ORIGIN AND AGE OF FLUIDS AT THE CERRO PABELLÓN GEOTHERMAL SYSTEM, NORTHERN CHILE

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ABSTRACT

The Cerro Pabellón geothermal system in the Central Andean Volcanic Zone hosts the first geothermal power plant in South America (48 MW), and is located in northern Chile at 4500 m a.s.l. The geothermal area is hosted within a NW-SE graben structure, and is defined as a blind high-enthalpy geothermal system. Here we present the results of a geochemical and isotopic study that aims to understand the origin and age of the geothermal fluids at Cerro Pabellón. Brine and condensate samples obtained from production wells were analyzed for δD, $\delta^{18}O$ and $\delta^{13}C$. In addition, apparent ages of the geothermal fluid samples were constrained using ^{3}H and ^{14}C methods. δD-$\delta^{18}O$ values indicate a meteoric origin of fluids, which probably underwent fluid-rock interaction at temperatures of about 250°C. An andesitic water component can be inferred considering a lighter meteoric endmember. $\delta^{13}C$ values are also consistent with a magmatic input on fluids for the gaseous components. Tritium (^{3}H) and radiocarbon (^{14}C) analyses were carried out to assess the age and residence time of geothermal fluids. Taking into account the inherent limitations of these methods, a probable age of at least several thousands of years is estimated. These results should be expanded and complemented with further data to better understand the recharge dynamics of the Cerro Pabellón system and evaluate the long-term sustainability of the power plant.

1. INTRODUCTION

Stable and radioactive isotopes play a significant role in addressing the dynamics of groundwater systems. In particular, their use as geochemical tracers and dating tools is essential for groundwater characterization and assessment of resource exploitation. The same concept is applied to geothermal systems, where fluid origin and residence time need to be constrained for a sustainable design and development of a power plant. Groundwater recharge, as well as fluid mixing and the dynamics of circulation can all be evaluated using an environmental isotope approach (e.g. Panichi & Gonfiantini, 1977).

For example, the source(s) of geothermal fluids can be determined using stable isotopes of hydrogen and oxygen. In convective geothermal systems associated with active magmatism, δD, $\delta^{18}O$ and $\delta^{13}C$ data allow discriminating between fluid components such magmatic water, sedimentary pore fluids, seawater, and metamorphic or meteoric water. Dating geothermal fluids, on the other hand, allows estimating the fluid residence-time and therefore assess the efficiency of geothermal power plant generation. Few methods are available for dating groundwater (e.g., ^{3}H and ^{14}C), and for the particular case of geothermal fluids, contrasting results have made the correct estimation of residence times challenging. Tritium (^{3}H) cannot be detected in surface waters older than 50-60 years due to its short half-life (12.43 yr), limiting groundwater dating of older fluids to the ^{14}C method, with a half-life of 5730 yr (Sveinbjörnsdóttir *et al.*, 2000). Also, successful results have been recently obtained using chlorofluorocarbon (CFC) dating of geothermal fluids (see Held *et al*., 2018) suggesting that this methodology could provide reliable age determinations in active hydrothermal systems.

In this paper we couple stable H-O-C isotope data with radiocarbon (^{14}C) and tritium (^{3}H) ages determined in borehole fluids from the Cerro Pabellón geothermal system. Cerro Pabellón, previously known as the 'Apacheta geothermal project' (Urzúa *et al.*, 2002) is a high-enthalpy blind geothermal system located in the Andean Central Volcanic Zone (CVZ) in the Altiplano of 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. 1). The Cerro Pabellón geothermal system was discovered in 1999 (Urzúa *et al*., 2002), and hosts the first productive geothermal power plant of South America (Cappetti *et al*., 2020). The plant began its operation in 2017 with two twin binary (ORC) units of 24 MWe each one, which provide 48 MWe to the Chilean electricity grid and avoid the emission 166.000 tons/year of CO_2 into the atmosphere.

We integrate our geochemical results with available data from surficial geothermal manifestations in the proximity of Cerro Pabellón (El Tatio in Chile and Sol de Mañana, in Bolivia), including water and gas geochemical data published by Urzua *et al*. (2002) and Tassi *et al.* (2010). Our results aim to improve conceptual models for the Cerro Pabellón geothermal system (Maza *et al*., 2018; Taussi *et al*., 2019a; Giudetti & Tempesti, 2020; Morata *et al*., 2020), allowing a better understanding of the system for its sustainable development.

2. GEOLOGICAL BACKGROUND

The Cerro Pabellón geothermal system is located in the Altiplano-Puna Volcanic Complex (APVC) of the Andean Central Volcanic Zone (CVZ) (see Rivera *et al*, 2020 for a complete and detailed description of the regional and local geology of the geothermal field). The APVC is a volcano-tectonic silicic magmatic province generated by partial melting of thick continental crust (de Silva, 1989; Schmitz *et al.*, 1999). The area of the APVC coincides with the surface projection of the Altiplano-Puna Magmatic Body (APMB, Fig. 2a), a partially molten body within the upper crust, 4 to 25 km below sea level, recognized by geophysical methods 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).

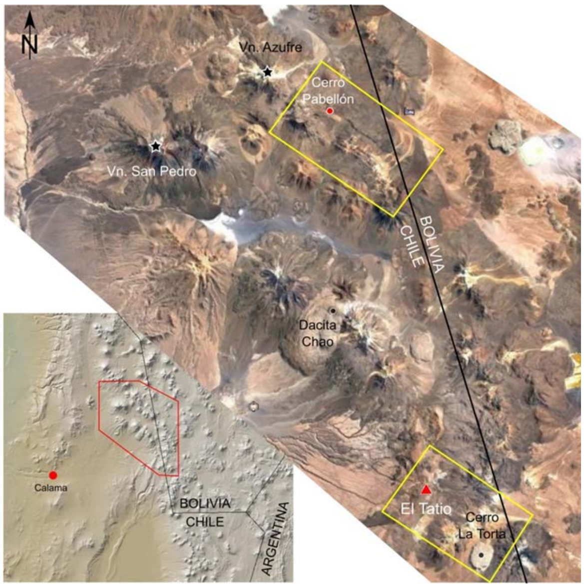

Figure 1: Location of the Cerro Pabellón geothermal system in northern Chile. The map shows the main NW-SE oriented dacitic domes, volcanic chains and other first order geomorphological elements, as well as the El Tatio geothermal system towards the south.

In the studied region, the CVZ is characterized by several NW–SE oriented eruptive centers (Figs. 1 & 2b) 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. 2b). In the geothermal area, the different geological units identified by Rivera *et al.* (2020) 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. 2b). A local Pliocene extensional phase 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 the Azufre volcano in the NW to the Inacaliri volcano in the SE (Tibaldi et al., 2017). 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, and hosts the Cerro Pabellón geothermal system. The main NE fault bounding the graben was sealed by the Cerro Pabellón dacitic dome (50±10 ka, biotite K-Ar, Urzúa *et al*., 2002; 80–130 ka, ^{40}Ar/^{39}Ar in biotite, Renzulli *et al*., 2006; Fig. 2c). The extrusion of this dome was favored by the structural weakness related to the normal faults of the graben (Tibaldi *et al*., 2009), and triggered by a mafic-intermediate magma injection (now represented by the enclaves in the dome) that intruded a relatively shallow dacite magma chamber (Taussi *et al.*, 2019b).

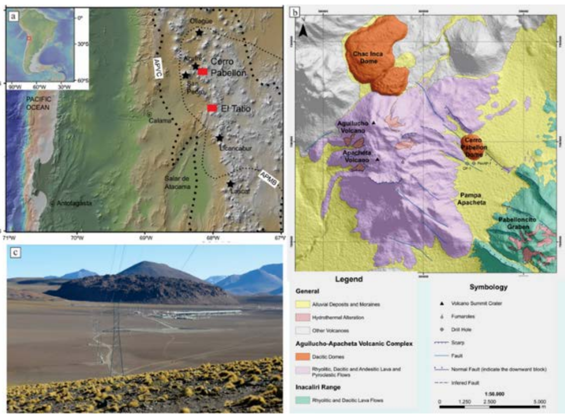

Figure 2: (a) Central Volcanic Zone (CVZ) in the Andean Cordillera showing the Altiplano-Puna Volcanic Complex (APVC), the main Pleistocene to Holocene volcanoes and the location of the Cerro Pabellón geothermal system; (b) Simplified geological map of the Cerro Pabellón geothermal field; (c) Photograph of the Cerro Pabellón geothermal power plant with the 80–130 ka Cerro Pabellón rhyolitic dome in the background. Figure taken from Maza *et al.*, (2018).

2.1 Geothermal fluid geochemistry

The Cerro Pabellón geothermal field does not show hydrothermal surface manifestations; consequently, it is therefore classified as a blind geothermal system (Maza *et al*., 2018; Taussi *et al*., 2019a; Cappetti *et al*., 2020; Morata *et al.*, 2020). The only exceptions are two superheated fumaroles (measured temperatures of 109 and 118°C) with high steam-discharge rates were recognized at 5,150 m elevation at the summit of Cerro Apacheta volcano (Urzúa *et al*., 2002) (Fig. 2b). The nearest warm (23ºC) springs are around 17 km SW of the power plant location (Urzúa *et al*., 2020).

Geochemical data of geothermal fluids are only available for borehole fluids retrieved from production wells (Giudetti & Tempesti, 2020). The geothermal reservoir is liquid dominated and the fluid shows a very low gas content. Giudetti & Tempesti (2020) reported that the fluid chemistry signature is typical of a mature, Na-Cl-rich volcanic hosted system. Solute geothermometry indicates apparent equilibrium temperatures between 280 and 290°C, higher than direct measures in the wells (255°C), suggesting that the system could be even hotter at depth (Giudetti & Tempesti, 2020).

3. SAMPLING AND METHODOLOGY

Geothermal fluids were sampled from production wells during several flow tests in 2010, 2016 and 2017 (see Giudetti & Tempesti, 2020).

Hydrogen, oxygen and carbon stable isotope ratios were determined using a Finnigan Delta Plus XL mass spectrometer at the CNR of Pisa (Italy) and the Estación Experimental del Zaidín (CSIC), Granada (Spain) according to standard protocols.

Tritium (^3H) was measured by electrolytic enrichment and liquid scintillation counting using Quantulus low-level counters at the Water Dating Laboratory at GNS in New Zealand (Morgenstern & Taylor, 2009). Radiocarbon (^{14}C) ages were also obtained at the GNS lab by accelerator mass spectrometry (AMS). Conventional radiocarbon ages and $\Delta^{14}C$ were reported as defined by Stuiver & Polach (1977).

4. RESULTS

4.1 δD-δ¹⁸O results

δD-$\delta^{18}O$ data are shifted from the local meteoric water line forming an apparent mixing line with the "andesitic" water end member (Fig. 3).

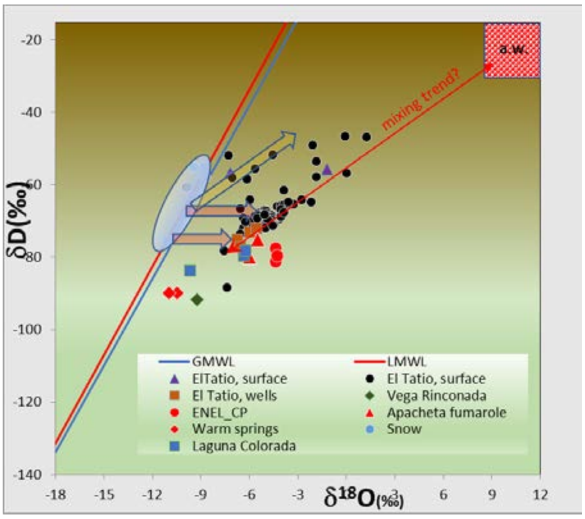

Figure 3: $\delta^{18}O$ *vs* δD (‰ V-SMOW) plot of the Cerro Pabellón geothermal fluids (from Giudetti & Tempesti, 2020). Data from Apacheta fumarole and a warm spring located more than 17 km SW of the Cerro Pabellón geothermal field from Urzúa *et al.* (2002) are also plotted. Available data from El Tatio (surface and wells, data from Giggenbach, 1978, Cortecci *et al.*, (2005) and Muñoz-Saez *et al.*, 2018) and Laguna Colorada (Bolivia, Scandiffio & Alvarez, 1992) are included. Red square: "andesitic water" (a.w.): blue ellipse: snow data (from Giggenbach, 1978, Cortecci *et al.*, 2005 and Muñoz-Saez *et al.*, 2018). Global Meteoric Water Line (GMWL) from Craig (1961); Local Meteoric Water Line (LMWL) from Tassi *et al.*, (2010).

The three available stable isotope data from Cerro Pabellón (total discharge fluid reconstructed at 250ºC) plot in a restricted domain and are consistent with meteoric water (snow and rain precipitation from the high Cordillera) that infiltrated and interacted with volcanic host rocks under reservoir conditions The noticeable oxygen isotope shift has been interpreted by Giudetti & Tempesti (2020) as the results of a system with very long residence time and strong interaction with the volcanic host rocks. Similar isotopic shift is also observed for El Tatio wells and surface data and Laguna Colorada geothermal field.

In Figure 4, the $\delta^{18}O$ and δD values are plotted as a function of Cl-, revealing a good correspondence between the signatures of snow and fluids from El Tatio wells (Giggenbach, 1978) and Cerro Pabellón (this study). These data point to a dominant meteoric component in fluids in both Cerro Pabellón and El Tatio geothermal systems but a magmatic component could not be ruled out as suggested in Fig. 4a.

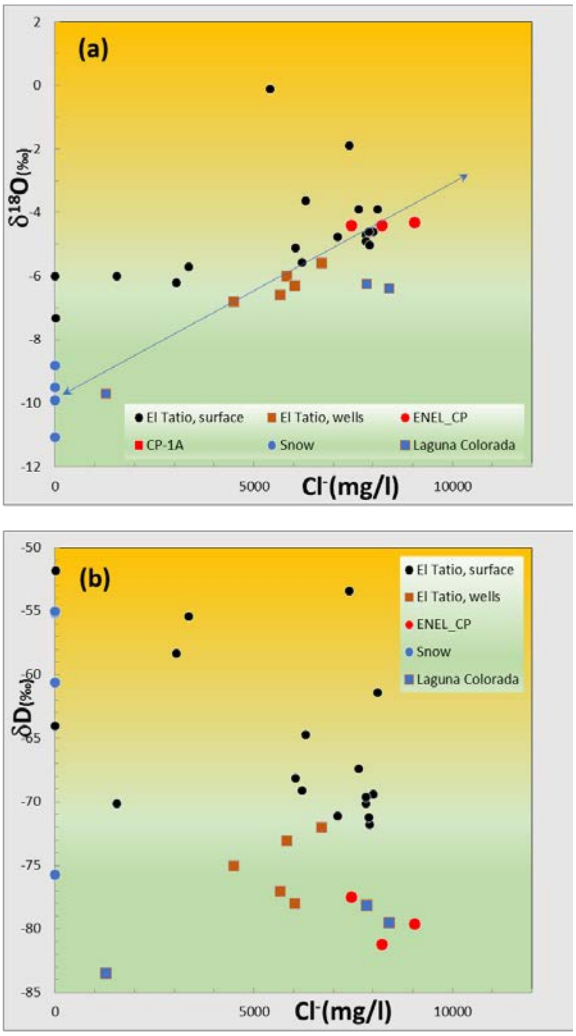

Figure 4: Binary plots of Cl^- *vs* $\delta^{18}O$ (‰ V-SMOW) (a) and δD (‰ V-SMOW) (b). Symbols as in Fig. 3. A simplified binary mixing line between a meteoric component and an "andesitic end member" (blue line in (a)) is proposed. Cl, $\delta^{18}O$ and δD data from Cerro Pabellón wells are from discharge fluid reconstructed at reservoir conditions of 250ºC (Giudetti & Tempesti, 2020).

4.2 Age results

The two samples measured for ^{14}C and tritium ages are reported in Table 1 & 2. Both samples, i.e., condensate and brine from production well CP-1 sampled in 2017 show low ^3H contents. ^3H and ^{14}C ages are suggest long residence times, in the order of several thousand years.

Table 1. ^{14}C results and conventional ages obtained.

Sample	$\delta^{13}C$ (‰) from IRMS	Fraction modern	$\Delta^{14}C$ (‰)	Conventional Age (years BP)
CP-1A brine	-2.3 ± 0.2	0.2130 ± 0.0036	-788.7 ± 3.6	**12421 ± 136**
CP-1A condensate	-1.3 ± 0.2	0.0226 ± 0.0043	-977.6 ± 4.3	**30442 ± 1526**

Table 2. Tritium results for Cerro Pabellón samples. Available data from Laguna Colorada and El Tatio are also included. 1 TR is a $^3H/^1H$ ratio of 1×10^{-18}. ±TR = 1 σ standard measurement error. The detection limit is approximately 0.025 TR.

Sample	TR	±TR
P1A-CP condensate	0.023	0.018
P1A-CP brine	0.046	0.019
Laguna Colorada*	0.04	
El Tatio (surface)**	0.28 - <0.05	

*Scandiffio & Alvarez (1992); **(Muñoz-Saez *et al* (2018)

5. DISCUSSION

5.1 Origin of fluids

As showed in Figure 3, geothermal fluids at Cerro Pabellón are characterized by a dominant meteoric component but an input of "andesitic water" could not be ruled out. In fact, Giudetti & Tempesti (2020) a possible 40% contribution of this "andesitic" compoenent. Recharge may be related with precipitation and snow melting in the high mountains, a few kilometers east of the system. This conclusion is also consistent with the proposed recharge zone for El Tatio geothermal field (Muñoz-Sáez *et al*., 2018). It is likely that the meteoric waters infiltrate and migrate from the recharge zone to the geothermal reservoir, interacting with the volcanic host-rocks at high temperatures (>250°C, following Giudetti & Tempesti, 2020), favoring a $\delta^{18}O$ shift during water-rock interaction under reservoir conditions.

A limited "andesitic water" (or magmatic) component in the geothermal fluids is also deduced based on the low $\delta^{13}C$ values reported in Table 1. The $\delta^{13}C$ values measured in the Cerro Pabellón fluids are similar to the $\delta^{13}C$ value of -4.76 per mil obtained by Tassi *et al.* (2010) in the fumaroles from Apacheta volcano. This is interpreted as a magmatic influence and suggests the existence of a volcanic heat source at depth. This is in agreement with Giudetti & Tempesti (2020), which proposed, as previously discussed, the possibility of an "andesitic water" component for fluids at Cerro Pabellón.

Our results concerning fluid origin are also consistent with Urzúa *et al.* (2002), who carried out the first studies on the Cerro Apacheta fumaroles. As mentioned previously, the only surficial manifestations at Cerro Pabellón correspond to two superheated fumaroles (109°C and 118°C) at 5150 m of elevation in the Cerro Apacheta Volcano (Urzúa *et al.*, 2002). Geochemical data of gas samples suggest a magmatic component (N_2/Ar: 564-470), evidence of low $^3He/^4He$ ratios (relative to air): Rc/Ra = 1.85, and a probable $T_{reservoir}$ in the range of 250-270°C. These features were interpreted by Urzúa *et al* (2002) as loss of the primary magmatic component in combination with contamination by radiogenic He through crustal assimilation. More recently, Taussi *et al.* (2019a) proposed a magmatic component for geothermal fluids, and stressed out the relevance of the thick clay-cap units that limit geothermal CO_2 degassing due to their limited permeability.

All these data confirm that, even geothermal fluid source is mostly of meteoric origin, a magmatic component (the so called "andesitic water end member") could not be ruled out, even if not a clear heat source is defined.

5.1 Fluid ages

Tritium values obtained in the two Cerro Pabellón samples are significantly low (< 0.05TU), suggesting ages older than 50-60 years. Shevenell & Golf (1995) used tritium in groundwater to determine mean residence time of fluids in caldera-related environments. The cited authors discussed the possibility of in-situ ^3H production within a reservoir through the neutron-induced reaction $^6Li(n,\alpha) \rightarrow ^3H$. Therefore, high concentration of U, Th and Li may result in additional ^3H being introduced into the geothermal reservoir. Shevenell & Golf (1995) calculated that an acidic tuff host with U = 12-16 ppm, Th = 40-43 ppm, Li = 14-47 ppm and B = 16-29 ppm can produce ^3H around 0.010-0.019 TU. Assuming a similar mechanism, and considering the relatively high U, Th and Li concentrations in the volcaniclastic reservoir host-rocks at Cerro Pabellón, a calculated residence time of ~10,000 years is calculated for the geothermal fluids.

This calculated residence time is consistent with ^{14}C age constraints (Table 1). Moreover, the addition of carbon from sources other than the atmosphere and organic soil would dilute the ^{14}C concentration of the water yielding higher apparent ^{14}C age (Sveinbjörnsdóttir *et al*., 2000). In consequence, it is possible that water-rock interaction processes can significantly dilute the ^{14}C concentration of geothermal fluids yielding apparent ages in the order of several thousand years.

Ages in the order of several thousand years could be consistent with some geological features identified in the area. In this sense, Slagter *et al.* (2019) reported ^{14}C ages on paleosinter deposits from El Tatio geothermal field. The sinter mounds range from 10,840 ± 30 to 230 ± 35 yr B.P., indicating that the El Tatio system has had active discharge over at least the past 10,000 years. These data support long-lived fluid circulation and continuous geothermal activity, probably triggered by deglaciation in the Altiplano (~20-10 ka, Blard *et al*., 2014).

Finally, and concerning the heat source, the most recent magmatic activity in the area corresponds to the Cerro Pabellón dacitic dome (80-130 ka), and no specific volcanic center is related to the geothermal system. On the other hand, the geometry of the edge faults of the graben and the accommodation of blocks in the extensional stage could have generated a space at about 4 km deep, facilitating the eventual emplacement of a shallow magma chamber (Rivera et al., 2020). This hypothesis is consistent with amphibole geo-thermo-barometric estimations from dacitic domes, supporting the existence of magmatic chambers at 3-7 km and 10-14 km deep (Piscaglia, 2012). Therefore, and as proposed in Maza *et al.* (2018) and Taussi *et al.* (2019a), it is likely that the heat source of the Cerro Pabellón geothermal system is possibly related to the anomalously high regional temperature gradient (APMB) or a local magmatic body closely related to the APMB (Rivera *et al.*, 2020).

6. CONCLUDING REMARKS

Our data point to long residence times for fluids at Cerro Pabellón, within the order of several thousand years. The recharge area is most likely located in the higher peaks of the Andean Cordillera, a few kilometers east of the geothermal field. Even though more detailed geochemical and isotopic studies are needed to better understand the Cerro Pabellón geothermal reservoir, our results suggest that precise monitoring and reinjection are critical to ensure the sustainable operation of the power plant.

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