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The Unexpected Awakening of Chaitén Volcano, Chile

PAGES 205–206

On 2 May 2008, a large eruption began unexpectedly at the inconspicuous Chaitén volcano in Chile's southern volcanic zone. Ash columns abruptly jetted from the volcano into the stratosphere, followed by lava dome effusion and continuous low-altitude ash plumes [*Lara,* 2009]. Apocalyptic photographs of eruption plumes suffused with lightning were circulated globally.

Effects of the eruption were extensive. Floods and lahars inundated the town of Chaitén, and its 4625 residents were evacuated. Widespread ashfall and drifting ash clouds closed regional airports and cancelled hundreds of domestic flights in Argentina and Chile and numerous international flights [*Guffanti et al.,* 2008]. Ash heavily affected the aquaculture industry in the nearby Gulf of Corcovado, curtailed ecotourism, and closed regional nature preserves. To better prepare for future eruptions, the Chilean government has boosted support for monitoring and hazard mitigation at Chaitén and at 42 other highly hazardous, active volcanoes in Chile.

The Chaitén eruption discharged rhyolite magma, a high-silica composition associated with extremes of eruptive behavior ranging from gentle lava effusion to violent, gas-driven explosions. As the first major rhyolitic eruption since that of Alaska's Katmai-Novarupta in 1912, it permits observations that are benchmarks for future such events. It also reignites the debate on what processes rekindle long-dormant volcanoes, justifies efforts to mitigate rare but significant hazards through ground-based monitoring, and confirms the value of timely satellite observations.

Background and Chronology of the 2008 Eruption

At 1122 meters high, Chaitén volcano (42.83ºS, 72.65ºW) stands 10 kilometers northeast of the town of Chaitén on the Gulf of Corcovado. Its last known major eruption occurred 9400 years ago and produced a caldera 3–4 kilometers in diameter, with deposits containing rhyolite pumice capped by mafic scoria [*Naranjo and Stern,* 2004]. On the basis of the caldera collapse volume, the previous eruption merited a volcanic explosivity index (VEI) of 5, ejecting nearly 4 cubic kilometers of material. Prior to May 2008, a large obsidian lava dome more than 5600 years old, with a volume of nearly half a cubic kilometer, occupied the caldera.

Before the 2008 eruption, Chaitén was unmonitored. Retrospective analysis revealed that precursory seismic activity detected by instruments up to 300 kilometers to the north [*Basualto et al.,* 2008], began on 30 April 2008 with volcano-tectonic (VT) earthquakes (magnitudes ranging from 3 to 5) located within 20 kilometers of Chaitén. Large VT events peaked at 15–20 per hour from 1 to 2 May, coincident with an explosive eruption around 0800 coordinated universal time (UT) on 2 May that lasted about 6 hours and lofted ash to an altitude of more than 21 kilometers. Seismicity declined abruptly on 3 May, probably reflecting erosion of a conduit to the surface, but sustained ash emission interspersed with stratospheric plumes continued for several days.

On 4 May, the Chilean Servicio Nacional de Geología y Minería (SERNAGEOMIN) deployed a seismic network around Chaitén. SERNAGEOMIN found that a persistent pattern of VT seismicity (about 70 events per day, average $M > 3.5$) occurred from 4 to 12 May [*Basualto et al.,* 2008]. Ash plumes continued for about a week, punctuated by two additional stratospheric columns (between 20 and 22 kilometers in altitude) on 6 and 8 May. Theoretical models of eruption columns [*Sparks,* 1986] imply discharge of about 1 cubic kilometer of magma in the eruption's first week, placing it among the largest since the August 1991 eruption of Hudson volcano, located about 300 kilometers south of Chaitén. Subsequent work on tephra volume [*Watt et al.,* 2009] suggests that the eruption fell in the middle VEI 4 range.

Eruption of a new lava dome through vents in the preexisting dome began around 10–12 May, extruding between 20 and 100 cubic meters of lava per second through late July. Nonetheless, seismicity declined from mid-May through June, suggesting ease of magma flow in the conduit. During July, ash and steam emissions subsided while lava extrusion continued, accompanied daily by up to 300 hybrid earthquakes, which have characteristics transitional between low- and high-frequency events. Earthquake magnitudes increased from less than 2.5 to 4 by the end of July, raising concerns about renewed explosive eruptions, but seismicity declined in August.

By late September 2008, the new lava dome volume was about half a cubic kilometer. A large dome collapse, a lateral blast, and pyroclastic flows occurred on 19 February 2009, resulting in further ashfall in Argentina. Since then, dome growth, frequent block and ash flows, and low-altitude ash and gas emissions are ongoing as of June 2009. Current seismicity is characterized by about 15 hybrid events daily (average $M < 4.5$). The current volcanic alert code is red, indicating that activity could escalate to dangerous levels at any time and without warning.

Satellite Observations

Chaitén's eruption demonstrates the value of satellite observations of unexpected natural hazards. Numerous spaceborne assets imaged the eruption clouds, elucidating their altitude and extent (Figure 1; see also the electronic supplement to this *Eos* issue at http://www.agu.org/eos_elec/). Altitude determines a volcanic cloud's effect on aviation and climate, and is used to assess eruption magnitude.

Key observations came from NASA's A-Train, a fleet of five polar-orbiting spacecraft with overpass times separated by about 8 minutes. A-Train sensors include the Ozone Monitoring Instrument (OMI) and the Atmospheric Infrared Sounder (AIRS), which measure volcanic sulfur dioxide (SO_2); the Moderate Resolution Imaging Spectroradiometer (MODIS), which provides visible images and measurements of ash mass loading; and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, which provides vertical profiles of aerosol. This sensor synergy permits direct measurement of volcanic

By S. A. Carn, J. S. Pallister, L. Lara, J. W. Ewert, S. Watt, A. J. Prata, R. J. Thomas, and G. Villarosa

cloud altitude, an improvement over indirect altitude determinations using infrared cloud top temperatures, observed cloud drift, or ground-based clinometry.

Geostationary Operational Environmental Satellite (GOES) images captured the eruption onset at around 0800 UT on 2 May, with the ash cloud top altitude estimated at about 12 kilometers, near the tropopause. On 3–4 May, CALIOP detected aerosol at about 30ºS and near 12 kilometers in altitude, collocated with SO_2 detected by OMI. CALIOP data were consistent with the presence of solid particles—possibly fine volcanic ash, ice crystals, or a mixture of both.

The next, and largest, explosive eruption occurred around 1200 UT on 6 May, emitting a cloud that drifted east and deposited ash over a large swath of Argentina (Figure 1). Ground-based observers reported eruption column altitudes of 30 kilometers. Cloud top temperatures and visible plume movement suggested altitudes of 18–20 kilometers; this was corroborated on 8 May when CALIOP detected aerosols at similar heights. These aerosols were interpreted as ash or an ice-ash mix [*Thomason and Pitts,* 2008]. GOES identified a third stratospheric eruption at approximately 0330 UT on 8 May, producing aerosol detected by CALIOP on 9 May at about 13 kilometers in altitude.

CALIOP subsequently detected stratospheric aerosol from Chaitén drifting over southeastern Australia, suggesting long-range transport of fine ash. The rhyolitic ash clouds also produced a distinctive spectral signature in AIRS data, suggesting that ash composition could be determined from satellite measurements.

OMI measured strikingly low SO_2 emissions during the eruption, only about 10 kilotons of SO_2 in the clouds emitted on 2, 6, and 8 May. At the low sulfur abundances typical of rhyolites (~50 parts per million), degassing of about 0.1 cubic kilometer of rhyolite would be commensurate with the observed SO_2 yield, also supporting an eruption VEI around 4. No significant climate impact is expected due to these low SO_2 emissions.

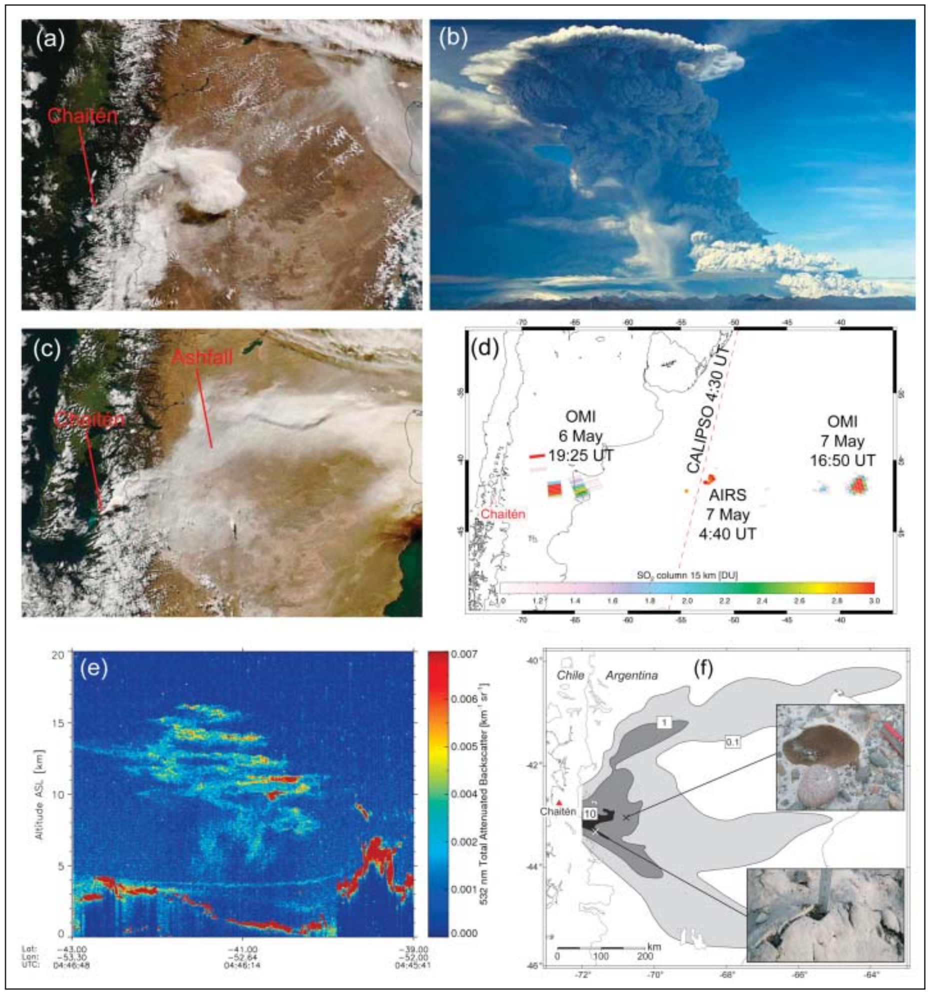

Fig. 1. (a) Terra Moderate Resolution Imaging Spectroradiometer (MODIS) image at 1505 coordinated universal time (UT) on 6 May 2008, showing the ash cloud that began erupting from Chaitén about 3 hours earlier. (b) Photo (from the north) of stratospheric eruption column on 2 May (courtesy of El Mercurio Online; http://www.emol.com). (c) Aqua MODIS image at 1915 UT on 6 May, showing ash deposited by the 6 May eruption cloud over southern Argentina. (d) Ozone Monitoring Instrument (OMI) and Atmospheric Infrared Sounder (AIRS) detection of sulfur dioxide (SO_2) in the drifting 6 May eruption cloud. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite track is indicated. (e) Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) backscatter data (0430 UT on 7 May) showing aerosols from the 6 May eruption between 5 and 16 kilometers in altitude (x-axis shows latitude and longitude). (f) Shaded isopach map (thickness in millimeters) of ashfall over Argentina, modified from Watt et al. *[2009]. Inset photographs show surface ash cover at two locations.*

Eruption Deposits

Chaitén ash samples contain fine particles (diameter < 100 microns) characteristic of silicic explosive eruptions. Because of extensive ash fallout over land, the eruption offers a rare opportunity to investigate the characteristics, distribution, deposition, and fate of fine ash following explosive eruptions, and permits evaluation of ash dispersion and fallout models [*Folch et al.,* 2008].

Teams from Argentina, the United Kingdom, and the United States sampled the ashfall and measured its thickness; estimates suggest that about 0.2 cubic kilometers (160 megatons) of ash was deposited over 200,000 square kilometers of Argentina [*Watt et al.,* 2009]. A complex ash dispersal pattern, with several discrete but overlapping depositional lobes, arose from changing wind patterns during the initial, and most explosive, eruption period (Figure 1f; see also the electronic supplement to this *Eos* issue at http://www.agu.org/eos_elec/). These data and material collected are being used to improve ash fallout models and investigate environmental impacts of fine ash deposition [e.g., *Martin et al.,* 2009].

Estimates of magma discharge for the first week of the Chaitén eruption vary widely. Some field data suggest total volumes of several cubic kilometers, and volumes based on eruption column models [*Sparks,* 1986] range from about 1 to 6 cubic kilometers, although the larger value neglects column height fluctuations and is clearly an overestimate [*Folch et al.,* 2008]. Determining the total volume discharged is important not just to assign a VEI but also to better understand the conduit, vent, and plume dynamics.

Analysis of deposits [*Castro et al.,* 2008; *Lowenstern et al.,* 2008; *Muñoz et al.,* 2008] shows that the eruption tapped an extremely crystal-poor rhyolite magma similar to the rhyolite erupted 9400 years ago, with evidence for 4–5% dissolved water by weight prior to final ascent. These conditions are similar to those of many other explosively erupted rhyolites. Calcium-rich cores in plagioclase crystals, aluminum-rich amphiboles, and relatively unevolved trace element abundances suggest rhyolite extraction from a more mafic crystal mush at depth. Lack of amphibole decompression rims indicates rapid magma ascent, consistent with the abrupt eruption onset. Unlike the event 9400 years ago, there is no evidence of mafic magma having erupted so far in 2008–2009. Like eruptions such as Pinatubo (Philippines) in 1991 and Usu (Japan) in 1663, basaltic magma at depth may have played a role in mobilizing silicic magma to drive an explosive eruption after centuries to millennia of dormancy.

Eruption Response

Because Chaitén was unmonitored before the eruption, precursory observations were unavailable and affected communities were unprepared. SERNAGEOMIN is now monitoring the volcano, assisted by the U.S. Geological Survey Volcano Disaster Assistance Program (VDAP). In late May 2008, real-time telemetered seismometers were installed around Chaitén by SERNAGEOMIN and VDAP. Because of ongoing volcanic activity, on 29 January 2009 the Chilean government announced that the town of Chaitén will be relocated to a more protected site 9 kilometers to the northwest.

The international nature of this event necessitated cooperation between Chile and Argentina, both of which are at high risk from the 122 active volcanoes close to their shared border. The Buenos Aires Volcanic Ash Advisory Center, the Argentine Space Agency, and the University of Chile's Center for Space Studies were primarily responsible for operational tracking of ash emissions for aviation safety using satellite data. Ash transport and fallout were also simulated using meteorological forecasts and dispersion models running in operational mode [*Folch et al.,* 2008].

Spectacular lightning displays inspired a team from the New Mexico Institute of Mining and Technology to deploy an autonomous electrical monitoring array on Chiloe Island (70–110 kilometers from Chaitén) in late May 2008. This array continuously maps electrical discharge, revealing the spatiotemporal distribution of charged particles (ash and volatiles) in the eruption plume. Data analysis alongside other monitored parameters (e.g., seismicity, infrasound) will permit evaluation of remote electrical activity monitoring as a proxy for eruption intensity.

Most important, the 2008 eruption of Chaitén focused the attention of the Chilean government on its volcano hazards and resulted in a new national volcano-monitoring program (Red Nacional de Vigilancia Volcánica), which over the next 5 years will build real-time monitoring networks at Chile's highest-risk volcanoes. Such efforts, combined with continued international monitoring, the refinement of models, and the elaboration of the eruptive histories of the region's volcanoes, are needed to mitigate the impacts of future eruptions.

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Author Information

Simon A. Carn, Michigan Technological University, Houghton; E-mail: scarn@mtu.edu; John S. Pallister, U.S. Geological Survey Cascades Volcano Observatory, Vancouver, Wash.; Luis Lara, Servicio Nacional de Geología y Minería (SERNAGEOMIN), Santiago, Chile; John W. Ewert, U.S. Geological Survey Cascades Volcano Observatory; Sebastian Watt, Oxford University, Oxford, UK; Alfred J. Prata, Norwegian Institute for Air Research, Kjeller, Norway; Ronald J. Thomas, New Mexico Institute of Mining and Technology, Socorro; and Gustavo Villarosa, Instituto de Investigaciones en Biodiversidad y Medio Ambiente, Consejo Nacional de Investigaciones Científicas y Técnicas, Universidad Nacional del Comahue, Bariloche, Argentina