Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geothermal Exploration Survey of Domuyo Geothermal Field

Carlos Luis Esteban

ADI-NQN, Geothermal Division, Antártida Argentina 1245, Building 4, floor 3 (8300) Neuquén, Argentina

cesteban@adinqn.gov.ar

Keywords: Domuyo, geology, fluid geochemistry, MT survey, water dominated reservoir, conceptual model, drilling target, resource assessment

ABSTRACT

Domuyo Geothermal Field is located in the western slope of Domuyo volcanic complex in the Northwest of Neuquén Province, Patagonia, Argentina. This study is a summary of nine-month exploration works carried out by the government of Neuquén Province supported by the National Energy Secretariat through the Energy Sector Study Program (PESE by its initials in Spanish). The goals of the study were to outline the geothermal potential of the field and define drilling targets for a further stage. A geological, geochemical and geophysical survey was carried out over an area of 220 km^2, in the southwestern part of the Domuyo volcanic complex where many surface thermal manifestations are present.

The geological survey includes a characterization of surface geology, mapping and sampling of geological units and regional and local structural geology with focus on the study area. Samplings of thermal manifestation from major thermal areas were carried out. Then chemical analysis of water and vapor, geothermometry and water classification were made. All the previously mentioned works were focused on defining temperature of the reservoir and pattern of fluid circulation. The geophysics includes magnetotelluric (MT), TEM and gravity surveys. It is important to mention that it is the first time that MT and TEM methods have been employed in this geothermal field; while a widespread grid of gravity survey was made by JICA, 1984. The geophysical survey comprises the measurement of 91 MT stations, 40 TEM stations for correction of the static shift in magnetotelluric, and 130 gravity stations. This survey allowed definition of zones of geophysical anomalies and their possible correlation with the geology and thermal anomalies detected in the previous thermal gradient holes made by JICA, 1984. Finally, a geoscientific integration with all the geological, geochemical and geophysical information was made. Geothermal resource estimations with gradual decompression method and volumetric method were made and 3 drilling targets were defined.

1. INTRODUCTION

Domuyo Geothermal Project is located in the NW of Neuquén province (Argentina); situated in Minas Department, only 30 km North from the town of Varvarco (Figure 1). The area has been studied in multiple geological, geochemical and geophysical surveys such as Groeber (1947), Jurio (1978), Palacios y Llambias (1978), Pesce (1983), Llambias et.al. (1987), Japan International Cooperation Agency (JICA) and Ente Provincial de Energía de Neuquén (JICA-EPEN 1984), Panarello et al., (1990), Miranda (1996), Pesce (2013) y Chiodini et al., (2014).

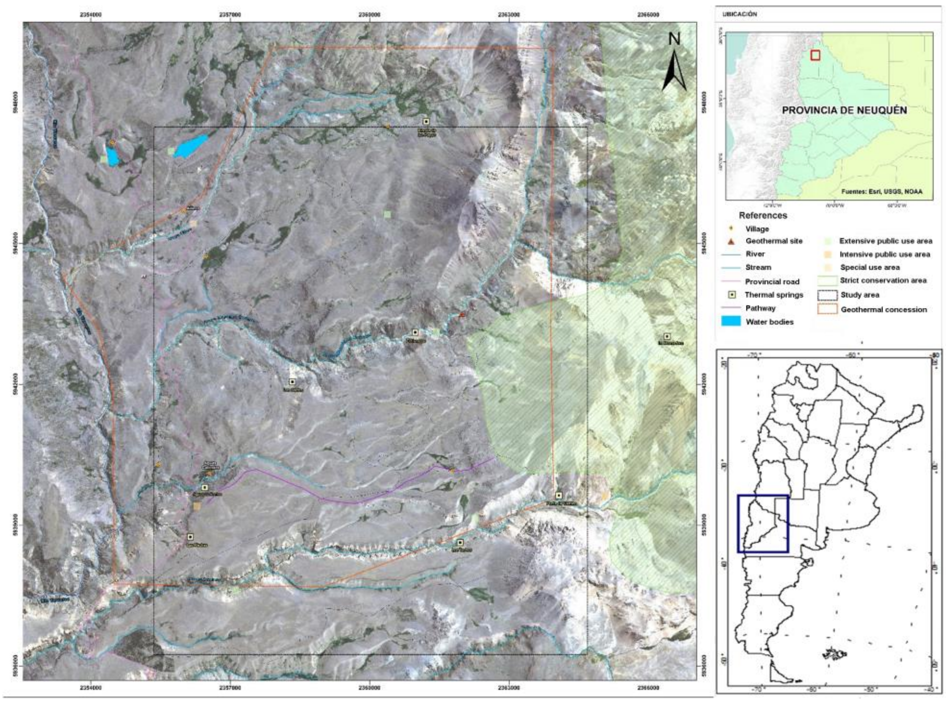


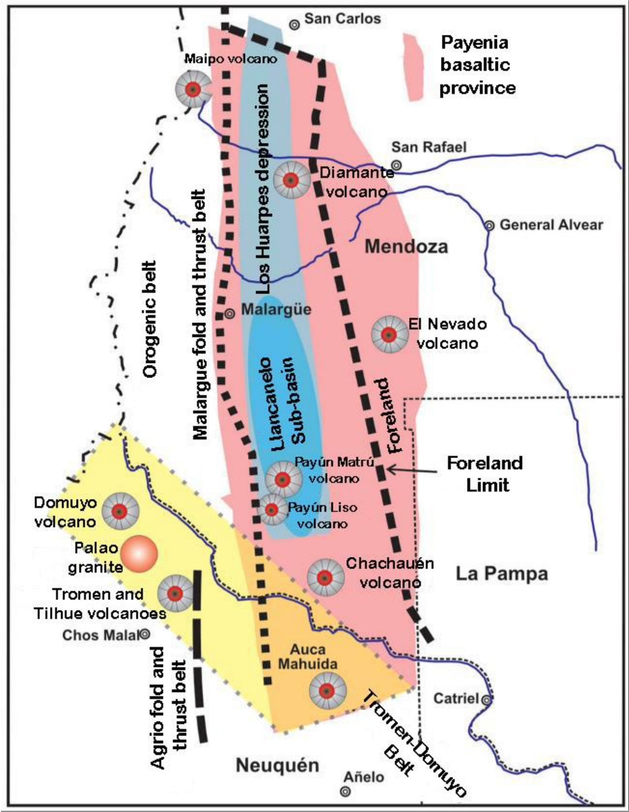
Figure 1: Location of Domuyo geothermal area

In 2015 the Mexican/Argentinean consortium ENAL-PROINSA was awarded the bid for the study called "Conceptual Model of the Domuyo Geothermal Field". The study was funded by the Development Bank of Latin America (CAF) through the Argentinean Energy Sector Study Program (PESE by its initials in Spanish). Between October and December 2016 the field survey was carried out while the final report, on which the present work is based, was delivered in June 2017.

The works began by integrating previous information and then proceeded with photointerpretation of satellite images and planning field campaigns. Initially, geological studies consisted of observation and description of geological units, stratigraphy, structural control and sampling for petrographic analysis and dating. Subsequently, water and gas sampling of 7 points were carried out, collecting a total of 8 water samples and 3 gas samples. Finally, the geophysical survey consisted of 91 magnetotelluric soundings, 40 transient electromagnetic soundings for "static shift" correction and 130 gravimetric stations.

2. GEOLOGY

Domuyo Volcano belongs to the Southern Volcanic Zone (SVZ: 33°S to 46°S), where the orogenic belt is controlled by the subduction of the Nazca plate beneath the South American plate. Between the volcanic front and the retroarc zone of the SVZ (Payenia volcanic province) there is a transversal alignment of basaltic, andesitic and rhyolitic volcanic edifices, which together form a NW oriented belt called Tromen-Domuyo. The orientation of Tromen-Domuyo belt is oblique to the general N-S trend that characterizes the Andean compressive structures, which are mainly folds, thrust faults and overthrusting ridges of N-S direction (Agrio and Malargue fold and thrust belt), Figure 2, Llambias et.al., 2010.



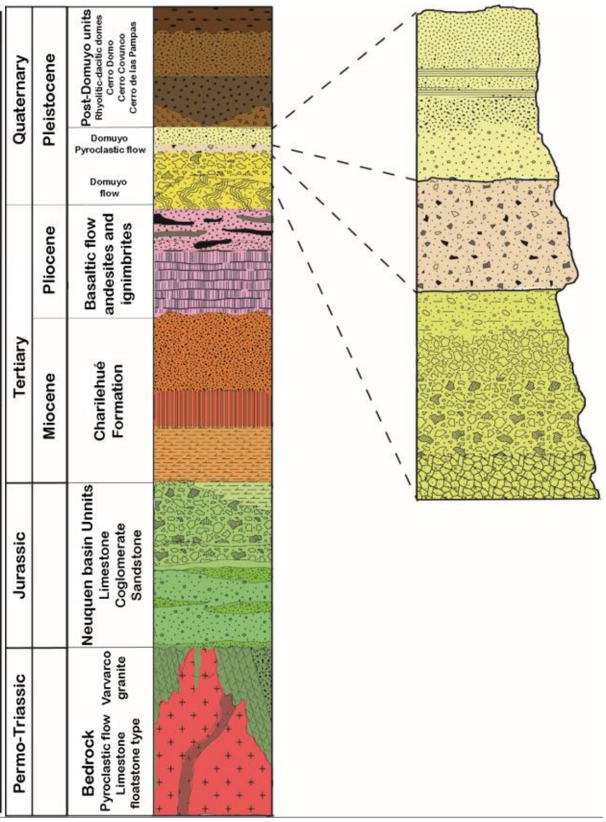


Figure 2: Location of Tromen-Domuyo belt **Figure 3: Lithostratigraphic column of the identified units**

The oldest rocks of the Domuyo region are represented by a volcano-sedimentary sequence, which is part of the Neuquén basin bedrock. These rocks have been grouped in the Choiyoi Group (Groeber, 1946) outcropping mainly in the southern part of the study area, where they are cut by the Atreuco stream. This stream, with a direction practically E-W, exposes the terminal part of the Cordillera del Viento, a set of N-S anticlines that involve Carbonic to Triassic rocks formed by conglomerates, sandstones and andesitic lava flows that are interdigitated with ignimbrites and rhyolites. In general, Choiyoi Group sequences are intruded by pervasively altered granite bodies rich in micas, replaced by chlorite. Common features of the granitic outcrops are the N-S and NNE-SSW fractures that correspond to the dominant folding direction in the Cordillera del Viento. In this work, a granitic body intruded to sandstone of the Choiyoi Group (DOM-71) was dated to the south of the Atreuco river obtaining an age U-Pb in zircon of 288.9±1.6 Ma, similar to the K/Ar ages reported by other authors: 260±10 (Llambias, 1986); 287±9 Ma (Suarez y de la Cruz, 1997) y 259±18 Ma (JICA, 1984)

Sedimentary units of Neuquén basin outcrop to the south of Domuyo volcano and belong to formations of Jurassic and Cretaceous age. The first identified unit is the Tordillo Formation (Groeber, 1946) composed of medium- to fine-grained sandstone of reddish color, interbedded with very fine gray-green sandstone. Overlaying concordantly there is a 60 cm-thick layer of laminated limestone of dark shades, attributable by Kietzmann et al., 2011 to Vaca Muerta Formation comprised between the lower Tithonian and the upper Berriasian. This unit is characterized by high content in bioclasts, silicification and lamination, and is associated with an environment of basin and external ramp, dominated by deposits with high micritical mud content and microbial elements.

The upper limit of Neuquén basin units is discordant with Tertiary volcanoclastic and pyroclastic rocks of the Charilehue Formation. All volcanic rocks of the Miocene age are grouped in this unit, clearly distinguishable by the subsequent Pliocene volcanism characteristic for its degree of erosion. This unit is located on the left bank of Varvarco River, formed by rhyolitic lava covered by a deposit of pyroclastic flow (pumice and ash in similar proportions). From this last sequence an age U-Pb of 12.28±0.32 Ma was obtained, which falls within the ages reported for this Formation further south along the same Varvarco River (Burns et al., 2006).

Pliocene volcanism includes volcanic products that overlay discordantly over Charilehue Formation, such as basaltic flows that come from polygenetic volcanic center of Sierra de las Flores. It also includes deposits of ignimbrites and lavas of different composition coming from monogenetic buildings of dacitic and rhyolitic composition that Pesce (1983) groups as Manchana Covunco Formation, obtaining K-Ar ages 3.22±0.42 Ma; 3.08±0.41 Ma and 2.92±0.37 Ma.

A significant part of the study area is covered by units associated with Domuyo volcanic activity grouped under the denomination of Domuyo Pyroclastic Flows. This unit is a large domic complex that had an important explosive phase during its development. In particular, we identified sequences of deposits of flows and pyroclastic surges that filled a depression of E-W direction in the western part of Domuyo volcano and in part of Varvarco River valley. This sequence of pyroclastic deposits is probably associated with the collapse of the western flank of Domuyo volcano. Overlaying low density epiclastic deposits are formed by a matrix of medium-to-coarse sand, rich in pumice and ash which supports angular and rounded lithics of lavas of different texture. A second eruptive phase is represented by a series of pyroclastic deposits with different degrees of dilution, composed by a matrix rich in pumice and coarse-to-fine sand sized ash and angular lithics of dacites and rhyolites.

The Rhyolitic Domes and lavas of the Quaternary are the most recent products. The volcanic edifices located in the area, as well as its lava products are: Cerro Domo, Cerro Covunco, Cerro La Guitarra and Cerro de las Pampas. This unit consists of rhyolitic and dacitic lavas with porphyritic texture and phenocryst of plagioclase, quartz and a lower portion of piroxenes and micas, supported by a very vitreous aphanitic matrix. In the presented study two samples were dated by the U-Th method in zircon, obtaining an age of 0.32±0.03 Ma for a sample taken from Cerro Domo and 0.25±0.03 Ma for a sample taken from the western flank of Cerro Covunco

In addition to the silicic volcanism of the western flank of Domuyo volcano, there is a mafic volcanism emplaced through monogenetic cones grouped under the name of Monogenetic Mafic Quaternary Volcanism. It is abundant in the southern part of Domuyo volcano where it forms lava flows of olivine basalts reported on the eastern margin of Curi Leuvu stream. In the study area, this volcanism is represented only by a basaltic lava flow that covers Domuyo Pyroclastic Flows deposits and Sierra de las Flores flows on the western margin of Varvarco River.

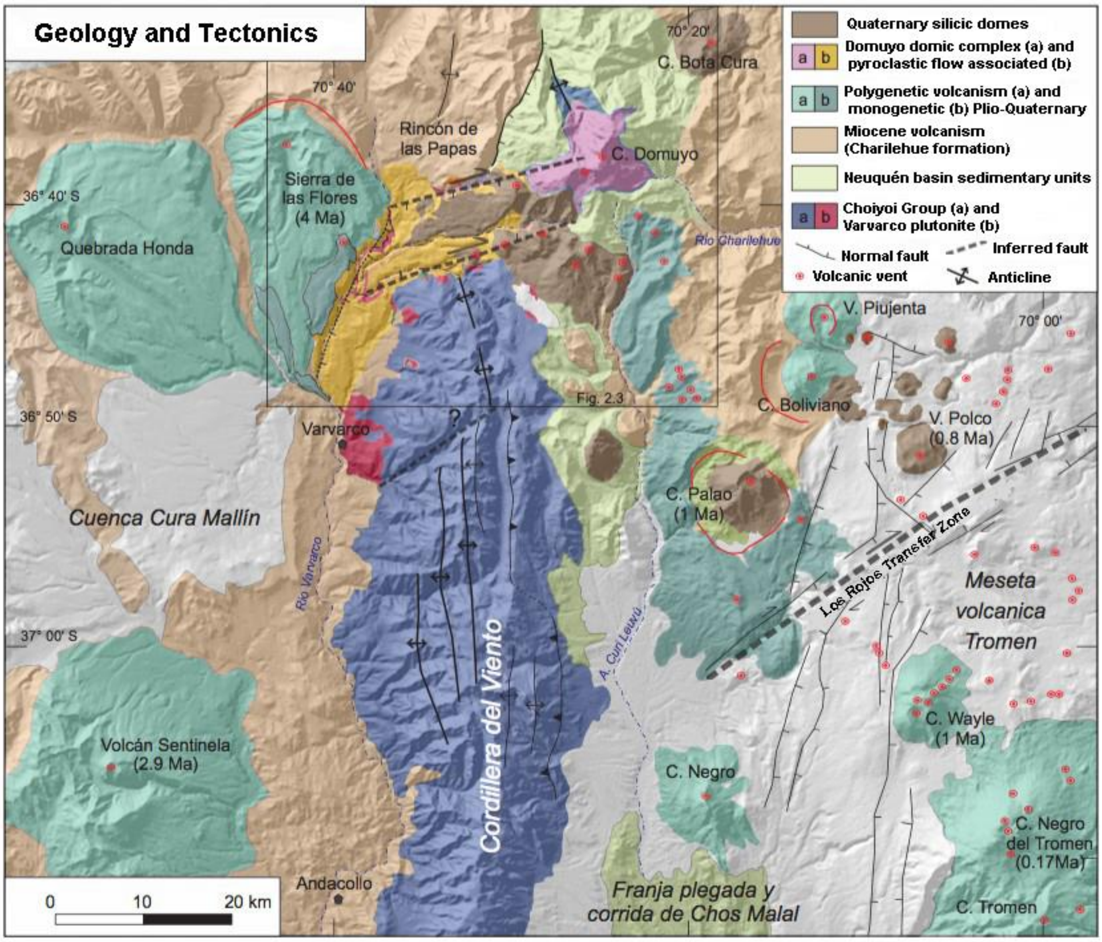


Figure 4: Regional geological map of the northern part of the Patagonian Andes.

3. REGIONAL AND LOCAL STRUCTURE

3.1 Regional Structure

The geothermal area of Domuyo is located at the northern end of Cordillera del Viento, which represents the highest elevation of the Andean basement in these latitudes. The Cordillera del Viento is a N-S structure formed by a series of anticlines underlying by a low angle overthrust fault with eastern vergence (Sagripanti et al., 2014). It is interpreted as the product of the inversion of a Triassic age basin during two tectonic phases. The first deformation event was the most intense and occurred at the end of the Cretaceous according to trace age of fission and K-Ar (Burn, 2002; Kay et al., 2006). The second phase of deformation occurred in the late Miocene based on thermochronological studies (Burns, 2002).

To the west of Cordillera del Viento we find Cura Mallin basin, an Oligocene-Miocene tectonic depression whose filling is constituted by a sequence (1500 meters on average) of fluvio-lacustrine deposits. These deposits are covered by middle and upper Miocene ignimbrites and lavas which may correspond to the Charilehue Formation, covered unconformably by Pliocene polygenetic volcanic edifices (Burns et al., 2006). The distribution of sedimentary facies and their relationship with the geological structures in Cura Mallin basin indicates that the basin itself is limited by extensional faults, with no strike slip component (Burns et al., 2006). The basin registers a phase of soft shortening that involves the rocks of middle Miocene, but not those of Pliocene (Miranda et al., 2006).

Folguera et al., (2008) document an extensional phase to the East of Cordillera del Viento that produced the formation of basins partially buried by the so-called Tromen volcanic plateau (Figure 4). The dominant N-S extensional faulting was developed mainly between 1.7 and 0.7 Ma. The strip of normal N-S faults is intersected by a transfer zone called Los Rojos of ENE-WSW direction that has a right lateral kinematic with an extensional component (Folguera et al., 2008). This extensional fault does not seem to have affected Domuyo's area, but it does infer the existence of a structure similar to Los Rojos transfer zone.

The Plio-Quaternary magmatism of the region can be subdivided into 3 dominions: 1) west of Cordillera del Viento: Cura Mallin basin is dominated by polygenetic volcanoes of mainly andesitic composition (Sentinela, Quebrada Honda and Sierra de las Flores; Miranda et al., 2006); 2) southeast of the Cordillera del Viento: the Tromen volcanic plateau characterized by polygenetic volcanoes (Cerro Tromen, Tilhue, Cerro Wayle and Cerro Negro) and a large number of monogenetic cones of basaltic composition; 3) northeast of Cordillera del Viento: volcanism becomes bimodal, coexisting both basaltic with domes of rhyolitic and dacitic composition (Cerros Palao, Polco, Domo, Covunco, Bota Cura and Domuyo). The occurrence of bimodal volcanism suggests that the rise of mafic magmas produce the fusion of crust rocks generating voluminous silicic volcanism in Domuyo region.

3.2 Local Structure

Previous works had suggested the existence of normal E-W faults along the main streams: Manchana-Covunco fault in the north and Covunco fault in the south. These two structures would delimit a graben of the same direction located to the west of Domuyo volcano that contains the majority of the thermal manifestations (Pesce, 1983, 2013). The field work made it possible to determine that although there must be faults of an orientation similar to those proposed by Pesce (1983), these do not affect the units subsequent to Charilehue Formation. In fact, the top of Domuyo pyroclastic deposit is not displaced from either side of Covunco stream and, in general, its flat surface does not present any fault scarps. However, this deposit filled a depression that we infer to be of a tectonic nature. Evidence of this is that the Cordillera del Viento is truncated at Atreuco stream and that both Permo-Triassic rocks of the Choiyoi Group and Varvarco plutonites (up to 2800 meters high), do not appear in Covunco stream -located 2 km to the north- whose riverbed is approximately 1750 to 1900 meters high. Then, in Manchana-Covunco stream the rocks of Choiyoi Group, Varvarco Plutonites and the sedimentary sequences of Neuquén basin come back to outcrop up to 2200 meters high. The latter have a pronounced slope towards the NE, E and ESE whereas to north of the stream they are overlaying unconformably by the volcanic sequence of the Charilehue Formation that has a smooth folding with an approximately N-S axis. It is unlikely that Permo-Triassic and Jurassic rocks have been removed by erosion caused by an orthogonal drain to the anticline axis of Cordillera del Viento, so we infer the presence of ENE-WSW direction structures with an important normal component, buried below Domuyo Pyroclastic Flows deposits. The southern structure should be located a slightly further north of Atreuco stream, possibly below the alignment of Guitarra and Covunco domes while the northern structure could be located barely south of Manchana-Covunco stream, defining a graben similar to the one proposed by Pesce (2013). However, the course of both streams is controlled by the contact between Domuyo Pyroclastic Flow deposits and the older adjacent rocks and not by the trace of the fault. There are possibly other faults with the same kinematics buried under Domuyo Pyroclastic Flow deposits, as proposed in the geological sections.

On the other hand, observing regional geology we can formulate the hypothesis that the structures inferred in the previous section have a more complex history of deformation. To the northeast of the study area, the rocks of Choiyoi Group and Neuquén basin deposit outcrops widely to the north of Domuyo volcano, where they form an anticline with an axis in the same direction as Cordillera del Viento (NNW). The similarity in the direction of this axis suggests that the anticline north of Domuyo could be the northern end of the anticline of Cordillera del Viento, but displaced towards ENE (Figure 5). Based on this observation, we infer that below the Domuyo Pyroclastic Flow deposits there may be a shear zone with a right lateral component that accommodated the displacement of the fold towards ENE. It should be noted that the transfer area of Los Rojos, recognized by Folguera et al., (2008) to the SE of Domuyo has a similar orientation and kinematic, although it is characterized by a reactivation during the Quaternary period. In contrast, the age of the right lateral and extensional deformation of Domuyo is not known, but it ought to be prior to Charilehue Formation. It is possible that the shear zone was formed during the main phase of the folding and uplift of Cordillera del Viento in Pre-Oligocene time as a transfer structure, with a possible reactivation during the soft folding phase of late Miocene. It is also possible that the intrusion of Domuyo dome has contributed to emphasize this structure which currently has an elevation higher than that of Cordillera del Viento.

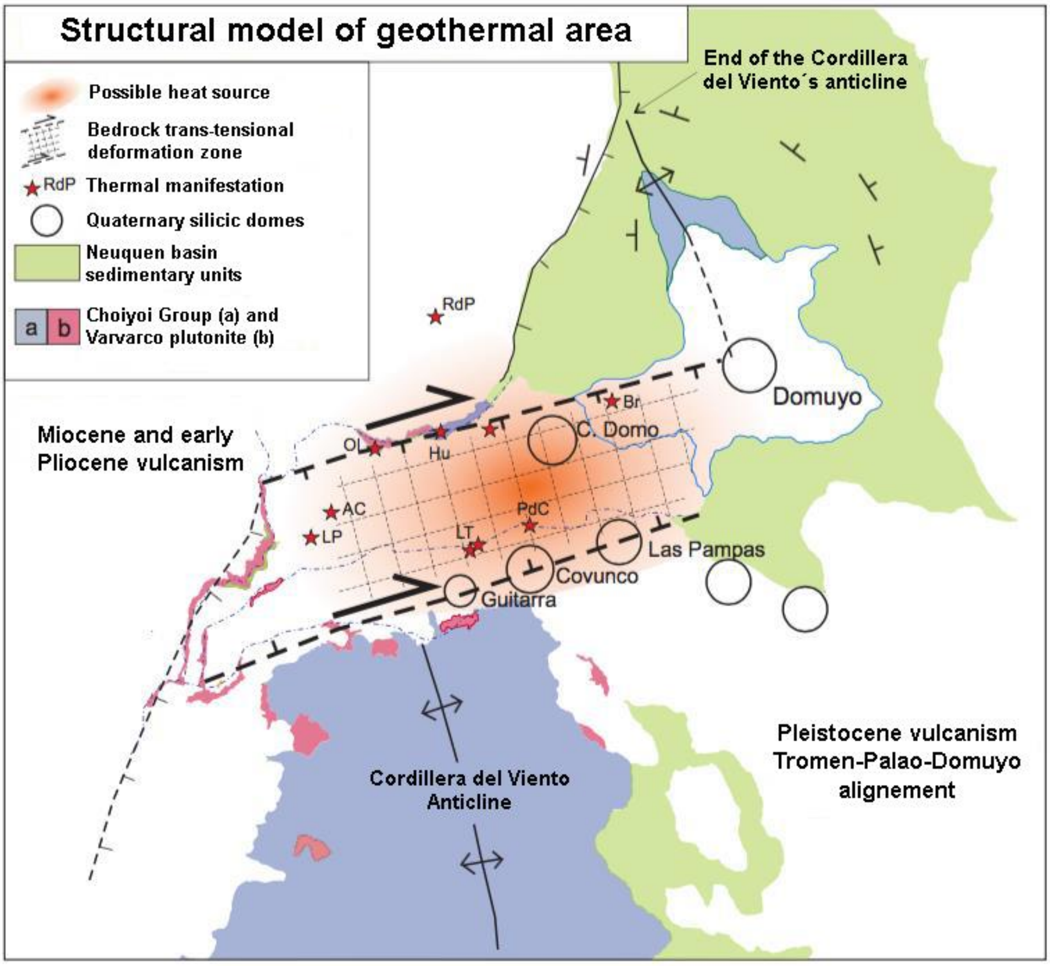


Figure 5: Tectonic framework of the Domuyo geothermal area.

It is interesting to note the abundance of Varvarco Plutonites outcrops in the Transfer Zone, which suggests that this might have been a Permian intrusion reactivated at another time during the late Cretaceous shortening.

4. GEOCHEMISTRY

Seven sites with thermal springs were examined, collecting 8 samples of water and 3 samples of gases, in addition to 2 samples of cold water, one taken from the snow found in Domuyo Volcano and another taken from a cold spring in Varvarco town.

Water samples for cation determination were analyzed in the Laboratory of the National Institute of Electricity and Clean Energy of Cuernavaca Morelos, Mexico, using the ICP-OES plasma spectrometry methodology. In order to determine the presence of NH4+ the ion-selective potentiometric method was used; however, to determine the alkalinity, the chosen method was acid/base reaction and for anions analysis (F, Cl, SO_4) the Ionic Chromatography method was used.

Table 1: Chemical analysis of anions and cations in water samples hot and cold springs.

Sampling site	Sample	Code	pH Lab 25°C	TDS mg/l	NH_4+ mg/l	Alkalinity mg/l			Cations mg/l										Anions mg/l			Balance %
						$CaCO_3$	HCO_3	SiO_2	Sr	Rb	Mn	SiO_2	Na	K	Ca	Mg	Li	B	Cl	F	SO_4	
Aguas Calientes	M1	DMY-3	8.0	2260	<0.1	310	189	133	0.429	<0.0001	0.003	162	638	59.3	27	2.4	6.1	5	829	3.70	91	5.2
Las Olletas	M2	DMY-11	8.0	3465	0.21	292	178	118	1.028	<0.0001	0.172	156	1028	78.0	49	1.2	10.5	8.2	1533	2.36	163	1.1
Los Tachos	M3	DMY-24	8.2	3780	0.19	343	209	153	1.076	<0.0001	0.356	169	1156	91.8	54	1.5	11.5	9.0	1597	3.25	164	4.6
El Humazo	M4	DMY-27	7.9	4360	0.30	328	200	154	1.248	2.83	0.087	207	1309	201.0	40	0.9	13.9	11.25	1964	1.22	228	2.1
Las Piedras	M5	DMY-35	6.9	710	<0.1	292	178	120	0.102	<0.0001	N.D	78	149	17.8	10	3.49	1.4	1.2	197	7.40	19	-7.8
Punta de Camino	M6	DMY-43	4.7	200	16.9	100	61	39	0.018	<0.0001	0.147	44	4.19	4.87	1.7	0.38	0.0003	0.057	4.24	3.00	5	5.4
Rincón de las Papas	M8	DMY-55	7.2	5480	0.86	1805	1101	784	5.644	<0.0001	0.252	97	1582	133	253	53	12	8.7	2663	4.07	120	-2.6
Rincón de las Papas St	M11	SITIO-2	7.1	2590	0.62	2117	1288	919	2.261	<0.0001	0.124	97	724	82.7	113	15	4.2	4.4	889	2.04	135	-8.9
Rainwater	M12	Rainwater	6.1	260	-	-	-	-	0.0006	<0.0001	0.0029	0.19	0.187	0.0001	0.11	0.01	<0.0003	N.D	0.5	N.D	N.D	2.2
M-Varvarco	M13	Varvarco spring	-	350	-	81	50	28	0.0591	<0.0001	0.0001	37	5.16	2.07	8.4	3.9	0.003	0.019	3.9	N.D	10	-5.1
N.D	Not Detected																					

Table 2: Isotope analysis of ^{18}O and D in water samples and condensed vapor, as well as ^{18}O in sulfates.

No.	Sampling site	ID*	Sampling date	manifestation	$\delta^{18}O$ ‰	δD ‰	$\delta^{18}O$ ‰ in sulfate
1	Aguas Calientes	M1	25-oct-16	Hot spring	-14.4	-111.0	-3.6
2	Las Olletas	M2	25-oct-16	Hot spring	-13.8	-112.1	-2.7
3	Los Tachos	M3	25-oct-16	Hot spring	-13.6	-112.2	-2.8
4	El Humazo	M4	26-oct-16	Hot spring	-13.0	-110.2	-6.5
5	Las Piedras	M5	26-oct-16	Cold spring	-14.5	-108.8	-3.3
6	Punta de camino	M6	27-oct-16	Hot spring	-12.9	-117.5	-9.8
7	El Humazo	M7	26-oct-16	Fumarole of low intesity	-18.5	-135.7	
8	Rincón de las papas	M8	28-oct-16	Hot spring	-13.6	-113.2	1.4
9	Punta de camino	M10	28-oct-16	Fumarole of low intensity	-19.1	-146.7	

The samples to determine stable isotopes of water (^{18}O and ^{2}H) and of ^{18}O from SO_4, were analyzed in the Environmental Isotope Laboratory, Geoscience Department, University of Arizona, USA.

Gas samples were collected according to the methodology of Giggenbach and Goguel R., (1989) and Arnorsson, S., (1991) and were analyzed in New Zealand Geothermal Analytical Laboratory, based at GNS Science in Wairakei, Taupo.

Table 3: Chemical analysis of gases, corrected by air pollution.

Chemical composition of gases (molar basis) Dry gases (% mol)											
Name	ID	Gas % mol	CO_2	H_2S	NH_3	Ar	N_2	CH_4	H_2	He	O_2
Los Tachos	M9	100	95.8	<0.1	8.0e-6	0.15	3.9	0.15	4.5 e-5	<0.001	0.001
El Humazo	M7	0.13	93.8	2.81	0.203	0.0503	3.05	0.11	0.0031	0.0008	0.001
Punta de Camino	M10	0.05	98.1	<0.1	0.112	0.13	1.53	0.14	0.0059	<0.001	0.001

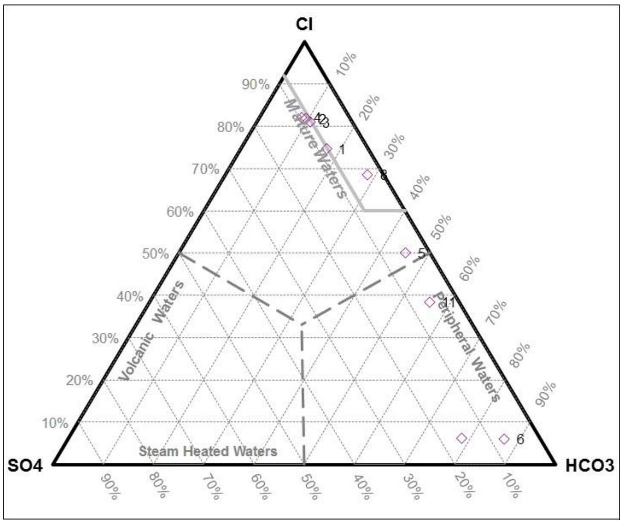


Figure 6: Piper diagram.

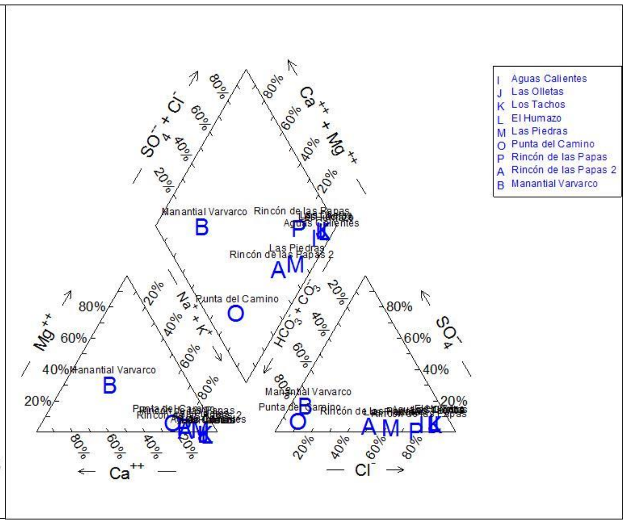


Figure 7: Anion ternary diagram.

According to laboratory results and data measured in the field, it can be determined that the springs of Aguas Calientes, Las Olletas, Los Tachos and El Humazo form a homogeneous group of the sodium chloride type (Figure 6). The amount of Total Dissolved Solid (TDS) varies from 2260 mg/l (Aguas Calientes) to 4360 mg/l (El Humazo). The pH measured in the field varies from 6.7 (Aguas Calientes) to 8.0 (Las Olletas). The surface temperature varies from 68°C (Aguas Calientes) to 90°C (Las Olletas). These hot springs are clearly a discharge from a dominant liquid geothermal reservoir.

El Humazo is the most representative of reservoir fluids, as it has the lowest dilution by shallow water circulation, and is also the closest to the geothermal fluid rise zone; while the other manifestations are lateral discharges to both south and SW. The two springs of Rincon de las Papas, also of the sodium chloride type, represent a lateral discharge of the reservoir to the north. The manifestation of Punta de Camino is a partially condensed steam. Meanwhile Las Piedras spring represents the local groundwater with a small contribution of geothermal water (less than 10%), as does Varvarco cold spring.

The isotope composition of Deuterium and Oxygen-18 (^{18}O) obtained from the samples of Aguas Calientes, Las Olletas, Los Tachos, El Humazo and Rincon de las Papas shows a shift from the global meteoric line that is characteristic of high temperature geothermal waters. The shift ranges from a minimum in the samples of Aguas Calientes (1), Las Olletas (2), Los Tachos (3), Rincon de las Papas (8) to the maximum of El Humazo spring (4). Las Piedras (5), a low salinity spring (710 mg/l of TDS and 197 mg/l of Cl^-), also presents a slight shift, although due to its proximity to the global meteoric line it can be considered representative of the isotopic composition of local precipitation (snow). Fig 8

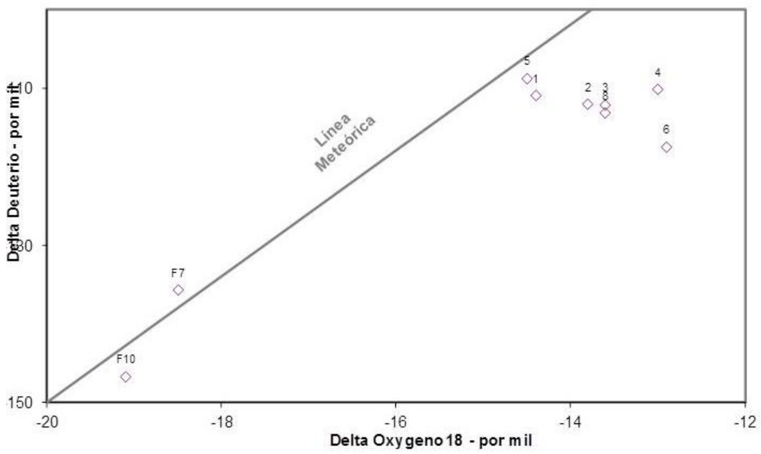


Figure 8: δD‰ vs δ^{18}O‰ graphic.

The values of samples F7 (fumarole El Humazo) and F10 (fumarole Punta de Camino) are significantly more negative than the above mentioned springs. If we accept that El Humazo sample (4) is the best representative of reservoir water then we infer that both fumaroles could not represent the reservoir fluid. A vapor in equilibrium with the reservoir water, with temperatures between 210 and 270°C (this values will be justified later with the geothermometers) could have isotopic values of δD‰=-111.9, δ^{18}O‰=-15.3 (210 °C) or of δD‰=-106.2, δ^{18}O‰=-14.4 (270 °C)[1]; very different from those of the sampled fumaroles. A steam sample from a boiling spring located at 2766 meters above sea level at Calabozos volcano in Chile (about 116 km north of Domuyo), has isotopic values of δD‰=-102.8, δ^{18}O‰=-15.13, similar to the ones in Domuyo[2].The most reasonable explanation for these very negative values of El Humazo and Punta de Camino fumaroles is that they are secondary and do not come from the geothermal reservoir but are formed in the same discharge at around 90°C. The separated steam under these conditions could have the following isotopic values: δD‰=-142, δ^{18}O‰=-18.7[3]. These values are similar to those measured in the fumaroles sampled (Figure 9). The isotopic values of Punta de Camino water (6) are compatible with the fact that it is vapor (F10) partially condensed, as mentioned before.

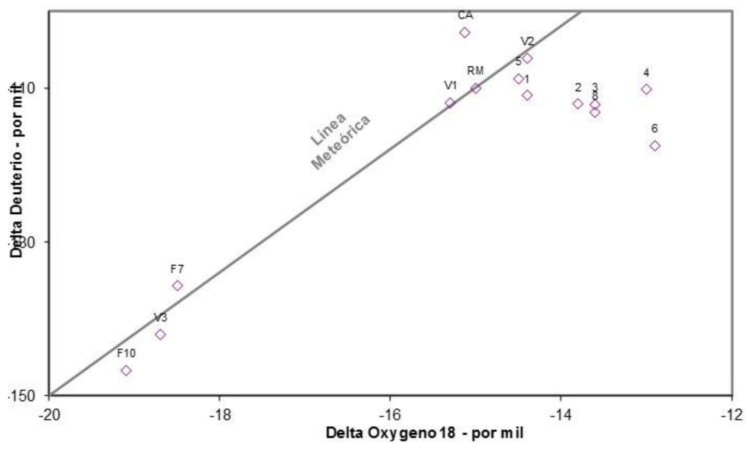


Figure 9: δD‰ vs δ^{18}O‰ graphic adding the estimated reservoir water recharge (RM) composition, the estimated vapor composition separated at 210°C (V1), 270°C (V2) and 90°C (V3) and from Calabozos volcano in Chile (CA)

---

[1] The fractionation factors (1000lnα) for the^{18}O are from 2.30 to 210°C and 1.35 to 270°C, while those corresponding to D are from 1.7 to 210°C and -4.0 to 270°C.

[2] Benanvente Zolezzi, Oscar Matias, 2015. Origin and nature of the volcanic and hydrothermal fluids of Central Chile. Thesis to qualify PhD in geological science. Santiago de Chile.

[3] The fractionation factor (1000lnα) for the^{18}O to 90°C is 5.65, while that corresponding to D is 31.7

In figure 10 of Cl^- vs $\delta^{18}O$‰, we can see a mixture and dilution line formed by El Humazo (4) to Las Piedras (5) springs. The sample Rincon de las Papas (7) does not fit the line because it has an excess of chlorides due to vapor loss. On the other hand, water of Punta de Camino (6) is very low in chloride content probably suggesting a steam condensation.

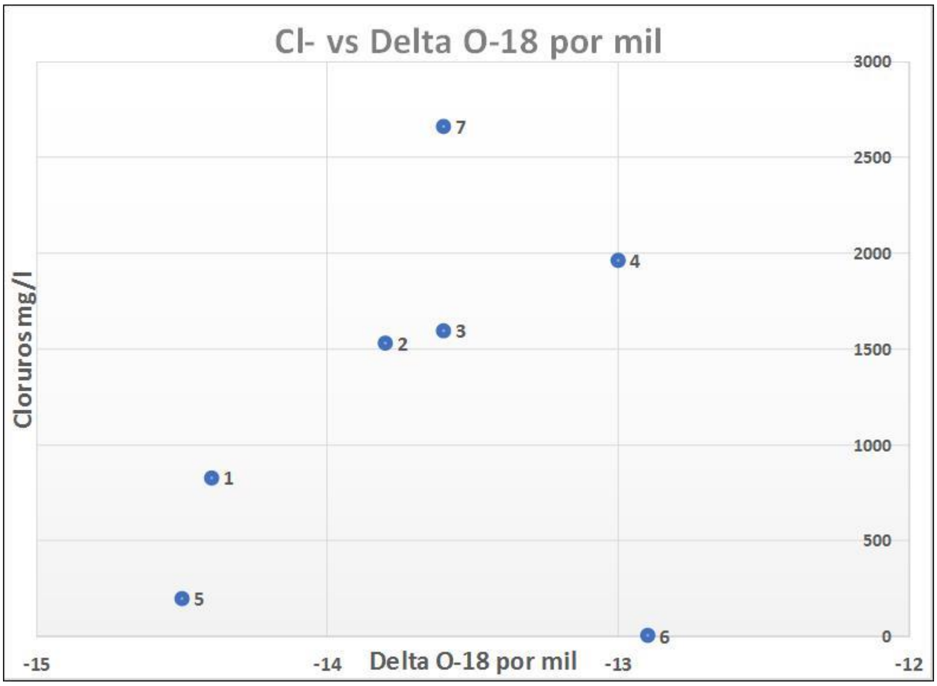


Figure 10: Chloride vs $\delta^{18}O$‰ graphic. Aguas Calientes (1), Las Olletas (2), Los Tachos (3), El Humazo (4), Las Piedras (5), Punta de Camino (6) and Rincón de las Papas (7)

The geothermometry of dissolved silica shows values of 170-183°C for El Humazo and 155-169°C for the hot springs that represent the lateral discharges. Values of Na/K geothermometers for El Humazo vary from 242 to 269°C and from 190 to 227°C for lateral discharges (Table 4). The dissolved sulfate-water oxygen-18 isotope geothermometer presents values of 246-249°C for El Humazo and 162-172°C for lateral discharges.

Table 4: Geothermometric values utilized in the interpretation.

Name	Cristobalite beta	Conductive Quartz	Adiabatic Quartz	Na-K-Ca	Na/K Fournier 1979	Na/K Giggenbach 1988	K/Mg Giggenbach 1986
Aguas Calientes	66	166	157	198	211	227	136
Las Olletas		164	155	190	194	211	157
Los Tachos		169	159	194	198	215	159
El Humazo	83	183	170	242	257	269	201
Las Piedras	25	124	121				95
Punta de Camino		96	97				90
Rincón de las Papas	36	136	131	189	203	219	113
Rincón de las papas 2		136	131	199	229	246	117

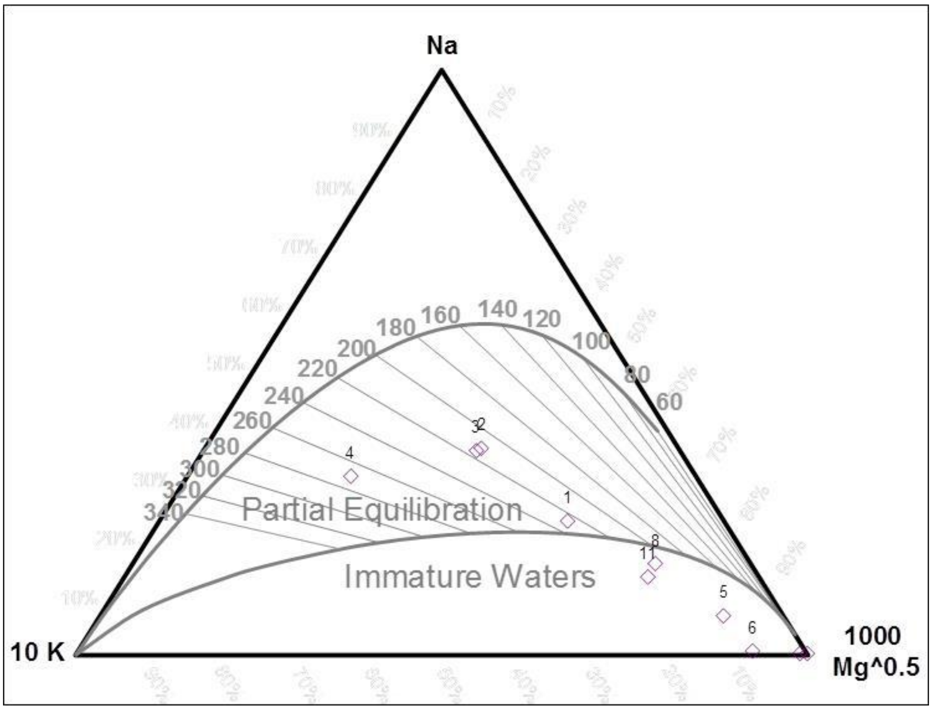


Figure 11: Na-K-Mg diagram. Samples: Aguas Calientes (1), Las Olletas (2), Los Tachos (3), El Humazo (4), Las Piedras (5), Punta de Camino (6), Rincón de las Papas (8), Rincón de las Papas 2 (11), snow (12) and Varvarco spring (13). Samples in the lower right corner are 12 and 13.

Regarding gas analysis in the ternary diagram N_2-Ar-He, samples are grouped around the air saturated water point (ASW); in congruence with the fact that those are secondary fumaroles formed in the discharge of the springs. Punta de Camino (10) presents an excess of Ar. The chemistry of gases in these secondary fumarole samples does not represent the equilibrium conditions of the reservoir, it is rather a temporary disequilibrium manifestation. Figure 12.

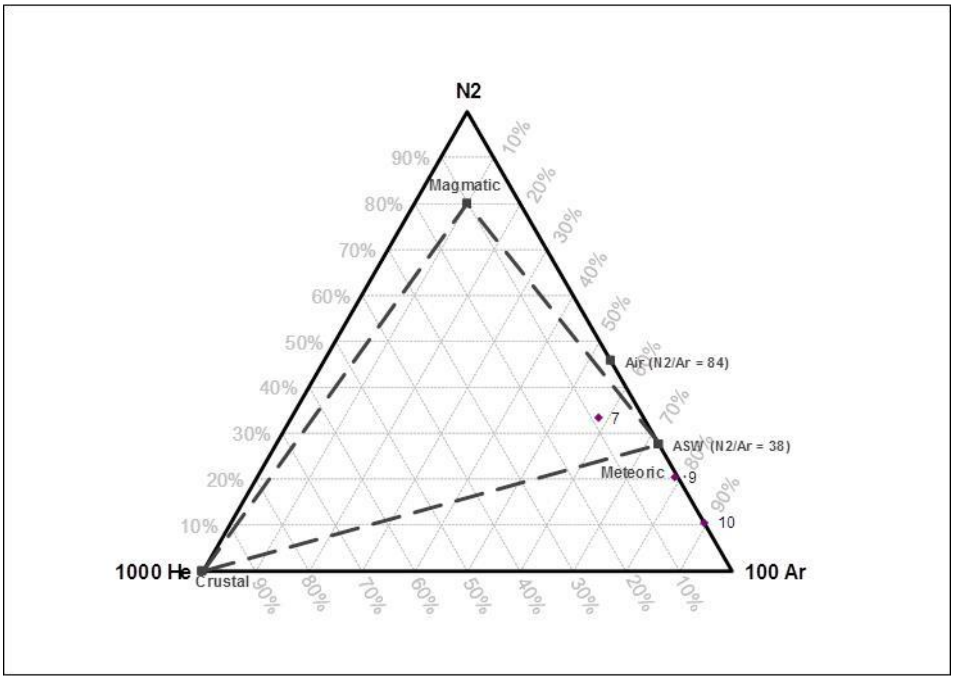


Figure 12: Ternary diagram N_2-Ar-He. Samples: EL Humazo (7), Los Tachos 2 (9), Punta de Camino (10)

Summarizing, the probable concentration of chlorides of approximately 2300 mg/l to 3800 mg/l might indicate the presence of a water dominated type reservoir. The upflow zone of the geothermal fluid is around El Humazo. Fluid moves laterally and discharges mainly to the south and southwest, and to a lesser extent to the north. Temperatures inferred with geothermometers vary from 240 to 270°C in the upflow zone (most likely 250°C) and 190 to 220°C in the lateral flow zone. Because sampled fumaroles are secondary, no inferences can be made about the content and chemical composition of reservoir gases.

5. GEOPHYSICAL SURVEY

A geophysical survey (MT, TDEM, gravity) has been conducted by ENAL-PROINSA in 2016. A total of 103 MT sounding, 40 TEM and 130 gravity stations were measured over a surface of 100 km^2 (Figure 13)

After acquiring, processing and interpreting geophysical data, profiles and maps were made, some of which are presented below.

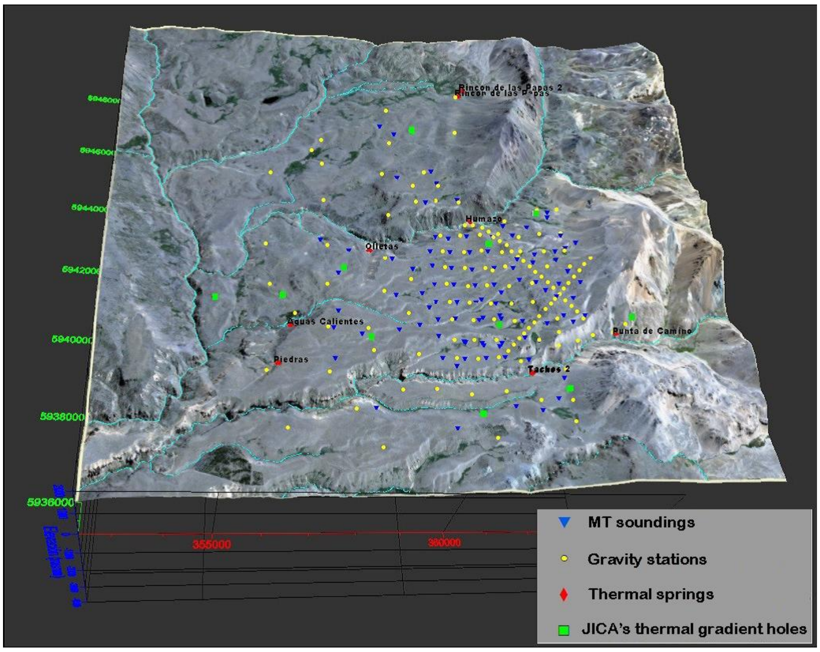


Figure 13: Location of MT sounding and gravity stations of geophysical survey

In Figure 14 a gravimetric residual map is superimposed on a resistivity map at 1400 m.a.s.l. (meters above sea level), obtained from the 2D MT inversion. This map shows that resistive and gravimetric anomalies can be correlated. High resistivity coinciding with high density areas are observed in the central zone, as well as discontinuities to the north and south with respect to the fault reported in the geological survey. In Figure 15 the same gravimetric residual map is superimposed on resistivity map 200 meters deeper, at 1200 m.a.s.l. The correlation of high resistivity with some areas of higher density especially in the region between El Humazo and Los Tachos is remarkable. This is interesting because it could have some relationship with the inferred heat source for this geothermal system.

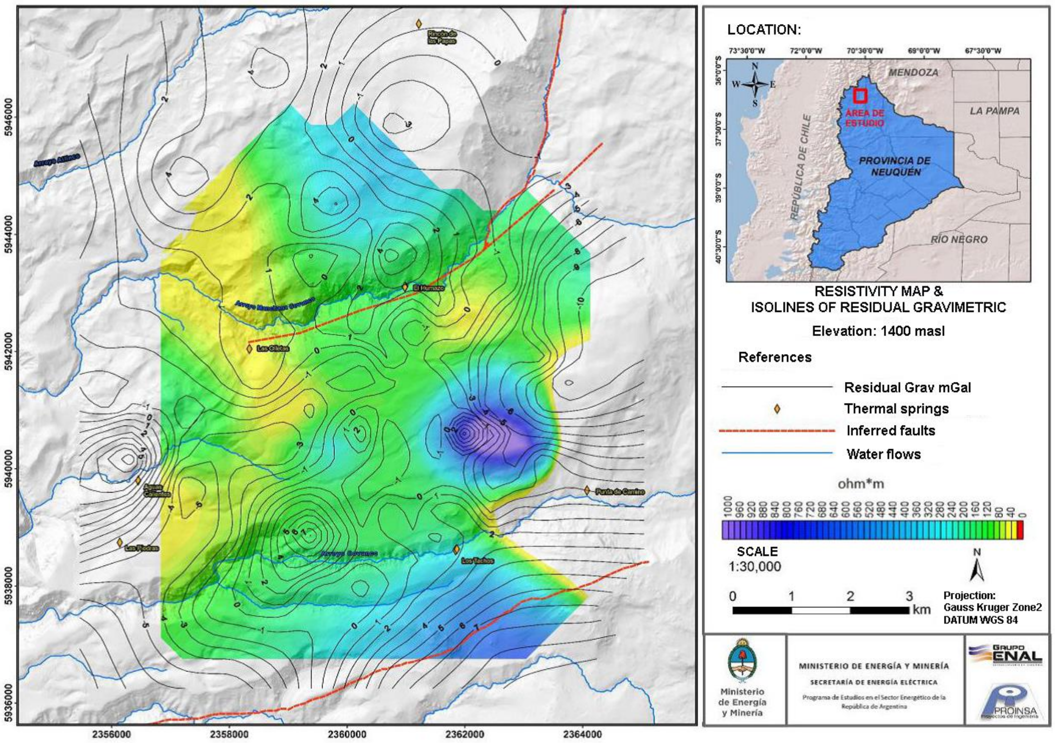


Figure 14: Resistivity at 1400 masl and gravimetric residual map

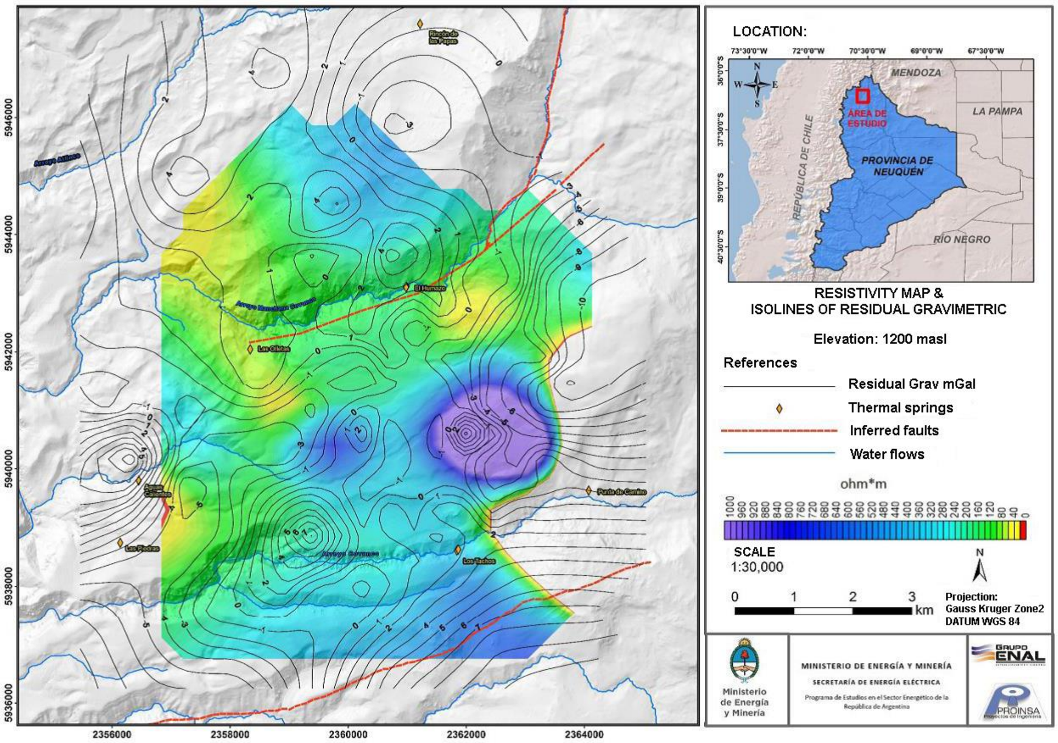


Figure 15: Resistivity at 1200 masl and gravimetric residual map

Based on the analysis of the results obtained in the geophysical study and its interpretation, it was possible to verify the existence of a zone of high resistivity with the magnetotelluric sounding in the central zone of the study area, as well as the shallow zones near the hydrothermal manifestations with low resistivity, possibly associated with a hydrothermal alteration.

The results of the gravimetric survey showed that the anomalies reported in previous exploration works and the new MT soundings have very similar forms, which validates the proposed conceptual model. A very good correlation with the geological structures that could indicate some limits of the reservoir, given by the Covunco and Manchana Covunco streams, demonstrates that the coverage of both survey grids was adequate for the characterization of the geothermal system.

Having integrated all the information and analyzed the results the existence of an area of interest, located between the El Humazo and Los Tachos hot springs, is evident. It is possible that the heat source of the system comes from the east flank of Cerro Domo and fluids are transported laterally until they are discharged in the aforementioned hot springs.

6. CONCEPTUAL MODEL

The conceptual model that best adapts to the results of the geological, geochemical and geophysical studies is that of a high temperature reservoir of liquid dominated type with a probable concentration of chlorides of approximately 2300 mg/l to 3800 mg/l. The upflow zone of the geothermal fluids could be located to the south of El Humazo. The fluid moves laterally and discharges mainly towards south and southwest and, to a lesser extent towards north. The temperatures inferred with geothermometers are around 240-270°C in the upflow zone and 190-220°C in the lateral flow zone.

The inferred upflow zone could be to the southeast of El Humazo and also corresponds to an area where the resistive bedrock is shallower. An anomaly of density appears with a variation of up to 10 mGal, approximately between El Humazo and Los Tachos hot springs Figure 16.

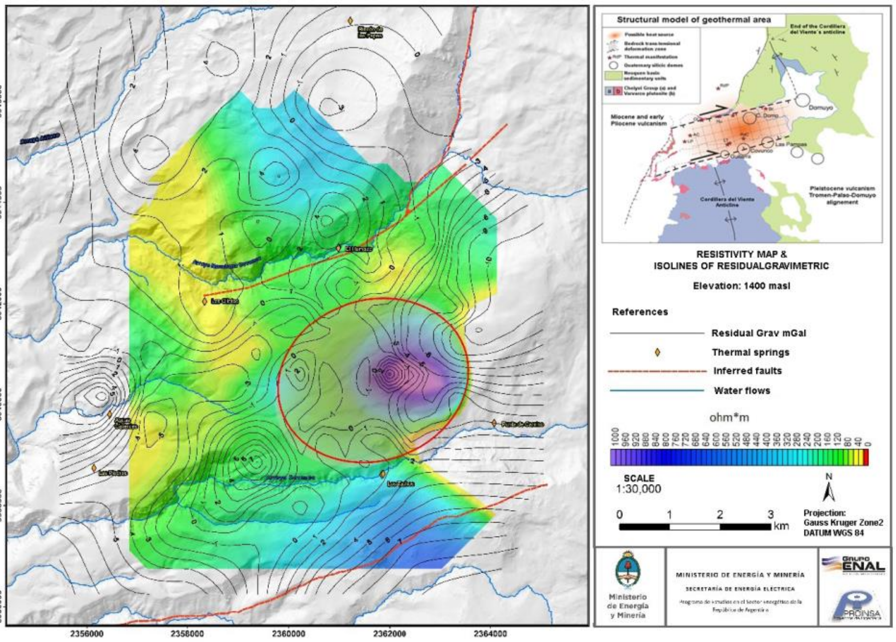


Figure 16: Resistivity at 1400 masl map with gravimetric residual isolines. Red circle indicates the resistive anomaly at inferred bedrock depth.

On the other hand, as we get closer to hot springs, we observe a decrease in resistivity and an apparent increase in the bedrock´s depth which could be due to clay products of hydrothermal alteration. This process is the result of nearby thermal manifestations, being El Humazo the most effusive.

The reservoir could be hosted in polydeformable rocks of the Choiyoi Group, Plutonitas Varvarco and part of the Sedimentary sequence of Neuquén basin, which corresponds to high resistivity. The primary permeability of the rocks is variable, although more important is the secondary permeability produced by faulting and fracturing induced by two phases of deformation (late Cretaceous and late Miocene). The deposits of Domuyo Pyroclastic Flow as well as Rhyolitic Domes and Lavas of Cerro Domo, could constitute the cap rock of the reservoir

As a result of the study, it was proposed to drill 3 exploratory wells at a minimum depth of 1500 meters, with the purpose of reaching the sequence of Neuquén basin and Choiyoi Group, where a geothermal reservoir could be hosted, expecting to find permeability and temperatures above 200°C at a depth of 1000 meters Figure 17. The recommendation is to drill the first well vertically for verification of geological units and geothermal conditions, temperature, permeability. For the following drillings, using an even more constrained model and the additional information retrieved from the exploratory well, it could be decided whether directional wells should be drilled or not.

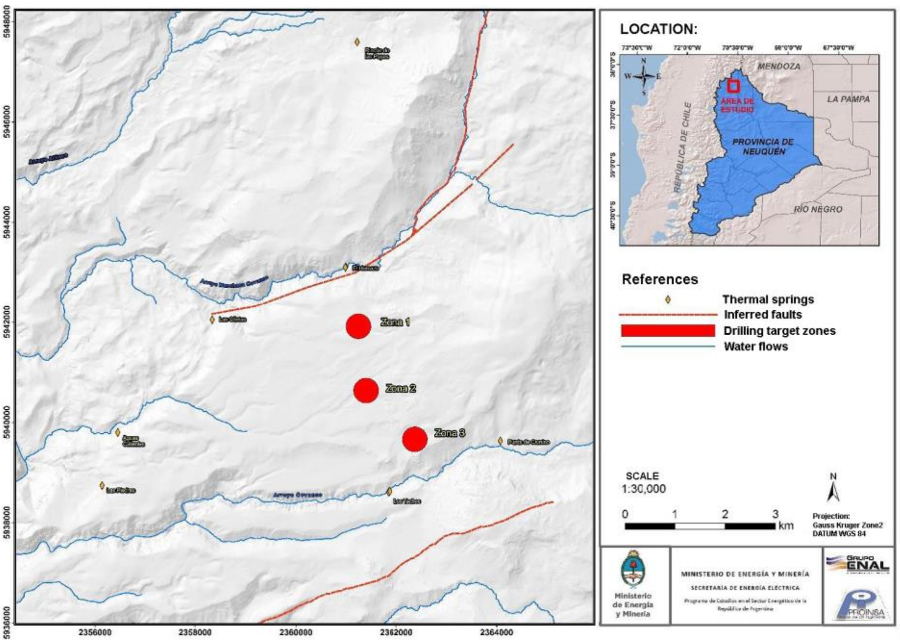


Figure 17: Location of proposed geothermal drilling holes.

Zone 1 is located to the south of El Humazo, based on the geothermal conceptual model it is inferred that the best conditions of temperature and permeability were found. Based on the geophysical results, it is expected to reach the reservoir at 1000 meters deep.

Zone 2 and 3 could also have good temperature and permeability conditions, and have been determined by geological-geophysical correlation with the purpose of cutting across the resistivity gradients in depth, which suggests the existence of the units where the geothermal reservoir is located.

7. RESOURCE ASSESSMENT

For the estimation of the geothermal potential, the volumetric model USGS "Heat in Place" with Monte Carlo simulation and the simplified model of gradual decompression were used. In order to obtain the estimation, it was first necessary to determine certain estimated specific parameters which are summarized in the following table:

Table 4: Parameters used in the resource assessment

Parameter	Minimum value	Expected value	Maximum value
Project life (years)	25	30	35
Reservoir area (km²)	42	44	46
Reservoir thickness (km)	0.45	0.5	0.55
Reservoir Temperature (°C)	220	240	260
Recovery factor Rg (%)	7	8.5	10
Reference temperature (°C)	20	25	30
Rock porosity (%)	3	5	8
Reservoir rock density (ton/m³)	2.6	2.7	2.8
Rock specific heat (kj/kg°C)	0.9	1	1.1

The reservoir area was estimated in 44 km^2 based on distribution of hydrothermal manifestations, geological structures and changes in resistivity and gravimetry. Thickness was defined based on interpretations of electrical resistivity taking into account the considerations of the USGS methodology, obtaining an approximate value of 500 meters. For the temperature, the Giggenbach Na/K geothermometer was considered as reference, defining a probable temperature of 250°C and a range of temperatures fluctuating from 220°C minimum and 260°C as the maximum. The rest of the parameters were determined according to field observations and/or reference values defined by circular 790 of the USGS.

On the other hand, a single flash power plant was considered for the calculation of the reservoir potential. It also assumes a separation pressure of 9 bars, a specific steam consumption of 7 tons/MWh and a plant life of 30 years.

In order to keep the study more conservative, it was decided to evaluate the USGS model taking into consideration a range, varying the parameters of the base scenario and observing its effect on the final result of the potential, thus evaluating a lower limit and an upper limit, through the statistical method (Monte Carlo), while for the case of the gradual decompression model, the expected value of each parameter was used

Using the volumetric model coupled to Monte Carlo probabilistic method, the result was that Domuyo geothermal field has an electrical potential of 100 MW with a standard deviation of 15MW and the confidence interval of 90% is between 60 and 182 MW.

Finally, the gradual decompression model was applied. This model is simpler than a complete numerical model (finite element), but with considerably more precision, since it presents a greater complexity than volumetric analysis. This model is based on the methodology developed by Hiriart and Sanchez (1985) where mass and energy conservation equations are solved according to thermodynamic properties of the fluid (water-steam) and set out differential equations that simulate the behavior of a geothermal deposit that is considered as a container with finite permeability. This would obviously affect the number of wells required to develop it but not the thermal quantity and average thermodynamic evolution when decompressing it.

Applying the gradual decompression model, an electrical potential of 93 MW was obtained. This value is between the range of results obtained in the USGS methodology with Monte Carlo.

8. CONCLUSIONS

Domuyo geothermal field can be considered one of the geothermal projects with the greatest potential in Argentina, second to Copahue. The abundance of thermal manifestations and its water chemistry are supporting the existence of a giant high-temperature and liquid-dominated reservoir. According to Na/K geothermometers the reservoir temperature ranges between 242°C to 269°C. From a geological point of view we infer that the heat source is a magma chamber in cooling process. This heat source, of approximately 60 km^3, could be located between Cerro Domo and Cerro Covunco.

The geothermal reservoir is hosted in multi-deformed rocks of Choiyoi Group, Plutonitas Varvarco and part of the Sedimentary sequence of Neuquén basin. The secondary type permeability was produced by faulting and fracturing in two deformation phases (late Cretaceous and late Miocene). The impermeable layers of Domuyo pyroclastic flows constitute the cap rock of this geothermal system.

Aguas Calientes, Las Olletas, Los Tachos and El Humazo hot springs are of a sodium chloride type and clearly represent the discharge of a liquid-dominated geothermal system. El Humazo hot spring is the closest to the geothermal fluid rise zone. The other thermal manifestations are lateral discharges to the southwest and the south, whereas Rincon de las Papas springs is a lateral discharge of the reservoir to the north.

According to the geophysics survey, there is a high resistivity zone in the central part of the study area between El Humazo and Los Tachos hot springs, assumed as the core of this geothermal system. Meanwhile the shallow zones around these thermal manifestations are characterized by low resistivity, possibly associated with hydrothermal alterations.

Based on the results of the survey, three drilling targets were defined. The exploratory drilling wells should reach at least 1500 meters and its locations are shown in Figure 17.

The geothermal system presents a potential of 100 MW according to the volumetric model coupled to Montecarlo probabilistic method, while an electric potential of 93 MW was obtained using the gradual decompression model.

REFERENCES

Arnorsson, S., 1991. Geochemistry and geothermal resources in Iceland. In application of geochemistry in geothermal reservoir development. Ed. Franco D'Amore. UNITAR: 145-196.

Benavente Zolezzi, O. M., 2015. Origen y naturaleza de los fluidos de los sistemas volcánicos e hidrotermales activos de los Andes de Chile central (32.5-36°S). Tesis Doctoral. Departamento de Geología, Universidad de Chile.

Burns, W.M., 2002. Tectonics of the Southern Andes from Stratigraphic, Thermo-chronologic, and Geochemical Perspectives (PhD Thesis). Cornell University, Ithaca, p. 218.

Burns, W. M., Jordan, T. E., Copeland, P., & Kelley, S. A. (2006). The case for extensional tectonics in the Oligocene-Miocene Southern Andes as recorded in the Cura Mallín basin (36°–38°S). In Special Paper 407: Evolution of an Andean Margin: A Tectonic and Magmatic View from the Andes to the Neuquén Basin (35°-39°S lat) (Vol. 407, pp. 163–184). Geological Society of America.

Chiodini, G., Liccioli, C., Vaselli, O., Calabrese, S., Tassi, F., Caliro, S., Caselli, A, T., Agusto M. R., D'Alessandro, W., 2014. The Domuyo volcanic system: an enormous geothermal resource in Argentine Patagonia. Elsevier Science; *Journal of Volcanology and Geothermal research*; **274**; 3-2014; 71-77.

Folguera, A., Bottesi, G., Zapata, T., & Ramos, V. A. (2008). Crustal collapse in the Andean backarc since 2 Ma: Tromen volcanic plateau, Southern Central Andes (36°40′–37°30′S). *Tectonophysics*, **459**(1-4), 140–160.

Garg, S.K. and Combs, J. (2010), Appropriate use of U.S.G.S. volumetric "heat in place" method and Monte Carlo calculations, *Proceedings,* 34th Workshop on Geothermal Reservoir Engineering, Stanford university, Stanford, California, U.S.A., 7 pp.

Garg, S.K. and Combs, J. (2011), A Reexamination of USGS Volumetric "Heat in Place" Method, *Proceedings,* 36th Workshop on Geothermal Reservoir Engineering, Stanford university, Stanford, California, U.S.A., 5 pp.

Giggengach W. F. and Goguel R. L., 1989. Collection and analysis of geothermal and volcanic water and gas discharges. 4th Edition Chemical Division. Department of Scientific and Industrial Research, Petone New Zealand: 81 p.

Groeber, P., 1946. Observaciones geológicas a lo largo del Meridiano 70. I-Hoja Chos Malal. *Revista de la Asociación Geológica Argentina* **1**: 1977-208.

Groeber, P. 1947, Observaciones geológicas a lo largo del meridiano 70°. 3. Hojas Domuyo, Mari Mahuida, Huarhuarco y parte de Epulauken. 4. Hojas Bardas Blancas y Los Molles. *Revista de la Asociación Geológica Argentina,* **2(4)**: 347-433.

Hirart, G., and Sanchez, E., 1985. Thermodynamic behavior of simplified geothermal reservoirs, *Proceedings,* 10th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 22-24.

JICA-EPEN, 1984. Pre-Feasibility study for the Northern Neuquén Geothermal Development Project. *Unpublished* Third Phase Report, Japan International Cooperation Agency. Japan.

Jurio R.I., 1978. Algunos aspectos geotérmicos de las manifestaciones hidrotermales del Cerro Domuyo. Provincial del Neuquén. Argentina. *Revista Minería*, v. **179**, p 45-52.

Kay, S.M., Burns, M., Copeland, P., Mancilla, O., 2006. Upper Cretaceous to Holocene magmatism and evidence for transient Miocene shallowing of the Andean subduction zone under the northern Neuquén basin. In: Kay, S.M., Ramos, V.A. (Eds.), Evolution of an Andean Margin: A Tectonic and Magmatic View from the Andes to the Neuquén Basin (35°–39°S Latitude). *Geological Society of America, Special Paper*, v. **407**, pp. 19–60.

Kietzmann, D. A. y Vennari, V. V., 2013. Sedimentología y estratigrafía de la Formación Vaca Muerta (Tithoniano-Berriasiano) en el área del cerro Domuyo, norte de Neuquén, Argentina. *Andean Geology*, **40(1)**, 41-65.

Llambias, E., Palacios, M., Danderfer, J.C., Brongioni, N., 1978. Las rocas ígneas cenozoicas del Volcán Domuyo y áreas adyacentes, *Proceedings,* 7°Congreso Geológico Argentino, Neuquén, 2, pp. 569-584.

Llambias. E., 1986. Intrusivos pérmicos del sur de la Cordillera del Viento, provincia del Neuquén. *Revista de la Asociación Geológica Argentina* **41** (1-2), 22-32.

Llambías, E. J., Bertotto, G. W., Risso, C., y Hernando, I. R., 2010. El volcanismo cuaternario en el retroarco de Payenia: una revisión. *Revista de la Asociación Geológica Argentina*, **67 (2):**278-300.

Miranda, F. J., 1996. Caracterización petrográfica y geoquímica del Cerro Domuyo, Provincia de Neuquén – Argentina (Tesis de licenciatura). Buenos Aires. Universidad de Buenos Aires. Facultad de Ciencias Exactas y Naturales p. 118.

Miranda, F., Folguera, A., Leal, P. R., Naranjo, J. A., & Pesce, A. (2006). Upper Pliocene to Lower Pleistocene volcanic complexes and Upper Neogene deformation in the south-central Andes (36°30′–38°S). In Special Paper 407: Evolution of an Andean Margin: A Tectonic and Magmatic View from the Andes to the Neuquén Basin (35°-39°S latitude). *Geological Society of America, Special Paper*, v. **407**, pp. 287–298.

Palacio, M., Llambias, E. J., 1978. Las fuentes termales del volcán Domuyo. Provincial del Neuquén, *Proceedings,* 7° Congreso Geológico Argentino, 9-15 de Abril, 1978. Neuquén (Argentina), 2 pp. 145-159.

Panarello, H., Sierra, J., D'Amore, F., Pedro, G., 1990. Isotopic and geochemical study of the Domuyo Geothermal field, Neuquén, Argentina, *Proceedings*, Geothermal investigations with isotopes and geochemical techniques in Latin America: San José, Costa Rica, final research coordination meeting, 12-16 November 1990, OIEA, 1992, p. 31-56.

Pesce, A.H., 1983. Estudio de prefactibilidad: Evaluación geotérmica área del Cerro Domuyo, provincia del Neuquén, República Argentina. Síntesis de los Resultados; Estratigráficos, Vulcanológicos, Estructurales y Geoquímicos. Modelo Geotérmico. Grupo de Trabajo Vulcanología. *Reporte inédito,* Servicio Geológico Nacional, Buenos Aires, Argentina, 43 pp.

Pesce, A. H., 2013. The Domuyo Geothermal Area, Neuquén, Argentina. *Geothermal Resources Council Transactions*, Vol. **37**, 2013.

Pesce, A.H., 1983, Evaluación geotérmica del área del cerro Domuyo (Neuquén): SEGEMAR (Servicio Geológico Minero Argentino) Argentina Open-File Report, Serie Contribuciones Técnicas, *Geotermia*, v. **1**, 46 p.

Sagripanti, L., Folguera, A., Giménez, M., Rojas Vera, E. A., Fabiano, J. J., Molnar, N., et al. (2014). Geometry of Middle to Late Triassic extensional deformation pattern in the Cordillera del Viento (Southern Central Andes): A combined field and geophysical study. *Journal of Iberian Geology*, **40(2)**, 1–18.

Suarez, M. y De la Cruz, R., 1997. Volcanismo pliniano del Lías durante los inicios de la cuenca de Neuquén, Cordillera del Viento, Neuquén, Argentina, *Proceedings,* 7° Congreso Geológico Chileno, 1: 266-270.

U. S. Geological Survey (1979). Assessment of Geothermal Resources of the United States - 1978. Geological Survey Circular 790. L.J.P. Muffler, Ed.

U. S. Geological Survey (2008). A Review of Methods Applied by de U. S. Geological Survey in the Assessment of Identified Geothermal Resources. C. F. Williams, Ed.