THE HIGH TEMPERATURE GEOTHERMAL FIELD OF THE APACHETA-AGUILUCHO VOLCANIC COMPLEX (NORTHERN CHILE): GEO-PETROGRAPHIC SURFACE EXPLORATION, CRUSTAL HEAT SOURCES AND CAP-ROCKS

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INTRODUCTION

The Apacheta-Aguilucho geothermal field is located in the Altiplano-Puna Volcanic Complex (APVC, Northern Chile, Andean Central Volcanic Zone). This is the area with the thickest crust (up to 70 Km) in the world (Schmitz *et al*., 1999). The geothermal field was discovered in 1999, by the Chilean mining company CODELCO, in the Pampa Apacheta, during a shallow water exploration well (Urzua *et al*., 2002). From 2006 the Apacheta-Aguilucho geothermal concession is property of a joint venture society controlled by Enel Latin America (51%) as well as the nearby concessions of El Tatio and La Torta (Fig. 1).

The Apacheta-Aguilucho geothermal field is considered one of the most promising areas in northern Chile for electricity production by means of a geothermal power plant. In December 2010, the Chilean Energy Office declared that 170 new geothermal exploration sites will be granted by 2012, with the aim to increase the geothermal installed power of the country up to 1.000 MWe. This work is focused on three fundamental aspects of a geothermal field exploration and characterization: *i)* the surface geology and structural evolution of the Apacheta-Aguilucho Volcanic Complex (AAVC) were carried out through a geo-petrographic survey and geochemical analyses of the collected samples; *ii)* the main magmatic crustal sources were investigated by correlating geophysical investigations available from literature and "ad hoc" geothermobarometric applications; *iii)* the hydrothermally altered volcanic formations (*i.e.*, cap-rocks) forming a possible shallow impermeable barrier of the geothermal system were studied, on a mineralogical point of view, through an exploration deep borehole. Of course, the presence of the cap rocks play a fundamental role, allowing to maintain pressurized the geothermal fluids that circulate in the reservoir which can be therefore exploited to produce electricity from the high temperature geothermal resource.

Fig. 1- Landsat TM image of the northernmost sector of the APVC.

ANALYTICAL METHODS

Petrographic thin section analysis was coupled with EMPA (Electron Micro Probe Analyses), performed at IGG-CNR (Istituto di Geoscienze e Georisorse del Consiglio Nazionale delle Ricerche, Padova). Whole rock, major and trace elements were determinated by ICP-OES/ICP-MS at the ACMELabs laboratories (Vancouver, Canada). In order to obtain P-T crystallization conditions of the youngest magmas erupted in the AAVC, the amphibole thermobarometric equations by Ridolfi *et al.* (2010) and Ridolfi & Renzulli (2012) were used. Finally, the hydrothermally altered volcanic rocks coming from a deep borehole (courtesy of Enel Latin America) were also studied by X-Ray Diffraction (XRD) analyses. Bulk XRD analyses were coupled with the investigation of the clay mineral components on the basis of the Biscaye's method (1965).

APACHETA-AGUILUCHO VOLCANIC COMPLEX (AAVC)

The AAVC is located in the northern part of the NW-SE trending Inacaliri graben, hosting a series of Plio-Pleistocene eroded volcanoes and young (*ca.* 100 ka) lava domes, 120 Km east from the city of Calama and 60 Km NNW from El Tatio geothermal field (Fig. 1). The volcanic products have been classified on the basis of whole rock compositions and modal mineralogy. Through this approach, we obtained the following petrographic classification: *i)* basaltic andesite and andesite (*stricto sensu*), *ii)* high-silica two-pyroxenes andesite, *iii)* dacite, and *iv*) ryolite. All of them belong to the high-K calc-alkaline magmatic series (Fig. 2). This classification, together with the November-December 2007 field trip which is part of this work, permitted to better define the geological map of the AAVC (1:50.000) whose survey was performed by Sergio Ahumada C. and Josè Luis Mercado N. (Universidad Catolica del Norte).

The AAVC evolution has been divided into four eruptive periods grouped in two main events:

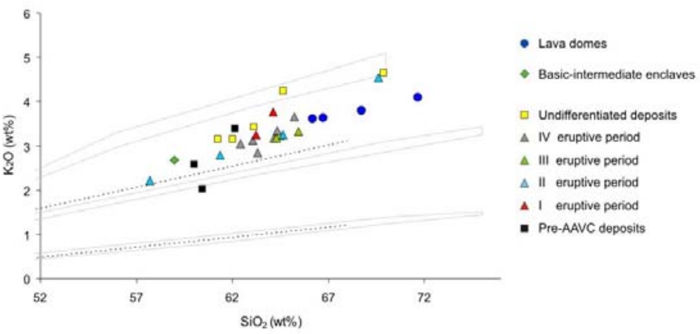

Fig. 2 - K_2O *vs.* SiO_2 diagram (continuous line after Peccerillo & Taylor, 1976; dashed line after Le Maitre *et al*., 1989).

<u>Periods I-II</u> (Plio-Pleistocene): building of the ancient Apacheta volcano. The erupted products vary in composition from andesite to dacite. This volcano is characterized by a succession of pyroclastic deposits, covered by a dacitic lava flow that extends for 2.5 km SW from the crater. The Apacheta volcano is eroded and shows a moderately fumarolic activity on its eastern flank.

<u>Periods III-IV</u> (Pleistocene): building of Aguilucho volcano. The erupted products are mainly dacitic lava flows, also comprising the youngest activity (80-140 ka Ar/Ar; Renzulli *et al.*, 2006) represented by two dacitic domes: Chac-Inca and Apacheta, respectively located in the northern and in the eastern side of Aguilucho volcano. The Chac-Inca dome is just built on the northern fault of the Inacaliri graben, postdating the youngest tectonic activity of the graben itself. A general view of the AAVC is given in Fig. 3.

Fig. 3 - General view of the Apacheta Aguilucho Volcanic Complex (AAVC).

RECENT MAGMATIC FEEDING SYSTEM

In order to define the uppermost storage of magmas of the most recent volcanic activity of the AAVC, probably representing the fundamental crustal heat source of the present geothermal system, the study was focussed on the dacitic lava domes of Chac-Inca (C-INKA; 80-140 ka) and Apacheta (CPB; 80-130 ka). These domes are also characterized by abundant basic-intermediate microcrystalline enclaves from 2 to 20 cm across. We used the amphibole geothermobarometric equations developed by Ridolfi *et al.* (2010) and Ridolfi & Renzulli (2012) on the amphibole phenocrysts both of the dacite domes and the enclaves to fix pressure (P) and temperature (T) conditions of crystallization of magmas. Consequently, considering a crust density beneath the AAVC of 2.6 g/cm^3 (Zandt *et al.*, 2003), it was possible to obtain information about magma chambers depth. The study has been extended to other nearby and young lava domes of the APVC, such as Chanka (CKA; 1.5 Ma) and La Torta (34 ka; Renzulli *et al.*, 2006) domes as well as two lavas (one andesite and one rhyolite) sampled in the AAVC.

Most of the amphibole phenocrysts (Mg-hornblende) of the dacitic lava domes from Chanka, Chac-Inca and Apacheta domes, and those from the rhyolitic lava (AA-064), crystallized at low pressure (80-164 MPa) in a temperature range between 723-866 °C (Fig. 4). These intensive parameters define the occurrence of typical evolved magma chambers at shallow depth (3-7 km).

These shallow magma chambers are obviously fed by basic to intermediate magmas from deeper crustal levels. In fact, other amphibole populations in the mafic enclaves from Chanka and Apacheta domes and in an andesite lava flow (AA-010) crystallized at P range between 206-527 MPa and T range between 859-1014 °C (Fig. 4). This implies deeper crystallization condition between 7 and 15 km up to 18-19 km, which is the evidence of basic/intermediate deeper intrusions.

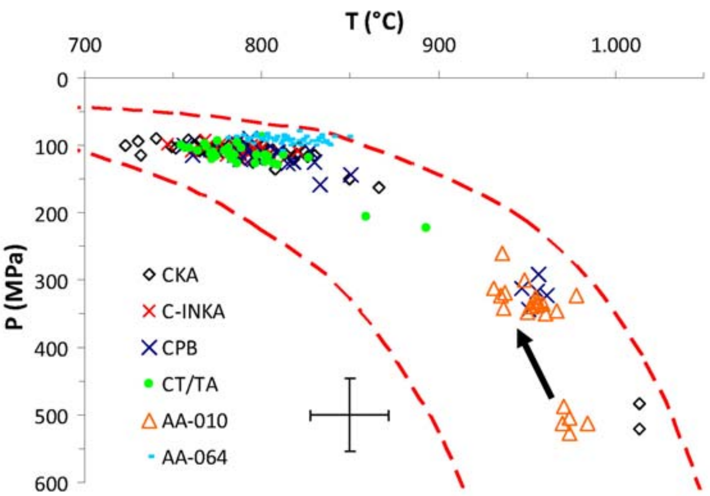

Fig. 4 - P (pressure) *vs*. T (temperature) diagram for the APVC amphiboles. The diagram shows the P-T conditions obtained for the amphibole crystals of Chanka (CKA), Chac-Inca (C-INKA), Apacheta (CPB), La Torta (CT/TA12) domes, AA-010 andesite lava flow and AA-064 rhyolite lava flow through the application of thermobarometric equations (Ridolfi *et al.*, 2010; Ridolfi & Renzulli, 2012). The dashed red lines indicate the stability field of the amphibole. Black arrow shows the P-T trend (from core to rim) in a direct zoning crystals of the andesite lava (AA-010). The crosses bars report the $2\sigma_{est}$ value (*i.e.*, P-T error) calculated at 500 MPa ($P\sigma_{est}$ = 10%, $T\sigma_{est}$ = 22.2 °C). At pressure lower than 150 MPa, the σ_{est} is of symbols dimension.

Some normally zoned amphibole crystals (found in the andesite AA-010) permitted to characterize the nucleation/growth history of these minerals: *i)* starting crystallization at high P-T (488-512 MPa, 970-984 °C), *ii)* loaded by the uprising magma, and, finally, *iii)* crystal growth at 300-350 MPa and 930-978 °C in a shallow magmatic chamber (Fig. 4).

According to the amphibole crystallization P-T stability field, we therefore suggest polybaric differentiation of magmas in the upper crust (in the last 20 km) beneath an area of the APVC, from Chanka (north) to La Torta (south) domes. This petrological evidence is in agreement with the existence of a partially melted zone in the upper crust of the APVC, the so-called Altiplano-Puna Magma Body (APMB) which was detected by geophysical data (Chmielowsky & Zandt, 1999; Zandt *et al.*, 2003). The proposed section of Fig. 5 along the APVC therefore combines petrological and geophysical data.

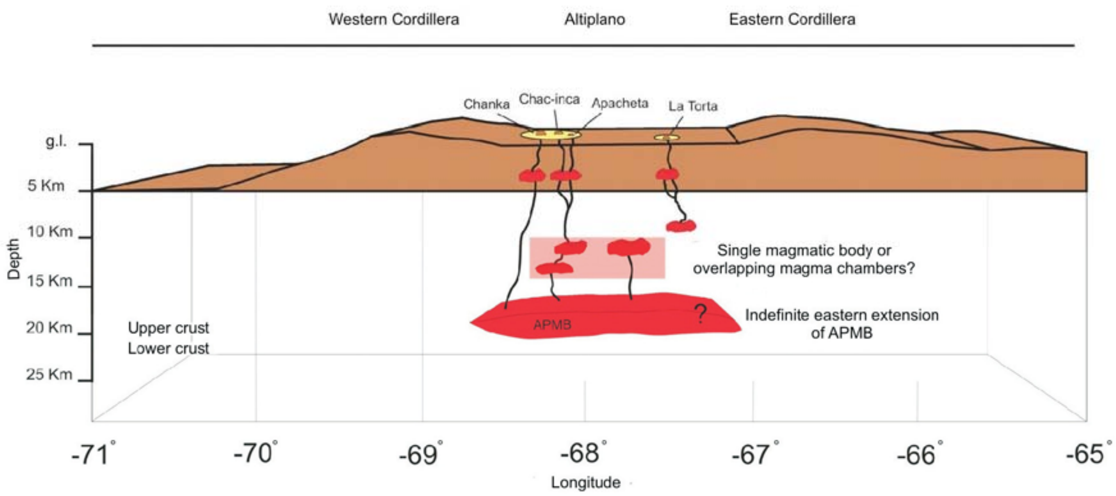

Fig. 5 - Representative diagram of the crust below the study area of the APVC. At 20 km depth the Altiplano Puna Magma Body is shown with 1-2 km thickness. The extension of the APMB is well defined to the west but not east. At 14-10 km depth we find a magma chamber system with different sizes, partially overlapping and continuously replenished by basic/intermediate magmas from the APMB. These basic/intermediate magmas are represented by the microcrystalline enclaves in the APVC domes. At 3-6.5 km depth magmas evolve before erupting as lava domes distributed in the APVC.

CAP ROCKS

Samples of the hydrothermally altered volcanic rocks, coming from a deep borehole, were studied through XRD analyses. We mainly focused this study on the samples from -175 m and -400 m of depth. The interpretations of the XRD data sets indicate that all the analyzed samples are characterized by a common mineralogical assemblage consisting of feldspar, calcite and clay minerals. In addition, in the shallower part of the investigated borehole, minerals related to the group of the zeolites (*e.g.*, clinoptilolite) were found, whereas in the deeper samples, other minerals, such as alunite, hematite, pyrite, and quartz, were detected. According to the clinoptilolite occurrence in the shallower samples (from -175 to -225 m) we can estimate a thermal range between 90 and 130 °C. In deeper samples we found a higher temperature mineral assemblage consisting of hematite, pyrite and smectite (temperature between 130 and 160 °C). At a depth of -275 m there is a considerable increase in the amount of smectite. Clay minerals abruptly decrease until reaching the minimum at depth of -375 m. At this depth they seem to re-increase but do not reach the abundances recorded in samples between -275 and -325 m. In the deepest studied sample (-400 m), pyrite, chlorite, quartz, and mixed layer minerals (chlorite/smectite) are present.

CONCLUSIONS

Geo-petrographic survey of the Apacheta-Aguilucho Volcanic Complex coupled with the available geochronological data indicate that volcanism in this area of the APVC is still ongoing. In addition, a thermobarometric approach on the amphibole minerals of the most recent erupted products (< 100 ka) emphasizes a polybaric differentiation of magma in the last 20 km of the crust, where the mean crustal sources of heat are located. This is in accordance with the main geophysical data. The mineralogical study of samples taken from the deep exploration borehole of the Apacheta-Aguilucho Volcanic Complex provide evidence that the less permeable layers of the hydrothermally altered volcanics, referred to as "cap-rocks", should extend to depths between -275 m and -325/350 m. At this depth range, clay minerals of the smectite group are mainly present. Mineral zonations of the cap rocks coupled with available model of Urzua *et al.* (2002) based on hydrogeological and geophysical (MT) data are summarized in Fig. 6. Below this level the amount of clay minerals decreases and optimal conditions for a circulation of hot fluids should occur.

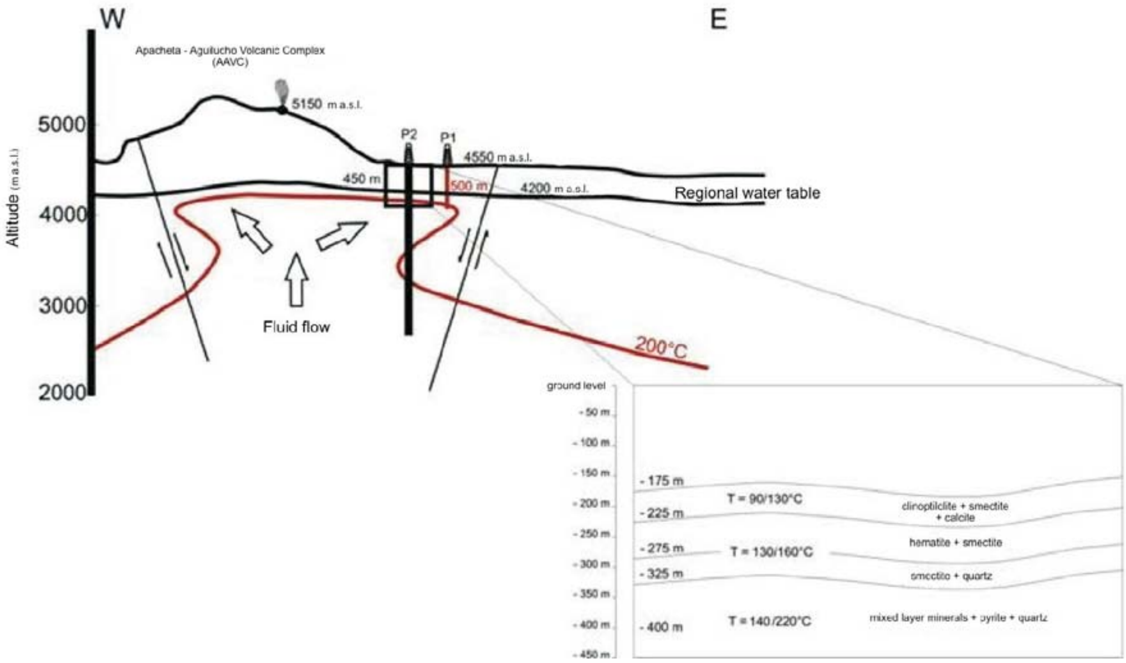

Fig. 6 - Cross section of the AAVC geothermal area coupling hydrogeological and geophysical (MT) data from Urzua *et al*. (2002) and hydrothermal mineral zonation (present work).

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