Journal of South American Earth Sciences 42 (2013) 144–149

Contents lists available at SciVerse ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Crustal-scale electrical conductivity anomaly beneath inflating Lazufre volcanic complex, Central Andes

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ARTICLE INFO

Article history:
Received 3 September 2012
Accepted 15 November 2012

Keywords:
Magnetotellurics
Central Andes
Volcanoes
Surface deformation

ABSTRACT

Large-scale surface deformation was observed at Lazufre volcanic center in the Central Andes of Northern Chile/Northwestern Argentina by means of Interferometric Synthetic Aperture Radar (InSAR). Uplift started there after 1998 and increased dramatically in the following years up to a rate of 3 cm/a. Lazufre is now one of the largest deforming volcano systems on Earth, but the cause for uplift – likely influx of magmatic material into the crust – is still poorly understood.

In the beginning of 2010 a magnetotelluric survey was conducted to delineate the electrical conductivity distribution in the area. Several long-period magnetotelluric (LMT) sites and two broadband magnetotelluric (BBMT) sites were set up on an EW trending profile crossing the volcanic center; furthermore some LMT sites were arranged circularly around Lazufre complex and adjacent Lastarria volcano. Data were processed using an algorithm for robust and remote reference transfer function estimation. Electrical strike directions were estimated and induction arrows were derived. Although electrical strike is rather ambiguous, in a first step a 2-D resistivity model was calculated. The most prominent feature of this model is a well conducting structure rising from the upper mantle to the shallow crust beneath the center of elevation. This can be interpreted as partial melts ascending from the asthenospheric wedge and feeding a potential magma reservoir beneath Lazufre volcanic center. An improved model is finally achieved by 3-D inversion, supporting this feature. We assume that these rising melts are the source of the observed uplift at Lazufre complex.

1. Introduction

Insights into the spatio-temporal development of volcanic centers have recently become available by images of Satellite Interferometric Synthetic Aperture Radar (InSAR). Pritchard and Simons (2002) created radar interferograms for about 900 of the approximately 1100 volcanic edifices in the Central Andes. Active deformation at four circular-elliptical volcanic centers was observed. In this work we focus on the area in the vicinity of the volcanoes Lastarria and Cordón del Azufre, which is often termed "Lazufre", an acronym of Lastarria and Azufre (Pritchard and Simons, 2002).

The Lazufre volcanic complex is situated in the Western Cordillera of the Central Andes, the location of the present magmatic arc, at approximately 25.1°S on the border between Argentina and Chile (Fig. 1). The magmatic arc has developed due to subduction of the Nazca plate beneath the South American plate and has migrated 200 km eastwards since 120 Ma (Scheuber et al., 2006). Eruptions of caldera complexes resulted in immense Late Miocene to Pliocene ignimbrite deposits in the magmatic arc and the southern end of the Altiplano plateau (Altiplano-Puna Volcanic Complex) covering an area of about 50,000 km^2 (de Silva, 1989). For an overview of spatial and temporal plateau development see, e.g., Allmendinger et al. (1997).

Surprisingly, the center of surface deformation at Lazufre is not associated with any known volcanic edifice, but lying between Lastarria and Cordón del Azufre volcanoes (cf. ellipse in 1). Both volcanic edifices are considered to be "potentially active". While no historical activity has been recorded at Cordón del Azufre, Lastarria shows persistent fumarolic activity (de Silva and Francis, 1991). The activity at Lastarria is thought to move to the north (Naranjo and Francis, 1987), although deformation has been observed to the south (Pritchard and Simons, 2004a). In later InSAR measurements a clear uplift signal is visible at Lastarria (Fig. 1, Ruch et al. (2009)). Surface elevation at Lazufre volcanic complex is time-depending: While no deformation was observed in the interferograms before

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http://dx.doi.org/10.1016/j.jsames.2012.11.002

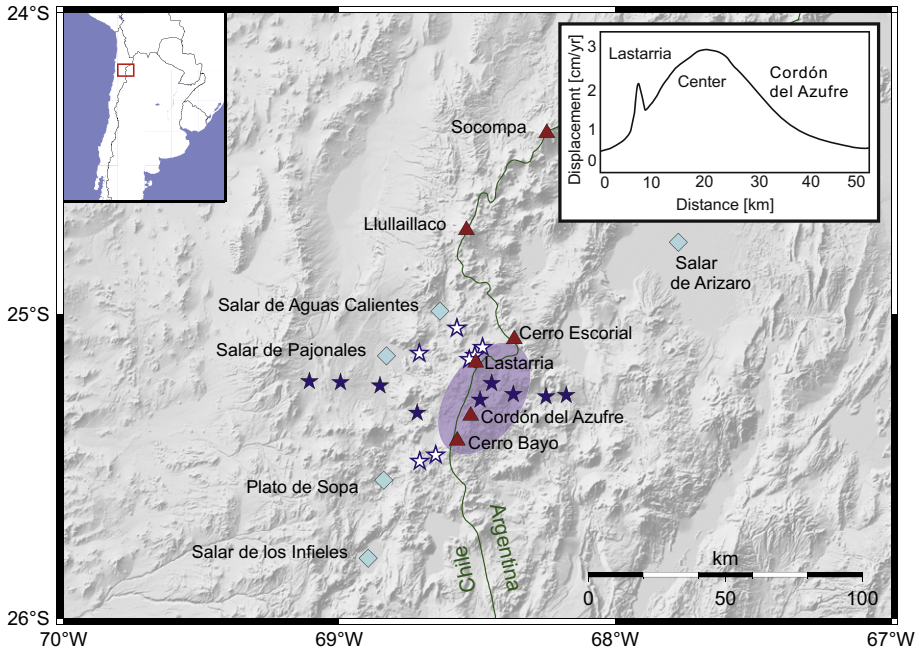

Fig. 1. SRTM-based shaded relief map of the study zone and location of MT sites in the Central Andes, Northern Chile/Northwestern Argentina. Blue stars indicate those sites which were used for 2-D modeling. Blue framed stars indicate stations, which were arranged circularly around Lazufre volcanic complex. Red triangles mark prominent volcanic edifices; maximal uplift occurs between Lastarria and Cordón de Azufre volcanoes. Transparent ellipse indicates center of surface deformation after Ruch and Walter (2010) and isoline of surface deformation in the upper right corner is redrawn after Ruch et al. (2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1998, there was a clear signal in three interferograms afterwards. Uplift at Lazufre increased drastically up to a rate of about 3 cm/a (cf. isoline of surface deformation for a N–S profile in Fig. 1) and a spatial extent of 1800 km^2, with a long axis up to 50 km (Ruch et al., 2009). It is now one of the largest deforming volcano systems on earth, comparable in size with Yellowstone and Long Valley (both USA) and could represent an evolving pre-caldera silicic system (Froger et al., 2007). Two possible scenarios explaining the inflation were hypothesized: It could either be a new intrusion of a sill expanding laterally at depth or a pre-existing magma chamber inflating at depth (Ruch et al., 2008). For a broader discussion on possible sources of deformations at volcanic complexes see for example Zurek et al. (2012).

Hydrothermal fluids and partial melts of volcanic systems are characterized by high electrical conductivity and therefore a good target for geophysical methods sensitive to conductivity, in particular for magnetotellurics (e.g., Brasse and Eydam (2008); Aizawa et al. (2005)). Natural geomagnetic variations – which are caused by variations of the solar wind for periods $T > 1$ s – induce electrical currents in the conductive earth which in turn give rise to a secondary magnetic field. A scale length is provided by the skin depth $\delta \approx 0.5\rho T$, with resistivity ρ. From the impedance, the principal transfer function is determined from the ratio of horizontal electric and magnetic fields, apparent resistivities and phases are calculated. Another transfer function is the tipper, the ratio of vertical to horizontal magnetic fields; from this so-called induction arrows or vectors are calculated which are indicative of lateral conductivity contrasts.

Previous long-period magnetotelluric measurements were conducted in the Central Andes by Brasse et al. (2002) and Brasse and Eydam (2008) along several transects crossing the magmatic arc and the Altiplano high plateau. Beneath the southern Altiplano at 21°S, a large high-conductivity zone in the mid-deep crust was interpreted as partial melts and fluids. It prohibits the resolution of upper mantle structures. Farther to the north at 17°S this conductor is missing; instead, an anomaly is modeled in the asthenosphere which is thought to originate from dehydration of the subducting Nazca slab. Although this interpretation is in agreement with the standard subduction model, the conductor is offset by almost 100 km from the volcanic arc. Notably, no enhanced conductivity was detected beneath the volcanoes themselves.

The high-conductivity zone in the backarc crust beneath the Altiplano is thought to extend farther south into the Puna, as was shown by Díaz et al. (2012). Again, this study found no evidence for enhanced conductivity beneath the volcanic arc. This is perhaps a hint at an emerging shift of the magmatic system in the Central Andes towards the east.

2. Data evaluation and strike directions

During a field campaign in January/February 2010 a magnetotelluric experiment was conducted in the Central Andes of Northern Chile and Northwestern Argentina. As part of this experiment 12 long period magnetotelluric (LMT) and two broadband magnetotelluric (BBMT) stations were arranged at the Lazufre volcanic complex. The other part of the experiment was centered around Lascar volcano farther north and is described in Díaz et al. (2012). Seven of the LMT stations and the two AMT stations were arranged along an approximately 100 km long EW trending profile at 25.1°S latitude, crossing the Western Cordillera with the present magmatic arc. The other stations were set circularly around the Lazufre volcanic complex (cf. Fig. 1). The LMT instruments cover a period range between $T = 10$ s–10,000 s and the BBMT a period range between $T = 0.005$ s–1000 s, respectively.

Unfortunately, due to serious logistical difficulties in the beginning of the field campaign not as many stations as originally planned could be installed. Hence there is a lack in station coverage, especially in the eastern part of the measuring area. Moreover, Lazufre is a remote region in the High Andes and many parts of the study area are difficult to access by car. This complicates the