SERNAGEOMIN
Ministerio de Minería
Gobierno de Chile

# FIELD GUIDE
## CHAITÉN VOLCANO: FEATURES AND IMPACTS OF THE 2008-09 ERUPTION

*'Understanding volcanoes and society: the key for risk mitigation'*

PRE-CONFERENCE FIELD TRIP
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CITIES ON VOLCANOES 9
Puerto Varas - Chile
November 20th to 25th, 2016

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## INTRODUCTION

[The following synopsis is from Major and Lara (2013)]

Chaitén volcano, located near 42.8°S latitude in southern Chile (Fig. 1), is a relatively small, remote rhyolitic volcano that sits about 17 km west-southwest of the much larger and heavily glaciated Michinmahuida volcano (2,400 m elevation). It consists of a 3-km-wide caldera that, before 2008, contained an ~0.5 $km^3$ lithic-and-obsidian rhyolite lava dome. In contrast to the abundance of repetitive eruptive activity of many other volcanoes in southern Chile (Dzierma and Wehrmann, 2012), Chaitén was perceived as being inactive and thought to have erupted last in the early Holocene, about 9,400 yBP (Naranjo and Stern, 2004). Owing to its apparent lack of activity, and despite its proximity to the important port town of Chaitén (Fig. 2), the volcano was not considered to be a significant threat and was not actively monitored. Prior to 2008, the nearest seismic station was located approximately 300 km north. Perceptions of Chaitén, and the threat it poses to society, changed when the volcano erupted unexpectedly and explosively in May 2008 in one of the largest eruptions worldwide since the early 1990s. That eruption of crystal-poor, high-silica rhyolite (73–76 wt% $SiO_2$; Castro and Dingwell, 2009) produced one of the few rhyolite eruptions since the early 1900s, and the largest since the great eruption of Katmai volcano, Alaska, in 1912. Even though the region surrounding the volcano is sparsely populated, the eruption wreaked considerable havoc. The violent VEI 4–5 eruption (Carn *et al.*, 2009) ejected tephra to altitudes of 18–20 km, and winds widely dispersed that tephra eastward across Argentina and out to the South Atlantic Ocean (Carn *et al.*, 2009; Watt *et al.*, 2009; Durant *et al.*, 2012). Distal tephra dispersal upset commercial airline traffic and disrupted daily life in downwind communities (Wilson *et al.*, 2009a,b; 2012). Flooding and sediment transport associated with tephra erosion severely damaged the small port town of Chaitén (population ~4,600) located 10 km south of the volcano (Pierson *et al.*, 2013; Major *et al.*, 2016), loaded regional rivers with large amounts of sediment and wood (Umazano et al., 2014; Ulloa *et al.*, 2015a,b, 2016; Major *et al.*, 2016), and disrupted local aquaculture, tourism, and other economic endeavors. Following a short-lived explosive phase, the eruption transitioned to a prolonged effusive phase that lasted through 2009 (Bernstein *et al.*, 2013; Pallister *et al.*, 2013).

Chaitén volcano, at 1,122 m elevation, sits atop a high-relief (600-800 m) ridge about 10 km inland from the Gulf of Corcovado (Fig. 2). The volcano is surrounded by steep, dissected, high-relief, volcanic and glaciated terrain that is densely covered in temperate rainforest vegetation. Two principal river systems drain the volcano—the Rayas River to the north and the Chaitén River (also called Blanco River) to the

*Cover photo: Oblique aerial view to southwest of deltaic deposits at mouths of original and avulsed channels of Chaitén River. P. Duhart, SERNAGEOMIN, February 2009.*

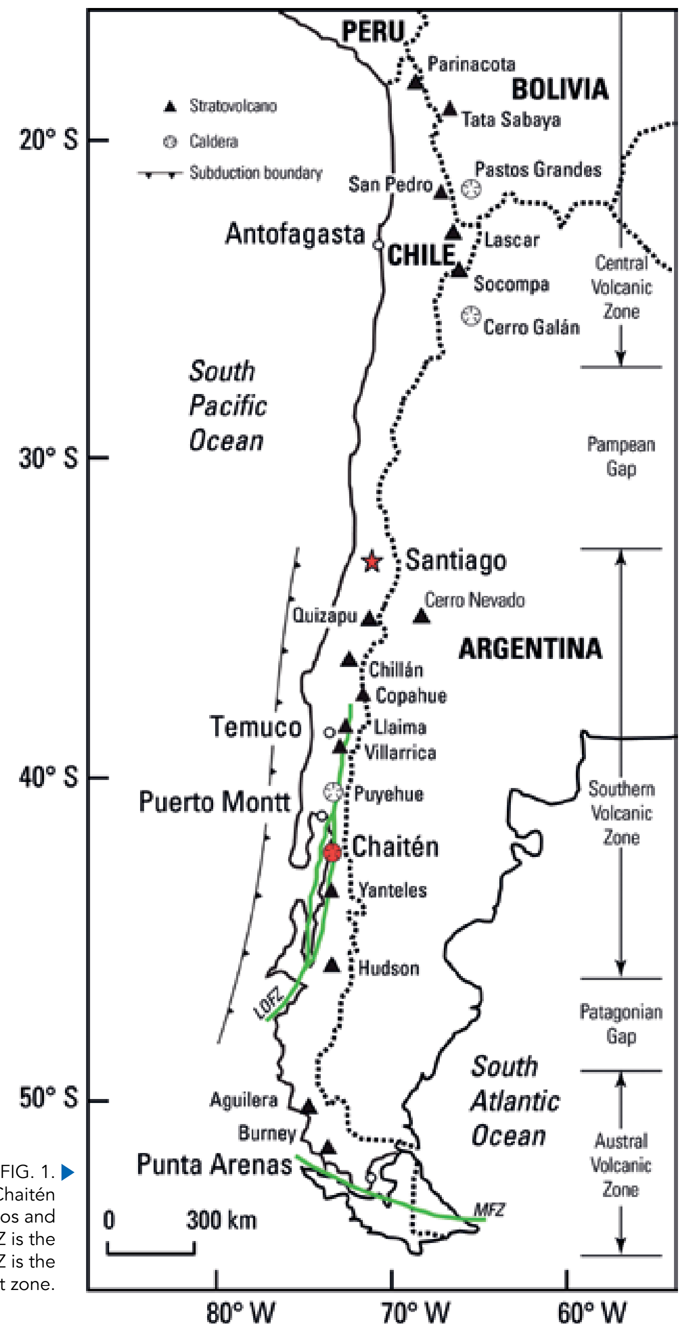


FIG. 1. Regional setting of Chaitén volcano. A few major volcanos and calderas are shown. LOFZ is the Liquiñe-Ofqui fault zone; MFZ is the Magallanes fault zone.

south (Fig. 2). Channels on the west, north and east flanks of the volcano drain into the Rayas River. One tributary of the Chaitén River, informally referred to as Caldera Creek, drains the caldera through a breach in the south rim (Fig. 2).

This part of Chile is dominated by the generally wet climate of the Andean Patagonia region (Garreaud *et al.*, 2013). Moisture-laden airflow from the southern Pacific Ocean delivers prolonged, and sometimes intense, rainfall. Frontal storms cross low-relief offshore islands and locally narrow coastal plains before encountering and ascending 1–2-km-high mountain ridges. Orographic precipitation increases with altitude by a factor of about 2–3 from the coast to the western front of the Andes (Garreaud, 2009); annual mean precipitation in western Patagonia ranges from about 5,000–10,000 mm (Garreaud *et al.*, 2013). Precipitation in the broad region around Chaitén volcano varied from about 2,500 to 7,000 mm from 2004 to 2009 (Pierson *et al.*, 2013; Dirección General de Aguas, unpublished data; Fundación Huinay, unpublished data).

## ERUPTIVE HISTORY OF CHAITÉN VOLCANO

Prior to the 2008–09 eruption, very little was known of the eruptive history of Chaitén volcano. Naranjo and Stern (2004) examined outcrops on both the Chilean and Argentine sides of the Andes between 42.5° to 45°S, and identified evidence for many Holocene eruptions from several stratovolcanoes. But only one of those eruptions was correlated to Chaitén. Outcrops north of the volcano expose pyroclastic density current (PDC) and tephra fall deposits. Fragments of charcoal from within the PDC deposit had a radiocarbon age of 9,370 yBP and a tree trunk underlying it had a radiocarbon age of 9,810 yBP. The fall deposit overlying the PDC deposit consists of white to yellow rhyolite pumice capped by a thin layer of mafic scoria. There is no soil developed between the PDC and fall deposits. On the basis of these dates, deposit compositions, and the lack of soil development between the PDC and fall deposits, Naranjo and Stern (2004) inferred that the PDC and rhyolite pumice fall are products of a single eruption about 9,400 yBP. A 'thick tephra layer' exposed in a road cut 4 km north of the town of Chaitén and west of the volcano dated at <10,260 yBP and a tephra layer in another outcrop near the mouth of the Rayas River (Fig. 2) dated at <9,580 yBP may be from the same explosive event (Naranjo and Stern, 2004). The age of the pre-2008 intracaldera dome is uncertain but older than 5,600 yBP, because obsidian cobbles from the dome fashioned into artifacts have been found in archeological sites of that age as far as 300 km distant along the Pacific coast (Stern *et al.*, 2002), and some even as far as 1,200 km distant along the Atlantic coast of Argentina (Stern *et al.*, 2012).

Naranjo and Stern (2004) did not recognize downwind tephra fall deposits from Chaitén east of the volcano. But deposits of rhyolite pumice dated between 3,820 and 1,840 yBP were found in Argentina near the city of Esquel and along the shores of Futalafquén lake, 80–100 km downwind from Chaitén (Naranjo and Stern, 2004). These deposits, geochemically similar to the Chaitén rhyolite pumice, were attributed instead to an eruption of Michinmahuida volcano even though it is not known to have erupted rhyolite, because the dispersal pattern of that tephra fallout matched the dispersal pattern of another tephra fallout from Michinmahuida. All other tephras they found in the region were of basalt to dacite composition, and not related to eruptions of Chaitén. On the basis of the outcrops they observed and sampled, Naranjo and Stern (2004) concluded that the last major eruption of Chaitén occurred about 9,400 yBP. No historical accounts of eruptions of Chaitén were known about at the time of their study.

More recent studies by Amigo *et al*. (2013), Lara *et al*. (2013), Watt *et al*. (2013), and Moreno *et al*. (2015) discuss new evidence and new analyses that show Chaitén has been far more active during the Holocene than was previously thought. Watt *et al*. (2013) provide evidence for three substantial eruptions (not including the 2008 eruption) in the past 5,000 years. On the basis of reconstructed isopachs, they conclude that the mid Holocene rhyolite pumice (~4,200 yBP calibrated) that Naranjo and Stern (2004) attributed to an eruption of Michinmahuida volcano is actually from the largest-volume Holocene eruption of Chaitén. Amigo *et al*. (2013) discuss new stratigraphic observations and new radiocarbon ages obtained from a suite of proximal outcrops which help constrain the record of large Holocene eruptions from Chaitén and Michinmahuida volcanoes. They show that at least 11 Holocene eruptions have occurred between these two volcanoes, including three large Plinian eruptions and one ignimbrite-forming eruption. In contrast to Watt *et al*. (2013), they conclude that the early Holocene eruption of Chaitén identified by Naranjo and Stern (2004) (~9,400 yBP) was the largest-volume eruption from this volcano. Lara *et al*. (2013) present evidence for a 17$^{th}$ century eruption of Chaitén, witnessed by travelers, which produced impacts and deposits similar to those of the 2008–09 eruption. Moreno *et al*. (2015) examined cores from Lake Teo (above Chaitén town) which document ~20 Holocene eruptions between Chaitén and Michinmahuida. Rhyolite products attributed to eruptions of Chaitén are clustered from 9,460 to 9,680 yBP, 5,080 to 7,700 yBP, 600 to 850 yBP, and the most recent pre-2008 event at 420 yBP. They estimate a median recurrence between major eruptions of ~200 years for Chaitén over the past millenium.

## SYNOPSIS OF THE 2008-09 ERUPTION

Owing to the pre-2008 perceived lack of eruptive activity of Chaitén during the Holocene, the volcano was not considered to be a significant threat and thus was not actively monitored. As a result, when it erupted in 2008, it appeared to have reawakened with little precursory unrest. Lack of detection of precursory activity may be largely a function of a lack of instrumentation on or near the volcano. But there is evidence that unrest escalated rapidly to eruption. Residents of the town of Chaitén felt earthquakes and the Chilean Servicio Nacional de Geología y Minería (SERNAGEOMIN) began detecting volcano-tectonic (VT) earthquakes only about 24 hours before the eruption produced ashfall, and petrological evidence suggests that the rhyolite magma that fueled the eruption ascended rapidly from depths of 5–9 km in as little as 4 hours (Castro and Dingwell, 2009). Analysis of Interferometric Synthetic Aperture Radar (InSAR) images indicates magma ascended an inclined sill that originates beneath Michinmahuida volcano (Wicks *et al*., 2011). Once the eruption began, it went through a brief (~2 week) but energetic explosive phase and then entered a prolonged (~18–20 month) effusive phase (Pallister *et al*., 2013).

### Explosive phase

The first Plinian eruption began on 2 May at ~03:30 UTC (local time = UTC–4 hrs) and was confirmed a few hours later by visual observations. That eruption lofted ash to an altitude of more than 20 km (Carn *et al*., 2009). By approximately 16:00 UTC, PDCs were observed on the north and northeast flanks. An overflight on 3 May revealed that two vents had opened on the north-northwest side of the lava dome (SERNAGEOMIN, 2008a). The early tephra plumes were dispersed broadly downwind across Argentina and out to the South Atlantic Ocean (Watt *et al*., 2009; Osores *et al*., 2013). Explosive activity waned slightly over the next few days, but maintained sustained eruption columns achieving heights of <10–12 km. On 6 May, the intensity of explosive activity increased sharply leading to a climactic explosion that lofted an eruption column to at least 18–20 km altitude (Folch *et al*., 2008; Carn *et al*., 2009; Durant *et al*., 2012). During the day, explosive activity waxed and waned. By that time, the town of Chaitén had been fully evacuated. On 7 May, explosive activity again waned, with sustained eruption columns achieving altitudes of about 7–10 km. Small PDCs were observed advancing down the east flank (SERNAGEOMIN, 2008b). A third episode of vigorous explosive activity occurred on 8 May, with an eruption column reaching an altitude of 20–22 km (Carn *et al*., 2009). By this time, the two vents through the dome had merged into a single vent

(Basualto *et al.*, 2008). After 8 May, explosive activity waned for the last time. By 12 May sustained column heights were only about 4–5 km, and the volcano entered a transitional phase from explosive to effusive activity (Pallister *et al.*, 2013).

## Effusive phase

As explosive activity waned, effusive activity began. From 8 to 12 May, the predominance of low-magnitude (≤M2.5) VT earthquakes transitioned to hybrid and long-period low-frequency earthquakes, which in hindsight suggest the onset of lava effusion (Basualto *et al.*, 2008). Owing to inclement weather, newly effusing lava was not confirmed visually until 21 May (SERNAGEOMIN, 2008c). A transitional phase of the eruption, which included simultaneous explosion and effusion, lasted from about 8 to 12 May until the end of the month (Pallister *et al.*, 2013).

The effusive phase of eruption can be segregated into three distinct phases (Pallister *et al.*, 2013): a dominantly exogenous growth phase; a phase of simultaneous spine extrusion and endogenous growth; and a dominantly endogenous growth phase. The exogenous phase, which lasted from early June through September 2008, produced multiple lava lobes that buried much of the pre-2008 lava dome (Fig. 3). Approximately 0.5 $km^3$ of rhyolite lava was erupted at an average rate of 45 $m^3s^{-1}$ during this four-month period (Pallister *et al.*, 2013). Spine extrusion began in October 2008 and continued until mid-February 2009, accompanied by localized endogenous growth. Between June 2008 and mid-February 2009, collapses from the lava dome produced rockfalls and minor PDCs within the caldera and two major PDCs that entered the Chaitén River valley through the breach in the south caldera wall (Major *et al.*, 2013). After a substantial dome collapse on 19 February 2009, which produced the largest PDC in the Chaitén River valley (Fig. 4), the eruption entered a renewed and dominantly endogenous phase of dome growth that lasted until late 2009 or possibly earliest 2010 (Pallister *et al.*, 2013). Seismicity during the period of lava effusion was dominated by hybrid earthquakes having magnitudes ranging from M<2 to ~M4 (Basualto *et al.*, 2008).

## BROAD IMPACTS OF THE 2008 EXPLOSIVE ERUPTIVE PHASE

The explosive phase of the eruption and PDCs associated with subsequent dome collapses caused considerable damage to proximal forest vegetation, affected commercial airline traffic, and disrupted daily life in downwind communities (e.g., Wilson *et al.*, 2009a,b, 2012; Swanson *et al.*, 2013). Close to the volcano, approximately 480 $km^2$ of forest were heavily damaged (Swanson *et al.*, 2013). PDCs associated with the explosive phase of the eruption leveled patches of forest north and northeast of the volcano, and a rain of coarse lapilli-rich tephra (Alfano *et al.*, 2011) stripped foliage and limbs from trees along plume trajectories out to tens of km distance (Swanson *et al.*, 2013) (Fig. 5). Extensive tracts of forest were damaged by a delayed, but physiologically uncertain cause related to fine-grained ash fall and possibly to release of volcanic gases (Lowenstern *et al.*, 2012; Swanson *et al.*, 2013) in the weeks to months following the explosive phase of eruption.

Minor rainfalls in the days following extensive ash deposition led to rapid runoff and ash remobilization, which caused swift and abundant sediment loading of proximal river systems (Pierson *et al.*, 2013; Major *et al.*, 2016). That sediment loading led to rapid aggradation of the Chaitén River channel, overbank flooding, river avulsion, and severe damage to the town of Chaitén (Pierson *et al.*, 2013; Major *et al.*, 2016) (Fig. 6). Flushing of sediment from the Rayas, Chaitén, and Negro rivers to the sea affected local aquaculture, and formed a pair of deltas at the former and new mouths of the Chaitén River (cover image). Burial of the Chaitén airport in sediment and impingement of the Chaitén ferry dock by rapid delta growth seriously affected the two main modes of transportation to this region. Even now (2016), small debris flows and floods from tephra- and PDC-affected tributary channels continue to wash out local roads and disrupt regional ground travel.

Extensive downwind ash fall in Chile and Argentina (Watt *et al.*, 2009) broadly affected infrastructure, agriculture, and population. Electrical distribution networks suffered damage directly from ash fallout and from tree fall associated with ash deposition, municipal surface-water supplies were subjected to increased turbidity levels, and ground transportation networks suffered disruption owing to reduced visibility (Wilson *et al.*, 2009a, 2012). Minor disruptions to telecommunication devices occurred as a result of ash penetration. Substantial pasture and cropland downwind were coated with <1 mm to as much as 10 mm of fine ash (Watt *et al.*, 2009) leading to crop and livestock loss; ingestion of ash by livestock led to fungal infections and tooth wear (Wilson *et al.*, 2009b). Studies of downwind environmental impacts show ash fallout released a number of volatile trace elements to the environment that resulted in significant, but ephemeral, compositional changes to the biogeochemistry of soil, biota, and lakes in the region (Martin *et al.*, 2009; Ruggieri *et al.*, 2012). But because their impacts were ephemeral, these changes posed little threat of environmental harm. Of greater concern was the potential environmental hazard posed by the thoracic (<10μm) and respirable (<4μm) fractions of extremely fine ash. Resuspension of distal fine ash by wind and especially vehicular activity caused persistent air quality problems (Martin *et al.*, 2009). Even when traffic activity and wind speeds were low, concentrations of respirable particulates exceeded World Health Organization guidelines (Martin *et al.*, 2009). The ash also contained respirable crisobalite nanofibers, raising concerns about possible adverse health effects to long-term exposure (Reich *et al.*, 2009; Horwell *et al.*, 2010). Ash from the initial eruption plume on 2 May also induced downwind cooling of the troposphere of up to 10°K (Wang *et al.*, 2009).

The eruption of Chaitén posed a significant challenge to the emergency response system in Chile. Owing to the absence of a monitoring network at the volcano, an adequate eruption forecast was not possible at the time. An initial response to the eruption included rapid deployment of a seismic network around the volcano by SERNAGEOMIN scientists, supported in part by scientists from the U.S. Geological Survey–U.S. Agency for International Development Volcano Disaster Assistance Program. On the basis of a rapid hazards assessment by SERNAGEOMIN scientists, national authorities decided within days to evacuate the town of Chaitén. A full evacuation was complete by 6 May. Evacuation of the town spared injuries or fatalities from the rapid and extensive flooding that occurred less than a week later (Pierson *et al.*, 2013) (Fig. 6). The eruption also motivated an unprecedented response by the national government in terms of long-term social support of the displaced community. A pilot study for the possible relocation of the town was ordered, which recommended a more secure settlement be established ~10 km farther north. Chile's highest level of volcanic alert (red alert) was maintained for two years until May 2010 when eruptive activity had clearly ended. Following cessation of the eruption, the national government decided to allow limited resettlement of Chaitén town and many former inhabitants returned.


FIG. 2. Photograph showing light-colored Chaitén lava dome, major drainage channels, and the larger and glaciated Michinmahuida volcano. Note the heavily damaged forest east to southeast of Chaitén volcano and the plume of sediment entering Chaitén Bay. International Space Station image ISS018-E-035716, 24 February 2009.


FIG. 3. Oblique aerial view to northwest of Chaitén lava dome. Caldera is about 3 km wide. Photograph by John Pallister, U.S. Geological Survey, 24 January 2010.

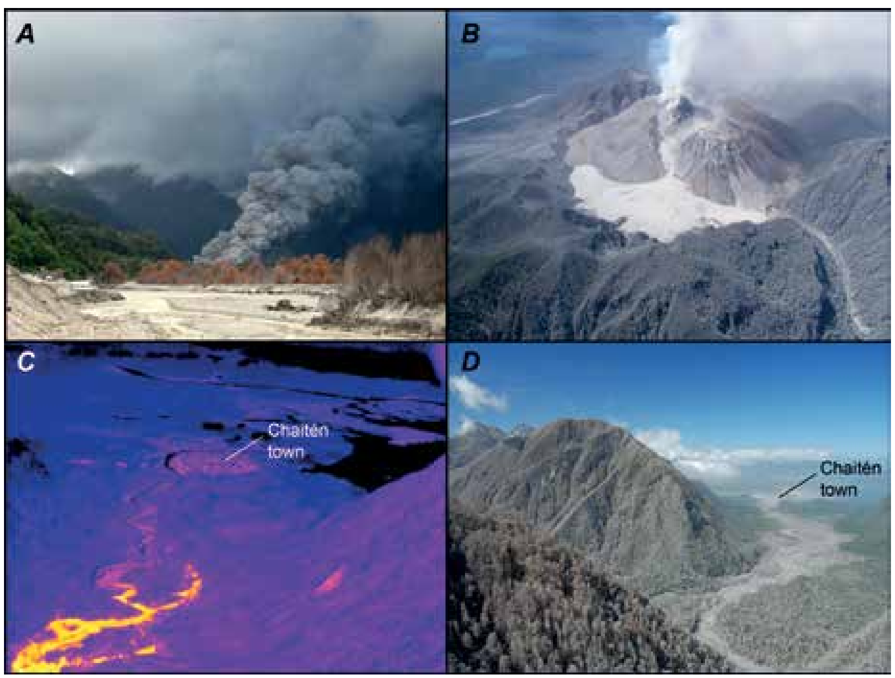


FIG. 4. Images of 19 February 2009 pyroclastic density current and extent of deposit in caldera and Chaitén River valley. **A**. PDC flowing into Chaitén River valley at 1043 local time viewed from bridge in Chaitén town. Image courtesy of Dagoberto Guzman, Parque Pumalín. **B**. Aerial view of PDC deposit in western side of caldera. Photograph by P. Duhart, SERNAGEOMIN, 24 February 2009. **C**. Oblique aerial thermal image looking downstream along Chaitén River valley. Image courtesy of A. Pavez, Departamento de Geofisica, Universidad de Chile, 25 February 2009. **D**. Oblique aerial view looking down Chaitén River valley. Photograph by J. Major, 24 January 2010.

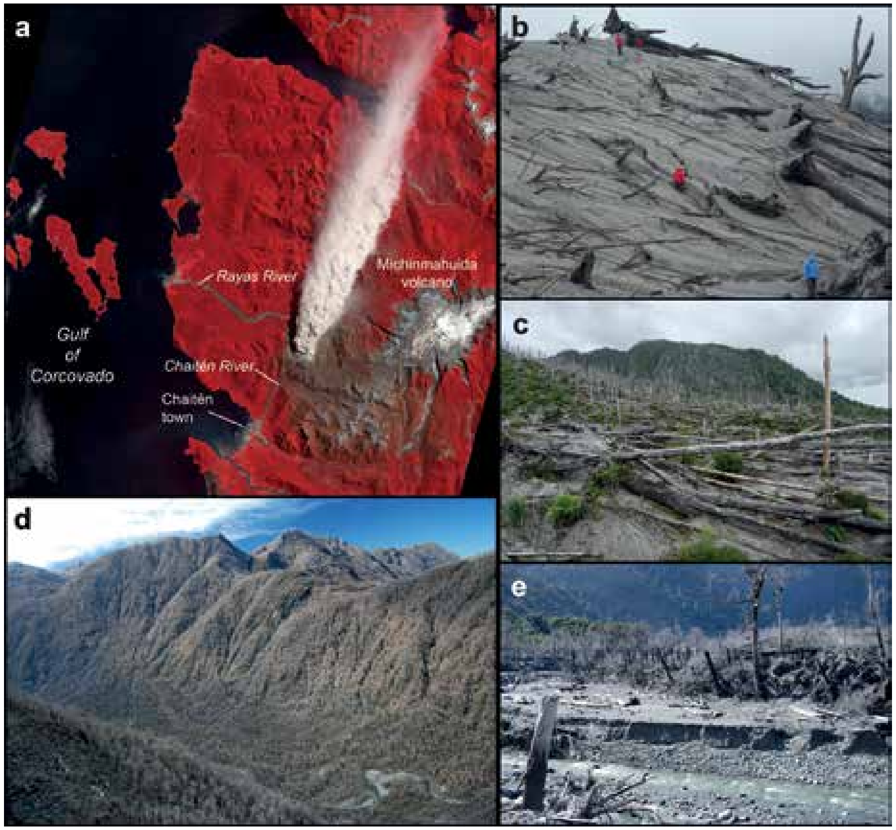


FIG. 5. Images of forest damage. **A**. False-color ASTER image (20090119), 19 January 2009. Red color indicates green vegetation. Note extensive forest damage to east and southeast (brown shades). **B**. North rim of caldera affected by blast-like PDC. See Major *et a*l. (2013) and Swanson *et al*. (2013) for details. Photograph by Fred Swanson, U.S. Forest Service, 21 January 2011. **C**. Trees toppled by blast-like PDC on north side of volcano. Photograph by J. Major, 19 January 2011. **D**. Extensive tract of damaged forest in upper Chaitén River valley. Photograph by J. Major, 23 January 2010. **E**. Trees buried by hot PDC deposit in Chaitén River valley. Photograph by J. Major, 5 March 2012.

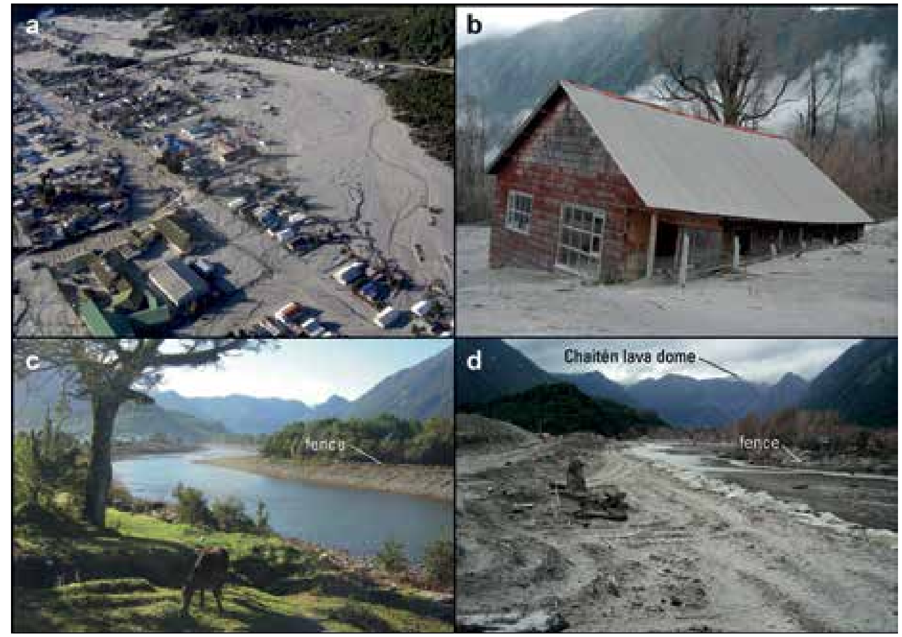


FIG. 6. Images of damage in Chaitén town caused by flooding and sediment transport. **A**. Channel aggradation and avulsion of river through Chaitén town. SERNAGEOMIN, 26 May 2008. **B**. House buried by overbank flood sediment. Photograph by J. Major, 22 January 2011. **C**. Pre-eruption view looking upstream from bridge in Chaitén town. Photograph © A. Alderete, 1 August 2007. Used with permission. **D**. Post-eruption view looking upstream from bridge in Chaitén town. Note stump of tree pictured in panel C. Photograph © H. Ulloa, Universidad Austral de Chile, 28 January 2010. Used with permission.


◀ FIG. 7. Map of field trip stop locations.

# FIELD TRIP

## DAY 1

### Stop 1-1.
### Hydrogeomorphic response to volcanic disturbance (Chaitén town)

The latter part of the explosive phase of the 2008 eruption, which mostly diminished by 11 May, emplaced fine to extremely fine ash over most of the 73 km$^2$ Chaitén (Blanco) River drainage basin (Pierson *et al.*, 2013). The total ash blanket varied from more than 2 m in thickness near the vent to only a few centimeters near the river mouth. Distant rain gauges north, west, and south of the basin suggest that rain that began falling late on the evening of 11 May delivered only about 20 mm of rainfall over about 14 hours to the basin at intensities that did not exceed 3 mm/h. Although this initial pulse of rain to the volcanically disturbed landscape was modest, the sedimentation response of the river was extraordinary. Extremely low infiltration of water into the ash mantle, combined with steep slopes and widespread destruction of hillslope forest vegetation, resulted in runoff ratios approaching 100%. Rapid runoff easily eroded and entrained the freshly deposited tephra, sending a complex lahar–flood down Chaitén River (with surges ranging in concentration to near the debris-flow/hyperconcentrated-flow transition) and causing the lower reach of the river channel to aggrade nearly 5 m in less than 24 hours. Another rainfall pulse the following day aggraded the channel an additional 2 m and set the stage for the channel to avulse through the town of Chaitén a day or two later (Fig. 8).

Before the channel avulsed, the delta at the original mouth of the river (delta 1) added 0.5–1.5 x 10$^6$ m$^3$ of sediment (Major *et al.*, 2016). After the channel avulsed, very high sediment-transport rates continued and a new delta (delta 2) began growing out into Chaitén Bay, its distal edge extending about 800 m out from the river mouth (Fig. 9). By 26 May delta 2 had accumulated a volume of nearly 2 x 10$^6$ m$^3$ of traction-load sediment. Through the remainder of 2008 and into early 2009, the rate of bed-load sediment delivery declined but remained high; delta 2 grew at a logarithmically decreasing rate until late 2011, when it reached a maximum volume of about 11 x 10$^6$ m$^3$ (Major *et al.*, 2016).

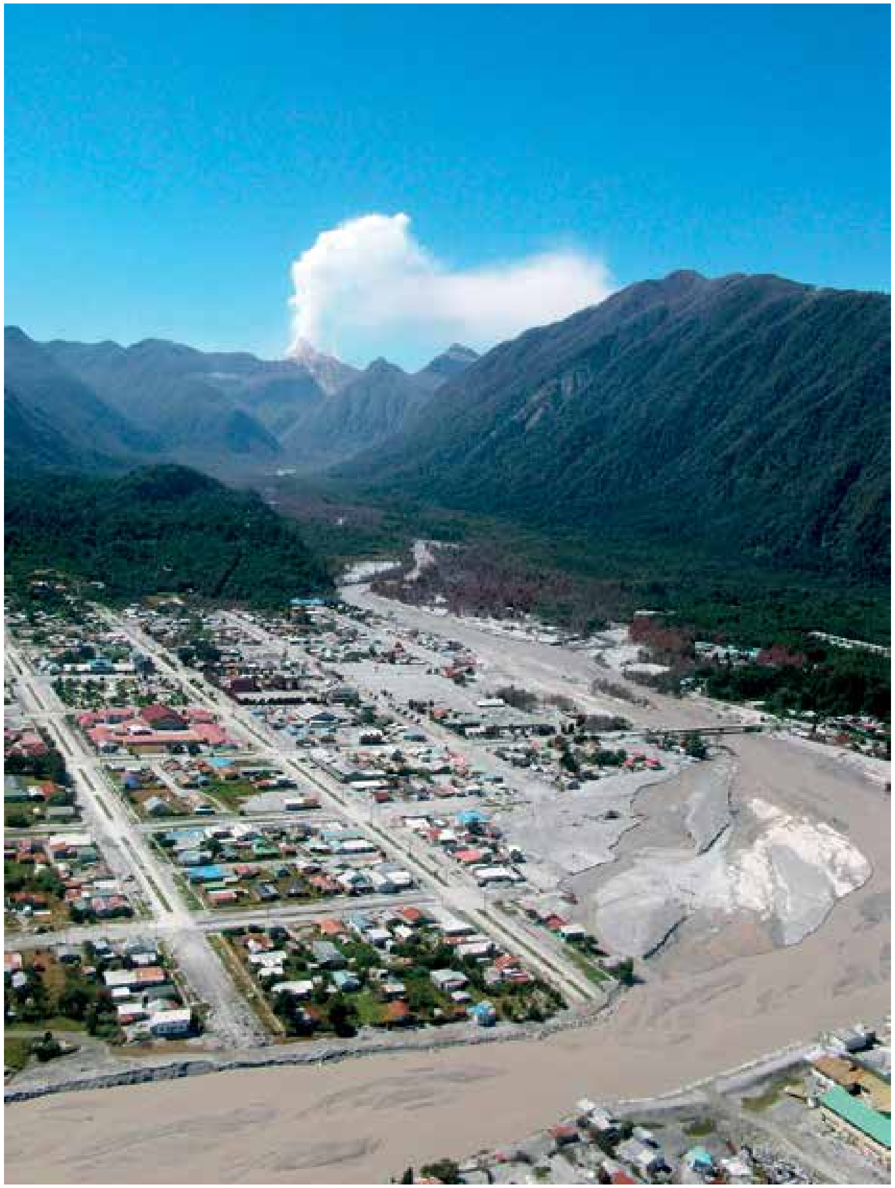

FIG. 8. Chaitén River channel in town of Chaitén, where channel infill caused the channel to avulse, turning right about 90 degrees and cutting through the middle of the town. Photo by P. Duhart, 2009.

FIG. 9. Outer edge of delta 2, where delta front (approximately 800 m out from the river mouth) is nearly impinging of the town's ferry dock. Photo by T. Pierson, 2011.

## Stop 1-2.
## Sedimentation along lower Chaitén (Blanco) River valley

Modest, low-intensity rainfall triggered abundant erosion of ashfall deposits in basin headwaters during waning stages of explosive activity in mid-May 2008. Subsequent dome collapses produced at least two substantial block-and-ash pyroclastic flows and possibly a modest pyroclastic surge. The largest of the block-and-ash flows, in February 2009, swept the valley to within 3 km of town. The initial sediment flush from the watershed generated a hyperconcentrated flow followed closely by a complex, multiday muddy flood. Mobilized sediment filled the lower 4 km of river channel with up to 7 m of sediment within 72 hours, 5 m of which aggraded within the first 24 hours (Pierson *et al.*, 2013). The 2009 block-and-ash flow deposited about 3–5 million $m^3$ of very poorly sorted, lithic-rich gravelly sand as much 8 to 10 m deep (Major *et al.*, 2013). Locally, the flow was hot enough to thoroughly char vegetation. Fig. 10 depicts our interpretation of the principal deposition and erosion in the Chaitén River valley during the 2008–09 eruption. At this stop upstream of Chaitén town, we will examine flood deposits related to the initial sediment flush and the distal edge of the 2009 block-and-ash flow deposit.

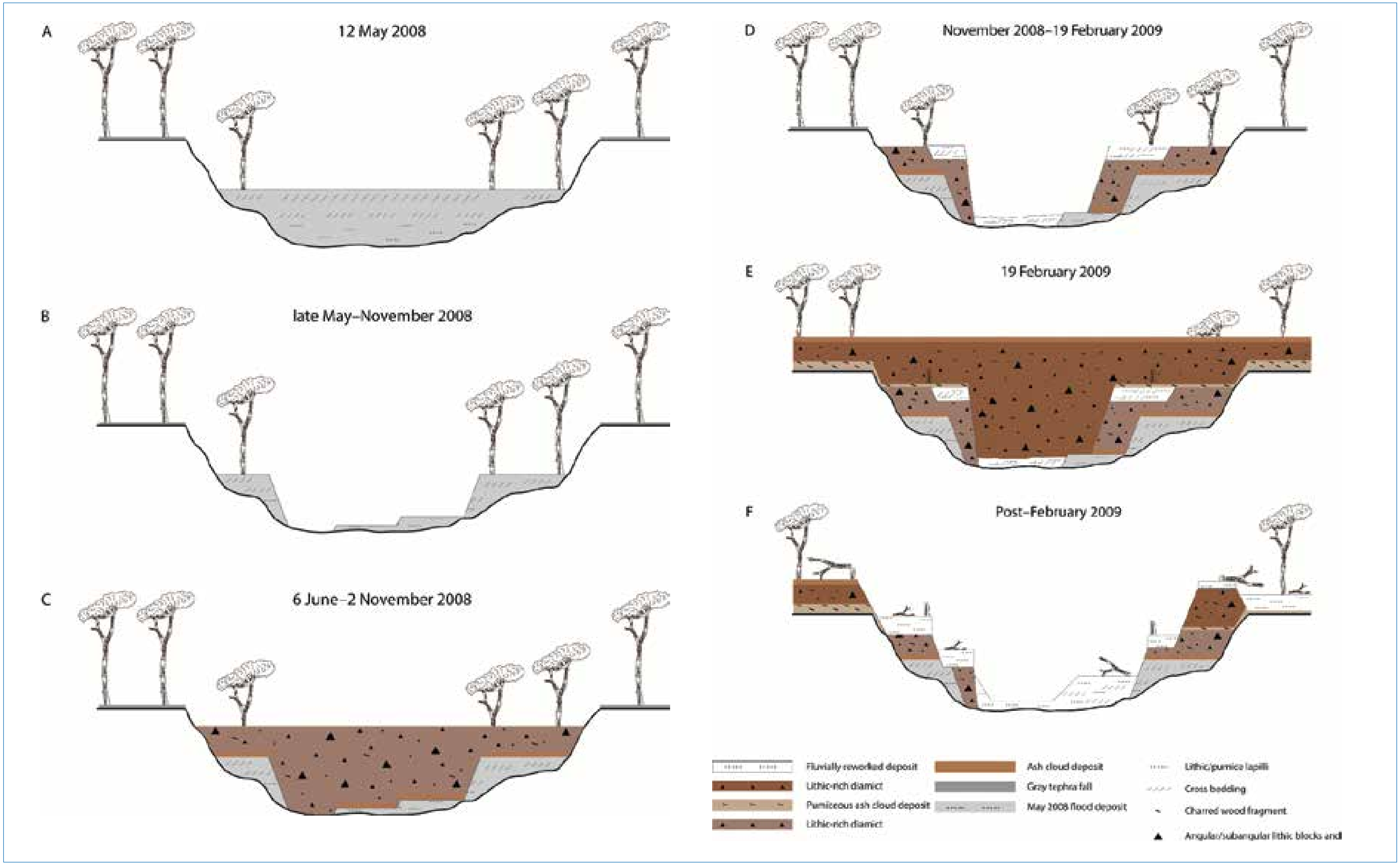


FIG. 10. Inferred sequence of deposition and erosion in Chaitén River valley during 2008-09 eruption (from Major *et al.*, 2013).

# DAY 2

## Stop 2-1.
## Site of the "Nuevo Chaitén" town aborted project (Santa Bárbara)

With the destruction of property from flooding and burial reaching ~80% of the town area and with the continuation of hazardous conditions, in 2009 the national government declared Chaitén town unsuitable for habitation. Basic services were shut off, property buy-outs were offered, and former residents were encouraged to rebuild homes and businesses in the small settlement of Santa Bárbara, 10 km (6.2 miles) to the north and rebranded as "Nuevo Chaitén." In March 2009, construction work on the new town's administrative facilities started. But the original Chaitén town site offered a deepwater harbor and provided a strong emotional sense of home for the residents; Santa Bárbara had neither.

As volcanic activity diminished, hundreds of residents began to reoccupy and rebuild the town in late 2008, using portable electric generators and an improvised water delivery system in order to carry on with daily life. In the face of growing political pressure, the government in 2011 reversed plans by the previous administration to move the town to a different location. Some services were partially restored and resettlement in the northern part of the town was permitted, despite a continuing, but albeit lessened, threat from the volcano. Presently, the government is evaluating whether to rebuild the southern part of town, where several families currently live.

At this stop we will examine the site where the town would have been re-established and discuss the perceptions that Chaitén residents had at that time.

## Stop 2-2.
## Pre-2008 volcanic depostis (north side of Chaitén volcano)

A new stratigraphic sequence was exposed along the road about 2 km NW of the caldera rim, following erosion during the early stages of eruption. In May 2008, extensive flooding and secondary lahars from steep slopes leading down from the caldera rim resulted in ash re-deposition and vegetation death in the Rayas River valley. Here Route 7, the main overland transportation route, appears to have acted as a flood conduit, leading to extensive roadside erosion and exposure of a fresh stratigraphic sequence (Watt *et al.*, 2013). At this stop we will observe a sequence that includes multiple volcaniclastic and pyroclastic deposits.

The basal deposit is composed of a coarse, several meters-thick lahar deposit having a poorly-sorted matrix of mud and sand supporting angular lithic blocks and also containing several large pieces of uncharred wood. Lithics within the deposit are aphanitic grey or red rhyolite, apparently derived from an old Chaitén dome. Juvenile material is scarce. The lahar deposit is overlain by a sequence of PDC and fall deposits less than 1 meter-thick. These deposits are composed largely of pumice but contain minor lithic and obsidian fragments (Watt *et al.*, 2013).

Overlying this sequence of deposits is a sequence of three well sorted pumice fall deposits, each a few centimeters-thick, separated by organic-rich soils. They contain yellow-grey to white pumices and are moderately rich in angular grey lava fragments. Most of the pumice grains are aphyric, although biotite phenocrysts occur in the upper fall deposit. The lowermost of these three fall deposits is attributed to an eruption of Michinmahuida volcano, whereas the upper two are attributed to eruptions of Chaitén (Watt *et al.*, 2013).

The basal sequence is inferred to represent a large, multistage event associated with a large Plinian eruption of Chaitén volcano (dated at around 5,000 yBP). Watt *et al.* (2013) correlate this deposit sequence with the mid-Holocence rhyolitic tephra fall deposit found in Argentina by Naranjo and Stern (2004), but which they attributed to an eruption of Michinmahuida volcano. The subsequent pumice-fall deposits attributed to Chaitén represent relatively smaller explosive eruptions, likely similar to the 2008 explosive event. Those eruptions occurred within the past few millennia.

## Stop 2-3.
## Ecological observations (north side of Chaitén volcano)

The U.S. Forest Service and Universidad Austral de Chile have studied ecological recovery following disturbance caused by the explosive phase of activity. During that phase, a small 'blast-like' PDC swept the north flank of the volcano (Major *et al.*, 2013). Ecological studies have focused on: (1) documenting the spatial distribution of impacts along a disturbance gradient (Swanson *et al.*, 2013); (2) tracking long-term response of plants and ground-dwelling arthropods; and (3) documenting physical and chemical characteristics of the buried forest soil and newly emplaced volcanic substrate. Below is a brief summary of part of that work provided by Charlie Crisafulli (U.S. Forest Service).

## Vegetation studies on the north side of Chaitén volcano

*Methods and design.* The study established four monitoring sites, each with three replicate 250 m² plots. Disturbance intensity, and thus impact on biota, decreased from the caldera rim to the distal limit of flow. The total area disturbed is about 4 km²; it includes three distinct zones: tree-removal (0.7 km²); tree blowdown (2.5 km²); and scorched forest (0.7 km²). Three study sites in the blowdown zone were established in 2011, and one in the tree-removal zone in 2013. In each plot, investigators documented surviving species, measured plant-species richness and abundance (percent cover by species), tagged tree seedlings to assess survivorship and growth rates, measured the type and amount of organic material on the ground surface, and measured the thickness, texture and chemical characteristics of the volcanic substrate.

*Initial patterns of plant survival.* The number of surviving species is inversely related to disturbance intensity. Individual survivorship is partly related to size; both large (overstory trees) and small (mosses and low statured herbs) species sustained high or complete mortality, whereas mid-sized taxa (robust herbs and shrubs) experienced high survivorship. In the blowdown zone plots, 10 to 16 species survived whereas few species survived in the tree-removal zone. Impact force was the dominant mechanism affecting many species. Force of the PDC toppled or sheared overstory trees, and consequently caused demise of canopy epiphytes. By contrast, burial was modest; at sites in the blowdown zone deposit thickness ranged from 25 to 45 cm, and was only about 60 cm at the tree-removal site near the caldera rim.

*Blowdown zone species richness.* Plant species richness in the blowdown zone increased rapidly during the first five years after eruption (2009 through 2013), then slowed dramatically (Fig. 11). The increase is attributed to numerous surviving species that emerged through deposits, and largely wind-dispersed colonizer species (herbs, grasses and shrubs). One pioneering tree, *Embothrium* (Notro), colonized rapidly and produced seeds by 2016. The levelling of richness across all blowdown plots likely owes to emergence of all surviving species and exhaustion of potential colonists. Future changes in species richness will likely be caused by low-probability dispersal events and shifts in plant dominance that change environmental conditions (e.g., light regime).

*Tree-removal zone species richness.* Plant species richness near the caldera rim increased slowly from 2013 through 2016, and is 2 to 3 times less than that at blowdown zone sites (Fig. 11). The slow rate of change at tree-removal plots is likely caused by fewer surviving species, relatively thicker deposits, a lack of organic material (i.e., downed wood) and a shorter growing season.

*Blowdown zone plant cover.* Extent of plant cover in the blowdown zone experienced little change from 2009 to 2013, but then increased substantially by 2016 (Fig. 11). Plant cover initially hovered around 1–3 % by 2011 but then increased to 30–60% by 2016. The initially low values result from loss of much pre-eruption flora and the slow emergence of surviving plants. The rapid increase is a result of growth and spread of survivors and establishment of colonizers (Figs. 12,13).

*Tree-removal zone plant cover.* Plant cover at the caldera rim has remained low during the limited study period (Fig. 11). Exceedingly low numbers of surviving individuals, few colonizers, and harsh site conditions (hard substrates, steep slopes, short growing season) have limited plant growth near the rim (Fig. 14).

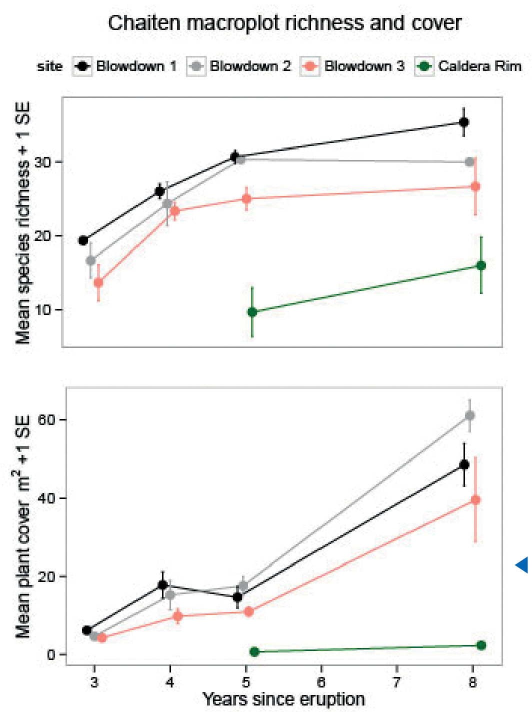


FIG. 11. Plant species richness (number of species) and abundance (percent cover) for three sites in the blowdown zone and one site in the tree-removal zone near the caldera rim. Each site has three replicate plots. Means and standard errors plotted. Data from C. Crisafulli, U.S. Forest Service.

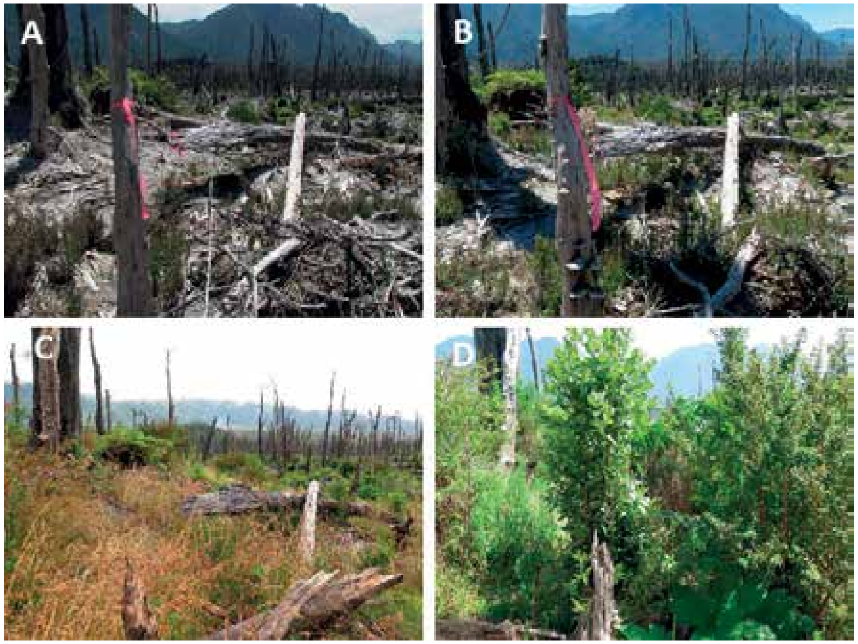


FIG. 12. Photo sequence showing changes in plant community from 2013 to 2016 at blowdown zone site #3: (A) 2012, (B) 2013, (C) 2014 and (D) 2016. The 2012 image, taken four years after the eruption, shows a mix of initial survivors and early colonizers, mainly *Gamochaeta spicata*, a wind-dispersed herb. By 2014 the grass colonizer *Polypogon australis* has become the dominate species. By 2016, surviving herbs (e.g., *Gunnera chilensis*), shrubs (e.g., *Fucshia magellanica*) and colonizing trees (e.g., *Eucryphia*) have largely taken over the plot. Photos by Charlie Crisafulli, U.S. Forest Service.


FIG. 13. Photo sequence showing changes in plant community from 2013 to 2016 at blowdown zone site #2: (A) 2012, (B) 2013, (C) 2014 and (D) 2016. The 2012 image, taken four years after the eruption, shows a mix of initial survivors (e.g., *Lophosoria quadrapinnata*) and an early colonizer, *Gamochaeta spicata*, a wind-dispersed herb. By 2013, native survivors begin to exert dominance. By 2016, the tree *Weinmannia* and shrub *Azara* fill the field of view. Photos by Charlie Crisafulli, U.S. Forest Service.

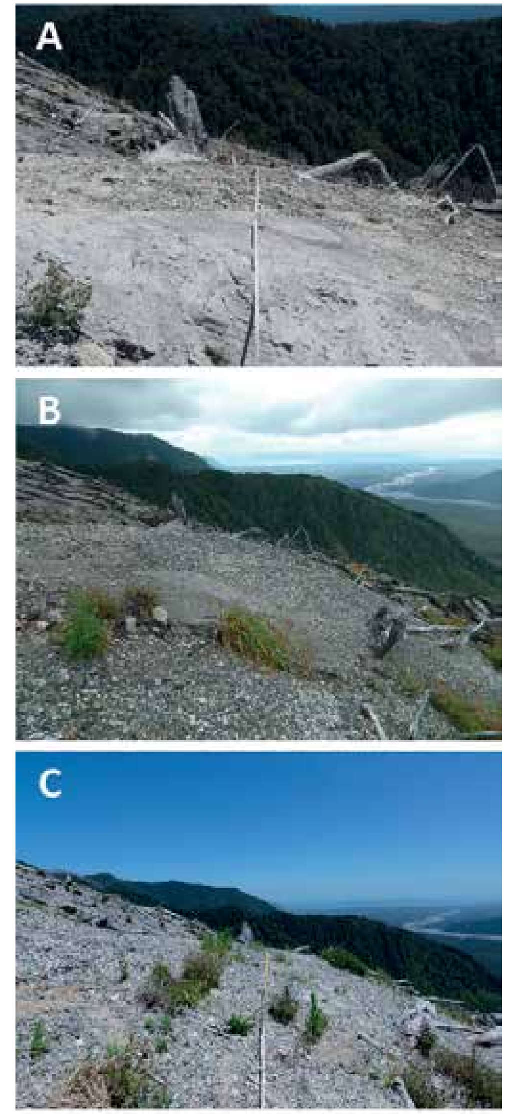


FIG. 14. Photo sequence depicting changes in plant community in the tree-removal zone near the caldera rim. A (2013), B (2014) and C (2016). Note the removal of fine ash between 2013 and 2014, which left a coarse gravel surface. Few survivors, harsh site conditions (high winds, cold temperatures) and steep slopes have slowed plant community development. Photos by Charlie Crisafulli, U.S. Forest Service.

## Stop 2-4.
## Caldera rim—Chaitén lava dome

The 2008–09 lava dome began extruding as explosive activity waned in mid-May 2008, and continued to grow until the end of the eruption in late 2009 or earliest 2010 (Figs. 15,16). A transitional phase of eruption consisting of simultaneous tephra columns and lava extrusion lasted from about 11–31 May. From June to September 2008, the dome grew mainly by exogenous lava extrusion. From October 2008 to February 2009 it experienced a phase of spine extrusion and endogenous growth. From mid-February 2009 to late 2009 or earliest 2010 the eruption consisted largely of an endogenous growth phase (Pallister *et al.*, 2009). The 2008–09 lava dome has a volume of about 0.8 $km^3$, roughly 60% more volume than the pre–2008 lava dome. Initial extrusion rates of lava in the first two weeks of the eruption were as great as 66 $m^3 s^{-1}$. About 60% the lava dome volume was erupted at an average rate of 45 $m^3 s^{-1}$ during the first four months of the eruption (Pallister *et al.*, 2013). These are among the highest rates estimated for historical lava-dome-forming eruptions. Pallister *et al.* (2013) attribute such high extrusión rates to low magma viscosity (the rhyolite magma was hot and had low phenocryst content) and high ascent rate. The high ascent rate allowed retention of volatiles and high magma pressure, which sustained the high effusion rates. Alfano *et al.* (2011) estimated the erupted bulk tephra volume to be between 0.5 and 1.3 $km^3$. Assuming a bulk deposit density of about 1100–1500 kg $m^{-3}$, and a dense rock density of 2300 kg $m^{-3}$, the explosive phase of eruption released about 0.25–0.85 $km^3$ DRE. Thus, the lava dome accounts for 50 to 75% of the total volume of magma erupted.

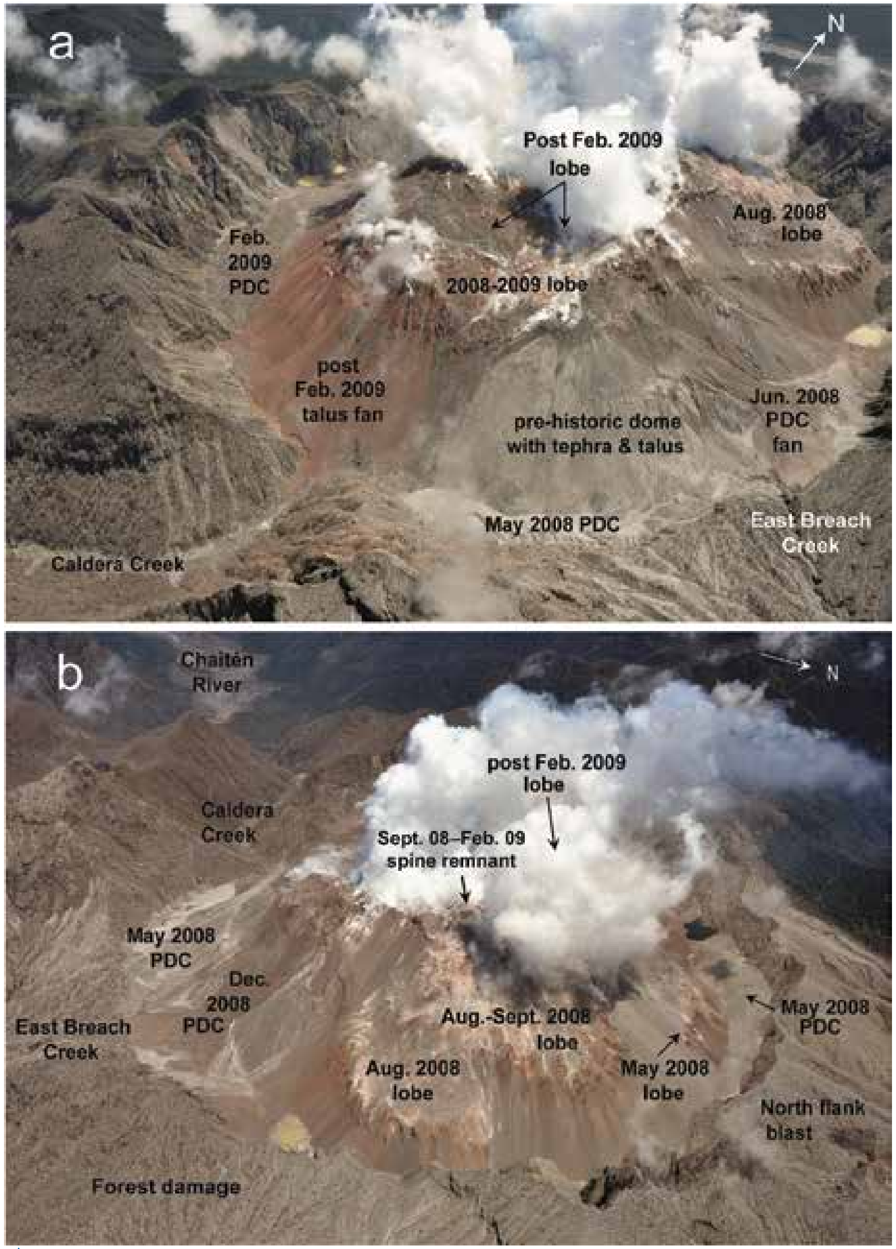


FIG. 15. Oblique aerial views of Chaitén volcano caldera taken on 24 January 2010. A. View to northwest. B. View to southwest. Caldera diameter about 3 km. From Pallister *et al.* (2013).

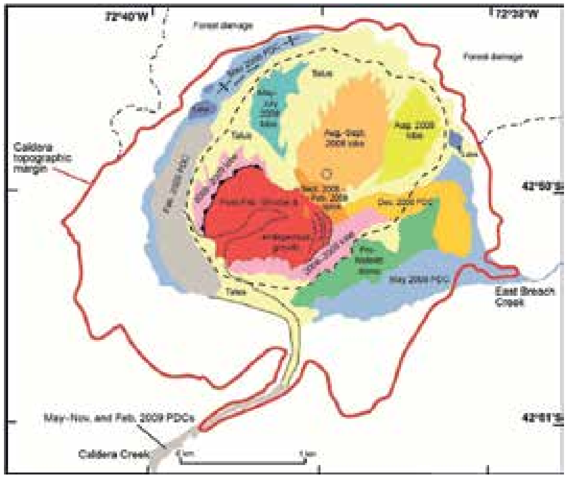


FIG. 16. Geologic map of Chaitén volcano lava dome as it appeared in January 2010. Dotted lines show former position of February 2009 PDC deposit resulting from dome collapse. Dashed line shows contact of lava dome dome buried by talus. Line with half circles marks faulted boundary produced by endogenous growth after February 2009. Hachured lines show normal faults produced in response to collapse and lateral spreading. Dashed circle shows approximate position of main vent from May to September 2008. Dash-dot lines show areas of forest damage. From Pallister *et al.* (2013).

## DAY 3

### Stop 3-1.
### Volcano Monitoring Network (El Amarillo school)

The eruption of Chaitén spurred the national government to implement a new national plan to address the country's considerable volcano hazards. Chile has within its borders nearly 90 active volcanoes, only a handful of which had any monitoring in place before 2008. The resulting Red Nacional de Vigilancia Volcánica (RNVV) of SERNAGEOMIN is in charge of the permanent surveillance of the 45 most actives volcanoes in the country as well as the publication of both geological and volcano hazards maps. Chaitén and Michinmahuida volcanoes are currently monitored through broad-band seismic stations and web cameras. In the future, the goal is to set up multiparameter stations including seismic, tiltmeter, GPS, DOAS, web and thermal cameras, and acoustic stations.

Currently, analyses of data are done at the Southern Andes Volcano Observatory (OVDAS) located in Temuco, in a 24 hours/7 days per week surveillance scheme. Due to the particular geography of Chile, SERNAGEOMIN is evaluating establishing two additional observatories, one located in Coyhaique, Aysén region, (more than 300 km south of Chaitén) that will be responsible for volcano surveillance from Chaitén to the Magallanes region (an arc segment more than 1,000 km long).

The Amarillo school is one of the nodes where signals from several stations are transferred to the OVDAS. Here, the current network of seismic stations will be discussed along with the main features of seismic activity recorded since 2012.

### Stop 3-2.
### Pumalín Park

Pumalín Park is Chile's largest private nature reserve, operated as a public-access park. It is one of the largest (ca. 300,000 ha; 3,000 km$^2$) and most diverse environmental conservation efforts in South America. It extends from the Cordillera de los Andes to the fjords of the Pacific Coast, protecting pristine Valdivian temperate rainforest. The park contains trails, campgrounds, and public facilities that allow thousands of visitors a year to experience the majestic landscape of Patagonia. Beyond the park's borders, the Pumalín Project includes a network of organic farms restored from ecological degradation, social initiatives that promote healthy livelihoods and conservation values in surrounding communities, and activist campaigns around larger conservation issues in the region. For over two decades, this diverse approach to conservation has enabled the project to expand its impact far beyond the park's borders.

Pumalín Park is going to be given as a donation to the Chilean State by the family of the recently deceased Douglas Tompkins. The transfer process will end near the year 2020, when the administration of the lands will be under the charge of CONAF (National Forestry Corporation), the Chilean institution responsible for the management of protected areas.

El Amarillo sector (at the southern entrance of the park) experienced the greatest damage as a consequence of the Chaitén eruption, requiring massive restoration work. Just months after a major landscape restoration project there had been completed, the eruption covered the area in volcanic ash. Closing the park to the public from 2008 to 2010 permitted park employees to concentrate their efforts on repairing damaged infrastructure and assisting natural recovery. Heavy rains progressively washed away much of the ash until only a small quantity remained, which was turned over into the soil and reseeded. Campgrounds were dug out and repaired. Ash-filled rivers had altered course and washed out large sections of road, which required complete rebuilding. After seasons of diligent work, the entire El Amarillo sector is restored, with the new administrative office open and the park receiving thousands of visitors once again.

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# FIELD GUIDE
## CHAITÉN VOLCANO: FEATURES AND IMPACTS OF THE 2008-09 ERUPTION

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