The Andean Southern Volcanic Zone: Deformation, Eruptions, and Thermal Anomalies Before and After the 2010 Mw 8.8 Maule Earthquake

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Abstract. Historically very active, the Andean Southern Volcanic Zone lends itself to the study of active magmatic and eruptive processes and its relationship to earthquakes. We use satellite remote sensing, both radar and thermal infrared, to survey the deformation and thermal activity of the volcanoes in the SVZ before and after the 2010 Mw 8.8 Maule earthquake. In response to the Maule earthquake, 5 volcanic regions, all within the Maule rupture zone, experienced co-seismic subsidence of 5-13 cm in the line-of-sight of the satellite. On the other hand, Cordón Caulle volcano did not exhibit triggered activity from the Maule earthquake, nevertheless InSAR reveals complex deformation patterns prior to its 2011 eruption. We find that Cordón Caulle experienced an episode of inflation that spanned from 2008 to 2010. The uplift of about 12 cm maximum LOS is consistent with growth of a shallow rhyodacitic magma chamber at 6-8 km depth, but may also be due to hydrothermal processes. Thermal infrared data from ASTER reveal that at least 13 of the 86 volcanoes in our survey demonstrate thermal anomalies, or hotspots, between 2000 and 2010. Analysis of MODIS data shows that thermal activity at SVZ volcanoes was not heightened following the Maule earthquake.

Keywords: trigger, Maule earthquake, InSAR, hotspots, Cordon Caulle

1 Introduction

The 2010 Mw 8.8 Maule earthquake occurred near the Andean Southern Volcanic Zone (SVZ), a region of active volcanism, making the SVZ an ideal setting to study the interplay between great earthquakes and volcanism. The causal relationship between great earthquakes (Mw > 8) and volcanic eruptions worldwide has been documented in the literature. For example, Watt et al. (2009) found that the 1906 and 1960 Chile earthquakes triggered at least 3-4 volcanic eruptions in the Andean Southern Volcanic Zone (SVZ) within 12 months of the earthquakes. However, not all great earthquakes trigger eruptions, and the relationship between earthquakes and volcanoes is complex and dependent on many factors such as the state of the magmatic system at the time of the earthquake, the location of the earthquake relative to the volcanoes, and the static and dynamic stress fields imposed by the earthquake. We investigate the effects of the Maule earthquake on the SVZ using radar and thermal infrared remote sensing. Satellite remote sensing is an excellent tool to study these volcanoes due to its synoptic coverage of the whole volcanic arc. In this study, we use Interferometric Synthetic Aperture Radar (InSAR) to measure ground deformation at all the volcanoes of the SVZ since 2007. We also use thermal infrared data from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and MODIS (Moderate Resolution Imaging Spectrometer) to detect thermal anomalies, or hotspots, between the years 2000 to 2010.

2 Methods and Results

2.1 Seismically Triggered Deformation

Using InSAR, we find that 5 volcanoes in the SVZ – "Caldera del Atuel", Tinguiririca, Calabozos, Cerro Azul, and Nevados de Chillán – demonstrated significant co-seismic subsidence (Figure 1) in response to the 2010 Mw 8.8 Maule earthquake. These volcanoes subsided between 5 and 13 cm in the radar line-of-sight, and the semi- major axes of all of the subsidence patterns are oriented north-south. According to published slip models for the Maule earthquake (e.g., Lorito et al., 2011) there is predicted east-west extension in the volcanic arc, but it is unclear if this was related to the cause of the ground deformation. All five volcanoes are located within the rupture zone of the earthquake. The subsidence signal is short-lived and can only be observed in interferograms that span the date of the earthquake. Interestingly, Laguna del Maule, a deforming caldera with an active geothermal system (Fournier et al., 2010), is located in the center of the Maule rupture zone but did not respond to the earthquake. The observation of one earthquake triggering deformation at multiple volcanic centers has not been previously documented, though deformation at Long Valley Caldera seems to have been triggered by 3 different earthquakes (1992 Landers, 1999 Hector Mine, 2002 Denali Fault) (e.g., Johnston et al., 2004). In Japan, subsidence of several volcanic centers was observed by InSAR following the 2011 Mw 9.0 Tohoku earthquake (Fukushima et al., 2011).

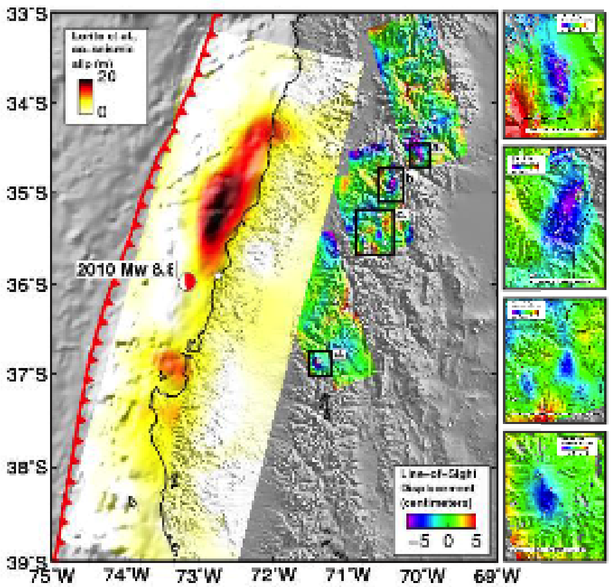

Figure 1. Five regions of volcanic subsidence triggered by the 2010 Mw 8.8 Maule earthquake. a) Caldera del Atuel; b) Tinguiririca; c) Calabozos and Cerro Azul; d) Nevados de Chillán. The earthquake slip map is from Lorito et al. (2011).

Our preferred mechanism for triggering of deformation involves shaking-induced removal of hydrothermal deposits and increased permeability of crustal rocks, allowing previously trapped fluids to escape. A similar mechanism was proposed by Brodsky et al. (2003) to explain sustained groundwater pressure changes following large distant earthquakes. Changes in the streamflow of rivers in the Bío Bío Region of Chile have been documented (Mohr and Wang, 2011) and may be related to the observed deformation.

2.2 Cordón Caulle Deformation and Eruption

Cordón Caulle volcano, located about 500 km south of the Maule epicenter, does not appear to exhibit activity triggered by the Maule earthquake in remote sensing observations, but InSAR has revealed a deformation history that is quite complex. InSAR observations of ground deformation at Cordón Caulle have been available since 1996, but data acquired prior to 2007 is poorly recorded by C-band radar satellites. Nevertheless, between 1996 and 1999, 8 cm of subsidence was observed in a pattern oriented along the strike of the Cordon Caulle fissure, NW-SE (Pritchard and Simons, 2004). In interferograms spanning 2003-2005 and 2004-2006, uplift rates of 1 cm/yr and 3 cm/yr were observed (Fournier et al., 2010). These uplift signals occurred in the same location and with the same spatial pattern as the 1996-1999 subsidence signal. Between 2007 and 2008, the uplift signal retained the same pattern but accelerated to nearly 20 cm/yr (Fournier et al., 2010). Modeling of the deformation pattern using two inflating point sources gave the location of the two sources at 7 and 4 km depth, and the cause of inflation was inferred to be either hydrothermal or magmatic.

This short-lived burst of inflation was followed by a change in location, shape, and extent of the deformation pattern beginning in early 2008. In an interferogram that spans 27 May 2008 to 18 Jan 2011, we find a maximum uplift signal of 18.5 cm at the center of deformation. This signal is oriented N-S and is broader than the 1996-2008 deformation patterns (Figure 2). Initial modeling of the deformation pattern using three inflating point sources puts the dominant source at a depth of 6-8 km with a volume change on the order 0.001 km^3 (compared to the volume of DRE erupted material of <0.6 km^3 (Amigo et al., 2011)). Since interferograms spanning 2010-2011 do not exhibit a clear deformation signal, we think that the deformation event ended in 2010. Due to a lack of InSAR data in 2009, we do not know if the rate of deformation was constant between 2008 and 2010. The inflation could be related to either magmatic or hydrothermal processes. The inferred source depth of 6-8 km is consistent with the depth of a shallow rhyodacitic magma chamber (Gilbert et al., 2011).

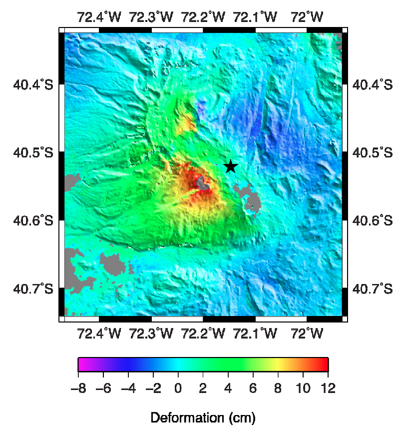

Figure 2. A stack of six interferograms over Cordon Caulle spanning January 2008 to March 2011 showing the inflation episode prior to the June 2011 eruption. The black star indicates the 2011 eruptive vent. SAR data is from the ascending path 119 of the ALOS satellite.

2.3 Thermal Anomalies

We analyzed thermal infrared data from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and MODIS (Moderate Resolution Imaging Spectrometer) instruments to look for both background thermal activity as well as activity triggered by the Maule earthquake. In the survey of background activity, we examined 86 volcanoes and geothermal areas in the SVZ for temperature anomalies, or hotspots, between 2000-2010. At least 13 volcanoes have ASTER hotspots temperatures ranging from 4-100 K above background temperatures (Figure 3). Our survey reveals that low amplitude volcanic hotspots detectable from space are more common than expected based on lower resolution data. Most of these hotspots can be attributed to fumaroles, hot springs, geothermally heated lakes, lava lakes, and eruptions.

In order to assess the possibility of triggered thermal activity by the Maule earthquake, we used data from the MODIS instrument, which has a lower spatial resolution than ASTER but acquires one image per day over every volcano in the SVZ. We analyzed MODIS data from bands 21 and 22 between 7 February and 19 March 2010, or 20 days before and after the earthquake, and found that no new hotspots were triggered. The hottest pixels in our search were the previously known hotspots at Chaitén and Villarrica volcanoes, and their temperatures did not significantly increase following the earthquake.

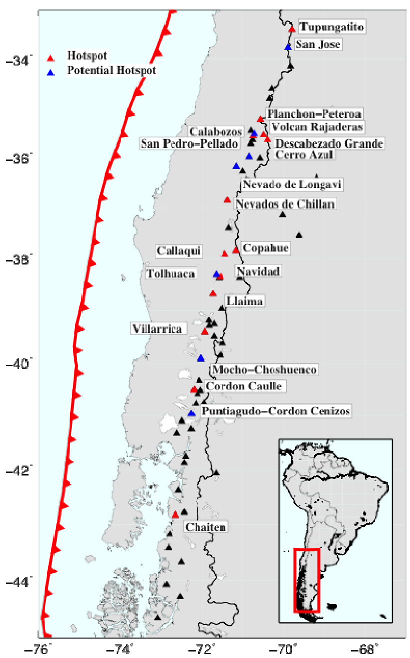

Figure 3. Reference map of hotspots and potential hotspots in the SVZ. Other volcanoes from the Smithsonian Institution database (Siebert and Simkin, 2002-2012) are shown as black triangles.

3 Discussion and Conclusions

Satellite-based remote sensing of the volcanoes in the SVZ has revealed complex patterns of activity in response to the Maule earthquake as well as prior to eruption. The subsidence of volcanic regions immediately following the Maule earthquake is possibly related to the hydrothermal system. Potential mechanisms to explain the subsidence include the response of a weak hydrothermal zone to the static stress change of the Maule earthquake or the escape of fluids to the surface caused by seismic shaking. In contrast, Cordón Caulle volcano did not demonstrate an obvious response to the Maule earthquake. InSAR models of the pre-eruptive deformation of Cordón Caulle volcano, constrained with geochemical and petrological observations, will provide information about magma accumulation and storage prior to a large silicic eruption. Thermal infrared data from MODIS does not reveal thermal activity triggered by the Maule earthquake, but a review of higher spatial resolution ASTER data immediately following th eearthquake is in progress. In any case, our study shows that ASTER is an ideal tool to analyze thermal behavior of the SVZ as it detects hotspots that cannot be seen with the lower resolution MODIS data.

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