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Eruption of Alaska Volcano Breaks Historic Pattern

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In the late morning of 12 July 2008, the Alaska Volcano Observatory (AVO) received an unexpected call from the U.S. Coast Guard, reporting an explosive volcanic eruption in the central Aleutians in the vicinity of Okmok volcano, a relatively young (~2000-year-old) caldera. The Coast Guard had received an emergency call requesting assistance from a family living at a cattle ranch on the flanks of the volcano, who reported loud "thunder," lightning, and noontime darkness due to ashfall. AVO staff immediately confirmed the report by observing a strong eruption signal recorded on the Okmok seismic network and the presence of a large dark ash cloud above Okmok in satellite imagery. Within 5 minutes of the call, AVO declared the volcano at aviation code red, signifying that a highly explosive, ash-rich eruption was under way.

AVO geologists observed the eruption from aircraft on 21 July and 2–3 August and found ash and steam plumes rising from several new explosion craters within the caldera's eastern sector. Satellite images revealed that the ash plume contained a high water fraction, making the Okmok eruption the first predominantly phreatomagmatic event in the United States since Ukinrek Maars, another Alaska volcano, erupted in 1977. Unlike Ukinrek, the 2008 Okmok eruption was one of relatively few such events monitored with ground-based instrumentation.

The 5-week-long Okmok eruption was unexpected because it was preceded by less than 5 hours of seismicity, noted by AVO scientists in hindsight as precursory. It had no notable short-term geodetic precursors, and as the eruption progressed the observed ash cloud heights were not always directly linked with the gross seismic amplitude. Satellite detection of volcanic ash also was difficult because of the plume's high water content, which obscures ash signals.

The complex, sudden, and water-rich nature of the Okmok eruption highlights important lessons for volcano monitoring, underscoring the importance of understanding what drives a volcano from quiet to explosive in only a few hours. Moreover, because Okmok is located along the busy North Pacific air routes, rapidly informing the aviation community of potential ash hazards is critical. As a result, improved monitoring techniques and alarm systems to capture extremely short duration seismic precursors, and better tracking of water-rich ash plumes via satellite methods, are important objectives for volcanology research.

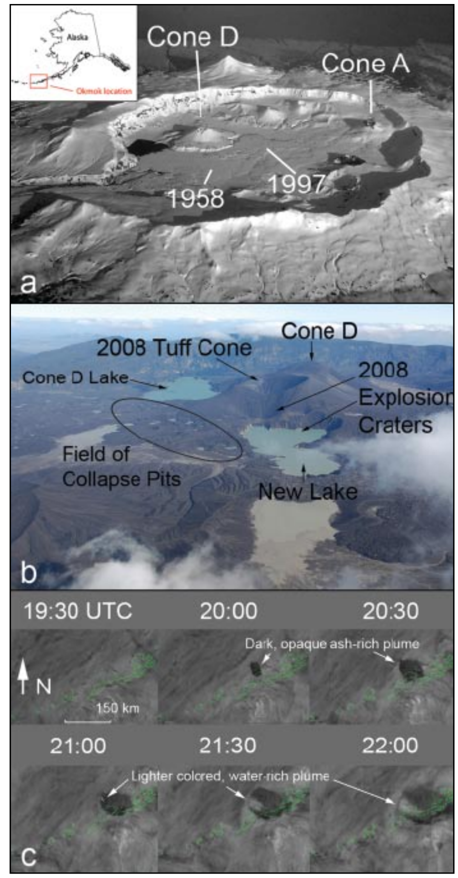

Fig. 1. (a) Photograph (looking south from north of the caldera) of Okmok caldera by Cyrus Read (Alaska Volcano Observatory (AVO)), showing Cones A and D, and the two most recent lava flows from Cone A from 1958 and 1977. The inset shows the approximate location of Okmok within Alaska. (b) Oblique aerial view showing the new tuff cone, explosion craters, lakes, and a field of collapse pits adjacent to Cone D. (c) Time series Geostationary Operational Environmental Satellite (GOES) visible satellite imagery from 12 July showing emergence of the first, dark, ash-rich plume and the second, white, water-rich plume. Images occur at 30-minute intervals, coordinated universal time (UTC).

Eruptive History, Monitoring, and Geophysical Observations

Okmok is one of the most active volcanoes in the Aleutian arc with 14 confirmed eruptions since 1817 [*Begét et al.,* 2005]. It consists of two nested calderas that formed about 12,000 and 2050 years ago, respectively. The three most recent eruptions, in 1945, 1958, and 1997, issued from Cone A (Figure 1a) in the southwestern margin of the caldera. The 1997 eruption produced modest ash clouds between 5 and 6 kilometers above mean sea level (AMSL) as well as lava flows crossing the caldera floor. In contrast, the 2008 eruption issued from several new explosion craters near approximately 1000-year-old Cone D (Figures 1a and 1b), and was highly explosive because of magma interactions with groundwater and surface water.

The 2008 eruption was the first at Okmok to be monitored by AVO using ground-based instrumentation. The AVO Okmok network consists of eight short-period and four broadband seismometers interlocated with four continuous Global Positioning System (GPS) stations. At the time of eruption, only two continuous GPS stations were operational. However, fixed-duration, "campaign" GPS surveys have been conducted at Okmok most summers since 2000 using 32 benchmarks within and outside the caldera. Real-time seismic and geodetic monitoring began in April 2003, recording 198 earthquakes with magnitudes of up to 2.0 before the eruption. Frequent periodic tremor occurred during volcanic inflation as the crustal reservoir that supplied magma during the 1997 eruption refilled.

The 2008 eruption was notable for its extremely short period of precursory activity. During the 2 months prior, Okmok

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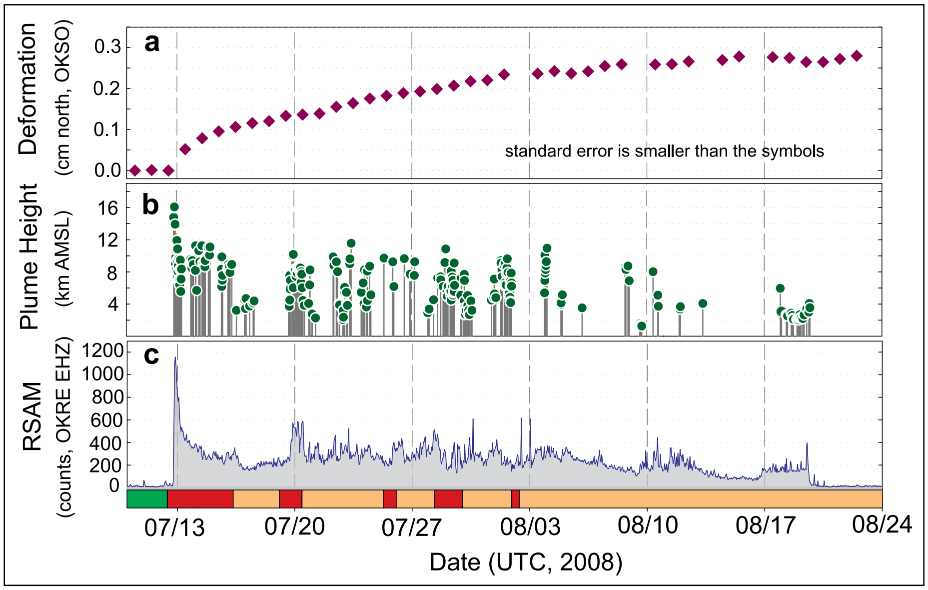

Fig. 2. Time series of principal monitoring data streams for the July–August 2008 Okmok eruption, drafted by Chris Nye (Alaska Volcano Observatory (AVO)), displaying correlations between seismicity, deformation, plume height, and aviation color code. (a) Northward displacement, averaged daily, at continuous Global Positioning System (GPS) station OKSO, located outside the caldera on the southwest flanks. (b) Satellite-derived volcanic plume heights above mean sea level (AMSL). Stratospheric plumes on 12–13 July were estimated using cloud displacement geometry; subsequent tropospheric plume heights were estimated by comparing thermal infrared brightness temperatures with the U.S. standard atmospheric lapse rate. (c) Real-time seismic amplitude (RSAM), an automated proxy for seismic intensity, at station OKRE (10 kilometers north-northwest of the vent). Color bars at the bottom of the figure indicate the aviation code assigned by AVO, which grades volcanic activity. For Okmok, the code varied from a normal background state (green) to an explosive eruption producing significant ash (red), and then fluctuated between codes red and orange as the eruption intensity waxed and waned. These codes help to rapidly inform the aviation community of potential ash hazards (see full explanation of aviation codes at http://volcanoes.usgs.gov/activity/alertsystem/). The figure shows a change in behavior after 1 August, where plume heights did not correlate well with the seismic amplitude.

produced only three earthquakes and no tremor episodes. On 12 July, tiny earthquakes began at 1436 coordinated universal time (UTC), about 5 hours before the eruption, visible only because of quiet conditions. Sparse earthquakes large enough to be located began at 1507 UTC, increasing in rate noticeably only an hour before eruption.

Continuous tremor lasting more than 10 hours marked the strongest phase of the eruption, which began at 1943 UTC (Figure 2). The eruption was characterized by extended periods of continuous nonharmonic tremor, tremor bursts, and low-frequency earthquakes. The tremor was noteworthy for its very long period (VLP) components with frequencies as low as 0.2 hertz. VLP tremor analysis revealed a tremor source located 1 kilometer northwest of Cone D within 2 kilometers of the surface. Interestingly, tremor amplitude after 1 August did not always correlate with ash plume heights, contrary to what is usually observed during explosive eruptions. Significant seismicity ended on 29 August, about 10 days after the last confirmed ash emission.

Okmok GPS data indicate almost continuous inflation from 1997 to 2005, and quiescence from 2005 to 2008, except for notable inflation in early 2008. Preeruptive displacements measured by GPS and interferometric synthetic aperture radar (InSAR) indicate inflation at the center of the caldera, 2.6–3.2 kilometers below sea level [*Lu et al.,* 2005; *Fournier et al.,* 2009]. The largest measured coeruptive displacement was 1.7 meters horizontally and 2 meters down at a GPS site inside the caldera.

Evaluation of deformation resulting from loading and groundwater withdrawal is currently under way. GPS-based models of the coeruptive deflation (Figure 2) suggest an erupted magma volume of 81 million cubic meters dense rock equivalent (DRE), which is almost twice as large as the volume estimated from the 1997 eruption [*Mann et al.,* 2002] and more than double the volume of the magma that had accumulated since 1997 [*Fournier et al.,* 2009].

Satellite Observations

Monitoring ash dispersion is best accomplished by studies of satellite imagery. The ash plume was first observed by Geostationary Operational Environmental Satellite (GOES) images starting at 2000 UTC on 12 July. By 2200 UTC the plume extended more than 100 kilometers in all directions. GOES visible-wavelength images show a dark, opaque ash cloud, followed 1 hour later by a white plume overshooting the darker cloud (Figure 1c). Geometric image analysis of GOES indicated a maximum initial column height of 16 kilometers AMSL. This result was confirmed by the University of Alaska's Puff volcanic ash transport and dispersion (VATD) model [*Tanaka,* 1994; *Searcy et al.,* 1998], used worldwide to track ash plume transport and dispersion.

The 12 July GOES split-window images showed little ash signal, attributed to the initial cloud's opacity, high water content, and particle coarseness, as well as to ice on the ash particulates [*Prata et al.,* 2001]. However, subsequent advanced very high resolution radiometer (AVHRR) satellite data showed a weak ash signal on the perimeter of the eruption cloud.

A Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image at 2225 UTC on 13 July shows a bifurcated plume, with an ash-rich portion extending to the southeast and a vapor-rich portion extending east-southeast of the volcano. By 20 July 2008, the plume was observed to originate from multiple vents on the caldera floor. Over the next several weeks, the volcanic cloud fluctuated in height from about 2 to 12 kilometers AMSL. Plume height generally declined from early August until ash emission ceased on 19 August (Figure 2).

Field Observations

Field observations and eyewitness accounts confirmed the dominant role of magma-water interaction throughout the eruption. For example, visual observations during 2–3 August fieldwork corroborated satellite evidence for separated steam and ash plumes, and physiographical changes to lakes in the caldera confirmed the role of surface water in the eruption. Tephra after 12 July was planar-bedded, fine-grained fall and surge deposits with abundant accretionary lapilli. Individual ash beds were porous, reflecting postemplacement dewatering.

During its first 2 weeks, the eruption produced a new cluster of explosion craters, extending about 2 kilometers across the northwest flank of Cone D and adjacent caldera floor. One crater formed next to, and eventually captured and drained, a preexisting lake northeast of Cone D. A tephra ring grew atop the longest-lived 2008 vent (Figure 1b), creating a 250- to 300-meter-high tuff cone. By 13 August, only the tuff cone was active. The new explosion craters had filled with water and formed a new lake that still covers at least 0.6 square kilometers. The preeruption lake northeast of Cone D refilled and now has a significantly modified shoreline. A field of collapse pits extends across the ash-covered 1958 lava flow surface to the north of the new tuff cone. They may have formed in response to groundwater withdrawal during the 2008 eruption.

Combining estimated volume from isopach mapping with the 16-kilometer initial plume height suggests a preliminary Volcanic Explosivity Index (VEI) of 4, making this the largest and most explosive eruption from Okmok within the past century.

Key Conclusions

The sudden and violent eruption from Okmok marked the first time in AVO's 20-year history that a volcano moved directly from aviation code green, signifying a normally quiet background state, to code red (highly explosive with significant ash emission) within a few hours of the start of precursory seismic activity. The 2008 eruption demonstrates that Okmok volcano has the capability of producing explosive eruptions with little warning, a hazard particularly important to local residents and international air carriers flying along North Pacific air routes. Further studies of this eruption and similar events by the volcanology community can contribute to practical applications in future monitoring and hazard mitigation efforts. More information about Okmok and the aviation color codes can be found at http://www.avo.alaska.edu.

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Today's Forecast: Higher Thinking With a Chance of Conceptual Growth

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Weather has all the characteristics of a motivating, authentic subject: Everybody has an interest in it and strong opinions about it. This interest has provided a way to tie science to a meaningful learning activity in an introductory meteorology course for nonscience students. The pedagogical foundation of such a course is that it is more important for students in science classes to learn to think like scientists than to accumulate facts; weather forecasting allows them to progressively apply their knowledge about the atmosphere by hypothesizing the next day's weather. By forecasting tomorrow's weather repeatedly throughout the course, students are given the opportunity to link what they are learning in class to a topic to which they all relate.

The educational challenge is to model a learning tool on the scientific foundation used in professional forecasting, including parameters that give a complete view of the weather beyond high and low temperature and chance of precipitation. Using the Dynamic Weather Forecaster (DWF), a program developed by the authors of this report, instructors and students can minimize technical challenges while significantly improving learning. Manually grading 50–60 forecasts for several hundred students would be impractical, so a Web-based tool was built to automate this process [*Yarger et al.*, 2000], and it was recently redesigned to increase flexibility. This open-source, free application can be easily adopted by any science high-school and college instructors in the United States who would like to engage their students in forecasting the local weather using the same tools and parameters used by scientists.

To assess the strength of this forecasting tool, the behavior of 201 students in Iowa State University's introductory meteorology course was evaluated last year. Results show that DWF results are a reliable predictor of the students' performance in exams and in the overall course.

A Dynamic, Web-Based Forecasting Exercise

The importance of using real data to engage students in learning has been extensively documented, and the weather provides a unique source of huge amounts of instantly available online data. Instructors have documented the benefits of including weather forecasting in their college courses [*Knox*, 2000; *Kahl*, 2001; *Kahl et al.*, 2004; *Hilliker*, 2008], but these activities are usually limited to a few parameters like surface temperature and wind or are time consuming.

To get students to deal with actual data, the WxChallenge (http://www.wxchallenge.com/) was developed by the University of Oklahoma in 2006 as an online weather forecasting contest used by meteorology majors, graduate students, instructors, and researchers. It is available for 13 weeks in the spring; currently restricted to North America, it covers a limited set of variables.

To expand forecasting over more variables, instructors at Iowa State University developed DWF, which is currently administered through https://portal.iastate.edu. Through this tool, instructors enroll students and determine the exercise duration (e.g., one semester). Every day of the exercise duration, students will have 24 hours to submit a forecast; each submission is automatically closed at midnight local time so that a computer program can assess the accuracy of students' next-day forecasts.

As a first step in each assignment, students select the four-letter International Civil Aviation Organization identifier for the weather station for which the forecast is done; this code determines which data will be used to score the forecast. This allows the instructor the flexibility to have students forecast weather in several different locations throughout the exercise duration.

Each assignment consists of 13 questions. Unlike the WxChallenge, students are asked a broad range of forecasting questions, including temperatures at 1200 and 1800 coordinated universal time (UTC); the potential of clouds, fronts, and advection to affect temperature at both times; wind speed and direction at 1800 UTC; and three precipitation factors (moisture content, frontal position, and instability) for the entire day. Detailed