 24 (13 days)	22,260	0.3
Oct. 3, 2018	184,300	2	368,600	28,600	Sept. 24–Oct. 3 (9 days)	3,180	0.04
Oct. 25, 2018	385,000	2	770,000	401,400	Oct. 3–Oct. 25 (23 days)	17,450	0.2
Nov. 5, 2018	385,000	2	770,000	0	No change	No change	No change
Nov. 9, 2018	457,000	2	914,000	144,000	Oct. 25–Nov. 9 (15 days)	9,600	0.11
Nov. 19, 2019	540,000	2	1,080,000	166,000	Nov. 9–Nov. 19 (10 days)	16,600	0.2
Dec. 27, 2018	600,000	2–3	1,200,000	120,000	Nov. 19–Dec. 27 (38 days)	3,160	0.04
Totals and ranges	**600,000**	**2–3**	**1,200,000–1,800,000**	–	**Sept. 7–Dec. 27 (113 days)**	**10,620–15,930**	**0.12–0.18**

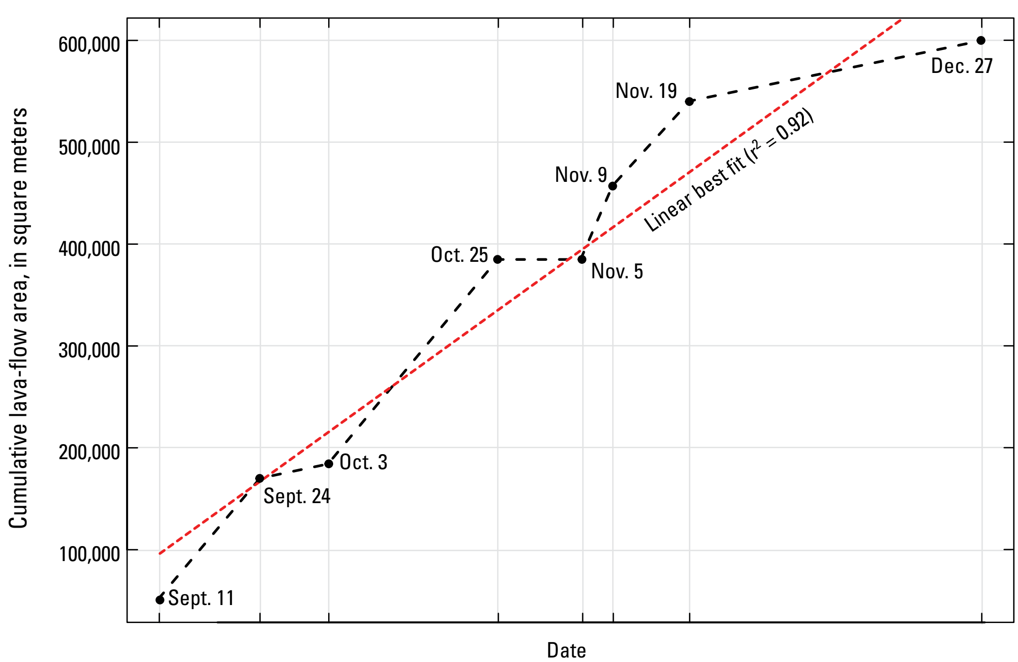

Figure 30. Plot showing cumulative lava-flow area as determined from satellite images of Mount Veniaminof, Alaska, from September 11 to December 27, 2018.

to the onset of tremor observed later in the day on September 2. The total volcanic radiative power (a measure of the total thermal output within the detected anomaly) is shown in figure 32. The number of pixels in VIIRS mid-infrared images above background temperature (anomalous pixels) through time is shown in figure 33. During the early part of the eruption on September 4–7, thermal output was minor, although the area of the thermal anomaly, as indicated by the number of anomalous pixels, increases over this period. After September 7, when lava effusion began, the total radiative power and number of anomalous pixels also increased (figs. 32, 33). Short-term fluctuations in thermal output from mid-September to late December likely reflect variations in cloud cover. During this period, the seismic tremor that is correlative with effusive activity (described in the previous section) was relatively continuous, indicating that the lava output was also relatively continuous. Many of the peaks in radiative power and number of anomalous pixels during October are broadly similar to

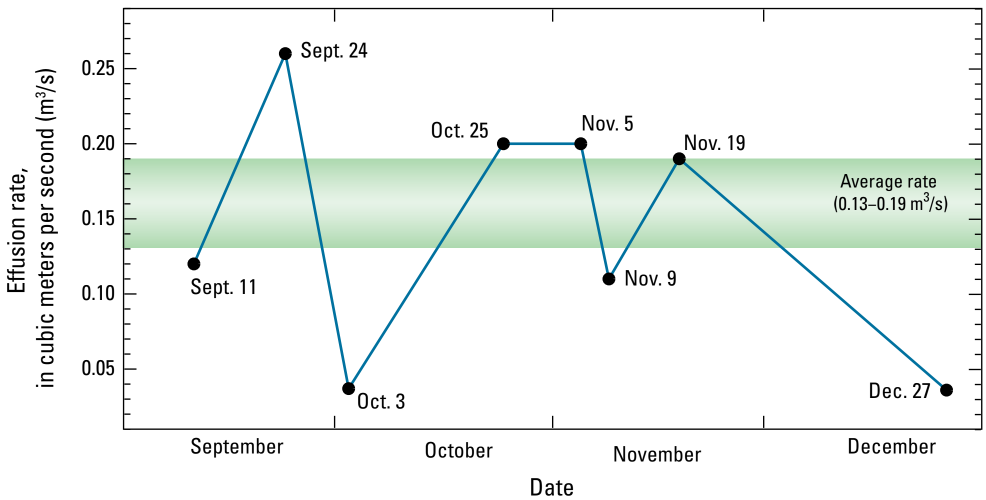

Figure 31. Plot showing estimated lava-effusion rate versus time for the 2018 Mount Veniaminof, Alaska, eruption.

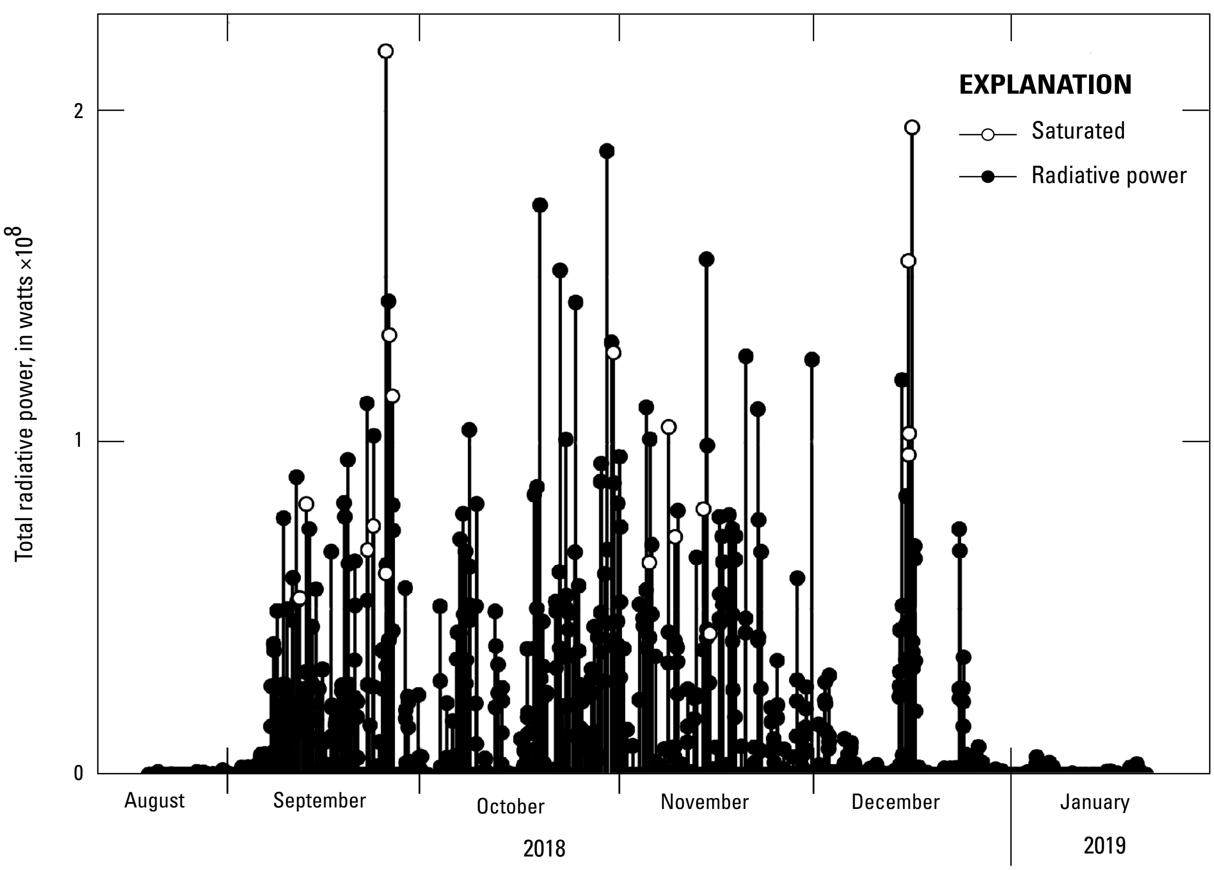

Figure 32. Plot showing thermal time series of the 2018 eruption of Mount Veniaminof, Alaska, derived from Visible Infrared Imaging Radiometer Suite mid-infrared satellite data.

values detected on clear days earlier in the eruption, indicating that the thermal output was relatively steady.

The satellite-derived heat output is converted to time-averaged discharge (fig. 34) using methods described by Coppola and others (2012, 2016). This conversion permits an estimate of the lava volume erupted over time. The cumulative lava discharge for the 2018 eruption is shown in figure 35. The two curves represent a daily time-averaged discharge calculated from the maximum and mean observed each day (Coppola and others, 2016). Portrayed this way, lava effusion shows some fluctuations from steady-state behavior. Assuming 111 days of lava effusion, the average lava-effusion rate is about 0.3 m^3/s using the daily mean flux. Using the maximum daily flux, the average lava effusion rate is 0.7 m^3/s. These estimates give a total bulk erupted volume of 3.2×10^6 to 6.8×10^6 m^3, which is comparable to the value of 1.2×10^6 to 1.8×10^6 m^3 estimated from the lava-flow area multiplied by an average thickness of 2–3 m. The satellite-derived estimates of volcanic radiative power (fig. 32) have an uncertainty of about ±30 percent (Coppola and others, 2012) largely owing to cloud cover; thus, these values are order-of-magnitude estimates of thermal output. The total volume of lava erupted during the 2018 eruption based on the two methods described above is on the order of 10^6–10^7 m^3.

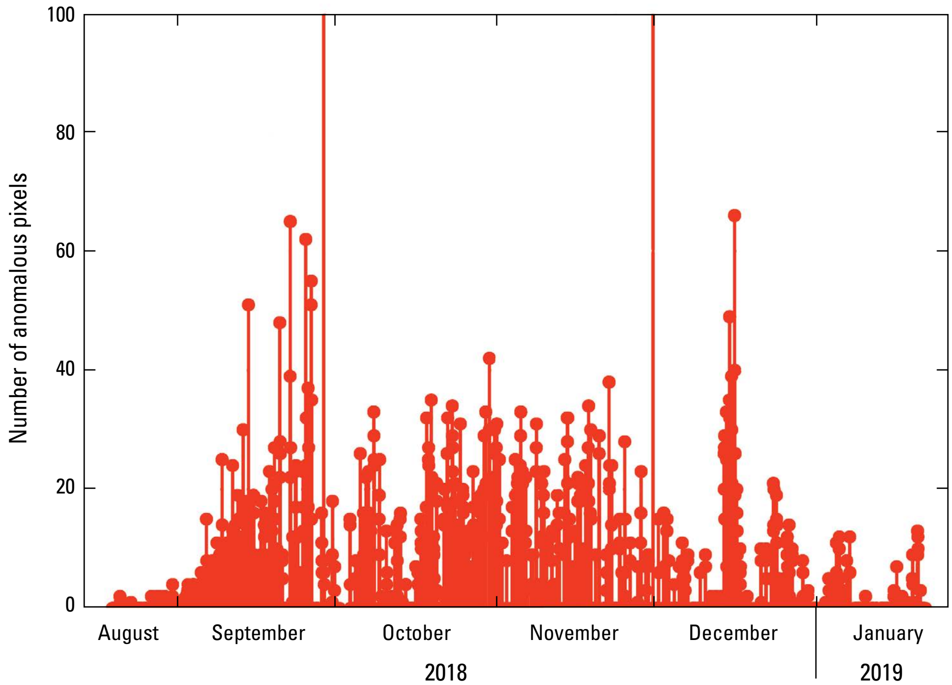

Figure 33. Plot showing the number of pixels above background (anomalous pixels) detected in Visible Infrared Imaging Radiometer Suite mid-infrared satellite data during the 2018 eruption of Mount Veniaminof, Alaska. Two values plot anomalously high and are cut off on this plot to allow the rest of the data to be visible.

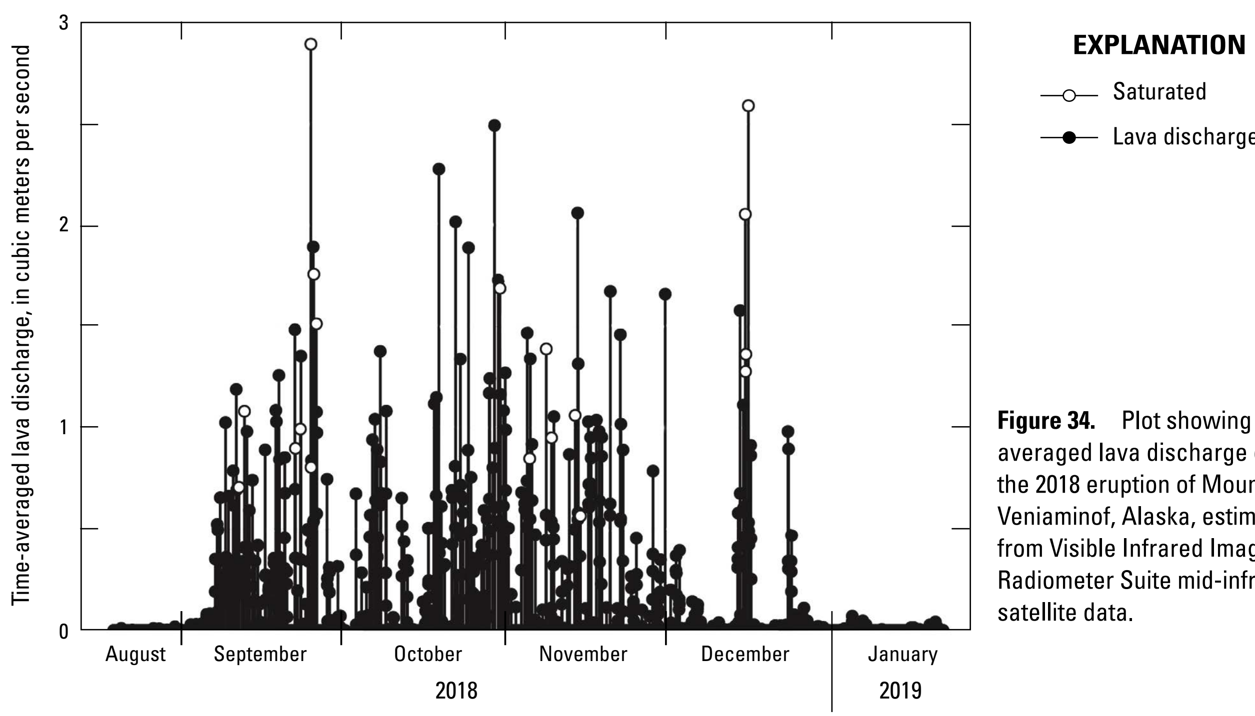

Figure 34. Plot showing time-averaged lava discharge during the 2018 eruption of Mount Veniaminof, Alaska, estimated from Visible Infrared Imaging Radiometer Suite mid-infrared satellite data.

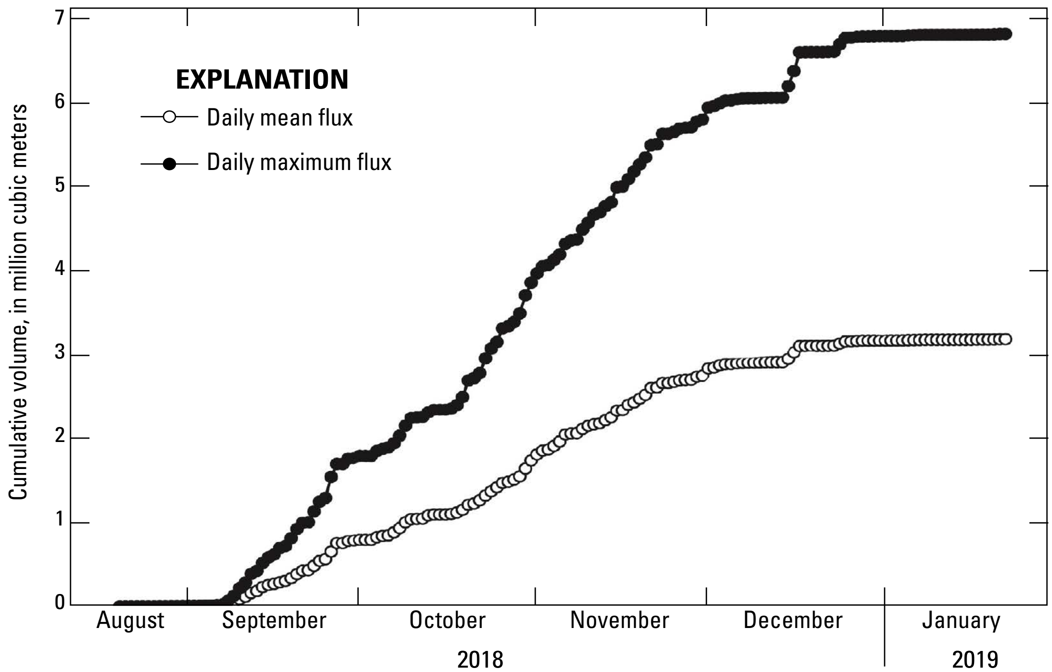

Figure 35. Plot showing cumulative lava volume erupted during the 2018 eruption of Mount Veniaminof, Alaska, derived from Visible Infrared Imaging Radiometer Suite mid-infrared satellite data.

Simultaneous Effusive and Explosive Activity

A high-resolution satellite image obtained on September 11 and aerial photographs obtained on September 26 (fig. 36) showed two distinct sets of active vents on cone A. One set was confined to the summit crater of the cone and was the origin of explosive ash and gas emissions, minor lava fountaining, and spattering. The second set of vents was located on the upper south flank of cone A, about 50–100 m south of the rim of the summit crater and at least 10 m lower in elevation (fig. 36). These two vent locations erupted simultaneously, with the summit area generating mostly ash and the flank location only effusive lava flows. Simultaneous explosive and effusive activity are characteristic of some cinder cone eruptions (Pioli and others, 2008) and has been observed at Etna in Italy (Spampinato and others, 2008) and at Paricutín Volcano in Mexico (Krauskopf, 1948). The simultaneous eruption of two related vents implies shallow gas-magma segregation within the conduit network (Krauskopf, 1948; Behncke and Neri, 2003; Pioli and others, 2009).

A conceptual model of the geometry of the magma-conduit system at cone A of Mount Veniaminof is shown in figure 37. This model shows a bifurcated conduit network that is a shallow feature of the magmatic system, likely not more than 1 km below the surface and possibly as shallow as a few tens of meters depth. Earthquake locations, the source area for tremor and occasional explosions, all occur within the upper 0.5–1 km of Mount Veniaminof's conduit system (DeAngelis and McNutt, 2007).

The shallow-magma delivery system is envisioned as having a T-junction geometry. Magma-flow separation at conduit T-junctions was examined by Pioli and others (2009). They found that this type of conduit geometry can affect the distribution of liquid and gas phases, such that exsolved gas stays within the larger, vertically oriented conduit and drives explosive activity at summit vents above. Smaller diameter lateral dikes feeding flank vents in this scenario would be gas-poor by comparison and erupt effusively. This type of conduit geometry could influence the explosivity of magma ascending a vertical conduit above the T-junction, because magma in this zone likely would be enriched in volatiles (Pioli and others, 2009). That we observe explosive activity only at the summit crater vents and not at flank vents supports this inference.

Measurements of the intracaldera-cone summit and flank vent geometry made from high-resolution satellite images (<1 m pixel resolution) indicate that the summit vents are on the order of 5–10 m in diameter and have areas of approximately 25–100 m^2. The flank vents are smaller, measuring 1–2 m in diameter and 1–4 m^2 in area. Using the estimated effusion rates derived from satellite observations (table 1) and the above measurements for maximum vent area, approximate exit speeds for magma reaching the summit vent are on the order of 0.001 meters per second (m/s) (for a vent area = 100 m^2) and 0.03 m/s for magmas exiting the flank vents (for a vent area = 4 m^2). The rise speed of magma reaching a vent has been related to the predominant eruptive style as either Hawaiian or Strombolian in a series of studies summarized by Parfitt (2004). Hawaiian eruptions are longer lived events that can produce spectacular lava fountains, sometimes rising up to 1 km above the vent (Wolff and Sumner, 2000). Observations presented by Parfitt (2004) indicate that Hawaiian-style eruptions have associated magma-rise speeds that range from 0.09 to 0.9 m/s (average = 0.51 m/s for 4 measurements [$n = 4$]). Strombolian eruptions are characterized by small to moderate scale intermittent explosions associated with the accumulation of exsolved gas in pockets or slugs beneath a cooled layer at the top of a magma column (Taddeucci and others, 2015). Rise-speed measurements tabulated by Parfitt (2004) indicate that Strombolian eruptions have associated rise speeds that range from 0.0035 to 0.01 m/s (average = 0.016 m/s, $n = 4$). The estimated magma-rise speeds for summit and flank vent activity at cone A show a difference that is somewhat consistent with the measurements presented by Parfitt (2004). The estimates presented here are general approximations based on measurements made from satellite images and are less well constrained than the rise-speed measurements given by Parfitt (2004). The difference in magma flux and observed behavior among the two vent locations could be a result of differing conduit geometry and its associated role in influencing the partitioning of gas and magma during ascent to the surface in a bifurcated conduit system (fig. 37).

The escape of volatiles from rising magma is an additional factor controlling the explosivity of an eruption. The study by Pioli and others (2009) showed that for the T-junction conduit geometry, magmatic gas can be preferentially distributed into the vertical section of the conduit unless the pressure at the T-junction is large, the lateral dike is wide, or both. Gas only

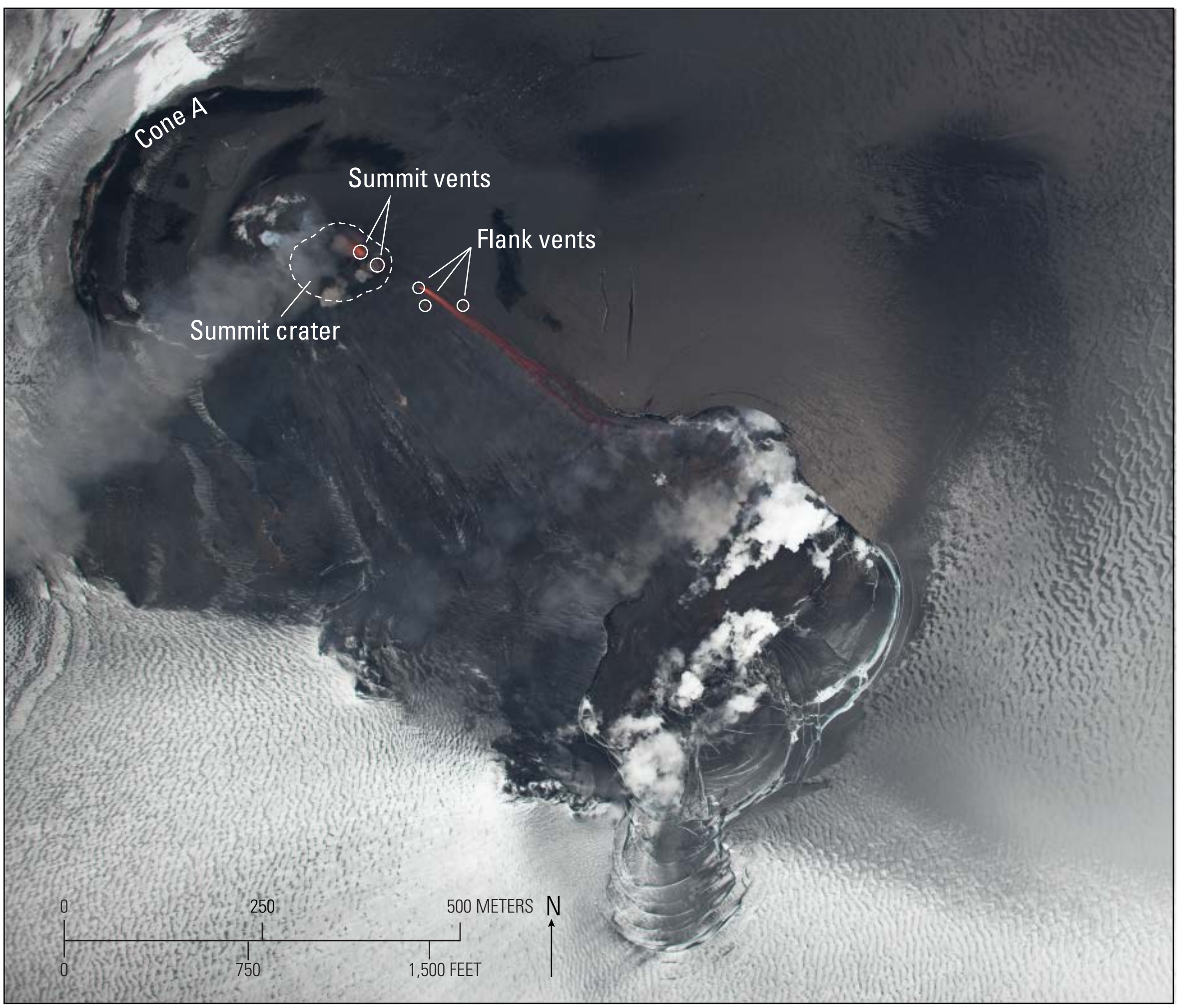

Figure 36. Vertical aerial photograph of cone A on Mount Veniaminof, Alaska, on September 26, 2018. Note the multiple vents on the intracaldera cone. U.S. Fish and Wildlife Service photograph by Mark Laker.

accumulates in the lateral dike when the volatile volume flux is low relative to the volume flux of the magma (Pioli and others, 2009). Lateral vent activity at cinder cones should occur when the mass eruption rate is low (<10^3 kilograms per second [kg/s]; Pioli and others, 2009). For the 2018 Mount Veniaminof eruption, the average mass eruption rate was approximately 6×10^2 kg/s and apparently low enough for effusive lateral-vent activity.

Lava-Ice Interaction

Lava flows erupting from as many as four small vents on the upper south flank of cone A were observed in a GeoEye-1 satellite image acquired on September 11, 2018 (fig. 6). The lava flow in this image covers an area of about 50,600 m^2 and the length of the flow is about 680 m. No significant ice melting is evident in the September 11 satellite image even though part of the flow extends over snow and underlying crevassed glacier ice (fig. 6). Taking September 7 as the starting date for lava effusion, the average flow rate during September 7–11 is 136 meters per day. At this rate, it would take about 2.4 days for the flow to reach the base of cone A and begin flowing over snow and ice (thickness unknown, but likely 1–10 m thick). The implication is that the lava flow could have been over snow and ice for about 2.5 days but still showed no obvious outward signs of significant melting. This suggests that there must have been a shallow thermal gradient from the core of the lava flow to its base. It is plausible that an insulating basal breccia layer had developed, similar to those described by Edwards and others (2012) during the 2010 Fimmvörðuháls eruption in south-central Iceland.

An aerial photograph of cone A from September 14 also shows no apparent steaming from lava flows resting on snow at the base of the cone (fig. 7). The viewing direction in the photograph is toward the west and not directly at the lava flow, so it is possible that any steam present is not observable,

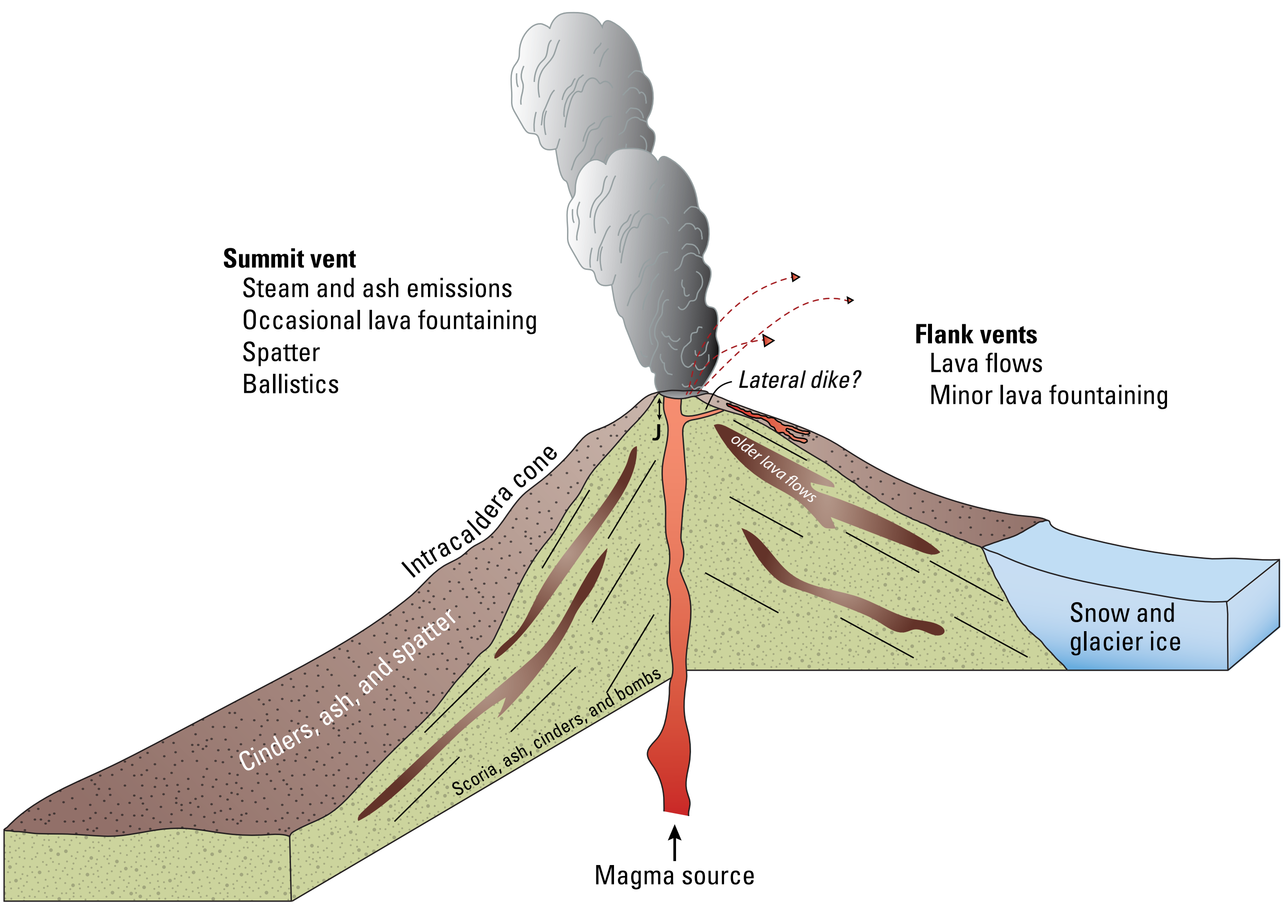

Figure 37. Diagram showing a conceptual model of the magmatic system feeding the summit and flank vents at cone A of Mount Veniaminof, Alaska. The depth of junction "J" is not known, but likely is within the upper 0.5–1 kilometers of the cone.

although no large, robust steam plumes are evident. However, a Sentinel-2 satellite image obtained 2 days later, on September 16, clearly shows a prominent steam plume issuing from the terminus of the lava flow (fig. 8), indicating melt was occurring by that time, approximately 6–7 days after lava reached snow and ice. However, the September 16 satellite image indicates that the active lava flow turned slightly southwest as a lava splay where it encroached on fresh snow and ice, which could have resulted in direct lava-snow/ice interaction. This lobe is slightly shorter in length than the lava flow observed in the September 11 satellite image and did not extend as far down the flank of cone A.

Melt depressions in glacier ice at the base of cone A were evident in a Landsat 8 satellite image obtained on September 25 (fig. 10). This was confirmed with aerial photographs taken on September 26 (fig. 11) by our colleagues in the U.S. Fish and Wildlife Service and the National Park Service who were doing a structure-from-motion survey of cone A and the ice-filled Mount Veniaminof caldera. Photographs taken during the overflight clearly showed the development of melt depressions peripheral to the lava flows and robust steaming along the lava flow margins where they were in direct contact with ice and snow (fig. 36).

A WorldView-3 satellite image obtained on October 3, 2018, showed continued advance of lava, additional development of melted areas on the glacier, and expanded areas of concentric depressions just beyond the lava flows (fig. 12). Robust steaming, possibly associated with boiling, is apparent along the southeast margin of the flow but ponded water is not apparent in the October 3 satellite image.

Intermittent lava effusion throughout October and early November increased the lava-flow area to 385,000 m^2 as determined from a WorldView-2 satellite image obtained on November 5 (fig. 19). This image indicates that active lava flows were nested above previously emplaced flows that had partial snow cover.

Clouds obscured Mount Veniaminof and cone A until early December 2018 when a Sentinel-2 image obtained on December 5 showed robust steaming associated with the advance of lava flows down the southeast and southwest flanks of cone A (fig. 25). By December 27, declining levels of seismic tremor and limited evidence for lava effusion in satellite data indicated that the eruption had ended, and observations of steaming became less frequent into 2019.

It was not possible to make field measurements of the depth of ice melt associated with lava flow emplacement over snow and ice, so it was estimated from photographs and satellite images to be 1–2 m, which is probably a minimum depth. If we take the total lava-flow area (600,000 m^2) and these estimates of ice melt depth, the approximate amount of ice melted is at least 0.6×10^6 to 1.2×10^6 m^3 or approximately 5,000–10,000 m^3/d. This works out to be an average melt rate of 10×10^{-6} to 20×10^{-6} m/s, which is broadly comparable to the melt rates associated with subaerial lava flows extending over glacier ice calculated by Wilson and Head (2007).

Discussion

The 2018 eruption of Mount Veniaminof lasted about 114 days from early September until late December. During this activity, lava flows were erupted from multiple, but closely clustered, flank vents on the upper south side of cone A, while intermittent ash and gas emissions occurred from vents within the summit crater of the cone. These two disparate styles of eruptive behavior (mild Strombolian ash emissions and passive lava effusion) often occurred simultaneously. The lava flows slowly melted into the snow and ice that surrounds cone A but did not generate significant amounts of meltwater. Analysis of satellite images showed that no unusual water flows occurred in the Cone Glacier and Muddy River drainage, the closest drainage to cone A (fig. 1).

Lava effusion was underway by September 7, but it took approximately 6–7 days after lava reached snow at the base of cone A for outward signs of ice melt to be recognized in photographs and satellite images. Circular melt depressions peripheral to the lava flows were first evident in a satellite image obtained on September 25 and confirmed with photographs taken on September 26 (fig. 11).

The simultaneous eruption of lava and ash from two different vent locations, as observed during the 2018 eruption, is characteristic of historical eruptions at cone A. This also occurred during the 2013 and 1983–1984 eruptions (fig. 38) and probably during the 1944 and 1993–94 eruptions, although these last two events are less well documented (Neal and others, 1996). The observations of simultaneous activity indicate that a bifurcated conduit network is probably a characteristic feature of cone A at Mount Veniaminof. This has important implications for the generation and remote detection of seismicity and infrasound during eruptions as each source should have a unique seismic-acoustic signature.

The remote location of Mount Veniaminof precluded on-site field documentation of tephra fallout until about 7 months after the eruption ended (Loewen and others, 2019). Thus, the total mass of tephra erupted and the time frame for tephra accumulation are not known with any degree of certainty. Based on the extent of tephra fallout observable in satellite images, the approximate amount of tephra fall is on the order of 20,000–30,000 m^3 and the erupted mass about 6×10^7 to 8×10^7 kg. The effusion-rate calculations (table 2) indicate an average mass-eruption rate of about 6×10^2 kg/s. Including an estimate for the mass-eruption rate for tephra would not change this value appreciably.

Data compiled by Pioli and others (2009) indicate that simultaneous eruption of lava and tephra at arc volcanoes occurs over a narrow range of mass-eruption rates on the order of 10^3–10^5 kg/s. Based on the information presented here, it appears that simultaneous eruption of lava and tephra can occur at mass eruption rates slightly less than 10^3 kg/s, although, as mentioned above, the mass-eruption rate for ash emissions is not well constrained and thus not included in the mass-eruption rate estimate.

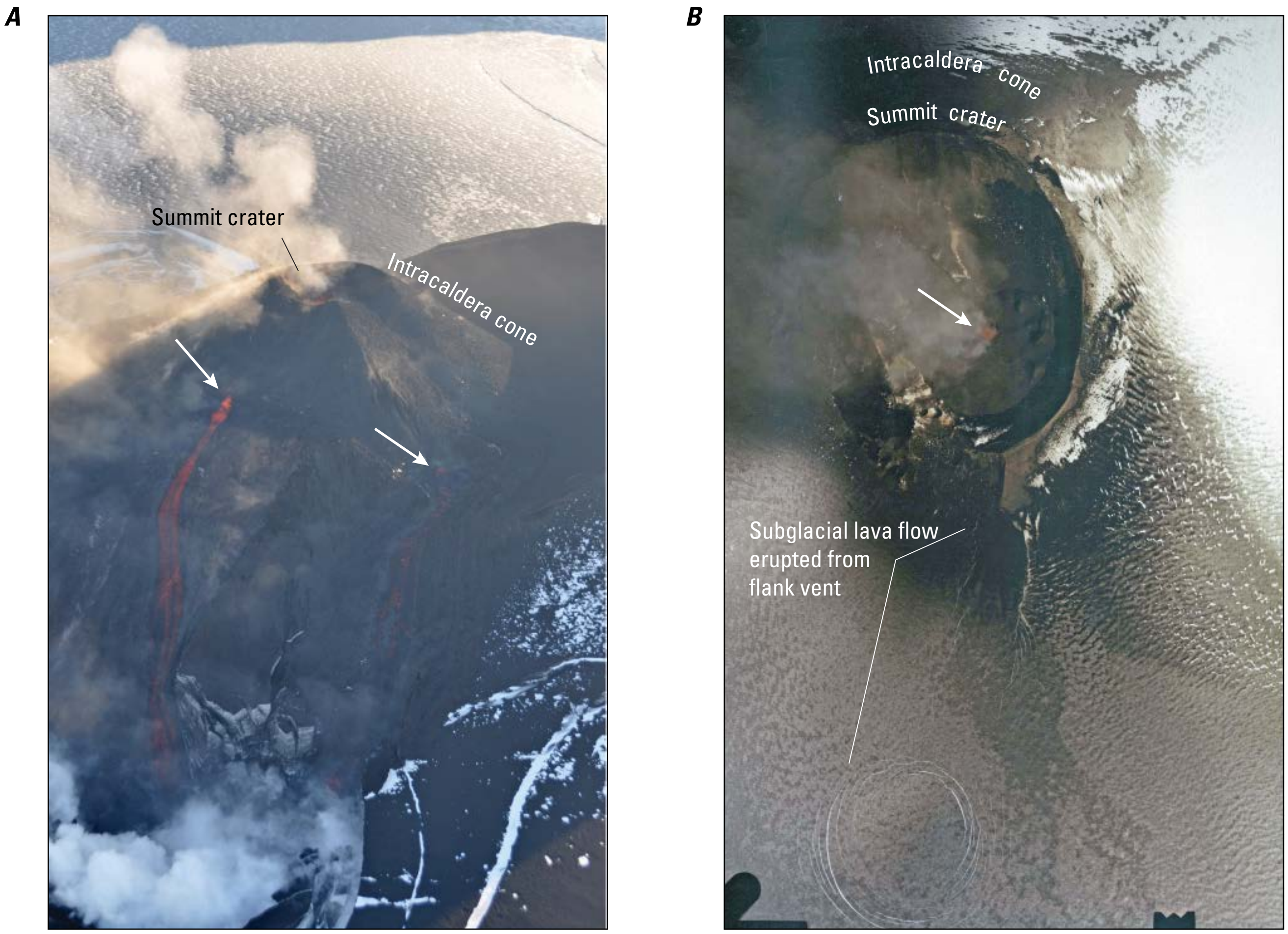

Figure 38. Photographs of cone A at Mount Veniaminof, Alaska, from 2013 (*A*) and 1983 (*B*). Both photographs show simultaneous activity from summit and flank vents. *A*, Two vents at the base of the intracaldera cone are erupting lava flows (white arrows), whereas the vents in the summit crater are generating intermittent spatter and ash. U.S. Geological Survey photograph by R. McGimsey, August 18, 2013. *B*, White arrow locates vent in summit crater with incandescent lava at surface. Subglacial lava flow has begun to form a small circular ice cauldron (~100 meters in diameter) and a graben-like linear depression on the south flank of the intracaldera cone. Aerial photograph from AeroMap, Inc., used with permission.

Conclusions

The 2018 eruption of Mount Veniaminof lasted about 114 days. The eruption began on September 6–7 and ended by about December 27. This eruption marked the 18th time the volcano has had documented historical eruptive activity, which was first recognized in 1830–1840. The 2018 eruption was characterized by effusive eruption of lava flows from multiple vents on the upper south flank of cone A and mild Strombolian explosive activity from vents in the summit crater of cone A. By the end of the eruption, lava flows covered an area of about 600,000 square meters (m^2) and had a volume of about 1.2×10^6 to 1.8×10^6 cubic meters (m^3) assuming an average lava-flow thickness of 2–3 meters (m). Using these values, the average effusion rate was 10,800–16,200 cubic meters per day (m^3/d) or 0.1–0.2 cubic meters per second (m^3/s). The greatest rate of lava effusion was 0.3 m^3/s over the period September 11–24. Lava-effusion rates derived from satellite-image thermal measurements indicate a slightly higher average daily effusion rate of 0.3–0.7 m^3/s, which yield a total bulk erupted volume of 3.2×10^6 to 6.8×10^6 m^3. These estimates indicate that the 2018 eruption produced about 10^6–10^7 m^3 of subaerial lava.

Lava flows erupted from vents on the upper part of cone A and eventually reached snow and ice at the base of the cone. It took approximately 6–7 days after lava reached snow for any outward signs of melting to be recognized in photographs and satellite images, although daily cloud-free imagery of the eruption was not available to confirm this. The total amount of snow and ice melted is about 10^6 m^3 based on 1–2 m of melt depth over the total area of the snow and ice field covered by lava. No flows of meltwater were observed exiting the eruption site because the rate of meltwater production was low. Meltwater generated by lava-ice interaction either boiled away as steam or seeped back into the substrate and probably refroze.

Ash emissions generated by explosive activity at the summit vents of cone A produced ash clouds that reached up to 6,000 m above sea level and were detected in satellite data as far as 400 kilometers beyond cone A. There were no known ash-aircraft encounters. Trace amounts of ash (<0.1 millimeter) fell on the community of Perryville on October 25 and November 21–22. Studies of samples of the ash collected during the eruption from Perryville, and later from snow excavations in July 2019 near cone A, showed the scoriaceous ashfall to be of basaltic andesite composition. Using observed criteria for eruption magnitude, the largest event of the 2018 eruption was a 1–2 on the Volcanic Explosivity Index.

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