Surface hydrothermal alteration and evolution at the Azufre volcano, Central Volcanic Zone, Chile

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ABSTRACT:
The Azufre volcano (21°47'S; 68°15'W) is a Pleistocene stratovolcano that forms part of the Azufre-Inacaliri Volcanic Chain located in the Central Volcanic Zone of the Andes. It consists of two coalescent structural units (Northern and Southern edifices) formed during four magmatic stages (I–IV) between ~1300 and 120 ka and exhibits extensive hydrothermal alteration at the surface. Several studies have described its volcanic and petrogenetic history [1, 2, 3]. Such studies, however, briefly described some of the hydrothermal alteration and related mineralogy. The present study aims to describe in detail the mineralogical characteristics of the surface alteration using remote spectral analysis together with X-ray diffraction analysis of altered rock samples from the Azufre volcano.

The alteration minerals identified include silica polymorphs (cristobalite, tridymite, opal-A, opal-CT and quartz), sulphates (jarosite, gypsum and alunite), K-clay minerals (kaolinite), and native sulfur. The mineralogical associations indicate acid-sulfate alteration, generally of a pervasive character, with obliterated textures, and silicification. Both acid-sulfate alteration and silicification develop under hyperacid conditions, with the former being associated with steam-heated environments. Furthermore, ancient fumarolic vents have been recognized, indicating past hydrothermal/volcanic discharge, as well as hot springs exhibiting slightly acidic pH (6.72) and elevated temperatures (42 °C), contrasting with the alkaline (pH generally >7.5) and cooler (temperatures generally <25 °C) waters of the Salar de Ascotán [1]. The presence of acid-sulfate

alteration, neutral-alkaline and acidic surface fluids, and the paleosurface discharge products suggest the development of a geothermal system [4].

1. Introduction

Understanding the evolution of the magmatic system that feeds a geothermal field is crucial for determining the processes that sustain it over time [5]. Detailed mineralogical analyses of areas affected by surface hydrothermal alteration associated with such magmatic systems are particularly valuable, as they are useful to constrain key parameters of the hydrothermal system [6].

Numerous geothermal areas are present in the Central Andes; however, Cerro Pabellón is currently the only operational geothermal power plant in South America. This facility is supported by the Cerro Pabellón Geothermal Field, which is estimated to cover an area of up to 25 km^2 [7] and is surrounded by volcanic structures ranging in age from the Miocene to the Holocene. Additionally, several nearby volcanoes show surface hydrothermal alteration, indicative of past active hydrothermal systems. One of the most prominent is Azufre Volcano (21°47'S; 68°15'W), located approximately 7.5 km from the Cerro Pabellón Geothermal Field.

The Azufre volcano is a Pleistocene stratovolcano that forms part of the Azufre-Inacaliri Volcanic Chain. It consists of two coalescent structural units (Northern and Southern edifices), developed during four magmatic stages (I–IV) between ~1300 and 120 ka, and displays extensive surface hydrothermal alteration. Although several studies have described its volcanic and petrogenetic evolution [1, 2, 3], the hydrothermal alteration and associated mineralogy have only been briefly addressed. The present study aims to provide a detailed characterization of the surface alteration mineralogy through remote spectral analysis and X-ray diffraction of altered rock samples from the Azufre volcano.

2. Methodology

Following the parameters outlined in [8], satellite image analysis of Azufre volcano was conducted using Google Earth Engine (GEE) as the geospatial processing platform, utilizing Landsat 8 OLI/TIRS Collection 2 Level-2 imagery. Indices proposed by [9] were calculated to map alteration mineral groups. These areas were subsequently surveyed in the field, where representative samples of altered rocks were collected. Petrographic analysis, together with X-ray diffraction (XRD) on bulk rock, were then performed to identify, semi-quantify, and characterize the alteration mineral assemblages. This integrated approach enabled the development of a genetic model to elucidate the hydrothermal processes and the evolution history of Azufre.

3. Results

Remote sensing results were visualized as intensity maps using a blue-to-red color scale, where cool tones (blue) represent low index values (indicating a lower probability of mineral presence), and warm tones (red) indicate high index values (suggesting a higher probability of presence). Integrated mineralogical maps were generated by combining these spectral indexes with the alteration minerals identified in the samples (Fig. 1).

The identified alteration minerals were classified into eight groups: (1) native sulfur; (2) silicic phases (cristobalite, tridymite, quartz, chalcedony, opal-A, and opal-CT); (3) sulfates (gypsum, anhydrite, alunite, natroalunite, jarosite, natrojarosite, alunogen, and zircosulfate); (4) sulfides (pyrite); (5) Fe and Ti oxides (hematite, rutile, and anatase); (6) clay minerals (kaolinite); (7) epidote; and (8) albite.

4. Discussion and conclusions.

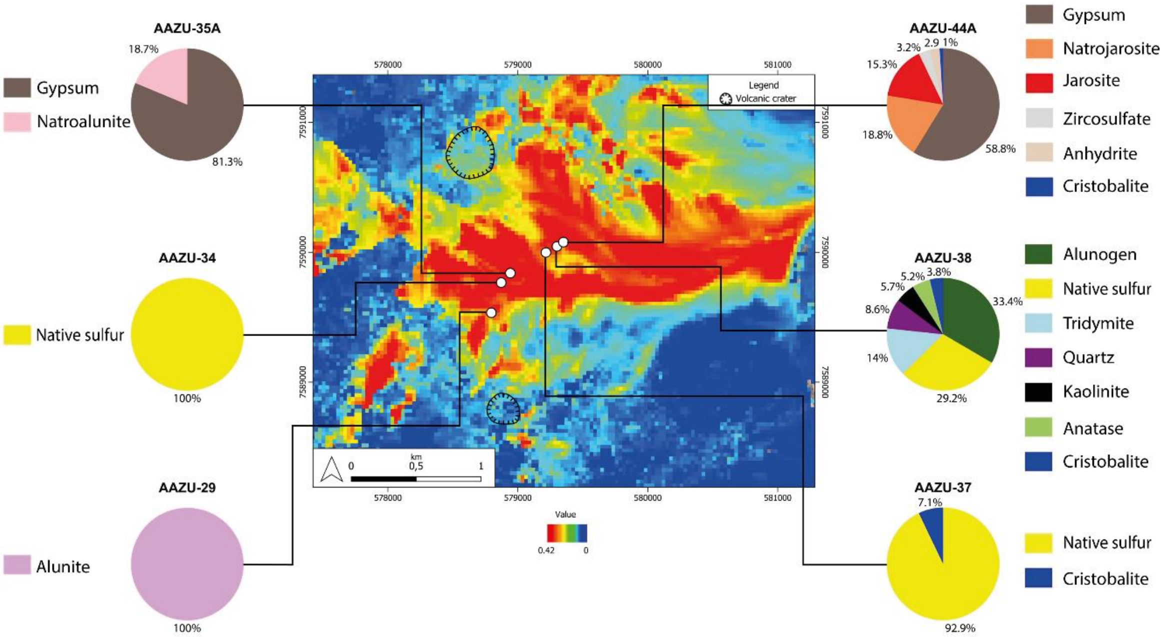
The identified alteration minerals from Azufre are grouped as: (1) alunite/natroalunite + jarosite/natrojarosite ± gypsum and (2) native sulfur ± cristobalite ± gypsum ± alunogen. These assemblages are characteristic of acid-sulfate alteration, commonly associated with steam-heated blankets [10].

In volcanic settings, intense magmatic activity can give rise to near-surface acid-sulfate alteration associated with steam-heated blankets, typically linked to geothermal systems [10]. Examples in the Chilean Andes include active fumarolic fields related to magmatic-hydrothermal systems, such as Nevados de Chillán [11], Cerro Pabellón [12] and the Cordón de Inacaliri Volcanic Complex [4]. The acid-sulfate stage typically forms when steam and gases (CO_2 and H_2S) separate from deeper chloride-rich boiling fluids in vapor-dominated environments, generating surface manifestations, such as fumaroles [10], as observed at the western flank of the northern edifice of Azufre volcano [1].

Steam-heated blankets form from H_2S-rich fluids within the vadose zone and may occur in high-(HS), intermediate-(IS), or low-sulfidation (LS) epithermal environments [13], as well as in active geothermal systems [14]. At Azufre volcano, remnants of ancient fumarolic vents and slightly acidic hot springs (pH

6.72, 42 °C) contrast with the cooler (<25 °C), alkaline waters (pH >7.5) of the nearby Salar de Ascotán [1]. Although conspicuous surface manifestations are not present, the presence of thermally anomalous waters and characteristic alteration assemblages suggest that hydrothermal activity at Azufre remains ongoing.

Figure 1. Landsat 8 band ratio (6/7 – 5/4) used to highlight clays, sulfates, and micas [9], integrated with the semi-quantitative distribution of alteration minerals on the eastern flank of the volcano.



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