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Cerro Pabellón Geothermal Field (Chile): Geoscientific Feature and 3D Geothermal Model

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ABSTRACT

Cerro Pabellón (formerly called Apacheta) geothermal field is mainly hosted inside the so-called Pabelloncito or Apacheta Graben, a main NW-SE structural feature, about 120 km north-east of Calama city (Antofagasta region, Chile) at an elevation around 4,500 m a.s.l.

The project was entirely managed by Geotérmica del Norte (GDN), a joint venture between Enel Green Power (EGP) and Empresa Nacional del Petróleo (Enap). The project started with a thorough surface exploration phase, inclusive of different geophysical surveys and a slim-hole, and prosecuted with a deep exploration phase (4 commercial diameter wells) and a following development phase (9 commercial diameter wells and the construction of a 48 MW power plant in parallel).

The geothermal resource found is a liquid dominated reservoir, Na-Cl type, showing a temperature of about 250-260°C in the wells drilled inside the Apacheta graben, while outside the latter, the wells measured about 30-40°C less at the same depth, even if still associated with a convective thermal gradient.

The 13 geothermal wells drilled so far provided a lot of direct subsurface data, such as lithology and hydrothermal alteration minerals from cuttings and core analyses. Also thermodynamic data from both injection and static T&P logs, performed during and after drilling respectively and physical-chemical data from fluid sampled during production tests are available. All of these data allowed performing spatial reconstructions of the main features of the geothermal system, like the geological setting, the hydrothermal mineralogical alteration facies distribution, temperature, pressure, and permeability distributions according to depth. Moreover, it was also done a comparison between the new data and the resistivity features coming from a magnetotelluric survey executed during the shallow exploration phase. The merging of all these geoscientific data was uploaded into the 3D modeling Petrel® software: this allowed having a 3D view for correlating data deriving both from surface surveys and deep drillings.

Based on the 3D Petrel® model, a geothermal model of the area is here proposed, in which the main elements of the system, as cover, reservoir and fluid circulation pattern, are defined and geometrically described as input for a numerical modelling.

1. INTRODUCTION

The Cerro Pabellón project is located in the Andean Ranges of northern Chile, Antofagasta Region, about 120 km far from Calama, 55 km NNW of El Tatio Geothermal Field and around 1300 km to the north from Santiago capital city. Placed at an altitude of 4,530 m a.s.l., Cerro Pabellón is the highest geothermal power plant operating in the world.

In the framework of the regional subduction regime of the Nazca Plate under the South American one, a local Pliocene extensional phase took place in the area generating NW-striking normal fault system, from Azufre volcano (NW) to Cordon de Inacaliri (SE), passing through the Aguilucho – Apacheta volcanic complex (Tibaldi et al., 2016). The geothermal area (Figure 1) is at the base of these volcanic complexes, which summits commonly exceed 5,000 m a.s.l., in a plane area inside the Apacheta graben. The graben is a morphologically depressed area having a vertical displacement of about 100 m and dimension 20 km length x 3 km large, comprised between two border faults with direction about N53-60°W (Rivera et al., 2020).

Pampa Apacheta was actually a "blind" geothermal area, due to the absence of natural manifestations, and for this reason it was not recognized for a long time. In 1993, Codelco (Corporacion Nacional del Cobre de Chile) drilled a well looking for industrial water in Pampa Apacheta (4,511 m a.s.l.): the drilling was stopped at 187 m, since the well, instead of tapping a cold water table, started producing steam at 88°C . From then, the area became interesting for geothermal perspectives and, from 2002, GDN (at present a joint venture between Enel Green Power and Empresa Nacional del Petróleo) started a new geothermal exploration project.

GDN carried out a shallow exploration program including different geophysical and geological surveys, that allowed to focus the most favorable zone for exploration drilling inside the structural depression of Pampa Apacheta (Figure 1). The drilling of a slim-hole (560 m depth) furtherly reduced the uncertainties and the risks for the deep exploration drilling, giving a direct temperature measurement and confirming the presence of hydrothermal alterations representative of a geothermal circulation (Morata et al., 2020; Maza et al., 2018). According to these results, four exploration wells (named CP-1 to CP-4) were drilled in the surroundings of Co. Pabellón acid dome, that confirmed the presence of a water dominated geothermal resource, hosted in volcanic rocks, as tuffs and andesitic-dacitic lavas and characterized by an undisturbed temperature of about 250°C, over 1,500 m depth. The succeeding development phase comprehended the construction of two high enthalpy ORC units (24 + 24 MW gross) and the drilling of further nine wells, all successfully completed (Cappetti et al., 2020).

The main geoscientific results of surface and deep drilling activity, collected in the different steps of the project, were used to create, at first, an integrated 3D model using the Petrel® software, and following to define the main input elements for a numerical model of the system.

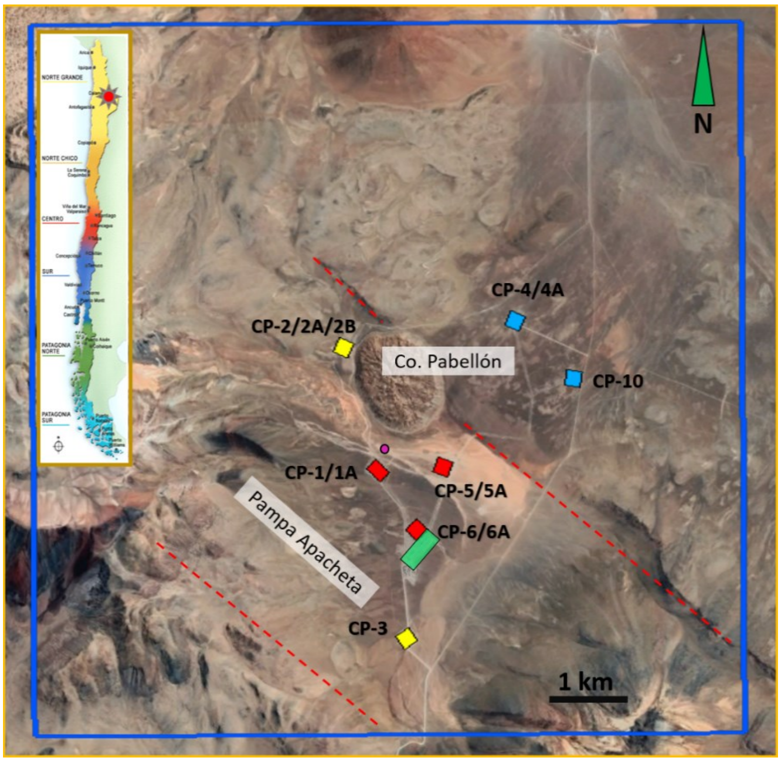

Figure 1: Location of Co. Pabellón geothermal field on satellite base map. Red squares: production wells; light blue squares: reinjection wells; yellow squares: currently not used wells; purple dot: deep monitoring well; green rectangle: ORC power plant; red dotted lines: border faults of the Apacheta Graben; blue line: geothermal development mining lease.

2. RECONSTRUCTION OF STRATIGRAPHIC-STRUCTURAL SETTING

In the area only volcanic and volcanoclastic rocks of Neogene to Quaternary age outcrop. The oldest rocks are Late Miocene ignimbrites. But, in addition to these pyroclastic deposits, the period was also characterized by an abundant effusive volcanism whose emission centers are, for the most part, always aligned in NW-SE direction (i.e. Co. Colorado, Co. Lailai, Co. de Colana in Figure 2).

The geologic samples collected from the exploration and development drillings are in forms of cuttings. They were analyzed to attempt a stratigraphic reconstruction, at first for each well, and then to create a correlation among the various stratigraphic logs. Mainly due to the typical volcanic environment of the area but also to the scope of our work, the stratigraphic reconstruction was done mainly with a lithological unit approach, better than identifying the geological formation.

The litho-stratigraphic unit reconstruction is summarized in Table 1 and a preliminary well correlation can be visualized in Figure 3, following a hypothetical cross section in S-N and NW-SE direction. The fractures distribution with depth is mostly concentrated in the DT and RDT Units, apart from a few shallow fractures, encountered in LT and BAL Units. It is worth noting that in general the fracture distribution, and so the main permeability characterizing the reservoir, is not linked to a specific lithology, but seems rather controlled by the graben structures.

Rivera et al. (2020) analyzed the litho-stratigraphic reconstruction derived from Co. Pabellón wells in the framework of the regional volcano-tectonic evolution and of the main structural elements present. When possible the Authors connect the litho-stratigraphy recognized at depth with the surface geology. In line with their regional volcano-tectonic reconstruction (six phases from Oligocene to present), the development during Pliocene of the Apacheta Graben represents the most important structural feature of the area, acting a strong influence into the evolution of the geothermal field.

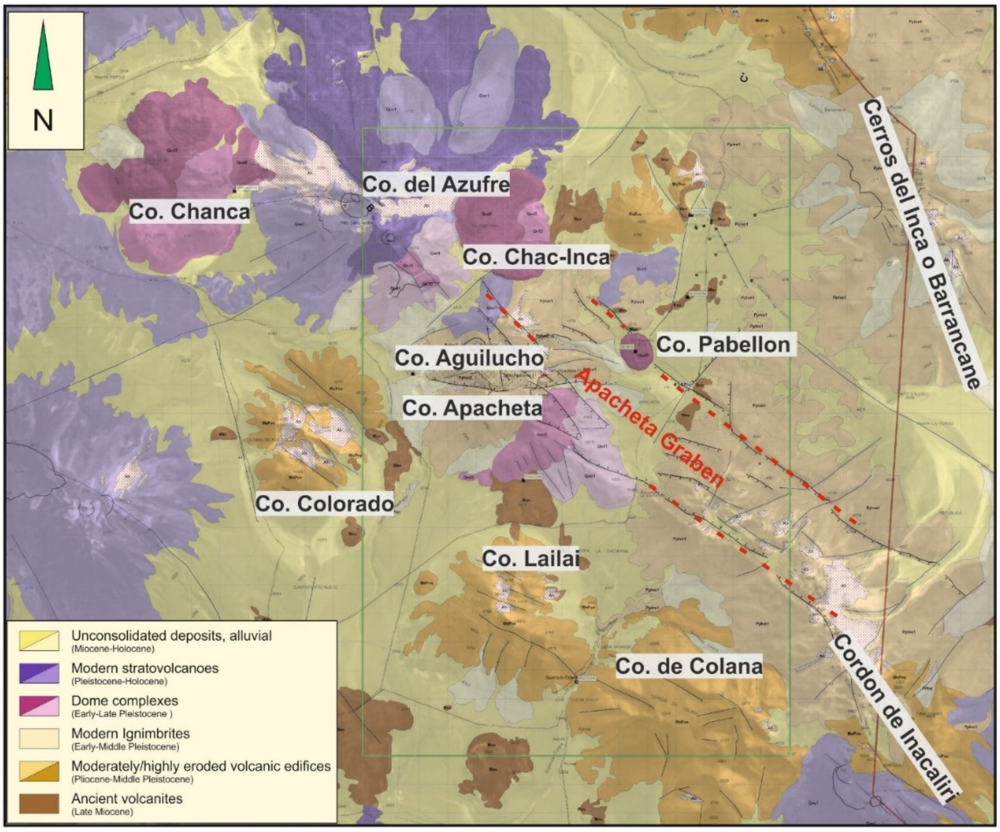

Figure 2: Geological map (modified from Rivera et al., 2007) of the Co. Pabellón area. Pampa Apacheta is the plain area inside the Apacheta Graben.

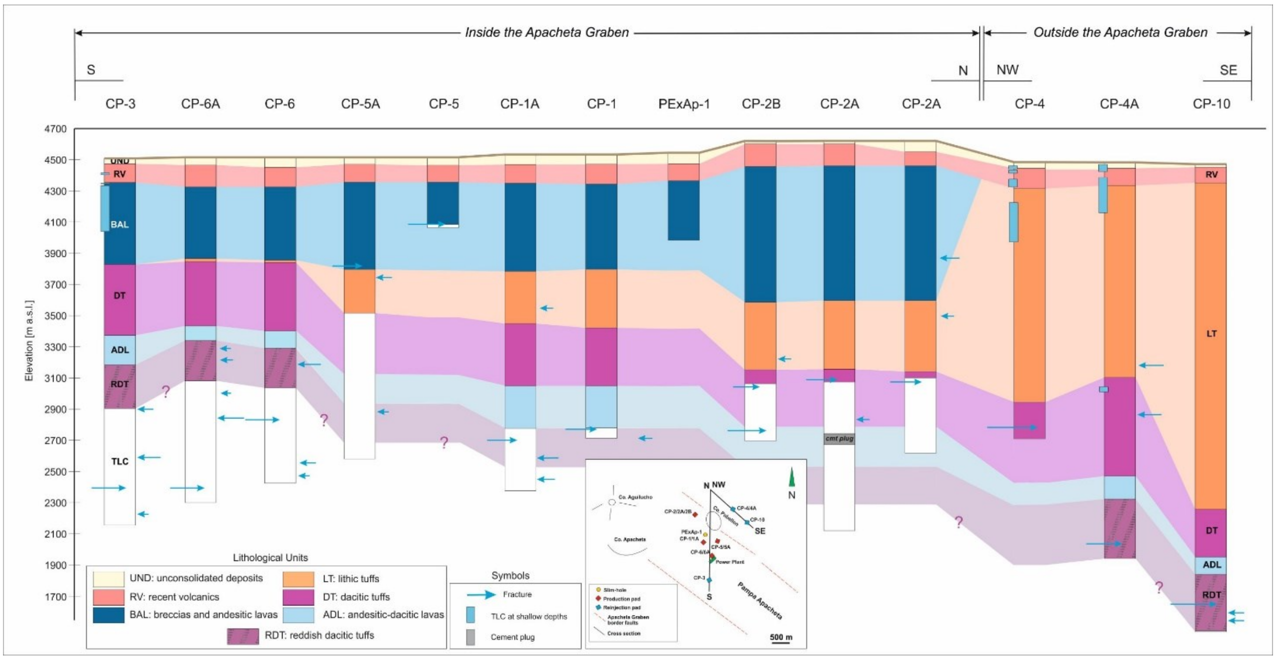

Figure 3: Litho-stratigraphic correlation among the Co. Pabellón wells. The wells are equally spaced, not in their real position. Light blue arrows are the fractures recognized into the wells: their length is according to their production/absorption capacity. Shortcuts as in Table 1.

Name	Shortcut	Age	Description	Average thickness [m]	Additional info
Unconsolidated Deposits	UND	Middle Pleistocene - Holocene	Unconsolidated polymictic fine gravel and sands, composed of fragments of andesitic lava, dark gray lava and partially vitreous, black and red scorias, white pumice-rich tuffs and free crystals of Q, Pl, Hbl and Bt.	0-65	
Recent Volcanics	RV	Early Pleistocene	Upper sequence of vitreous-crystalline tuffs, lapilli tuffs, andesitic scorias, andesitic lavas and sandstone lenses. Lower sequence of lapilli tuff, tuffites and brown sandstones.	130	Unit cut by NE graben fault; it shows minimum thickness difference inside and outside the Apacheta graben.
Breccia and Andesitic Lavas	BAL	Late Pliocene – Early Pleistocene	Volcanic breccias and lava flow intercalated. The top is dominated by breccias with minor lavas while going deeper the lavas become dominant. Lavas have porphyric textures with Pl and Cpx phenocrysts in a micro-crystalline to vitreous groundmass.	565	Present only in the wells drilled inside the Apacheta graben indicating a sintectonic deposition.
Lithic Tuffs	LT	Late Miocene – Late Pliocene	Tuffites and lithic tuffs intercalated with a small presence of lava flows. Pyroclastics generally have colors varying from white to red and crystals fragments are Q, Pl, Hbl. The lavas are very dark and show Pl and Cpx phenocrysts.	1,244	Not present in the southern part of the Apacheta Graben. High thickness outside the Graben. Possible interpretations by Rivera et al. (2020).
Dacitic Tuffs	DT	Late Miocene	Succession of biotite tuffs with different degrees of lithification. Rock colors vary from pink to green with crystal fragments of Pl, Bt, Q, as well as flames. Intercalated a sequences of dacitic lavas with crystals of Pl, Bt, Q are recognized.	270	DT, ADL and RDT Units show high uncertainties on litho-correlation and thicknesses estimation due to the absence of cuttings during TLC drilling.
Andesitic-Dacitic Lavas	ADL	Middle Miocene	Succession of gray-green to red lavas.	177	
Reddish DT and Sandstone	RDT	Oligocene – Middle Miocene	Reddish dacitic tuffs and sandstones.	260 (min.)	

Table 1: Description of the litho-stratigraphic units from Co. Pabellón drillings from the surface to the depth. Bt: Biotite; Cpx: Clinopyroxene; Hbl: Hornblende; Pl: Plagioclase; Q: Quartz; TLC: Total Loss of Circulation.

3. RECONSTRUCTION OF HYDROTHERMAL ALTERATION FACIES

The geologic samples collected from drillings were analyzed also to study the hydrothermal alteration distribution to highlight the hydrothermal fluid pathways during time. The alteration of Co. Pabellón geothermal area at depth is characterized by four different hydrothermal alteration facies (Table 2), similar to the ones described in Maza et al. (2018) for the slim-hole samples. The hydrothermal facies correlation performed among the wells is shown along the same cross section used for the litho-stratigraphic correlation (Figure 4), in which are represented:

- The argillic and transitional facies (A and T). These facies represent the impermeable cover of the fluid circulating system. In the section they present thicknesses up to 390 m in the core of the field, with a base at 400-450 m below ground level (b.g.l.), in the producing field core (pads CP-1, CP-5, CP-6), and considerably lower in the peripheral zone (~1,000-1,500 m b.g.l.).
- The **propylitic facies top**, with its dome shape. It has the apex on the best producing wells and the flanks falling towards the more peripheral wells up to 1,100 m towards the south, to ~900 m towards the north, and to 1,000-1,500 m depth on the northeast, outside the Apacheta Graben.
- All the main **reservoir-producing fractures.** They are located into the propylitic facies, as might be expected by the geo-mechanical behavior of these altered rocks.
- The **thermal top of the reservoir**, in correspondence of the flex from conductive to a convective regime in static temperature log. It is in good concordance with the propylitic facies top in the core of the field, whereas a significant discrepancy is evident in the CP-4 area.

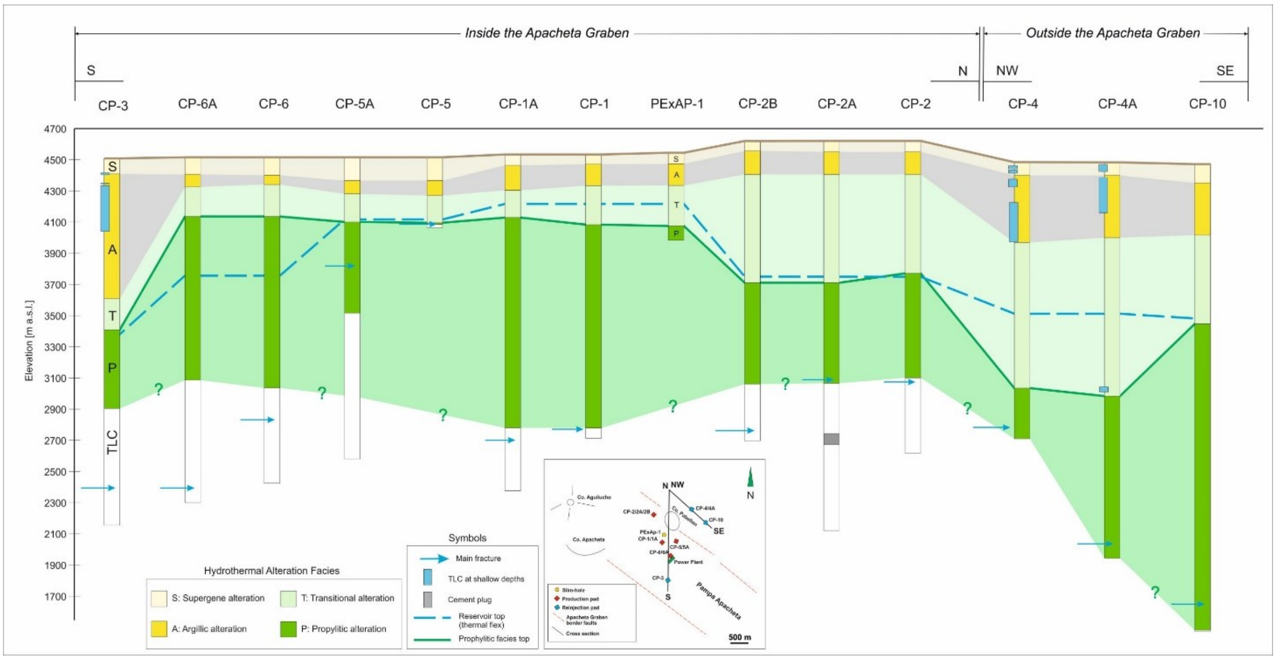

Figure 4: Hydrothermal alteration facies correlation among the Co. Pabellón wells. The wells are equally spaced, not in their real position. Light blue arrows are the main fracture for each well: their length is according to their production/absorption capacity. Shortcuts as in Table 2.

Facies name (Shortcut)	Temp [°C]	Mineralogical description	Permeability	Electrical signal	Thickness range [m]	Mean interval depth [m]	Note
Supergene (S)	<120	Zeolites and clay minerals that initially fill in the porosities and progressively replace the matrix	High	Moderately resistive	60-150	0-60/150	
Argillic (A)	130-200	Clay minerals, above all Smectite and Smectite-Chlorite group	Very low	Very conductive	60-800	60/150 - 180/900	Generally acts as sealing cap rock of the system
Transitional (T)	200-220	Transition from Phyllosilicates to Inosilicates.	Average	Moderately resistive	170-1,000	180/900-380/1,500	Fractures with low injectivity can be present
Propylitic (P)	>220	Dominant Inosilicates, Epidote, Titanite associated to Phyllosilicates as Illite and Chlorite	Only in localized fractures	Resistive, eventually conductive in localized permeable / porous zones	Verified up to ~2,000	380/1,500 – 3,000 (max b.h.)	Generally associated with the geothermal reservoir

Table 2: Description of the hydrothermal alteration facies in Co. Pabellón area. The hydrothermal alteration facies are associated to the MT electrical signal and to the permeability response of the altered rock. b.h.: bottom hole.

4. PHYSICAL-CHEMICAL RESERVOIR CHARACTERISTICS

For a reconstruction of the hydraulic and thermodynamic characteristics of the reservoir, the reservoir engineering and geochemical data deriving from tests performed on exploration and development wells were analyzed:

- Static T&P surveys on wells both at the end of the drilling activity and in stabilized conditions;
- Injection T&P surveys on the wells at the end of the drilling activity;

- Well testing and transient analysis;
- Chemical sampling during well production tests.

4.1 Reservoir temperature distribution

In Figure 5, examples of the static temperature gradients measured in the Co. Pabellón wells are shown. All the temperature profiles are characterized by a first section with a constant thermal gradient (conductive heat exchange) followed at depth by a convective zone with a thermal gradient near to zero. The transition point between the two zones characterized by a different temperature gradient, can be considered as the limit between the impermeable cover and the permeable geothermal reservoir (see also the blue dotted line in Figure 4).

Currently, the production pads inside the graben measure a reservoir temperature around 250-260°C (example in Figure 5a): only the production from shallower wells shows lower temperature as they happened at a higher altitude than the others (example in Figure 5b). In the reinjection wells, the convective zone shows considerably lower temperature (200-220°C) and in the "conductive" part of their profiles, they are characterized by an important thermal inversion at 3,800-4,000 m a.s.l. (Figure 5c/d).

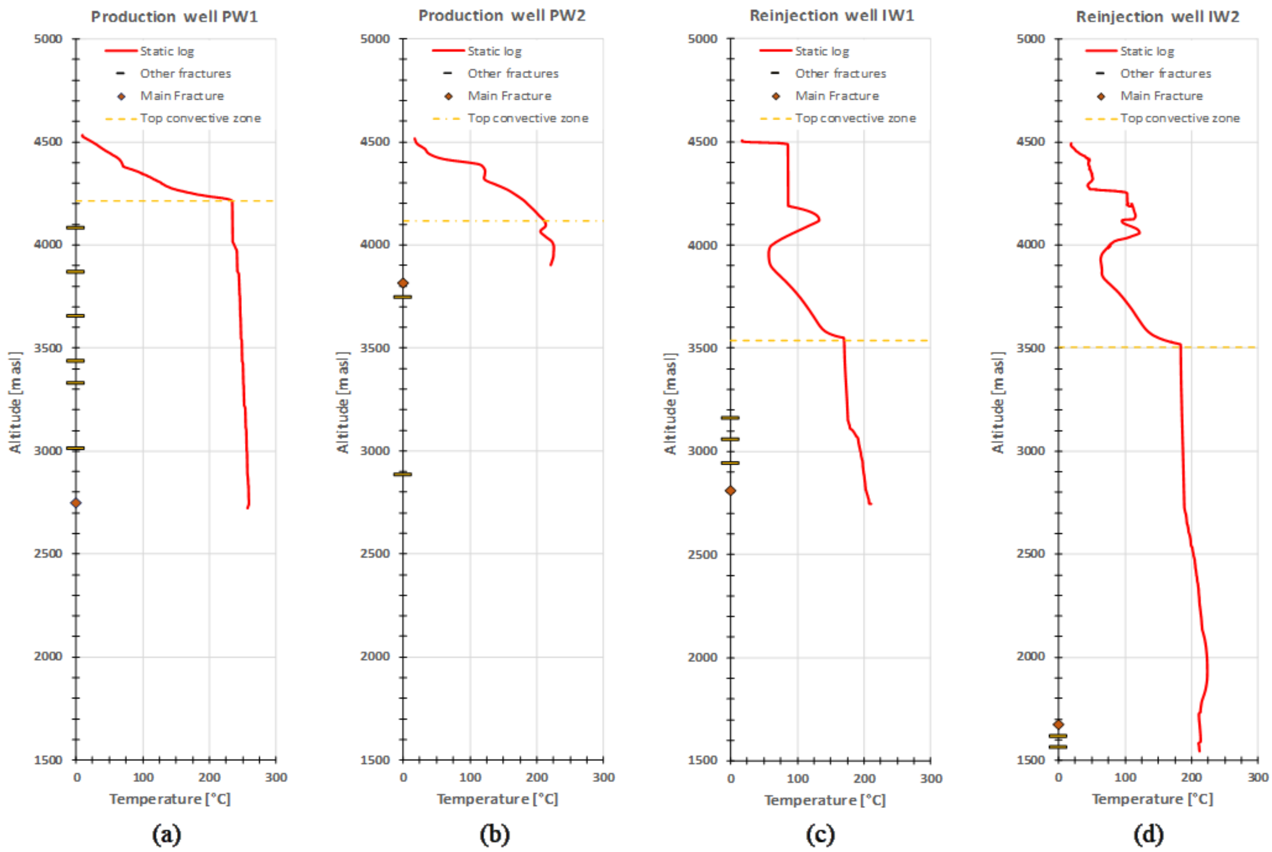

Figure 5: Example of temperature vertical profile with the location of fractures and the selection of the thermal flex (i.e. top convective zone). PW1 and PW2: profiles of production wells inside the Apacheta graben, respectively from a deeper and shallower horizons; IW1 and IW2: profiles of reinjection wells outside the Apacheta graben.

4.2 Reservoir pressure distribution

Figure 6 shows the pressure gradient of the Co. Pabellón geothermal field, a reconstruction based on static pressure data measured for each well at the main fracture depth. As expected in presence of a dominant liquid reservoir, all the static pressures are on a single line whose slope is determined by the density of the fluid at temperature and pressure reservoir conditions (830 kg/m^3). This fact confirms that, although characterized by fractures at different depths, all the drilled wells belong to the same geothermal system, which is in hydrostatic equilibrium, at least for a long time.

The present static level in the wells is at about 4,380 m a.s.l.. Taking into account that the shallowest reservoir zone shows 220-230°C, it is possible that here a localized steam dominated system exists, characterized by about 25 bar of pressure (saturation of 220-230°C). Therefore, a liquid/steam interface is present at about 4,100 m a.s.l. in the reservoir: CP-5 fracture could be in correspondence of this interface or just below it.

Outside the graben, the presence of shallow cold aquifers is well known and used by mining companies. In 2015, according to the requirement of the Environmental Authority, GDN drilled two shallow piezometric wells (≈100 m depth), called Cachimba-1 and

Perdiz-1, respectively for the monitoring of two aquifers, “Ojo de San Pedro-Cachimba” and “Quebrada la Perdiz”. Figure 5 comprehends also the static level measured in these two boreholes, set south and north of the graben: their static level in 2019 (green dot around 4,200 m a.s.l.) is clearly different from the hydrostatic pressure gradient measured in the geothermal system, evidencing that the two systems are not hydraulically connected.

4.3 Fractures distribution

As shown in Figure 3 and Figure 4, both production and reinjection wells have identified permeable horizons at altitudes varying between 4,100 m a.s.l (in the core field) up to 1,600 m a.s.l. (outside the graben).

In particular, CP-5 and CP-5A wells are characterized by a particularly superficial permeable horizon (3,800 – 4,100 m a.s.l.), with very high injectivity, supplying geothermal fluid with a greater enthalpy content. Apart from these wells, the other production wells have a distribution of the fractured zones concentrated in the range 2,300 – 3,200 m a.s.l. with injectivities usually comprised in the range 10 - 20 m^3/h/bar. Most of the wells identified the main fracture that guarantees over 70 - 80% of its total injectivity.

The performed injection tests indicate that the fractures of the three reinjection wells, usable at present, are capable of accepting more than 2,000 t/h of water.

4.4 Production and reinjection capacity

The average of total fluid flow rate from each production well is 260 t/h with a title of about 22%. It is slightly higher than expected considering an adiabatic flash starting from the enthalpy of the fluid at reservoir conditions (19%). As previously stated, this is due to the fluid delivered by the wells producing from shallower fractured zones that has a greater enthalpy content (excess of enthalpy).

The absorption capacity of the re-injection wells is only estimated as the current plant layout does not allow for the execution of pressurized prolonged injection tests. Nevertheless, it can be stated that the absorption capacity of the already drilled wells is sufficient also for the management of reinjection, even in case of a further production unit (same capacity as those already in operation).

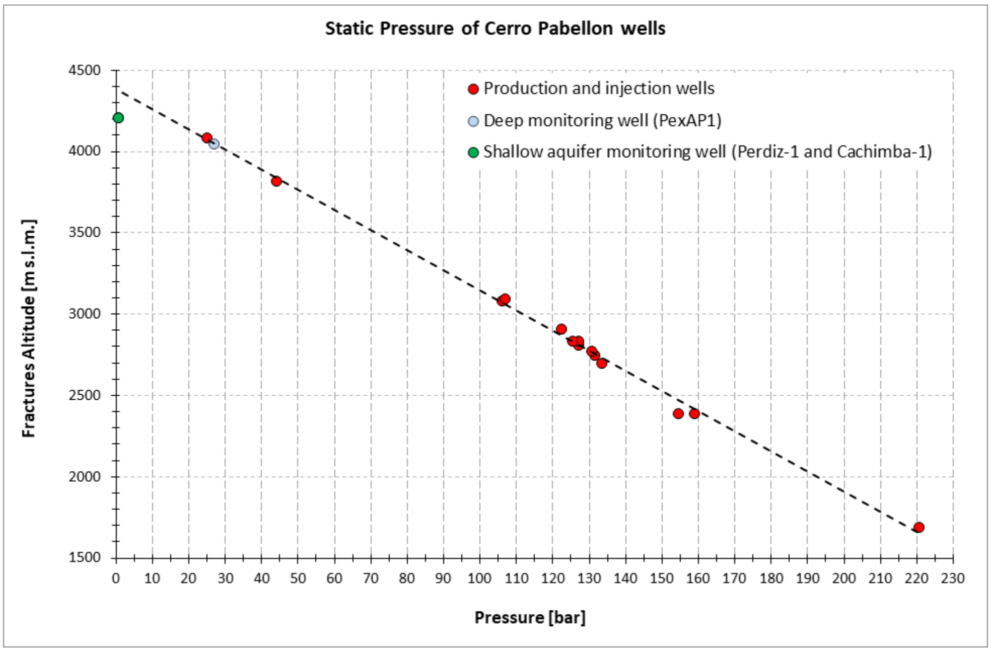

Figure 6: Comparison between the static pressures from Co. Pabellón deep geothermal wells, the deep monitoring well (slim-hole) and the two shallow monitoring borehole of the cold aquifer (Cachimba-1 and Perdiz-1).

4.5 Geochemical Characteristics

The first preliminary chemical data analyses on production test samples are presented and interpreted by Giudetti and Tempesti (2020). The fluid is a typical sodium-chloride water, slightly acidic in reservoir condition with TDS of 14-18 g/l. It shares typical characteristics shown by other systems in the region, i.e. high solutes content enriched in Ca, rare alkalies and low gas content. The salinity and the noticeable isotopic oxygen shift point out a system with very long residence time and strong interaction with the volcanic andesitic host rock.

The Na-K geothermometer and CO_2 based ones indicate an equilibrium temperature at 280-290°C, inferring hotter conditions at deeper depths.

A deep circulating water (natural recharge), not related to the shallow cold aquifer found in Perdiz-1, could be invoked to explain the thermal behavior of CP-4 area, alternatively the system is simply fading off, with the graben fault acting as a semipermeable barrier for fluid circulation.

Westward the relationships between the fumaroles on Co. Aguilucho and the geothermal reservoir are not clear at present, given uncertainty on the fumaroles origin so that the boundary of the system is still to be clarified. Degassing occurs at depth and gas rises through the fumarole conduit up to the surface (Giudetti and Tempesti, 2020).

5. COMPARISON OF MT ELECTRICAL MODEL WITH WELL RESULTS

The 3D magnetotelluric (MT) identifies two clear electro-structures in Cerro Pabellón (Figure 7): a conductive horizon (1-5 ohm.m), sub-horizontal and superficial, with 600-700 m thickness in the center of the graben, mostly related to the cap rock of the geothermal system (clay cap) and a deep resistive (> 50-100 ohm.m) with prevailing "dome" geometry towards the volcanic complex of Cerro Apacheta (SW limit of the Graben). This dome structure was considered - at least in part - associated with the upflow zone of the geothermal system, where hot fluids would upraise along high angle fractures (with very few interconnection among them) generating at the same time extended propylitic alteration within considerable volumes of rocks during the lifespan of the geothermal activity. This MT interpretation mostly followed the model known in geothermal literature as "Magnetotelluric Rock Driven System" (MT-RDS) where the rock state entirely influences the underground resistivity distribution.

In Cerro Pabellón area, this kind of interpretation fits in the areas out of the field core with a good according between thermal data, top of the propylitic facies and MT resistivity. Otherwise, there is a small sector of the reservoir (estimated at ~2 km^3), probably more porous and permeable, filled by hot and saline fluids that shows low resistivity anomalies (~ 5-10 ohm.m). In this sector, identified like a pulse just below the core of the field (FDS in Figure 7), the fluid conductive print was superimposed on the propylitic host rock. This signature is known as "Magnetorellurics Fluid Driven Systems" (MT-FDS) and in this sector, in Cerro Pabellón, the MT values do not fit the thermal data and the top of the propylitic facies.

Considering the 100 km^2 area covered by the MT survey this interpretation is useful to define the reservoir top in the area outside the field core as coincident with the top of the resistive horizon in MT-RDS condition (blue dotted line in Figure 7).

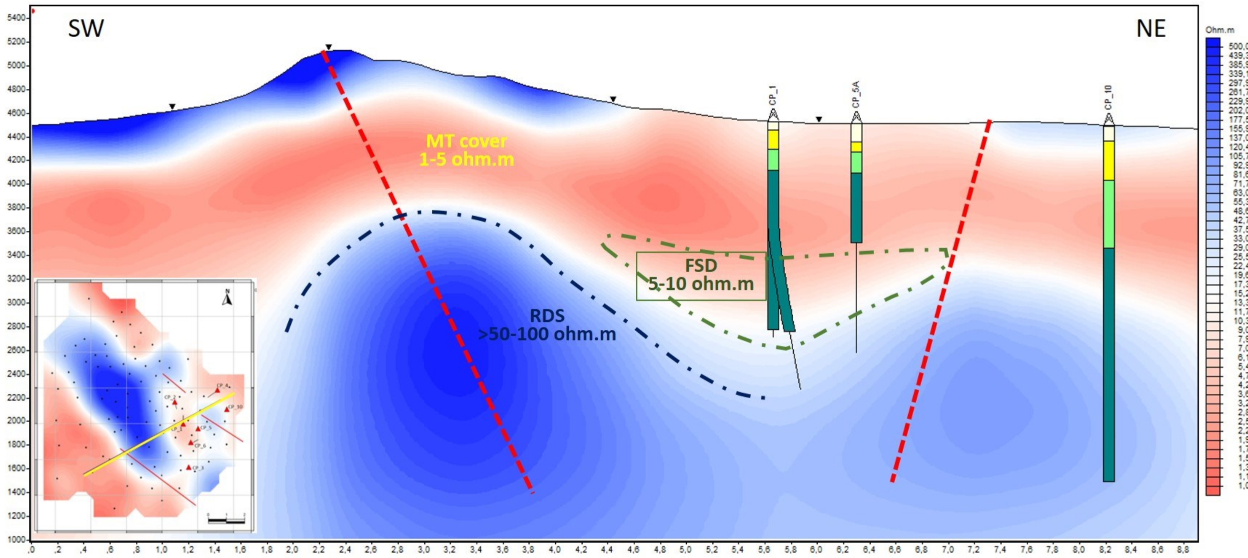

Figure 7: SW-NE cross section from 3D MT model. Red lines: structural limits of the Apacheta Graben. Along the well are the hydrothermal alteration facies, from top to bottom: supergene, argillic, transitional and propylitic. Section trace in yellow in the related map (model cut at + 3,000 m a.s.l.).

6. 3D MODEL

In order to integrate the different geoscientific data deriving from geology, geophysics and reservoir engineering collected during the development of this project, the data were uploaded into Petrel® and some screenshots of the model are presented in Figure 8 and in Figure 9.

In the following, the main elements are summarized:

- **Volcano-tectonic elements**: According to Rivera et al. (2020), Tertiary basement was folded during the Late Miocene – Late Pliocene compressive phase into an anticline that at present underlies the local extensional structure of the Apacheta Graben. Good permeability conditions are expected to be associated mainly to the graben border faults, to the secondary faults inside the graben, and to the NE damage zone of the anticline itself. The geometry of the border faults and the movement of the blocks during the distension stage, could have supported the location of a shallow magmatic chamber under Apacheta – Aguilucho complex (about at 500 m a.s.l.). This magma chamber is responsible at first of the extrusions of Cachimba dome and later the Chac-Inca and Co. Pabellón domes (Renzulli et al., 2006). This hypothesis is consistent with the results of some geothermal-barometric studies carried out in amphiboles of the domes of the area, which support the existence of magmatic chambers 3-7 km and 10-14 km deep (Piscaglia, 2012).

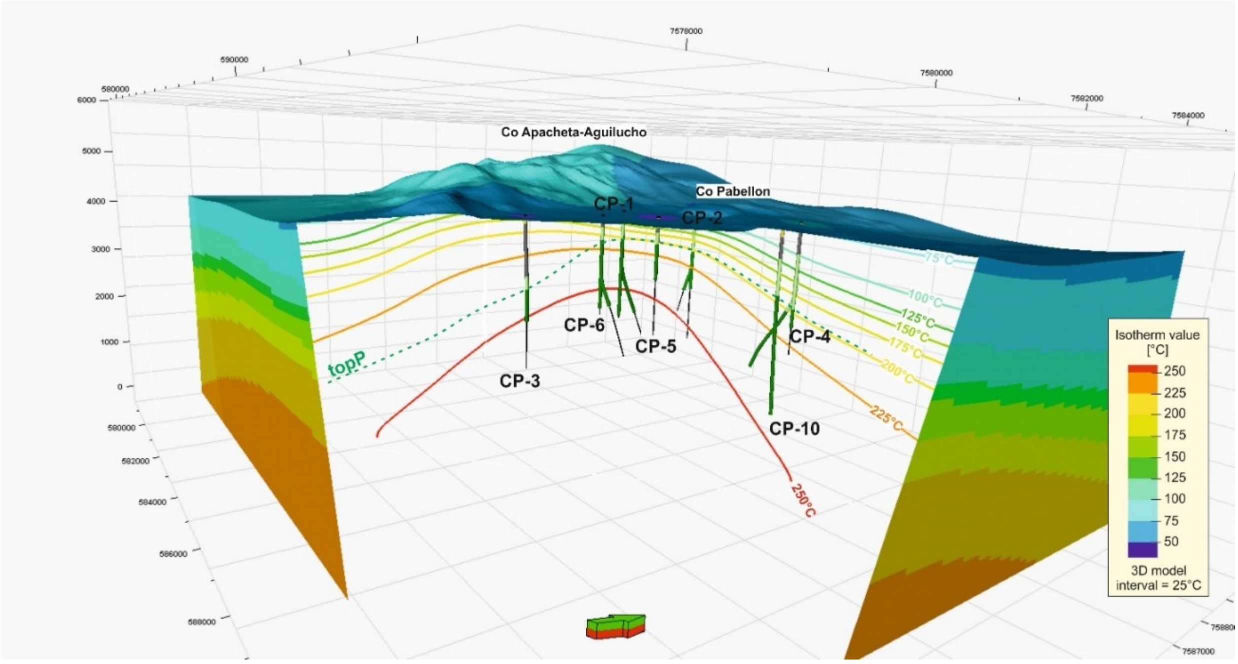

Figure 8: 3D view of the thermal model with a focus on some isotherms in the well area. The green dotted line (TopP) connects the top of propylitic alteration facies into the wells. In the background the Apacheta-Aguilucho Volcanic Complex.

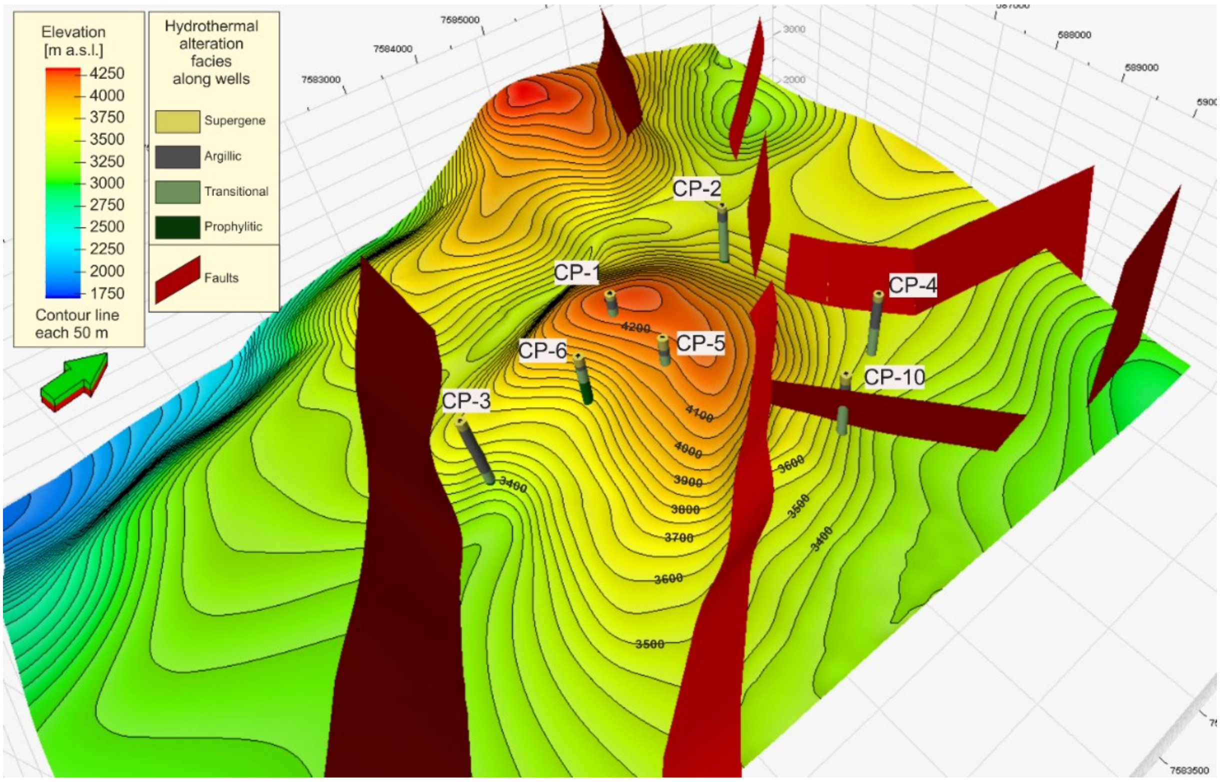

Figure 9: 3D reconstruction of the reservoir top on the base of both thermal and geophysical data.

- **Temperature distribution**: a view from Petrel® software (Figure 8) of the 3D thermal model, reconstructed from the static temperature profiles measured in well, shows both the 3D modeled area and the relative isotherms. The isotherms with higher values (225 and 250°C) indicate the high enthalpy reservoir environment suitable for the geo-thermoelectric generation. The isotherms generally show a dome shape rising in the NW edge of Apacheta Graben, in correspondence of the core field, i.e. on pads CP-1, CP-5 and CP-6 the wells having the greater production potential and total enthalpy values (MW_t). The isotherms gradually decrease towards pads CP-2 and CP-3, while they suddenly fall towards CP-4 and CP-10 pads. The graben play an important role in the geothermal field development and the most active sector (at least today) in terms of temperatures and fluid convection is located in correspondence of the "thermal dome apex" (hot core of the currently known field).

- **Hydrothermal alteration distribution**: In a similar way to the measured temperatures - also the alteration "rises" in certain sectors of the field, especially looking at the roof of the propylitic alteration (see topP line in Figure 8), a facies typically associated with the high temperature and therefore possible reservoir conditions.
- **Fracture distribution**: Fracture distribution with depth appears to be linked more to the alteration minerals than to the litostratigraphic unit. As expected by the geo-mechanical behavior of rocks in propylitic facies, almost all the reservoir-producing fractures are in fact located into this alteration assemblage. Exceptions are CP-2 and CP-4A wells that show fractures also inside the transitional facies but at temperature < 180°C.
- **Top Reservoir reconstruction**: The 3D reconstruction of the reservoir top is presented in Figure 9 and clearly evidence the high of the field core in correspondence of the more productive wells (CP-1, CP-5, CP-6 pads) and the deepening of the reservoir towards the northern and southern borders of the graben but above all outside the Apacheta graben. In order to predict the reservoir top also outside the current area of deep investigation, a picking of the MT-RDS signal (Figure 7) was performed for the surroundings of the field, in particular towards the Apacheta-Aguilucho Volcanic Complex. This creates the second dome shaped on NW, leaving an open possibility of reservoir condition in this direction.

According to this 3D model, elements such as the cover thickness, the reservoir top surface, the permeability graben lateral boundaries, and the temperature data were selected as input for the elaboration of a numerical simulation of the field (Cecioni and Cei, 2020).

7. CONCLUSIONS

The huge amount of data acquired during the developing of the project allowed us to reconstruct the subsurface features of the geothermal system. The latter developed in a typical volcanic arc domain. The reservoir is not influenced by a specific lithology, but instead by the graben structure. All these characteristics lead the system to be classified as a playtype CV-1b (Intrusive) following the definition of Moeck and Beardsmore (Moeck and Beardsmore, 2014).

From the 3D reconstruction, there is a good relationship among the alteration facies, thermal data and permeability distribution in the overall reconstruction of the cover and reservoir shapes and volumes. The circulation is mainly hosted in the graben while, outside it towards east, sharply deepens. Toward west, the model is less constrained, due to the lack of wells close to Co. Apacheta-Aguilucho. A possible expansion of the system in this sector is still to be ascertain.

Finally, the 3D Petrel® model was propaedeutic for a selection of elements - such as cover thickness, reservoir top surface, permeability graben lateral boundaries, and temperature data - utilized as input for the elaboration of a numerical simulation of the field (Cecioni and Cei, 2020).

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