Hydrothermal Alteration in Cerro Pabellón Geothermal Field: from Surface and Drill Core Data to Conceptual Model

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ABSTRACT

The systematic study of hydrothermal alteration mineralogy in the Cerro Pabellón geothermal field, the first geothermal area exploited in South America, helped to the elaboration of a more detailed conceptual model. Hydrothermal studies were developed both on surface and in a 560 m depth core-hole exploration well. Surface hydrothermal alteration is restricted to the NW and SE border of the geothermal field, where intense acid-sulphate alteration was identified. Remote sensing images, together with XRD and SEM-EDX analyses confirmed the nature of severe argillic alteration zones. Moreover, only in the Cerro Apacheta volcano, two superheated fumaroles were recognized, representing the only active surface manifestation of the thermal anomaly.

Hydrothermal mineralogy identified in the exploration well (petrography, fluid inclusions, XRD and SEM-EDX analyses) allowed to identify three main hydrothermal alteration zones: (1) argillic; (2) sub-propylitic, and (3) propylitic, with variable amounts of smectite, illite-smectite, chlorite-smectite, mixed-layer chlorite-corrensite, illite and chlorite appearing in the groundmass and filling amygdales and veinlets. Chemical and XRD data of smectite, I-S and illite showed, with some exceptions, a progressive illitization with depth. Moreover, our studies confirm the existence of a thick clay cap on which the two main clay-minerals reaction series were identified: the transition from smectite to illite and smectite to chlorite. This thick clay cap ($\approx$300 m at his minimum and up to 1,000 m towards the peripheral sectors of the system) could be the responsible of the almost absence of surface manifestation, preserving temperature and pressure in the geothermal reservoir. In this way, diffuse CO_2 survey conducted in the geothermal field confirmed the extreme sealing capacity of the clay cap, allowing the definition for the Cerro Pabellón as a blind geothermal system strongly controlled by local extensional setting.

1. INTRODUCTION

The cap-rock, the heat source, the reservoir and the recharge areas are the main four elements in hydrothermal convective geothermal systems. To be effective, a cap-rock should be impermeable enough to maintain the reservoir temperature, pressure and enthalpy of the system through time (*e.g.* Corrado *et al.,* 2014; Maffucci *et al.,*2016; Sánchez-Alfaro *et al.*, 2016 and references therein). In volcanic and volcaniclastic systems, the development of large, thick cap-rocks is favored by intense argillic alteration which leads to the formation of the impermeable cap. The efficiency of the clay cap is controlled by a significant extent of the intensity of the hydrothermal alteration. Consequently, the study of clay minerals should improve our knowledge on the spatial distribution and the relationship with temperature, besides other factors, to estimate the efficiency of the clay cap and its influence on the reservoir zone of the geothermal systems. This is of paramount importance where other subsurface data are scarce and in the case of blind geothermal systems, where surface thermal manifestations are lacking (e.g. Corrado *et al*., 2014).

The purpose of the present study was to examine the vertical distribution of the clay minerals forming the clay cap of the Cerro Pabellón active geothermal field, together with a surficial survey analyzing hydrothermal alteration, diffuse CO_2 and soil temperature measurements. The Cerro Pabellón (previously referred to as the 'Apacheta geothermal project', Urzúa *et al.*, 2002) might be considered a high-enthalpy blind geothermal field located in the Andean Central Volcanic Zone (CVZ) in northern Chile, at 4,500 m a.s.l., ~120 km NE of the city of Calama and ~60 km NNW of El Tatio geothermal field (Fig. 1a). This geothermal field, discovered in 1999 (Urzúa *et al.*, 2002), represents the first productive geothermal power plant of South America (Cappetti *et al.*, 2020), beginning its operation by 2017 with two twin binary (ORC) units (24 MWe each one) providing 48 MWe to the Chilean electricity grid and avoiding 166.000 tons/year of CO_2 into the atmosphere.

Blind (or hidden) geothermal systems have several conditions that prevent the resurgence of geothermal fluids towards the surface (Taussi *et al.*, 2019a and references therein): i) the presence of a thick and effective sealing cap (Corrado *et al.*, 2014; Carapezza *et al.*, 2015; Maza *et al.*, 2018); ii) the absence (or sealing) of faults and fractures that connect the geothermal reservoir with the surface (Faulds and Hinz, 2015; Dobson, 2016) and iii) the presence of a thick cold aquifer able to masks the uprising of deep-seated high-temperature fluids (Dobson, 2016; Minissale, 2018). Among these, the presence of a clay cap (or cap-rock) is one of the key components of high-enthalpy geothermal systems to guarantee adequate fluid pressure and temperature conditions at depth (Corrado *et al*.,2014; Maza *et al.*, 2018). Surface monitoring of CO_2 flux from the ground may provide useful information of gas leakage from the hydrothermal reservoir (Taussi *et al*., 2019a and references therein). Since hidden or blind geothermal systems can reduce the flux of volatile compounds at the surface, diffuse soil CO_2 flux surveys are often coupled with measurements of thermal anomalies of the ground and other complementary mineralogical and/or geochemical methodologies. Soil temperature can also be a useful

parameter to evaluate how efficiently the geothermal fluids are transported to the surface in relation to the depth of the gas source, even when CO_2 soil fluxes are low.

In this work, we present an integrated mineralogical (both on surface as by means of the exploration drill core PexAp-1, Maza *et al*., 2018) and diffuse soil CO_2 flux and temperature measurements, with the purpose to shed light on the processes that led to the lack of obvious clear surface expressions manifestations in the hidden geothermal system of Cerro Pabellón. We integrated our measurements and results with previously water and gas geochemical data published by Urzua *et al*. (2002) and Tassi *et al*. (2010), in order to produce an updated conceptual model of the geothermal system that accounts for the CO_2 flux and degassing processes at the hidden geothermal system of the geothermal field. Our results have allowed us to propose a relationship between the mineral formation-transformation processes and factors such as temperature, fluid–rock composition and time. This represents a contribution to the comprehension of clay-formation processes in blind geothermal systems with the aim of understanding the different mechanisms involved during their development.

2. GEOLOGICAL SETTING

Cerro Pabellón geothermal field is located in the Andean Central Volcanic Zone (CVZ), a huge magmatic province associated with the subduction of the Nazca Plate under the South American Plate, which gives rise to intense magmatic and hydrothermal activity (see Rivera *et al,* 2020 for a complete and detailed description of the regional and local geology of the geothermal field). The erupted magmas constitute the Altiplano-Puna Volcanic Complex (APVC), a volcano-tectonic silicic magmatic province generated by the partial melt of the thickest continental crust in the world (de Silva, 1989; Schmitz et al., 1999). The area of the APVC coincides with the surface projection of the Altiplano-Puna Magmatic Body (APMB), a partially molten body within the upper crust, 4 to 25 km below sea level, recognized by geophysical methods (MT, seismic analyses, etc.) and interpreted as an incrementally constructed upper-crustal batholith atop an upper crustal MASH zone (Brasse *et al*., 2002; Zandt *et al*., 2003; de Silva & Gosnold, 2007; Ward *et al*., 2014; among others).
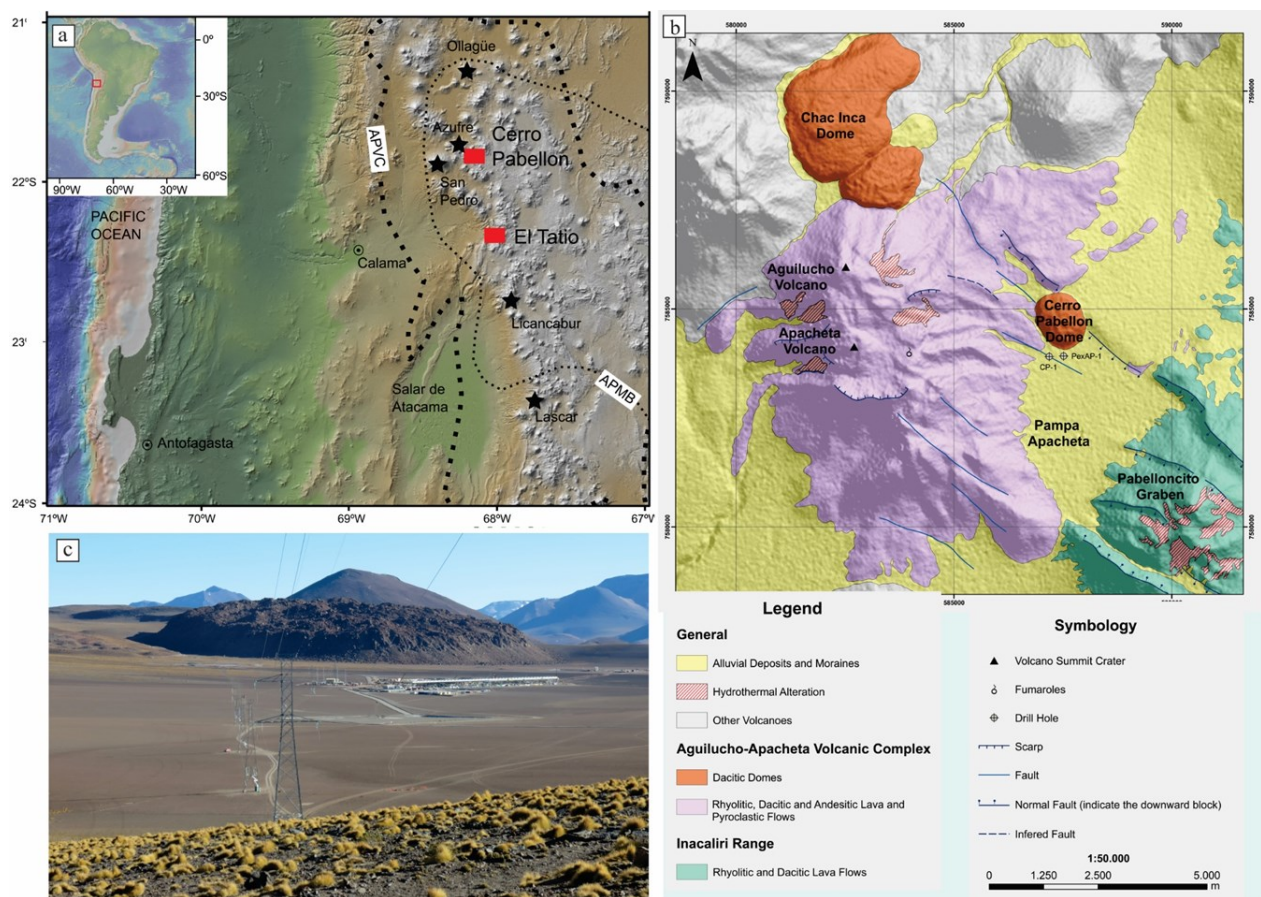

Figure 1: (a) Central Volcanic Zone (CVZ) in the Andean Cordillera showing the Altiplano-Puna Volcanic Complex (APVC), the main Pleistocene to Holocene volcanoes and the location of the Cerro Pabellón geothermal system; (b) simplified geological map of the Cerro Pabellón geothermal field; (c) general view of the Cerro Pabellón geothermal power plant with the 80–130 ka Cerro Pabellón rhyolitic dome in the background. Figure from Maza *et al*., (2018).

In the studied area (Fig. 1b), the CVZ is characterized by several NW–SE oriented eruptive centers dominated by the polygenetic Pleistocene to Holocene Azufre–Inacaliri volcanic range (Rivera *et al*., 2020), where stratovolcanoes of basaltic-andesite to dacitic composition (Apacheta-Aguilucho Volcanic Complex) and rhyolitic domes (Chac-Inca and Pabellón domes) are recognized (Fig. 1b). Locally, the different geological units have been identified by surface geological mapping and recorded from geothermal wells drilled by Geotérmica del Norte S.A. (GDN) (Rivera *et al*., 2020). They mainly correspond to Pliocene–Pleistocene andesitic to dacitic lava, breccias and tuffs, capped by a 100 m-thick welded ash flow, whereas the recent volcanic activity is associated with a series of Pleistocene dacitic lava domes (Pabellón, Chac-Inca and Chanka; Taussi *et al*., 2019b; Fig. 1b). A local Pliocene extensional phase, within a regional compressional regime related to the subduction of the Nazca Plate under the South American Plate, took

place in the area (Veloso *et al.*, 2019; Rivera et al., 2020 and references therein). This phase generated a NW-striking normal fault system which extends from Azufre volcano in the NW to Inacaliri volcano to the SE (Tibaldi *et al.*, 2017). In the investigated geothermal field, a topographically depressed area of ~100 km^2, ~20 km long and 3 km wide, is well defined by two major faults with converging dips and pronounced scarps (~100–150 m), which form a symmetric graben. This NW–SE graben structure (the Pabelloncito Graben, Francis & Rundle, 1976), affects the NW–SE aligned Pliocene stratovolcanoes. The main NE fault bounding the graben was sealed by the Cerro Pabellón dacitic dome (80–130 ka, ^{40}Ar/^{39}Ar in biotite, Renzulli *et al.*, 2006; Fig.1c), the extrusion of which was favoured by the structural weakness related to the normal faults of the graben (Tibaldi *et al.*, 2009), and triggered by a mafic-intermediate magma (now represented by the enclaves in the dome) which intruded a relatively shallow dacite magma chamber (Taussi *et al.*, 2019b).

Although at the summit of Cerro Apacheta volcano (Fig. 1b) two superheated fumaroles (measured temperatures of 109 and 118°C) with high steam-discharge rates were recognized at 5,150 m elevation (Urzúa *et al.*, 2002), the Cerro Pabellón geothermal field does not display any surface hydrothermal manifestations; consequently and it is therefore classified as a blind geothermal field (Maza *et al.*, 2018; Taussi *et al.*, 2019a; Cappetti *et al.*, 2020). Discontinuous altered clay zones, related to an acid-sulfate alteration, including native sulfur and clay minerals, affect the eastern flanks of the Apacheta-Aguilucho Volcanic Complex (AAVC; Fig. 1b).

3. METHODOLOGY

Surficial sampling for hydrothermal alteration studies were carried out in the only two restricted areas with surface alteration, both at the NW and SE ends of the graben (Figure 1b & 2). ASTER images were performed with the aim to a better identification of surficial alteration zones (Figure 3a) for sampling. Surface alteration studies were complemented with drill core and cutting samples from two wells provided by GDN (see Maza *et al.*, 2018 for details): a complete 557 m long exploration drill core (PexAP-1; 21°50′ 49.68″S, 68°09′21.35″W) and drilling cuttings from the 1,821.1 m deep production CP-1 well (21°50′56.55″S, 68°09′24.27″W; Fig. 1b). Samples were studied by optical petrography, X-ray diffraction (XRD) and scanning electron microscopy (SEM and FE-SEM with EDX detectors). Samples for bulk-rock analysis were dried at room temperature and 10 g samples, powdered in an agate mortar, were examined with XRD at 5–70°2θ and interpreted using the X′Pert Highscore software. The mineralogy of the <2 μm fraction was studied only for the samples of the PexAP-1 well, where a continuous core was available. The minerals in the clay fraction were identified according to the position of the basal reflections of air-dried (AD), ethylene-glycol solvated (EG), and heated to 500°C for 4 h (H) XRD patterns, using the criteria of Moore & Reynolds (1997).

Soil CO_2 flux and temperature measurements at the Cerro Pabellón area were carried out in November-December 2017 (with dry and stable atmospheric conditions). A total of 434 diffuse CO_2 flux measurements were carried out with the accumulation chamber method, using an Infra-Red spectrometer consisted of a LICOR Li-820 detector equipped with a sensor operating in the 0–20,000 ppm CO_2 range. Measurements were carried out along some of the principal morphological and/or structural lineaments of the Cerro Pabellón geothermal field and AAVC. Working areas are located as follows: (i) the eastern flank of AAVC, (ii) the western sector of Pampa Apacheta and (iii) the northernmost lineament bounding the Pabelloncito graben (Fig. 2).

Soil temperature was measured at each site, within 0.01 m from the accumulation chamber, using a Hanna HI-935005N K-Thermocouple (accuracy of ± 0.1 °C) in the first 10 cm. The different areas were covered as much as possible with a regular grid, whose nods were located with a portable GPS Garmin Etrex 10, at a 20–30 m grid spacing. Ambient air temperature and barometric pressure were recorded for each sample site. Soil temperatures at the fumarolic alteration zone on the top of the AAVC at about 5,150 m a.s.l. were measured in November 2016. A rectangular-like-shaped alteration field, with a NE-SW striking direction, with a length of ~400 m and a width of ~80 m characterized this fumarolic field. Temperature soil profiles at 10, 20 and 30 cm depths (99 points), located with the same portable GPS described above, were carried out every ~15 m with a Hanna HI 98509 thermocouple (accuracy of ± 0.3 °C). Detailed methodological protocol for sampling and analyses of soil CO_2 flux measurements are reported in Taussi *et al.* (2019a).
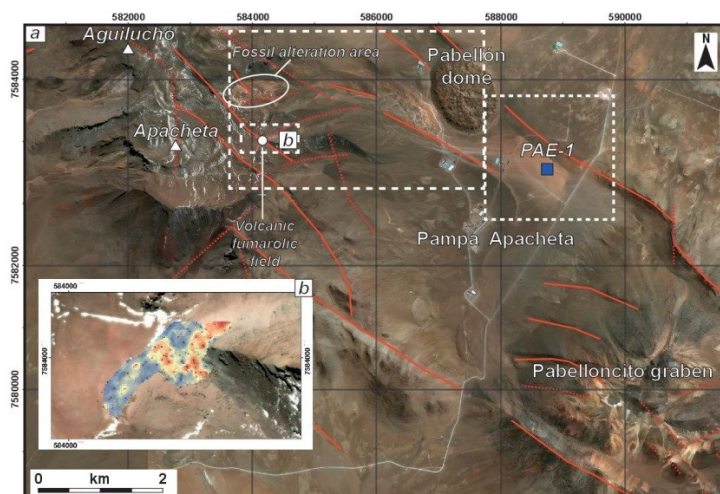

Figure 2: Google satellite image of the Pampa Apacheta showing the main structural elements, the location of the power plant, the exploration well, the surficial hydrothermal alteration zones and the areas investigated through soil CO₂ fluxes; b) temperature gradients map at the fumarolic field. Modified from Taussi *et al.* (2019a).

4. RESULTS

Analysis of ASTER image outlined the more intense alteration zones (Figure 3a), highlighting the two more (and almost unique) hydrothermally altered active surficial zones: the NW border of the Pabelloncito graben, where the active fumaroles are present in the AAVC (Figure 4) and the SE end of the Pabelloncito graben, where intense argillic alteration was detected and in situ soil temperature registered up to 80°C (Figure 3b).
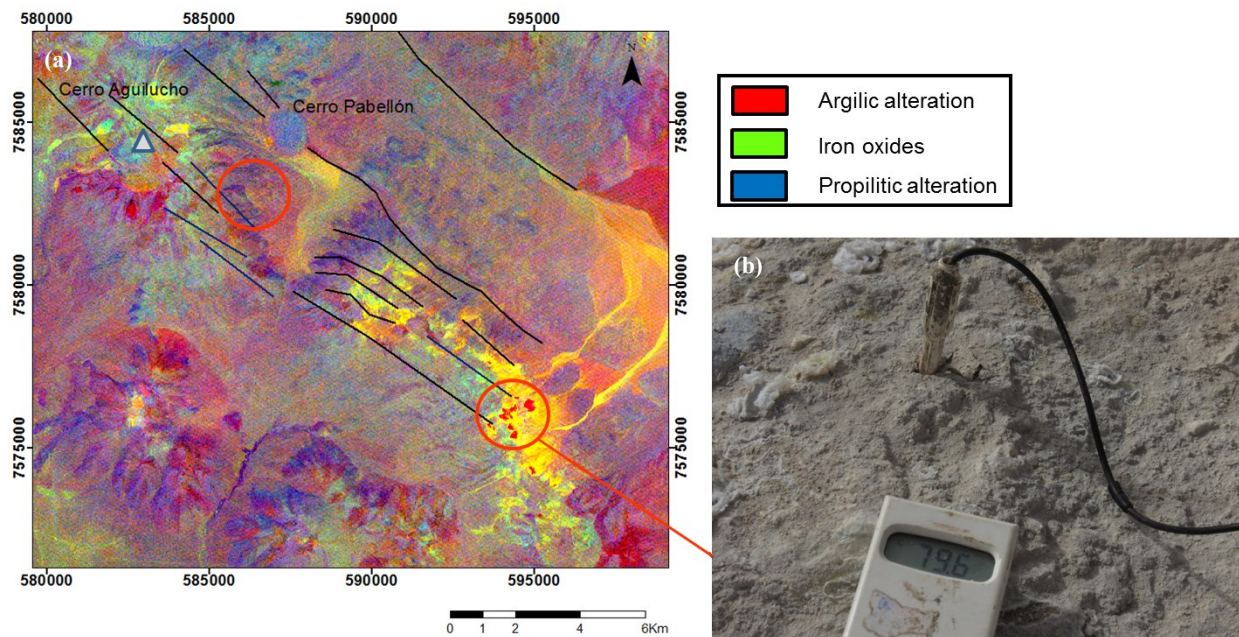

Figure 3: (a) ASTER images of the Cerro Pabellón geothermal field showing the only two more intense areas with surficial hydrothermal alteration evidences. (b) In situ soil temperature in the SE main alteration zone (red circle, around 5,000 m a.s.l.) evidencing pervasive argillic alteration and soil temperatures up to 80°C.

On the flanks of the AAVC, large areas of hydrothermal alteration are present (Figure 2). Two of them occur in the eastern flank of the Apacheta volcano and are associated with past and present fumarolic activity (Figs. 2 & 4). Presently, the fumarolic activity in the studied area is represented by two super-heated fumaroles with temperatures of 108° and 118 °C (Urzua *et al*., 2002; Tassi *et al*., 2010), mud pools, a diffuse degassing zone and numerous minor gas vents, distributed in an area of ~0.03 km^2 in the summit of the Apacheta Volcano at about 5,150 m (Fig. 4). Urzúa *et al*., (2002) and Tassi *et al*., (2010) showed that fumarolic gas discharges had very low gas/H_2O_{vap} ratio (0.01) with 2.5 wt% of non-condensable gases (NCG) dominated by CO_2 and N_2.

Figure 4: Active fumarolic field in the AAVC (NW border of the Cerro Pabellón geothermal field) with intense and pervasive surficial hydrothermal evidence.

The mineralogical association in the active fumarolic area is related to an argillic alteration process, dominated by clay minerals belonging to the smectite and kaolinite groups accompany by cristobalite (and opal CT), nacrite (zeolite) and goethite-hematite (Figures 5 & 6). The white-yellowish surface precipitates comprise mainly alunogen accompany by gypsum + jarosite ± native sulfur ± halloysite ± ilmenite associated with squelatales-like cristobalite. The fossil alteration area shows a mineralogical assemblage mainly consisting of cristobalite, kaolinite and alunite, with lesser amount of ± halloysite ± gypsum ± hematite ± quartz ± smectite ± interstratified I/S ± white mica and chlorite, evidence of a steam-heated alteration associated with acidic leaching and superimposed supergenic processes (Figure 6). These superficial alteration areas are weakened zones in the volcanic edifice which favored past

collapses, as confirmed by the presence of a debris avalanche deposit in the eastern flank of the AAVC, mainly consisting of hydrothermally-altered lava fragments originated from the fossil alteration zone (Godoy *et al*., 2017).
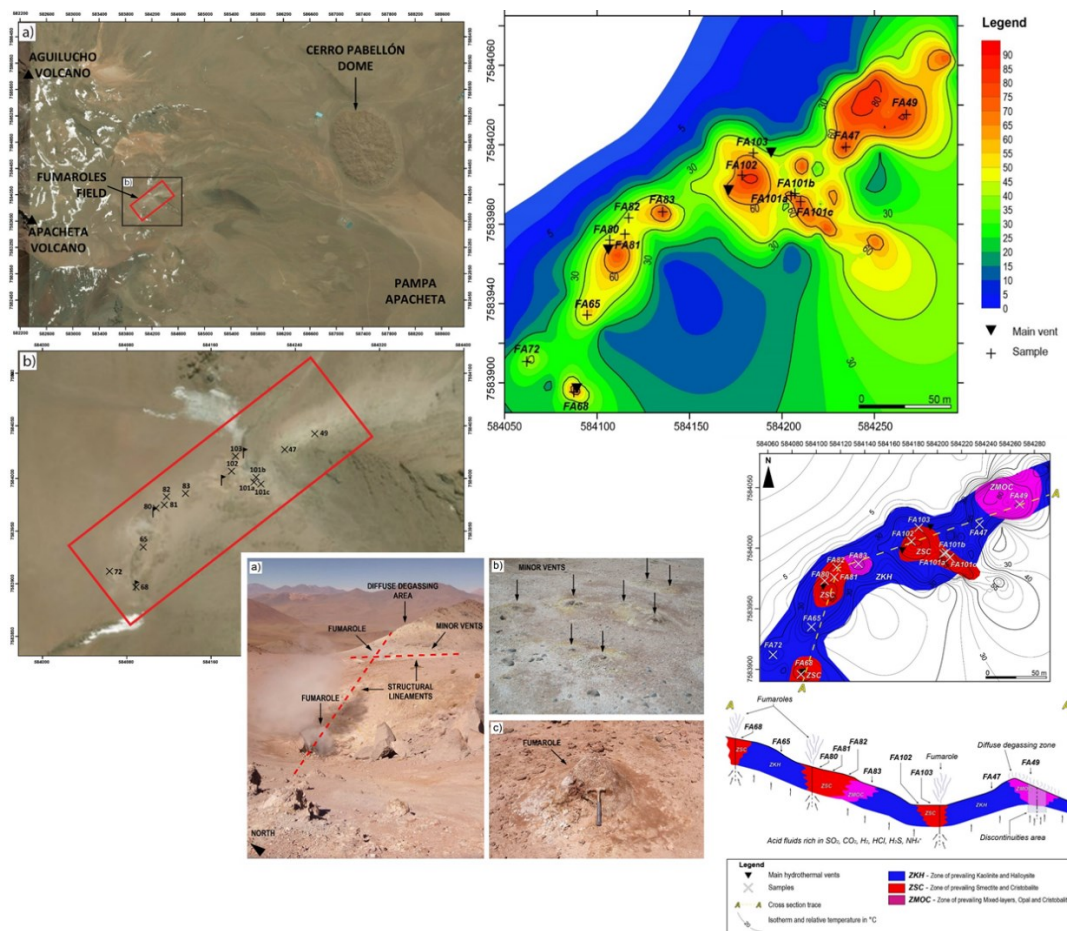

Figure 5: Soil temperature map in the active fumarolic field (AAVC) and zoning of the surficial alteration minerals. Temperature and fumaroles (active and fossils) distribution emphasizes a clear structural control.
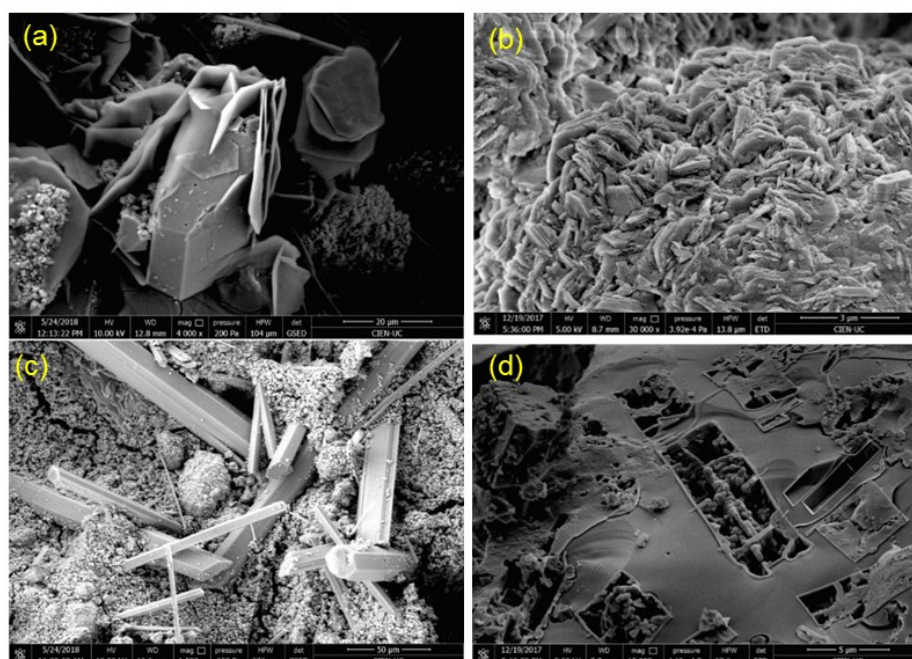

Figure 6: SEM images of hydrothermal minerals sampled on surface of the fumarolic field and formed by an intense and pervasive argillic alteration. (a) Native sulfur crystals associated with thin-tabular form of alunogen; (b) Poor vermiform kaolinites (irregular book-shaped), as conglomeration of particles; (c) Hexagonal prism of gypsum crystals associated with smaller crystals of jarosite; (d) Dissolution textures of primary plagioclase with amorphous silica microcrystals as consequence of acidic leaching.

Based on XRD mineralogy, petrographic observations and SEM-EDS analyses of samples from two boreholes by Maza *et al.* (2018), from ~165 and ~490 m depth the system is characterized by an argillic and a sub-propylitic zones, mostly dominated by clay minerals + calcite + clinoptilolite, and representing the thick clay-cap of the geothermal system (Figure 7). This zone is characterized by low permeability and temperatures < ~190 °C. Below ~490 m depth, a propylitic zone was recognized, likely representing the top of the geothermal reservoir domain, characterized by a chlorite-epidote-illite facies corresponding to temperatures >200 °C. Along the vertical distribution of the clay minerals in the stratigraphic sequence, a transition from smectite to illite (via mixed-layer) was also emphasized (Maza *et al.*, 2018). Eventually, distinct textures of pyrite along a ~500 m drill core were recognized by Román *et al.* (2019) and attributed to different boiling events (i.e. from vigorous to gentle boiling).
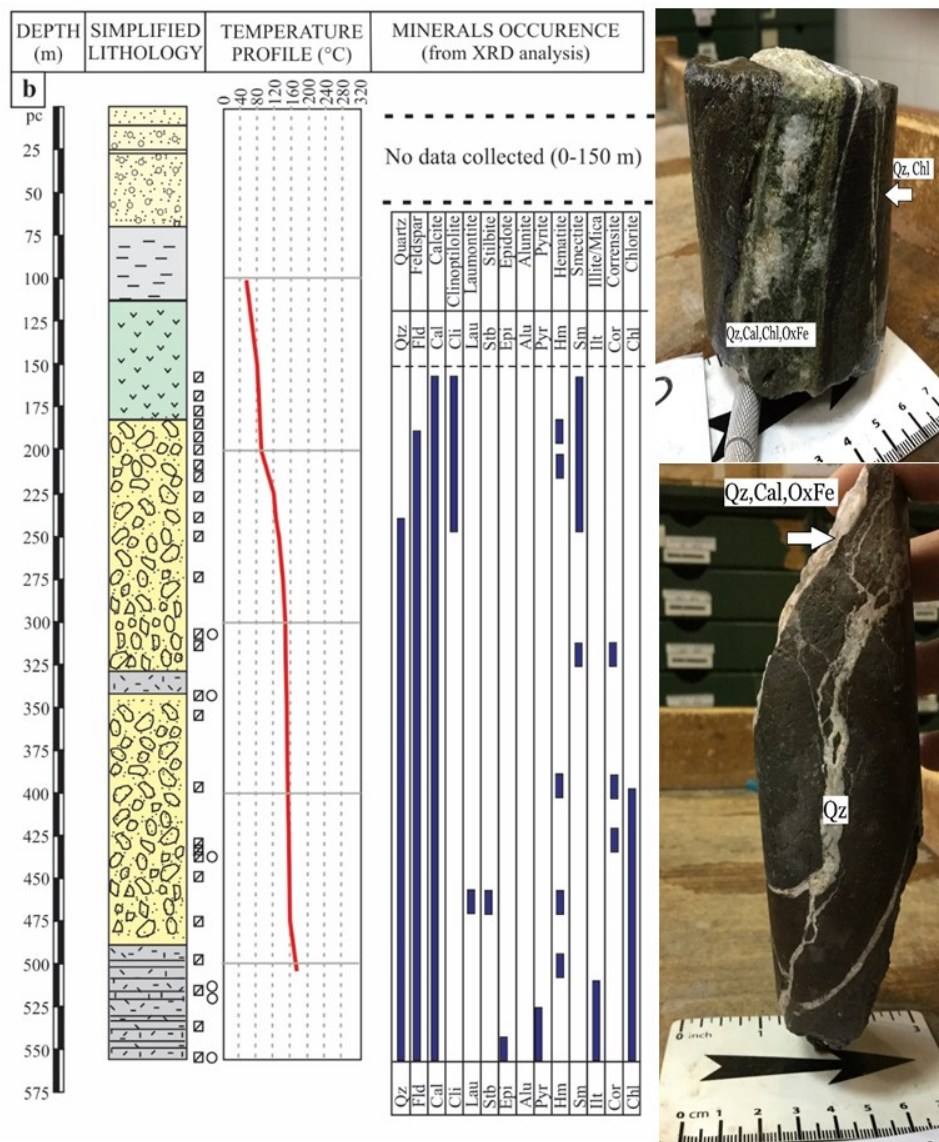

Figure 7: Distribution of hydrothermal minerals in the 575 m depth exploration drill-core PexAp-1 (from Maza et al., 2018) and core samples from the PexAp-1 intersected byfractures filled with quartz and clay minerals.

5. DISCUSSION AND CONCLUSIONS

The blind nature of the Cerro Pabellón geothermal reservoir might be related to the thickness and low permeability of the clay cap (~300 m) where two main clay minerals reaction series were detected: the smectite to illite and the smectite to chlorite transformations. In fact, the final phases of both reaction series, illite and chlorite, only prevail in rock samples from the reservoir domain, where mixed-layer I-S and C-S are almost absent (Maza *et al.*, 2018). In both reaction series, a continuous and slow decrease of the proportion of smectite layers in mixed layers with depth showing a sigmoidal variation in its percentage, with the conversion of smectite to R1 I-S at ~180–185 °C greater than those reported for other similar geothermal fields. Detailed studies by XRD of clay minerals might help to understand the formation processes of the hydrothermal minerals and how these mineralogical transformations might be controlled not only by temperature (and depth) but also by kinetics related to permeability/porosity enhancing (or preventing) mineral transformations. Consequently, detailed studies of alteration minerals in continuous drill cores or cutting samples from deep reservoir should improve the data available for a better understanding of the processes controlling the development of the alteration zones in active geothermal fields and thus the reliability of conceptual models.

Shallow geochemical signals can provide useful information concerning the presence of high-enthalpy geothermal reservoirs, although some difficulties may be encountered when these signals are masked by different processes. In this sense, more than 90%

of the measured CO_2 flux values were below background, estimated at 1.35 g·m^{-2}·day^{-1} whereas the associated soil temperatures (mean value = 19.4°C) carried out at ~10 cm depth were related, at least partially, to an endogenous, though weak, thermal anomaly. No spatial correlation was observed between soil CO_2 flux and temperature measurements, suggesting a minimal role played by the volcano-tectonic structures in the circulation of geothermal fluids. However, soil temperature gradients measured in the active fumarolic field (where acid waters and magmatic gases are discharged) revealed the only strong thermal anomaly (temperatures up to ~83 °C) of the area. The lack of soil CO_2 anomalies, even above the existing pressurized reservoir, are most probably the result of two main factors: 1) the continuous, ~300 m thick and impervious clay-cap that lies above the geothermal reservoir, and 2) the interaction between the (scarce) rising geothermal fluids and the shallower and discontinuous aquifer(s) below Pampa Apacheta. The thick argillic clay-cap (~300 m) located above the geothermal reservoir, has a pivotal role in preventing the resurgence of fluids, whereas an efficient interaction between the rising magmatic fluids and the liquid-dominated reservoir favours acidic gas scrubbing processes, thus allowing the ascent of a steam depleted in magmatic compounds. This steam interacts with the shallower, discontinuous aquifer(s) below Pampa Apacheta, with the consequent nearly complete dissolution of CO_2 and H_2S, and heating of the shallow groundwater. This results in low CO_2 fluxes and extended slight thermal anomaly at the surface. Finally, an integrated conceptual model using our results and available geological, mineralogical, geochemical and geophysical data of the Cerro Pabellón hidden geothermal system is presented in Figure 8, with the aim of providing criteria for geothermal exploration of similar high-enthalpy geothermal systems in the Andes that also exhibit a lack of thermal surface features. Below the geothermal area, the isotherms form a bell-shape pattern, curved below the fumarolic field (up-flow zone) where magmatic acid gases are discharged. In the geothermal reservoir, magmatic gas scrubbing processes occur (Tassi *et al.*, 2010) with the consequent pH-neutralization. The near-neutral pH fluids produced the propylitic alteration recognized at >490 m of depth in the stratigraphic sequence (Maza *et al.*, 2018), and the interaction with the shallower aquifer(s). This interaction led to the dissolution of the acidic gases (i.e. CO_2 and H_2S) and to the heating of the aquifer/s, resulting at the surface as a diffuse, slight thermal anomaly, recognized by a geostatistical approach, and at 187 m below the surface (i.e. at the bottom of the PAE-1 well; Urzua *et al.*, 2002) as a highly ^{18}O and ^2H depleted steam, with a measured temperature of 88°C. Our updated conceptual model also explains why the active fumarolic area, located at the summit of the AAVC, is the only visible evidence of the hidden geothermal system of the Cerro Pabellón area.
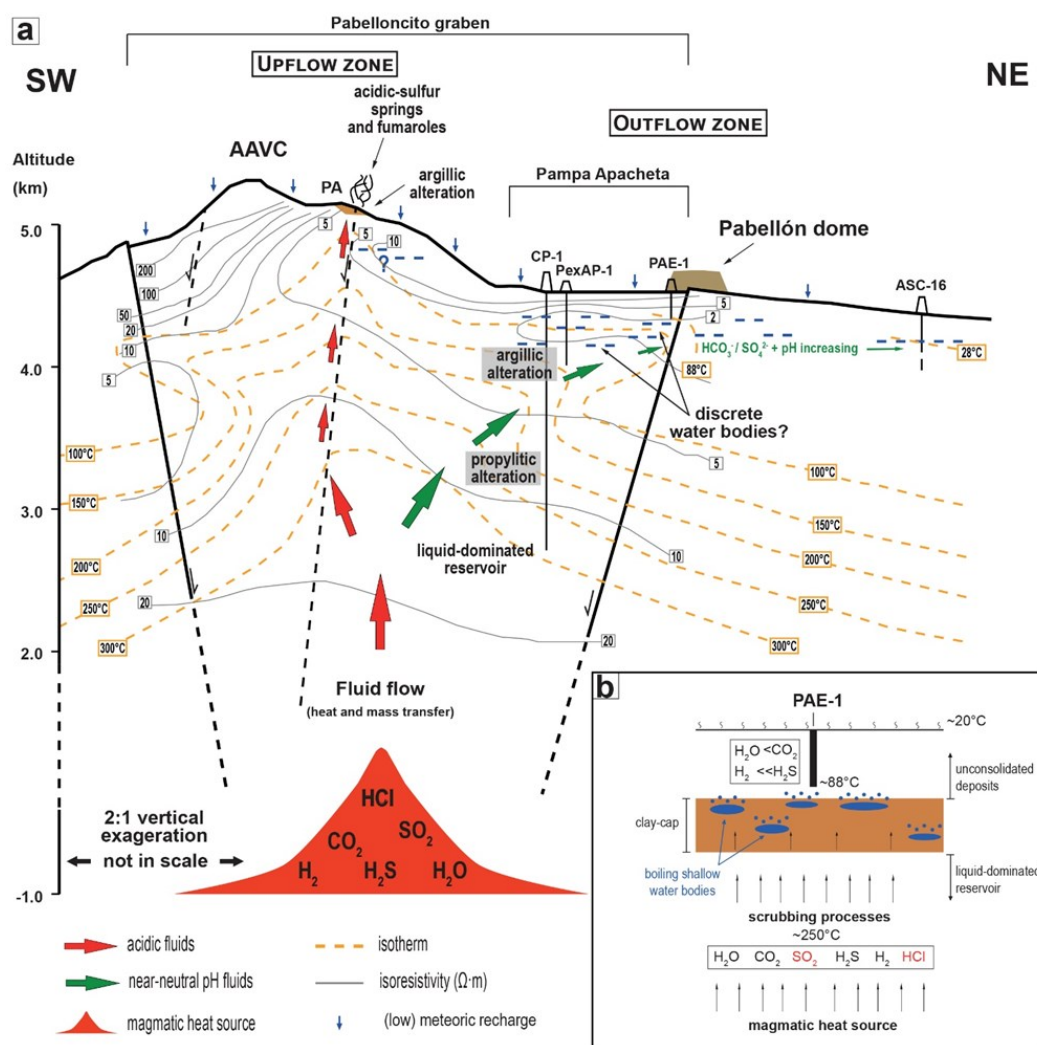

Figure 8: Conceptual model for the Cerro Pabellón geothermal field as proposed by Taussi *et al*, (2019a). a) SW to NE simplified profile of the Cerro Pabellón area showing temperature isotherms and MT resistivity data from Urzúa *et al.* (2002). b) Schematic evolution of the ascending geothermal fluids to the surface. Scrubbing processes characterized the liquid-dominant reservoir, resulting in the lack of magmatic compounds at surface (SO_2, HCl and to a lesser extent CO_2); the CO2-depleted steam rise, interacting with the shallower water bodies, dissolving CO_2, H_2S and producing boiling.

Finally, this work highlights the high efficiency of the sealing capacity of the thick and impermeable clay-cap, which is able to confine the high enthalpy geothermal fluids of the Cerro Pabellón system, but also the not negligible role of the shallow aquifer(s). The use of an integrated methodology (i.e. hydrothermal surficial mineralogy, diffuse soil CO_2 flux and temperature measurements) for the detection of possible thermal anomalous areas is of paramount importance in the exploration of hidden geothermal systems. Consequently, this approach and the working methodology can be extended to other blind geothermal systems where a low meteoric recharge is present, and the typical thermal manifestations are lacking.

ACKNOWLEDGMENTS

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