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Volcanic and Tectonic Evolution of Azufre – Inacaliri Volcanic Chain and Cerro Pabellón Geothermal Field (Northern Chile)

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ABSTRACT

Cerro Del Azufre – Cerro de Inacaliri Volcanic Chain (AIVC) is located at Central Volcanic Zone of The Andes range and at the NW edge of *Altiplano-Puna Volcanic Complex*, close to the Chile - Bolivia border. In this volcanic chain, *Cerro Pabellón Geothermal Field* (formerly known as *Apacheta*) lies and the homonymous geothermal power plant (the first one in Chile and South America) has been built.

Within this NW-SE chain, the *Graben Pabelloncito or Apacheta* stands out, which is a first order structure in this segment of the Andes. On the other hand, the rocks of the AIVC area account for a complex geological history, with multiple stages of volcanic and tectonic activity.

The stratigraphy observed, in the exploration and exploitation boreholes, added to the surface geological mapping, has allowed us to develop a better conceptual geological model.

Six major geological stages have been identified, associated to major changes of both, volcanic and tectonic activity:

1. Stage 1 (Oligocene - Middle Miocene): Deposition of fine detrital sediments of volcanic origin in a continental basin.

2. Stage 2 (Middle Miocene – Late Miocene): Eruption of andesitic-dacitic lavas and emplacement of several ignimbrites.

3. Stage 3 (Late Miocene – Late Pliocene): Deformation of the older units in the form of a NW-SE anticline, originated on a deep fault. Development of a first NW-SE chain of volcanos beside the anticline. Contemporaneously, deposition of volcanoclastic sediments and ignimbrites in a depocenter just to the NE of the anticline.

4. Stage 4 (Late Pliocene - Early Pleistocene): Starts the volcanic activity of the current AIVC, with approximate orientation NW-SE. At the same time, the anticline would have collapsed at the hinge zone, giving rise to the development of the current NW-SE structure of Pabelloncito or Apacheta graben, and its syn-tectonic filling.

5. Stage 5 (Early Pleistocene – Middle Pleistocene): In the AIVC, destruction of ancestral Apacheta Volcano summit, at the same time as the deposition of an ignimbritic unit, which culminates with the Aguilucho Ignimbrite. Extrusion of Chanca Dome, Cerro del Azufre Domes and Cachimba Domes.

6. Stage 6 (Middle Pleistocene to Holocene): The localized extension and subsidence of the graben goes on. Extrusion of Cerro Aguilucho volcano and the youngest lavas from Cerro Del Azufre. Extrusion of the unnamed domes of summit and SW flank of Apacheta Volcano, the youngest domes of Chanca domes complex, Chac-Inca domes and Cerro Pabellón dome, as the last volcanic buildings of this area. Deposition of debris avalanches, moraines and rock glaciers.

The geometry of the border faults of the graben and the volcanic history of the AIVC, are evidence to support the existence of a shallow magmatic chamber located under Apacheta – Aguilucho complex.

Both, volcanic and tectonic evolution of the area, have created especially favorable geological conditions (as the existence of a magmatic heat source, a permeability of fractured rocks and an important clay cap), to make possible the very existence of the *Cerro Pabellón Geothermal System*.

1. INTRODUCTION

Cerro del Azufre – Cerro de Inacaliri Volcanic Chain (AIVC) is located in Los Andes range of northern Chile about 100 km northeast of Calama, near the northeastern tip of the Antofagasta Region and close to the Chile - Bolivia border, approximately between 21º 45' and 22º South latitude and between 68º and 68º 20' West longitude. In this volcanic chain, Cerro Pabellón geothermal field (formerly known as Apacheta) lies and the homonymous geothermal power plant (the first one in Chile and South America) has been built by Geotérmica del Norte (GDN), a joint venture between Enel Green Power (EGP) and Empresa Nacional del Petróleo (ENAP, Chile).

The AIVC extends for about 40 km, from Cerro del Azufre volcano (by the NW) to Cerro de Inacaliri volcano (by the SE), as a part of the volcanic arc of the Upper Cenozoic of the Central Volcanic Zone (CVZ) of Los Andes range (Fig. 1). Within this NW-SE chain, the Graben Pabelloncito or Apacheta stands out, as a first order structure in this segment of the Andes.

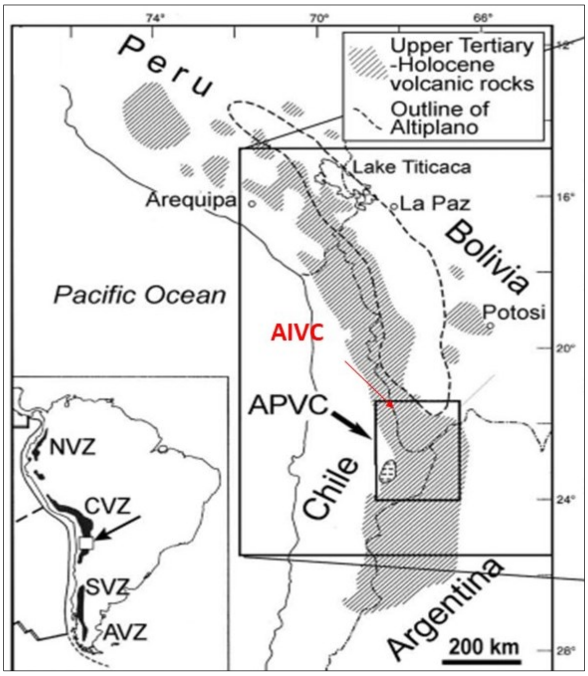

Figure 1: Approximate location of AIVC, Altiplano-Puna Volcanic Complex (APVC por su nombre en inglés) and Central Volcanic Zone (CVZ) of Los Andes range. (Modified from de Silva, 1989).

From a structural point of view, the region between 19° S and 23°S is characterized by a network of NW-SE and N-S trend lineaments (Tibaldi et al., 2008). The NW-SE trend lineaments, have been interpreted as sinistral strike-slip faults (Marrett et al., 1994, Riller et al., 2001; Matteini et al., 2002; Riller and Oncken, 2003) and as extensional structures (Tibaldi et al., 2008). De Silva et al. (1994) suggest that NW-SE fractures have played a possible tectonic control over the distribution of volcanic centers in the region, which are in the study area oblique to the general pattern of volcanism in the Central Andes of northern Chile.

On the other hand, AIVC overlaps the northwestern edge of the silicic magmatism province called Altiplano-Puna Volcanic Complex (APVC). APVC has been associated with the partial fusion of the crust, which in this sector has the greatest thickness of the Andes, of the order of 70 km (e.g. de Silva, 1989, de Silva et al., 1994, Matteini et al., 2002, de Silva and Gosnold, 2007; Salisbury et al., 2010).

Because of its tectonic and volcanological framework, the study of this area is therefore significant for the understanding of the structure of the Central Andes, the relationship between tectonics and volcanism (Tibaldi et al., 2008) and the relationship of this segment of the Andes with geothermal systems such as that of Cerro Pabellón.

2. GEOLOGY OF AIVC

2.1 Methodology

A surface geological study was done (Rivera et al., 2007; Rivera, in progress), including bibliographic research, analysis and interpretation of aerial photographs and ASTER satellite images, three campaigns of geological mapping, microscopic petrography, four K-Ar and two $^{40}Ar/^{39}Ar$ dates were done, by the geochronology laboratory of Sernageomin, as well as three U-Pb ages done by the geochronology laboratory of the Geology Department of University of Chile.

During the project exploration phase, GDN drilled a 560 m gradient well (PexAp-1) and four commercial diameter geothermal wells (Fig. 2): CP-1 (1821.1 m), CP-2 (2002.7 m), CP-3 (1130 m) and CP-4 (1775 m), so the stratigraphy and petrography performed in these wells were counted (Rivera et al., 2008; Ramírez et al., 2011).

Moreover, the stratigraphy and petrography of the 9 additional wells that GDN drilled as part of the construction phase of the Cerro Pabellón Geothermal Power Plant was used in this study (Ramírez et al., 2011; GDN, 2018; ENEL, 2019; Cappetti et al., 2020). In order of drilling, these are: CP-5 (452 m), CP-5A (1936 m), CP-10 (2997 m), CP-4A (2700 m), CP-1A (2260 m), CP- 6 (2091 m), CP-6A (2300 m), CP-2A (2500 m) and CP-2B (2000 m).

The available information has allowed the construction of two geological sections, a conceptual 3D geological model (mainly using the Rockworks 17 software platform; GDN, 2018; ENEL, 2019) and the interpretation of the geological evolution of the area.

2.2 Surface Geology

The AIVC corresponds to a main chain of volcanic centers, aligned in approximately NW-SE direction, along with a secondary chain of volcanic centers, parallel to the main one, which extends to the SW from the first one (Rivera et al., 2015; Fig. 2).

The main chain (*Moderately Eroded Volcanic Buildings Unit*), shows a bi-modal magmatism (e.g. Rivera et. al., 2007; Ahumada and Mercado, 2011; Sellés and Gardeweg, 2017) and is Pleistocene-Holocene (Fig. 2 and references in Table 1), as indicated by the radiometric ages of the Chanca Domes, Azufre Volcano, Chac-Inka Domes, Aguilucho Volcano, the nameless lava-dome at W flank of Cerro Apacheta, Pabellón Dome, Cachimba Domes, Cordón de Inacaliri Volcanic Complex and Cerro de Inacaliri Volcano.

The secondary chain (*Highly Dissected Volcanic Buildings Unit*), also shows a bi-modal magmatism (e.g. Rivera et al., 2007; Ahumada and Mercado, 2011, Sellés and Gardeweg, 2017) and is Upper Miocene – Pliocene (Fig. 2 and references in Table 1) as indicated by the radiometric ages for Cerro Colorado, Cerro Lailai and Colana Dome, confirming what Ramirez and Huete (1980) had estimated.

The rocks of the AIVC lie on a substrate of lavas and ignimbrites of intermediate to acidic composition (*Ancient Volcanics Unit*) of the Upper Miocene, as indicated by the age of 7.5 ± 0.6 Ma (K-Ar in biotite) in the La Perdiz Dome, that of 6.7 ± 0.3 Ma (K-Ar in total rock) in the andesitic-basaltic lavas at N of Pampa Apacheta (Fig. 2 and Table 1; Rivera, in progress). These ages agree with that estimated in the Ollagüe Geological Map (Ramírez and Huete, 1980).

Modern Ignimbrites Unit includes mainly the Aguilucho Ignimbrite (1.024 ± 0.033 Ma; $^{40}Ar/^{39}Ar$ in biotite; Sellés and Gardeweg, 2017), Inacaliri Ignimbrite and possibly other ignimbrites. This unit correlates with the destruction of the Ancestral Apacheta volcano summit, prior to the extrusion of the lava-dome of the summit and the lava dome of the W flank of Cerro Apacheta (0.7 ± 0.2 Ma; Rivera, in progress). It is cut by the NE main fault of the graben, as next to the main road, probably indicating an original deposition on a temporarily full graben and a subsequent reactivation of the fault (prior to the extrusion of the Cerro Pabellón Dome).

Unconsolidated Deposits Unit lies on to the *Modern Ignimbrites Unit,* mainly in the depressed relief of the Pampa Apacheta, but also on the more ancient geological units, in all depressed portions of the study area and mainly consists of alluvial sediments, tephras and debris avalanches deposits (e.g. Godoy et al., 2017).

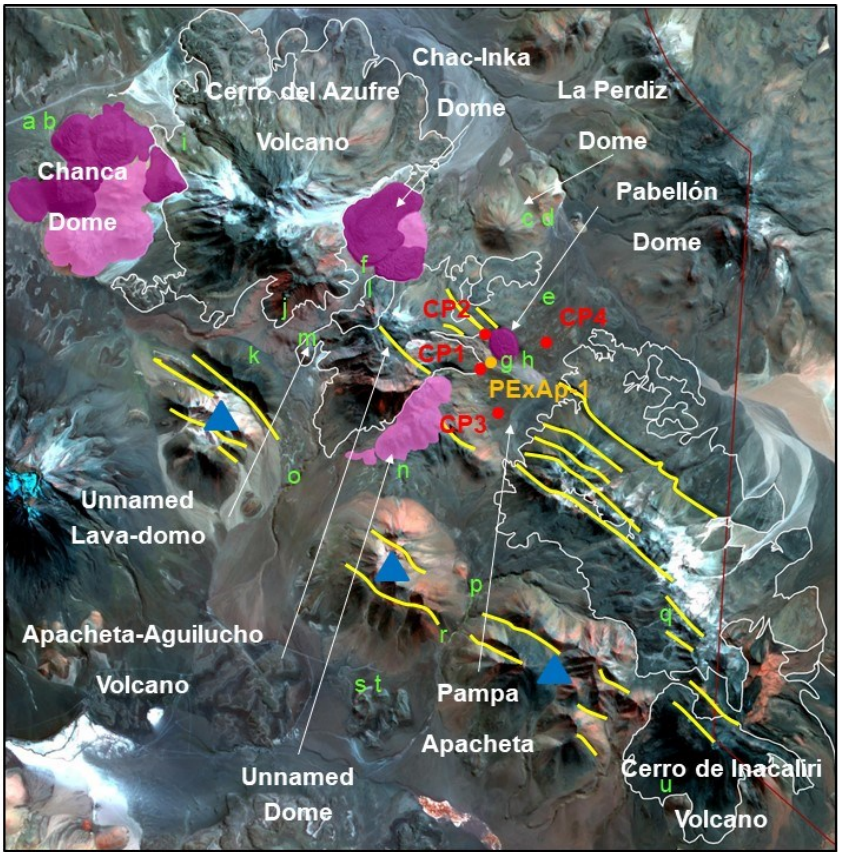

Figure 2: Map of the AIVC Area: the Main Chain (Pleistocene-Holocene, White Line Polygons), the Secondary Chain (Upper Miocene - Pliocene, Blue Triangles), the Main faults (Yellow Lines), GDN Gradient Well (Orange Circle), Exploration Wells (Red Circles) and Radiometric Ages (Green etters; see details in Table 1).

Table 1: Radiometric Ages of the AIVC Area (W.R.: whole rock).

ID	Unit	Method	Mineral	Age (Ma ± 2σ)	Reference
a	Chanca Domes	K-Ar	Biotite	1.5 ± 0.1Ma	Roobol et al., 1974; Francis and Rundle, 1976
b	Chanca Domes	Ar-Ar	Biotite	119.8 ± 5.4 ka	Tierney, 2011
c	La Perdiz Dome	K-Ar	Biotite	7,5 ± 0,6	Rivera et al., 2007
d	La Perdiz Dome	U-Pb	Zircons	6.57 ± 0.05 Ma	Rivera et al., en curso
e	Lavas at N of Pampa Apacheta	K-Ar	W.R.	6.7 ± 0.3	Rivera et al., 2007
f	Chac-Inka Dome	Ar-Ar	Biotite	114 ± 37 ka	Rivera, en curso
g	Pabellón Dome	Ar-Ar	Biotite	50 ± 10 ka	Urzúa et al., 2002
h	Pabellón Dome	Ar-Ar	Biotite	105 ± 25 ka	Renzulli et al., 2008
i	Azufre Volcano	Ar-Ar	Groundmass	0.605 ± 0.013 Ma	Sellés and Gardeweg, 2017
j	Azufre Volcano	K-Ar	Biotite	1.1 ± 0.2 Ma	Roobol et al., 1974; Francis and Rundle, 1976
k	Cerro Colorado Volcano	Ar-Ar	Groundmass	6.852 ± 0.076 Ma	Sellés and Gardeweg, 2019
l	Aguilucho Volcano	Ar-Ar	Groundmass	0.652 ± 0.012 Ma	Sellés and Gardeweg, 2020
m	W flank lava-dome of Apacheta Volcano	K-Ar	Biotite	0.7 ± 0.2	Rivera et al., 2007
n	Cachimba Domes	Ar-Ar	Biotite	0.91 ± 0.14	Rivera, en curso
o	Aguilucho Ignimbrites	Ar-Ar	Biotite	1.024 ± 0.033 Ma	
p	Cordón Inacaliri Volcanic Complex	Ar-Ar	Groundmass	1.109 ± 0.023 Ma	Sellés and Gardeweg, 2020
q	Cordón Inacaliri Volcanic Complex	Ar-Ar	Groundmass	1.094 ± 0.016 Ma	Sellés and Gardeweg, 2020
r	Cerro Lailai Volcano	K-Ar	W.R.	5.4 ± 0.5	Rivera et al., 2007
s	Colana Colana	U-Pb	Zircons	5.7 ± 0.3	Rivera, en curso
t	Colana Colana	U-Pb	Zircons	4.3 ± 0.1	Rivera, en curso
u	Cerro Inacaliri Volcano	Ar-Ar	Groundmass	1.612 ± 0.018 Ma	Sellés and Gardeweg, 2020

Within the AIVC, Francis and Rundle (1976) recognized a depression of graben they called *Graben Pabelloncito*. This is clearly exposed from the Cerro del Azufre volcano, at the Northwest, to the Cerro de Inacaliri volcano, at the Southeast, and is morphologically manifested as a locally depressed area about 100 meters vertically, approximately 20 km from long and 3 km wide, between two main faults, N53°W to N60°W direction (Fig. 2). Between the main faults, there is also a set of secondary faults, of apparent direction EW to WNW-ESE due to the topography, but which actually have the same direction of the main ones, N53°W to N60°W, and they would form a domino-type structural geometry. This structure seems to end towards the SE tip in an *echelon*, while towards the NW it is not observed directly beyond the Cerro del Azufre volcano,

On the other hand, it has been observed that the Miocene lavas and ignimbrites identified in the area (e.g. Ramírez and Huete, 1980; Rivera, in progress) corresponding to the substrate on which the AIVC has been built, would be gently folded, with NW-SE approximate axis direction (Rivera et. al, 2015; GDN, 2018; ENEL, 2019; Rivera, in progress).

2.3 Sub-surface Geology

The main geological results of wells executed during the construction phase of the project are presented below (location in Figure 3). About hydrothermal alteration, in this paper we will only highlight that an important clay-cap has been detected, which in the corehole PExAp-1 reaches around 300 m thick (Rivera et al., 2008; GDN, 2018; Maza et al., 2018; ENEL, 2019; Morata et al., 2020).

Figure 3: Location of All Wells Drilled During the Exploration and Construction Phases of Cerro Pabellón Project.

In order not to repeat the description of the geological units found for each well, all units are described first and then the stratigraphy by wells is summarized in Table 2 (GDN, 2018; ENEL, 2019):

Unconsolidated Deposits (UD): Unconsolidated polymictic fine gravel and sands, composed by fragments of andesitic lava, dark gray lava and partially vitric, black and red scorias, white pumice-rich tuffs and free crystals of Qz, Pl, Hbl and Bt.

Recent Volcanics (RV): Consists of an upper sequence of vitreous-crystalline tuffs, lapilli tuffs, andesitic scorias, andesitic lavas and sandstone lenses and a lower sequence of lapilli tuff, tuffites and brown sandstones.

Breccias and Andesitic Lavas (BAL): Volcanic breccias and lava flows intercalated. The top is dominated by breccias with minor lavas, while going deeper the percentage of lava levels increases, becoming dominant. Lavas have porphyric textures with phenocrysts of Pl and Cpx in a micro-crystalline to vitric ground mass.

Lithic Tuffs (LT): Tuffites and lithic tuffs intercalated with small presence of lava flows. Pyroclastics generally have colors varying from white to red and crystals fragments are Qz, Pl and Hbl. The lavas are very dark and show phenocrysts of Pl and Cpx.

Dacitic Tuffs (DT): Succession of biotite tuffs with different degrees of lithification. Rock colors vary from pink to green with crystal fragments of Pl, Bt and Qz. Fiammes are present also. A sequence of dacitic lavas, with crystals of Pl, Bt and Qz is intercalated.

Andesitic-Dacitic Lavas (ADL): succession of andesitic-dacitic lavas, from grayish green to red.

Reddish Sandstone and Dacitic Tuffs (RSDT): It consists mainly of reddish sandstones and crystal tuffs, of dacitic composition, of red, orange and pink colors, locally biotites rich; minor levels of white, light gray and greenish vitric tuff, brown to light grey crystal-lithic tuffs and localized levels of brown andesitic lavas.

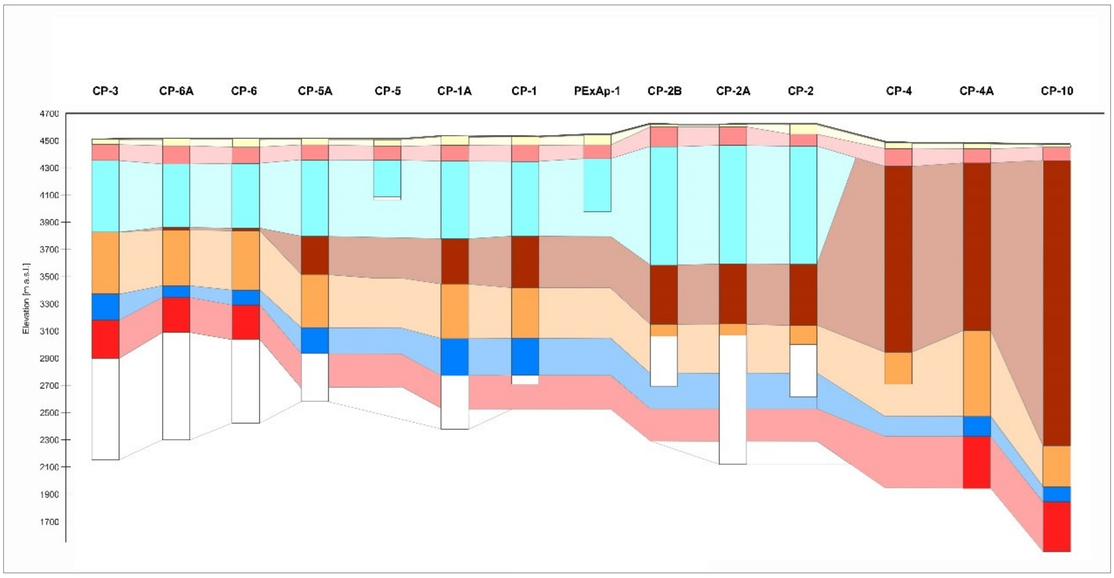

Figure 4: Stratigraphic Correlation between All Wells, Ordered from S (CP-3) to N (CP-10).

Table 2: Stratigraphic Summary of Geothermal Wells.

	PExAp-1	CP-1	CP-2	CP-3	CP-4	CP-5	CP-5A	CP-10	CP-4A	CP-1A	CP-6	CP-6A	CP-2A	CP-2B
UD	0-71	0-62	0-70	0-35	0-40	0-51	0-45	0-20	0-40	0-65	0-65	0-50	0-20	0-20
RV	71-180	62-190	70-160	35-156	40-170	51-160	45-160	20-120	40-150	65-185	65-190	50-190	20-160	20-165
BAL	180-561	190-738	160-1025	156-680		160-430	160-720			185-750	190-660	190-650	160-1025	165-1035
LT		738-1113	1025-1480		170-1540		720-1000	120-2215	150-1381	750-1085	660-675	650-670	1025-1465	1035-1468
DT		1113-1485	1480-1520	680-1135	1540-1775			2215-2520	1381-2014	1085-1485	675-1115	670-1082	1465-1555	1468-1558
ADL		1485-1755		1135-1325				252-2630	2014-2162	1485-1753	1115-1225	1082-1176		
RSDT				1325-1605				2630-2990	2162-2542		1225-1480	1176-1434		
No data		1755-1821	1520-2003	1605-2354		430-452	1000-1936	2990-2997		1753-2157	1480-2091	1434-2216	1555-2500	1558-1924

3. DISCUSSION

The *Unconsolidated Deposits Unit* (UD) corresponds to the homonymous unit identified in the surface exploration (Rivera et al., 2007; Rivera, in progress) and it would have a Middle Pleistocene – Holocene age, because is lying on Recent Volcanics Unit, of Lower Pleistocene age. Present in all the drilled wells, with a thickness between 20 and 65 m inside the graben and up to 40 m outside it, which is consistent with the depressed relief of Pampa Apacheta with respect to the land outside, but also with an active subsidence within the graben, as indicated by the presence of cortical earthquakes with normal fault mechanism in this area of Los Andes (Belmonte, 2002).

The *Recent Volcanics Unit* (RV) corresponds to the unit *Modern Ignimbrites* of the surface exploration (Rivera et al., 2007; Rivera, in progress) that includes the Ignimbrita Aguilucho as its roof. A Lower Pleistocene age has been estimated for this unit as correlating to the destruction of the Ancestral Apacheta volcano summit, prior to the extrusion of the lava domo of the summit and the lava dome of the flank W of Cerro Apacheta (0.7 ± 0.2 Ma, Rivera, in progress), which has been recently confirmed with an age of 1.024 ± 0.033 Ma for the Ignimbrita Aguilucho, in the homonymous stream ($^{40}Ar/^{39}Ar$ in biotite; Sellés and Gardeweg, 2017). It is present in all the wells, under the previous unit, and also exposed on surface at several points NE of the graben. It has a thickness of 109 to 125 m inside the graben and 100 to 130 m outside (practically the same) and is cutted by the NE edge of the graben, next to the main road, probably indicating an original deposition on a temporarily full graben and a subsequent reactivation of the fault (previously to the extrusion of the Cerro Pabellón Dome).

The *Breccias and Andesitic Lavas Unit* (BAL) is not observed on the surface, just in a number of wells. It would correlate in age with the unit *Moderately Eroded Volcanic Buildings* identified in the surface exploration (Rivera et al., 2007; Rivera, in progress; PPlve; Upper Pliocene - Lower Pleistocene) with a lateral transition. Present only in the wells set inside the Apacheta Graben with a thickness between 470 and 565 m. The bottom of BAL unit deepens from south to north in relation to the ground level, from 650-750 m depth up to about 1000 m depth in CP-2 pad's wells. As BAL is not present outside the graben, the wells of Quebrada La Perdiz (CP-4 and CP-10 pads) do not encountered this unit: this fact indicate that is a sin-tectonic deposit of the graben, corresponding to volcanic products from Apacheta-Aguilucho Volcanic Complex and Cordón de Inacaliri Volcanic Complex, as well as alluvial, lahar and avalanche deposits (Godoy et al., 2017; Phase 4 in Figure 5) possibly triggered by activity of the edge fault SW of the graben, shallow intrusions of magma in the fault zone or by the weakening of the volcanic buildings resulting from the strong hydrothermal alteration (e.g. Tibaldi et al., 2006; Vezzoli et al., 2008).

The *Lithic Tuffs Unit* (LT) would correlate in age with the unit *Highly Dissected Volcanic Buildings* (Upper Miocene – Upper Pliocene), identified in the surface exploration (Rivera et al., 2007; Rivera, in progress). Present in almost all the drilled wells, shows a very high variability in thickness, being absent towards south (CP-3 well), to only few meters in south-central part of the field (CP-6 pad, inside the graben), to about 300-450 m in the central-northern area (CP-5, CP-1, CP-2 pads). However, the peculiarity is represented by the actual sharp increase in thickness outside the Apacheta Graben where LT unit reaches ~1270 m in CP-4 pad and ~2100 m in CP-10 well. This fact and its dominant lithology led to interpret this deposit as syntectonic to the compressive phase, that deformation of the units shows, from the Late Miocene to the Pliocene (Phase 3 in Figure 5), in in accordance with what has been previously identified for this segment of the Andes (e.g. Charrier et al., 2009; Charrier et al., 2013). In an alternative model, the NE high thicknesses can be associated to the presence of the depression of Pastos Grandes Caldera, as described in the surroundings by Salisbury et al. (2010). Also, at the end of the exploratory phase, the existence of a crossed graben, previous to the Apacheta one (Graben Quebrada La Perdiz) was hypothesized (Ramírez et al., 2011), but a number of doubts remain on its reliability (GDN, 2018; ENEL, 2019).

The *Dacitic Tuffs Unit* (DT), due to its lithology, stratigraphic position and location, correlates with the unit *Ancient Volcanics - Subunit 2* (Upper Miocene) of surface exploration (Rivera et al., 2007; Rivera, in progress). Present in all the drilled wells, except CP-5 and CP-5A that came in total loss of circulation inside the LT unit. The thickness of this unit is difficult to estimate as the bottom is sometimes unknown due to TLC (total loss of circulation, which does not allow recovery of drilling samples): the wells inside the graben show an apparent thickness of 400-455 m while 235-635 m were found in the wells outside the graben. This difference is ascribable to the oblique intersection of some wells (and possibly to localized differences of real thickness) product of the compressive deformation of the Upper Miocene – Pliocene.

Andesitic and Dacitic Lavas Unit (ADL): Due to its stratigraphic position and location, this unit can be correlated with the unit *Volcanitas Antiguas – Sub-unit 1* (Middle Miocene, Rivera et al., 2007; Rivera, in progress). Present in all the wells that didn't go into TLC in LT and DT units. In the wells into the graben this unit has an apparent thickness of ~110-270 m and outside the graben ~110-150 m but this difference is estimated to answer to the non-horizontal arrangement into the graben, as already said for DT unit.

Reddish Sandstones and Dacitic Tuffs Unit (RSDT) does not correlate with any unit recognized in the surface exploration (Rivera et al., 2007; Rivera, in progress), but due to its lithology, stratigraphic position and location, it would correlate with the *Estratos del Cerro del Diablo* unit from the Lower Miocene (Sellés and Gardeweg, 2017), which outcrops on the homonymous hill north of San Pedro Volcano (outside the study area and 32 km to the ONO from Pampa Apacheta), or with *Sichal Formation* (Maksaev, 1978) or *Papajoy Formation* (Vergara, 1978) recognized at Sierra del Medio range (Oligocene to Middle Miocene; located 70 km to the west of the study area) or *San Pedro Formation* (Oligocene to Lower Miocene, Marinovic and Lahsen, 1984; Flint et al., 1993; Kape, 1996), which has been recognized in the area of El Tatio (45 km to the S; Marinovic and Lahsen, 1984) and further south, in the area north of the Salar of Atacama. Present in five wells, three into the graben and two outside. In the other wells, the presence is unknown due to TLC. The visible thicknesses is a maximum of 280 m (CP-3) inside the graben and 380 m (CP-4A) outside it.

Table 3: Equivalence between Surface Geology and Wells Geology.

Name	Shortcut	Age	Surface exploration	Apparent thickness [m]	Modeled thickness [m]
Unconsolidated Deposits	UD	Middle Pleistocene - Holocene	**TQsv** – *Unconsolidated deposits*	20-65 inside the graben; 0-40 outside the graben	0-65
Recent Volcanics	RV	Lower Pleistocene	**PPIvi** - *Modern Ignimbrites*	109-125 inside the graben; 100-130 outside the graben	130
Breccia and Andesitic Lavas	BAL	Upper Pliocene - Lower Pleistocene	**Age equivalent** and lateral transition to **PPIve** - *Moderately Eroded Volcanic Buildings –* Subunidad 1	470-565 just inside the graben	565
Lithic Tuffs	LT	Upper Miocene – Upper Pliocene	**Age equivalent** and lateral transition to **MsPve** - *Highly Dissected Volcanic Buildings*	0-450 inside the graben; 1230-2100 outside the graben	1244
Dacitic Tuffs	DT	Upper Miocene	**Msv2** - *Ancient Volcanics – Sub-unit 2*	400-455 inside the graben; 235-630 outside the graben	270
Andesitic-Dacitic Lavas	ADL	Middle Miocene	**Msv1** - *Ancient Volcanics – Sub-unit 1*	110-270	177
Reddish Sandstones and Dacitic Tuffs	RSDT	Oligocene – Middle Miocene	**Age and lithologic equivalent** to *Sichal Fm., Papajoy Fm. & San Pedro Fm. or Estratos del Cerro del Diablo*	280 m apparent inside the graben; 380 m apparent outside the graben	260 (minimum)

Based on the stratigraphy of the geothermal wells, it has been possible to build a plausible stratigraphic-structural model, which highlights a tertiary basement folded as an anticline, which underlies the Apacheta Graben extensional structure and also an updated conceptual model of the geothermal system (Baccarin et al., 2020; GDN, 2018; Enel, 2019). This model is represented below by the geological section of Fig. 5.

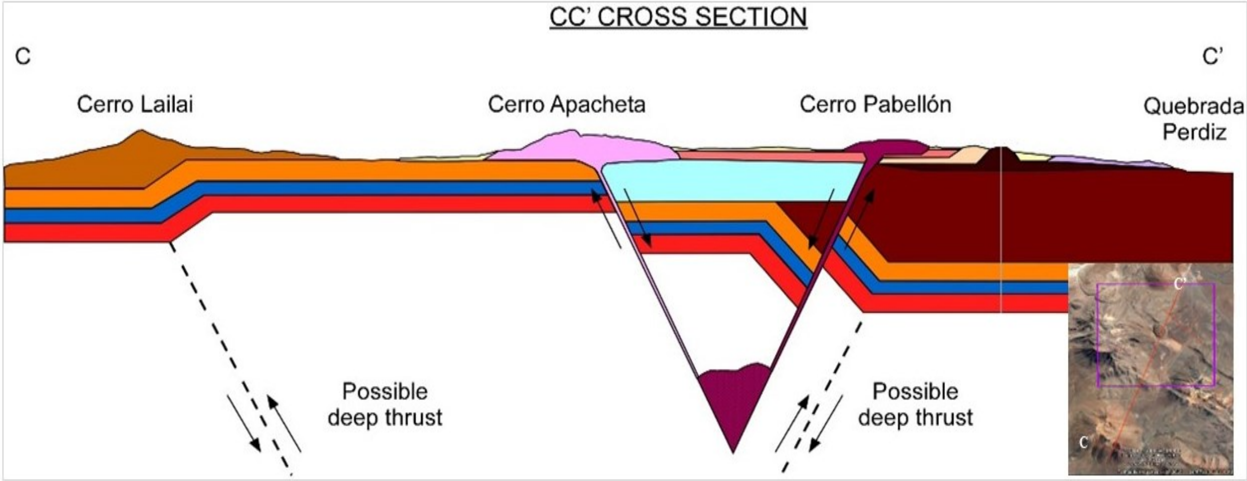

Figure 5: CC' Geological Cross-section, from Southwest Orientation (Cerro Lailai) to Northeast (Quebrada Perdiz), Passing Through the Cachimba Domes on the Southern Flank of Cerro Apacheta, Pampa Apacheta and Domo Pabellón.

As a consequence of the structural geology of the area, it is possible to expect conditions of good permeability, associated mainly with the normal faults that limit the graben, inner secondary faults of the graben and the northeastern damage zone of the anticline, facilitating the fluids flow in the reservoir of the geothermal system, as it is largely delineated with the location of the main fractures identified in the wells (Fig. 6).

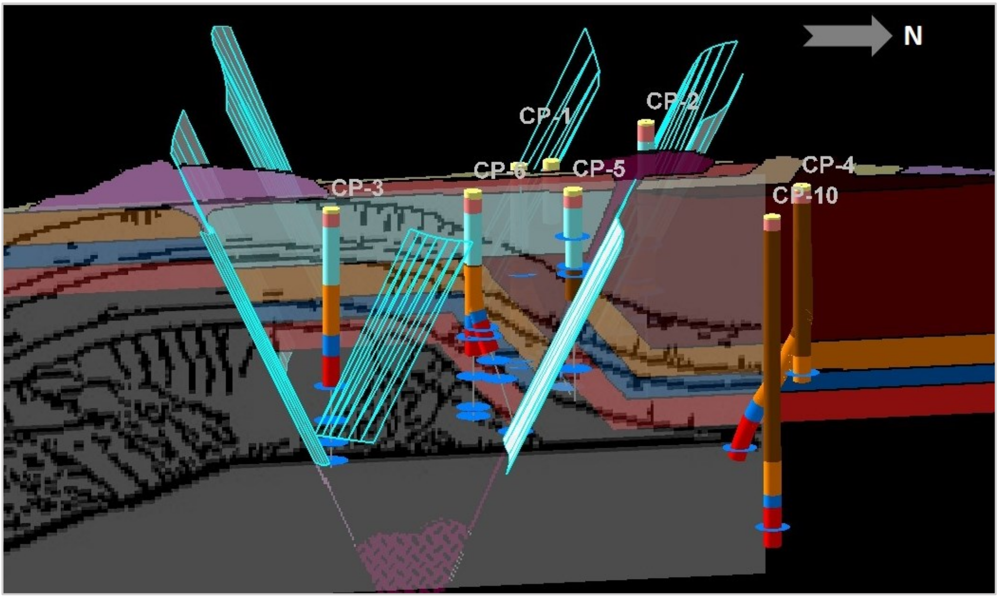

Figure 6: Spatial Correlation between Main Normal Faults of the Graben, Secondary Faults at the Interior of this one and the NE Damage Zone of the Anticline, with the Fractures Identified in the Wells (Light Blue Discs).

About hydrothermal alteration, the very thick clay-cap detected, which in the corehole PExAp-1 reaches around 300 m thick, is acting as a very impermeable cover of the geothermal system, giving rise to an almost blind geothermal system (Urzúa et al., 2002; Rivera et al., 2008; Ramírez et al., 2011; GDN, 2018; Maza et al., 2018; ENEL, 2019; Morata et al., 2020), with just two fumaroles and no diffuse gas at surface in almost all the geothermal field (Tausssi et al., 2019).

Likewise, the geometry of the graben edge faults and the accommodation of blocks in the distensive stage, could have generated *a space* at about 4000 m deep (with respect to the Pampa Apacheta level) under Pampa Apacheta, facilitating the eventual emplacement of a shallow magma chamber, which would have fed the extrusion of the unnamed domes of Cerro Apacheta and later the Chac-Inca and Cerro Pabellón domes (see Fig. 2). This hypothesis is consistent with the results of some geo-thermo-barometric studies conducted in amphiboles of the area's domes, which support the existence of magmatic chambers at 3-7 km and 10-14 km deep (e.g. Piscaglia, 2012), which in turn they would be related to the Altiplano Puna Magmatic Body (APMB; according to Chmielowsky & Zandt, 1999; Zandt et al., 2003). This magmatic chamber could be the main source of heat of the geothermal system (Fig. 7).

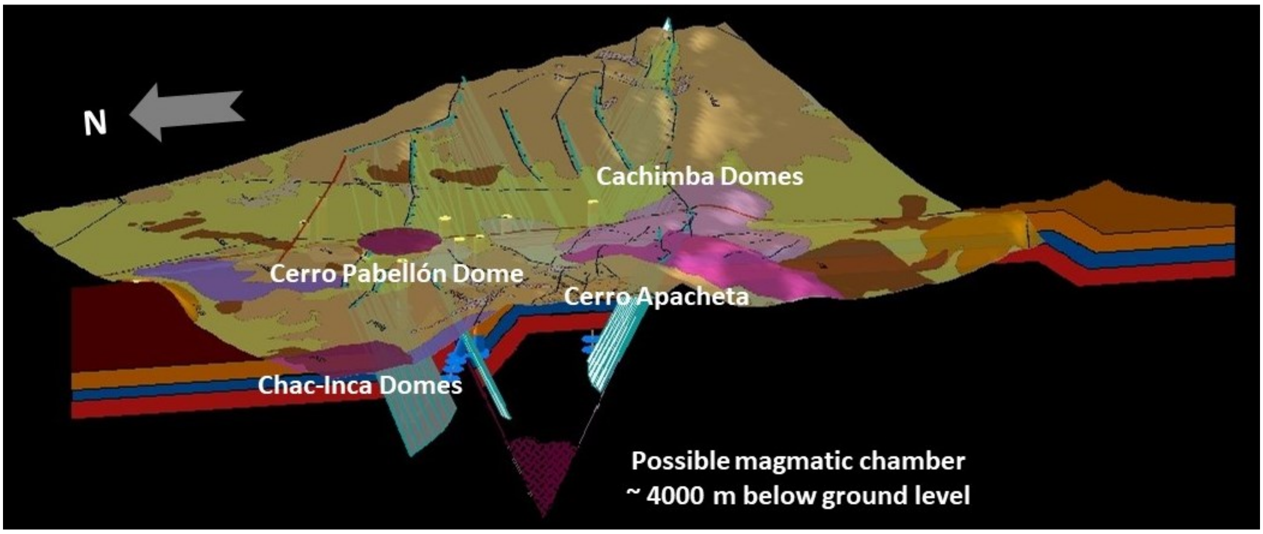

Figure 7: A Possible Magmatic Chamber could be Located about 4000 m below Ground Level in Pampa Apacheta and would be the Main Heat Source of the Geothermal System (Green Circle).

4. CONCLUSSIONS

A tentative reconstruction of volcanic and tectonic evolution of the area is summarized in the following (Figure 8), taking into account the previous discussion, data published by various authors (Rivera et al., 2015; Renzulli et al., 2006; Urzua et al., 2002; Sellés y Gardeweg, 2017) and the new data obtained from exploration and construction phase of Cerro Pabellón Project:

Stage 1 (Oligocene – Middle Miocene): In a lacustrine environment, deposition of fine detrital volcanic sediments from the *San Pedro Formation* or any equivalent formation.

Stage 2 (Middle Miocene - Late Miocene): Deposition of Middle Miocene andesitic-dacitic lavas and Upper Miocene ignimbrites, corresponding to the *Ancient Volcanics Unit* of the Rivera et al. (2007) geological map.

Stage 3 (Late Miocene – Late Pliocene): During a compressive tectonic phase of Late Miocene - Pliocene, a deformation of the older Tertiary units in an anticline form, over a pop-up structure, happened due to deep thrust structures with NE vergence. Contemporaneously, the deposition of *Lithic Tuffs Unit* and the extrusion of *Highly Dissected Volcanic Buildings Unit* (Upper Miocene – Upper Pliocene, Co. Colorado, Co. Lailai and Co. de Colana) with their emission centers already aligned NW-SE.

Stage 4 (Late Pliocene – Early Pleistocene): Starts the deposition of the *Moderately Eroded Volcanic Buildings Unit – Sub-unit* 1 (mainly Cerro Apacheta, Cordón de Inacaliri and Ancestral Cerro de Inacaliri) with approximate orientation NW-SE. At the same time, the NW-SE distension structure of Pabelloncito or Apacheta Graben, is formed and its syn-tectonic filling is deposited (BAL – *Breccias and Andesitic Lavas*), formed by volcanics from Apacheta – Aguilucho and Cordón de Inacaliri volcanic complexes, alluvial deposits, lahars and avalanches, as well as minor lagoon and possibly fluvial intercalations.

Stage 5 (Early Pleistocene – Middle Pleistocene): Destruction of the Ancestral Apacheta Volcano summit contemporaneously to the deposition of the *Recent Volcanics* (RV) or *Modern Ignimbrites Unit*, which culminates with the *Ignimbrita Aguilucho* deposition in Pampa Aguilucho (SW), in Pampa Apacheta (SE, flat area inside the graben) and on the NE edge, towards Quebrada Perdiz, and deposition of *Inacaliri Ignimbrite*. Extrusion of Ancestral *Chanca Domes, Domes of Cerro del Azufre and Cachimba Domes*.

Stage 6 (Middle Pleistocene – Holocene): The localized extension and subsidence of the graben go on, cutting the NE border fault to the *Aguilucho Ignimbrite* and forming a small apical graben on the summit of Cerro Apacheta. In the same period are ascribable the extrusion of *the domes at summit and flank SW of the Cerro Apacheta Volcano, Chac-Inka dome and Cerro Pabellón dome*. Extrusion of *Cerro Aguilucho Volcano* and new volcanics from Azufre Volcano and Inacaliri Volcano. Deposition of the *Unconsolidated Deposits Unit* (mainly alluvial and lagoons) in Pampa Apacheta, including at least two debris avalanches on the NE flank of Cerro Apacheta - Aguilucho, and more modern to recent moraines and rock glaciers.

As a consequence of the volcanic and tectonic evolution of the area, it has also been combined the existence of: 1) a fractures system that can constitute both the permeability of the geothermal reservoir and a means of recharging meteoric water into it, 2) a possible magmatic chamber as a heat source of the geothermal system and 3) a powerful clay layer, acting as an impermeable caprock or the cover of the geothermal system (although its age is unknown and it may be even older than this stage), all the key elements for the very existence of Cerro Pabellón or Apacheta Geothermal System.

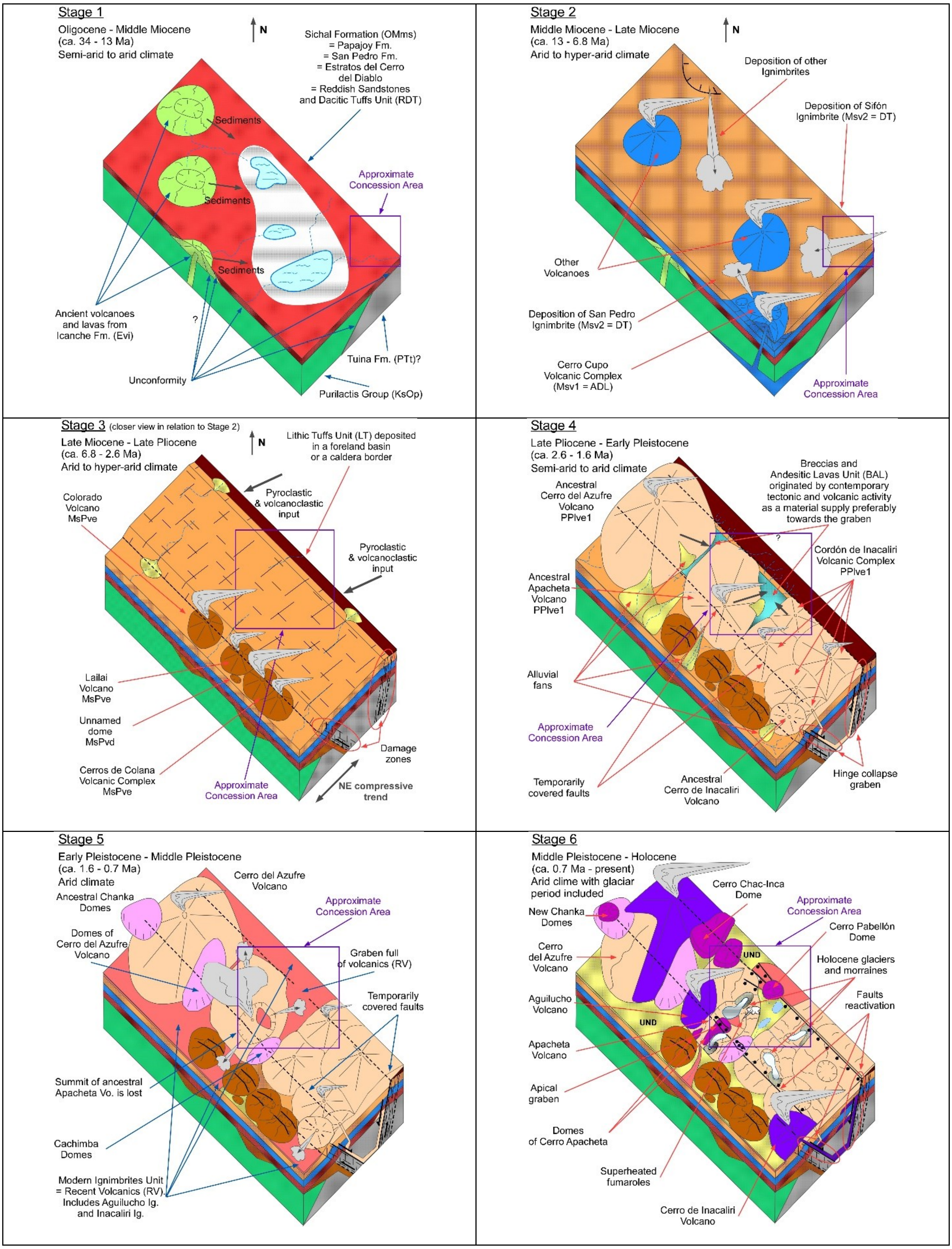

Figure 8: Stages of Volcanic and Tectonic Evolution of Azufre – Inacaliri Volcanic Chain and Cerro Pabellón Geothermal Field.

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