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# Spectacular Lightning Revealed in 2009 Mount Redoubt Eruption

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The explosive eruption of Alaska's Mount Redoubt volcano in March and April 2009 provided a superb opportunity for studying volcanic lightning. The energetic explosions produced powerful volcanic lightning storms, the largest of which rivaled the intensity of the massive supercell thunderstorms that frequent the midwestern Great Plains.

Although lightning often has been observed in the plumes of explosive volcanic eruptions, only a handful of detailed studies have delved into the origins of volcanic lightning. Active volcanoes tend to be situated in remote locations, where they are difficult to observe, and often have sudden, unpredicted eruptions. Even when the eruptions are observed close at hand, the volcanic clouds are intensely opaque, obscuring most of the lightning from view.

Because of heightened seismicity 2 months in advance of the Mount Redoubt eruption, a group of researchers from New Mexico Institute of Mining and Technology and University of Alaska Fairbanks were able to install lightning mapping instrumentation in time to observe the complete sequence of the volcanic lightning activity. Redoubt had already been heavily instrumented by the Alaska Volcano Observatory, with instruments in place to measure seismic and acoustic activity.

The study of volcanic lightning is important because it provides a means of remotely detecting or confirming eruptions that pose a threat to modern-day activities, such as global air traffic.

Mount Redoubt is situated at the northeastern end of the Aleutian volcanic arc and is on one of the busiest cargo and passenger airplane routes in the world. For example, during its 1989–1990 eruption a large commercial jetliner flew through an ash cloud from Redoubt, causing all four engines to temporarily shut down and the plane to experience a precipitous drop in altitude [*Brantley,* 1990]. Fortunately, the crew members were able to restart the engines and land safely in nearby Anchorage, Alaska. Detection of volcanic lightning could confirm the presence of ash-rich clouds and help prevent future incidents.

## *Imaging Volcanic Lightning*

Within days of learning about Mount Redoubt's increasing precursory activity, four portable very high frequency (VHF) Lightning Mapping Array (LMA) stations were deployed along the west coast of the Kenai Peninsula, 80 kilometers east of Redoubt, and in clear line of sight of the 3.1-kilometer-high (10,200-foot) volcano (Figure 1a). The mapping stations were set up outdoors in wintry conditions in late January and early February 2009.

When a lightning discharge occurs, it produces a succession of bursts of VHF radio emissions. The LMA remotely images lightning by locating the sources of these VHF emissions. Water and ash clouds, while opaque in the visible spectrum, are fully transparent to radio signals, enabling one to effectively see inside the volcanic plume. Each LMA station accurately records the arrival times of the impulsive VHF signals using GPS timing. The peak power of the incoming VHF radiation is recorded over successive 10-microsecond intervals, enabling tens to hundreds of impulsive events to be located per discharge [*Thomas et al.,* 2004].

Mount Redoubt erupted explosively between 23 March and 4 April 2009, producing more than 30 distinct explosive events of differing intensities and durations throughout the eruption (see http://lightning.nmt.edu/redoubt). The largest explosions triggered intense lightning storms that lasted from 20 to 70 minutes and produced thousands of lightning flashes. Smaller explosions produced fewer than 10 detected lightning discharges over spans of less than 10 minutes, and some produced no discernible lightning. All but two or three of the volcanic explosions were obscured from view by inclement weather, but all were readily detected at VHF. Clouds produced by the largest explosions reached altitudes of 10–19 kilometers, well into the stratosphere, and subsequently drifted downwind, with lightning extending from 10 to 150 kilometers into the downwind plume. The explosively active period of the eruption climaxed on 4 April 2009 with the most powerful event of the sequence. Following this, the eruption continued with the slow extrusion of a lava dome and no lightning.

## *Comparison With Mount St. Augustine Eruption*

The electrical activity observed at Mount Redoubt was similar to that detected during the January 2006 eruption of Mount St. Augustine, which sits farther to the south in Cook Inlet. The Augustine observations, the first made using the VHF lightning mapping approach, were obtained using two mapping stations that determined only the azimuthal direction to the lightning sources [*Thomas et al.,* 2007]. That study identified two distinct phases in the lightning activity: an explosive phase and a plume phase (Figure 1d), with the latter phase following the first after a slight delay. The same two phases are evident in the recent Mount Redoubt observations (Figure 1e), except that they tend to overlap in time [*Behnke et al.,* 2012]. The overlap is likely due to the Redoubt explosions being both more energetic and of longer duration than those of Mount St. Augustine.

The Mount Redoubt observations (Figure 1e) showed that at the beginning of an explosive event the lightning radiation was very intense and essentially continuous, similar to the electrical activity identified as the explosive phase in the Mount St. Augustine observations. Seismic and acoustic measurements (Figures 1f and 1g) made within 12 kilometers of the vent confirmed that this initially intense lightning was associated with the individual volcanic explosions. Animations of the located lightning data during the explosive event showed that the electrical activity initially consisted of innumerable small, randomly occurring discharges.

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Following this continuous period of lightning, the radiation in the plume phase became increasingly intermittent over time, similar to the Augustine observations, with discrete discharges toward the end of the plume phase being separated by minutes of inactivity. The observations showed discharges during the plume phase becoming larger in extent and duration and occurring progressively downwind of the volcano in the drifting plume. Flash rates during the explosive event presented in Figure 1b ranged from 100 to 150 flashes per minute during the plume phase. In the largest explosions, such as those on 23 March and 4 April, flash rates are estimated to have been at least twice as high, comparable to observed lightning rates in supercell thunderstorms in the United States.

*Electrification Processes*

Of particular interest in volcanic lightning studies is the question of how volcanic plumes become strongly electrified, including the roles of high temperatures, magma composition, ash, and gas content in this process. The Mount St. Augustine observations indicated that there are separate electrification processes for the explosive and plume phases. During the explosive phase, nearly continuous electrical discharges were observed occurring close to the vent. Further, the onset of the lightning activity was concurrent with the volcanic explosion, indicating that the ejecta were already highly electrified as they exited the vent. The combination of intense lightning at the vent of the volcano simultaneous with the onset of the eruption suggests that a silica-based charging process, in which ash is charged as magma fractures within the volcano, was acting during the explosive phase [*James et al.,* 2008].

The continuation of large-scale lightning in the downwind plume suggests that the same gravitational sedimentation processes that electrify thunderstorms dominated during the plume phase. In this process, oppositely charged particles of different sizes become segregated because of their differing fall speeds. The size-segregated charging could have been a remnant of the explosive charging or of subsequent in situ particle electrification processes, similar to those that occur in nonvolcanic thunderstorms. Redoubt's plumes generally reached above 10 kilometers in altitude, similar to thunderclouds, and contained abundant water and ice. Thus, contact electrification interactions among ice particles or ice-coated ash, water droplets, and supercooled ice pellets may also have played a role [*Williams and McNutt,* 2005].

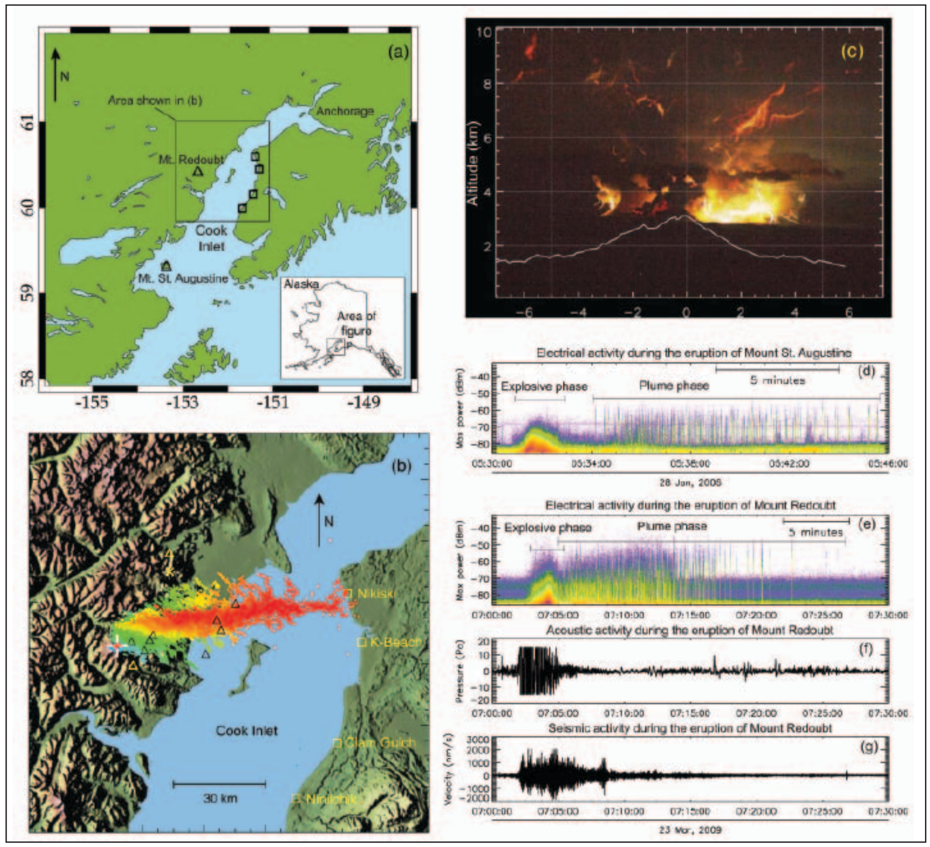


*Fig. 1. (a) Locations of the Mount Redoubt and Mount St. Augustine volcanoes (triangles) and lightning mapping stations (squares) in Alaska. (b) Map view of very high frequency (VHF)–detected lightning activity during the explosive eruption at 23:29 UTC on 28 March 2009 (courtesy of International Commission on Atmospheric Electricity). The uncertainties in the plan position of the lightning sources were approximately 200 meters or less. The lightning began over Mount Redoubt (marked with white crosshairs) and continued for 40 minutes as the plume drifted eastward toward Nikiski, Alaska (with increasing time coded by color). Twelve cloud-to-ground (CG) discharges (10 negative CGs (triangles) and 2 positive CGs (crosses)) were located by the Bureau of Land Management Lightning Detection System during the event. (c) Composite photograph of in-cloud and CG lightning during the explosive eruption at 07:19 UTC on 28 March 2009, including an outline of Mount Redoubt (photographs taken from Seldovia, Alaska, 125 kilometers to the south-southeast, by Brentwood Higman; http://www.groundtruthtrekking.org/blog/?p=849). (d and e) Electrical activity recorded during the explosive eruptions of Mount St. Augustine on 28 January 2006 and Mount Redoubt on 23 March 2009. The figures depict the peak power values recorded by a single station versus time, colored to indicate the number density of detected events (red is higher density; purple is lower density). The explosive phase is characterized by intense, nearly continuous VHF radiation. The plume phase is characterized by increasingly discrete individual discharges, corresponding to the vertical lines. (f and g) Acoustic and seismic recordings for the 23 March Mount Redoubt explosion. The onset of VHF radiation in the Mount Redoubt observations was delayed and less rapid relative to that of Mount St. Augustine and the acoustic Mount Redoubt recordings, likely due to the vent being on the far side of and 500 meters below the summit.*

*Progress in Volcanic Lightning Research*

The Mount Redoubt observations substantially extend the body of knowledge concerning volcanic lightning. The Mount St. Augustine lightning mapping observations, while being the first of their kind, were limited in that the instruments were installed after the eruption began, only two sensor stations were used, and the eruption itself was less energetic than that of Redoubt. The four sensors of the Redoubt study, on the other hand, recorded the entire eruption sequence and provided excellent two-dimensional observations of the lightning activity. Obtaining fully three-dimensional observations will require one or more sensors at locations closer to the volcano, which was not possible at the time for the Redoubt eruption. Progress toward this goal has been made using six-station lightning mapping measurements of the 2010 eruption of Eyjafjallajökull volcano in Iceland.

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