Searching for Activity in the Andean Central Volcanic Zone: Thermal Anomalies, Seismicity, and Deformation Over a Timespan of 1-20 years

Scott T. Henderson¹, Matthew E. Pritchard¹, Jennifer A. Jay¹, Mark Welch¹, Peter J. Mares¹, Marissa E. Mnich¹, Andrew K. Melkonian¹, Felipe Aguilera², José Antonio Naranjo³, Jorge Clavero⁴, Estela Minaya⁵, Mayel Sunagua⁶, Bianca Glass⁷, Sergio Barrientos⁸

¹Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, USA; ²Departamento de Geologia, Universidad de Atacama, Copiapó, Chile; ³SERNAGEOMIN, Santiago, Chile; ⁴Energia Andina, Dario Uruzúa 2165, Santiago, Chile; ⁵Observatorio San Calixto, La Paz, Bolivia; ⁶SERGEOTECMIN, La Paz, Bolivia; ⁷Universidad de Tarapacá, Arica, Chile; ⁸Universidad de Chile, Santiago, Chile

*E-mail: jaj88@cornell.edu

Abstract. We conducted a survey of the volcanoes in the Central Volcanic Zone in search of surface deformation, thermal anomalies, and volcanic seismicity. We use InSAR to monitor the arc for deformation and find two volcanoes with previously undocumented deformation (Putana and Cerro Otero). We also document continued deformation at Uturuncu, Lazufre, and Cerro Blanco. We use thermal infrared data from the ASTER instrument to detect thermal anomalies, or hotspots, at 64 volcanoes. We find that at least 23 volcanoes demonstrate hotspots that can be seen in high spatial resolution ASTER data, with most of these hotspots being attributed to fumaroles. We have deployed temporary networks of seismometers at 9 volcanoes and have found that Uturuncu and Guallatiri volcanoes both exhibit high rates of local volcanotectonic seismicity. Our study shows that the relationship between deformation, thermal anomalies, and seismicity in the CVZ is complex and, although some volcanoes such as Uturuncu exhibit all three manifestations of activity, in general they are not all evident at the same time.

Keywords: InSAR, CVZ, ASTER, hotspots

1 Introduction

The Andean Central Volcanic Zone (CVZ, 15° to 28° S) is home to hundreds of potentially active volcanoes, but only a few dozen of these have been monitored for activity. We employ satellite Interferometric Synthetic Aperture Radar (InSAR) to remotely sense ground deformation in the region exceeding rates of a few cm/yr. The synoptic coverage of InSAR makes it a good tool for detecting surface deformation; however, some volcanoes show evidence of magmatic activity (temperature anomalies, earthquakes, eruptions) without measurable surface deformation. Furthermore, the cause of ground displacements is often ambiguous; for example, surface deformation may be caused by shallow hydrothermal fluid circulation or deeper magma migration. Distinguishing between physical causes is an essential step in volcanic hazard assessment. In order to more comprehensively assess the activity of the volcanoes in these regions we use nighttime infrared satellite observations from the Advanced Space Thermal Emission Radiometer (ASTER) and the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments to detect thermal anomalies. Finally, we have deployed seismic arrays at 9 volcanoes in the CVZ in order to search for any connections between these three import indicators of magmatic activity: Surface deformation, seismicity, and thermal anomalies.

2 Methods and Results

2.1 Remotely Sensed Deformation

The advent of InSAR has dramatically increased the number of known deforming volcanoes in the world from 44 in the late 1990’s (Dvorak and Dzurisin, 1997) to more than 130 in 2011 (Fournier et al., 2010). Of the 69 active volcanoes (Smithsonian Global Volcanism Program) in the CVZ, there have been 13 with historic eruptions, and 9 of the volcanoes have deformed within the last 20 years. Some, but not all volcanoes have temporally variable deformation rates and some sites have started or ceased deformation since our earlier InSAR survey of the area (Pritchard and Simons, 2004).

In order to understand the temporal variation of deformation signals in the CVZ, we conducted a time series inversion of 631 ERS and Envisat interferograms from 1992 to the present covering up to 870 kilometers along the volcanic arc. Table 1 shows a summary of known deforming volcanoes in the CVZ documented by previous authors and by this study. Two deformation sources contained in the CVZ, Uturuncu and Lazufre, are particularly intriguing in that they are long-lived (>10 yrs), have large diameters (>50 km), and have modeled sources at mid-crustal depths (10-20 km). Results indicate continuing monotonic inflation styles at Uturuncu and Lazufre with maximum radar line-of-sight (LOS) uplift at 1.0 cm/yr over the past 20 years and 3.5 cm/yr over the past 5 years, respectively. Such high inflation rates are unsustainable over long time periods due to geomorphic constraints – uplift of 1 cm/yr over one million years would put Uturuncu at an unrealistic elevation of 10 km.
Assessment of the hazard posed from intrusions at Uturuncu and Lazufré is difficult because of many unanswered questions: Is the deformation caused by magma accumulation, will the magma we currently observe to be intruding ever erupt, and, if so, are we measuring an early, middle, or late stage in the accumulation?

2.2 Remotely Sensed Thermal Anomalies

We examined 64 volcanoes and geothermal areas in the CVZ for temperature anomalies, or hotspots, between 2000-2010 from two different satellite sensors: 1) those automatically detected by the MODVOLC algorithm (Wright et al., 2004) from MODIS and 2) manually identified hotspots in nighttime images from ASTER. At least 23 volcanoes have hotspot temperatures of 4–100 K above background temperatures. Most of these hotspots can be attributed to fumaroles, hot springs, and eruptions. At least 9 volcanoes in the same areas have exhibited ground deformation; however, there are many deforming volcanos without hotspots and many thermal anomalies without observed deformation. Our survey reveals that low amplitude volcanic hotspots detectable from space are more common than expected based on lower resolution data. Although there were 65 earthquakes with Mw>7 in our study area from 2000-2010, we found no evidence that the thermal anomalies were affected by seismic shaking.

2.3 Seismicity at Select Volcanoes

Individual volcanoes have distinct seismological personalities, and therefore it is important to characterize the types, locations, magnitudes, and rates of earthquakes that occur. We have installed seismometers at various volcanoes in the CVZ including Uturuncu, Ollagué, Olcaparuma, Irruputuncu, Sol de Manaña, Lastarria, Parinacota, Isluga, and Guallatiri. Using a network of 15 seismometers around the inflating Uturuncu volcano from April 2009 to 2010, we find an average rate of about 3 local volcano-tectonic earthquakes per day, and swarms of 5-60 events a few times per month with local magnitudes ranging from -1.2 to 3.7 (Jay et al., 2012). Over the last two years we have divided the array amongst other active volcanoes (exhibiting thermal anomalies or having recent eruptions, but not necessarily deforming) for reconnaissance studies lasting several months. To date we have found that the fumarolically active Ollagué, Olcaparuma, and Irruputuncu volcanoes located roughly 200km to the Northeast of Uturuncu exhibit much less local seismicity. For example, over a two-month period in 2010, we identified only 3 local earthquakes at Olcaparuma and 22 earthquakes at Ollagué. In northern Chile, Guallatiri volcano appears to be much more seismically active than Parinacota and Isluga with an average seismicity rate of 2 earthquakes per day, with many of the earthquakes occurring in swarms.

Soler and Amigo (2012) have documented microseismic activity at Putana volcano, which has also shown a fleeting uplift episode of 4 cm LOS in the InSAR data (Figure 2). The uplift episode occurred sometime between 18 October 2009 and 31 January 2010.

![Figure 2. Interferogram showing the uplift signal at Putana volcano on the border between Chile and Bolivia.](https://example.com/figure2.png)

3 Discussion and Conclusions

As of yet there do not appear to be general correlations between seismic activity, thermal anomalies, and surface deformation at active volcanoes in the Andean Central Volcanic Zone. There are some hints that distinct volcanic
arcs have differing relations between ground deformation and eruption. For example, the few deforming volcanoes found in the northern Andes, Kamchatka, and Central America are contradictory to the high level of eruptive activity in these regions and likely indicate different magma plumbing systems in these arcs relative to other arcs with many deforming volcanoes like Alaska or the central and southern Andes.

Acknowledgements

We thank the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) for funding for this project. We also thank the people of Caquena, Isluga, Parinacota, and Enquela in northern Chile and the Bolivian military for their hospitality and cooperation while doing fieldwork. Finally, we thank the Chilean Dirección Nacional de Fronteras y Límites del Estado (DIFROL), Corporación Nacional Forestal (CONAF), and the Bolivian Servicio de Areas Protegidas, especially the staff at the Reserva Eduardo Avaro, for permission to temporarily deploy geophysical instrumentation.

References


Fournier, T. J.; Pritchard, M. E.; Riddick, S. N. 2010. Duration, magnitude, and frequency of subaerial volcano deformation events: New results from Latin America using InSAR and a global synthesis. Geochemistry Geophysics Geosystems 11 (1).


Table 1. Summary of deforming volcanoes in the Central Volcanic Zone (1992 – present)

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Time of observed deformation</th>
<th>Max. LOS rate (cm/yr)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ticsani, Peru</td>
<td>2005</td>
<td>-6</td>
<td>Holtkamp et al., 2011</td>
</tr>
<tr>
<td>Uturuncu, Bolivia</td>
<td>1992-2011</td>
<td>1</td>
<td>e.g., Pritchard &amp; Simons, 2004</td>
</tr>
<tr>
<td>Putana, Bolivia-Chile</td>
<td>2009-2010</td>
<td>5</td>
<td>This work</td>
</tr>
<tr>
<td>Cerro Overo, Chile</td>
<td>1992-2010</td>
<td>-0.5 &amp; 0.5</td>
<td>This work</td>
</tr>
<tr>
<td>Láscar, Chile</td>
<td>1993-2010</td>
<td>-2</td>
<td>Pavez et al., 2005; Whelley et al., 2012</td>
</tr>
<tr>
<td>Lastarria, Chile</td>
<td>2001(?)-2011</td>
<td>1-2</td>
<td>Froger et al., 2007; Ruch et al., 2009</td>
</tr>
<tr>
<td>Lazufre, Chile-Argentina</td>
<td>1998(?)-2011</td>
<td>2.5</td>
<td>e.g., Pritchard &amp; Simons, 2004; Ruch et al, 2009</td>
</tr>
</tbody>
</table>