Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Hydrothermal alteration mineralogy and fluid inclusion studies in Cuyanausul geothermal area, El Salvador

Elizabeth Torio Henriquez

LAGEO S.A. de C.V. 15 Av. Sur, Colonia Utila, Santa Tecla, La Libertad, El Salvador

ehenriquez@lageo.com.sv

Keywords: Fluid inclusion, petrographic analysis, phyllitic facies

ABSTRACT

In 2005, two exploratory wells (TO-1 and TO-1A) were drilled in Cuyanausul geothermal area to evaluate the geothermal resource of the eastern part of the Ahuachapán geothermal field in El Salvador. Preliminary petrographic analysis of cuttings and core samples identified the mineral assemblage of the propylitic facies at depth, where mineralogical temperature indicated 240 – 260°C. Fluid inclusion studies undertaken by LAGEO (2021) and CNR, Italy (2005) in core samples of the two wells gave temperatures of homogenization similar to the measured temperatures, with well TO-1 (1500 m depth) having a mean temperature of 267°C both on primary and secondary inclusions of calcite crystals and the measured temperature of 259°C (2021), while well TO-1A (1180 m depth) with 251°C and measured temperature of 250°C (2021). This means that the fluid inclusions trapped in calcite crystals are in equilibrium with the present geothermal fluids. However, core samples at both depths belong to the phyllitic facies where mineralogical temperature is only 200 – 220°C, which might indicate that hydrothermal alteration occurred earlier than the formation of calcite crystals in the fractures and pores of the rocks (breccia and pyroclastic deposits).

1. INTRODUCTION

The Cuyanausul geothermal area is located East of the Ahuachapán geothermal field, El Salvador (Figure 1). Geoscientific studies were carried out in 2003 to 2005 and subsequently, two wells were drilled near the Tortuguero fumarole, based on the conceptual model of the geothermal area. The first well drilled was TO-1 (vertical well) to evaluate the geothermal resource of the area, with a final depth of 2334.5 m. The second well TO-1A was directed to the Tortuguero fumarole, to the East to verify the extension of the thermal anomaly identified in well TO-1, with a final depth of 2839 m MD (2721.35 m TVD). However, drilling results showed poor permeability despite having good temperature at depth.

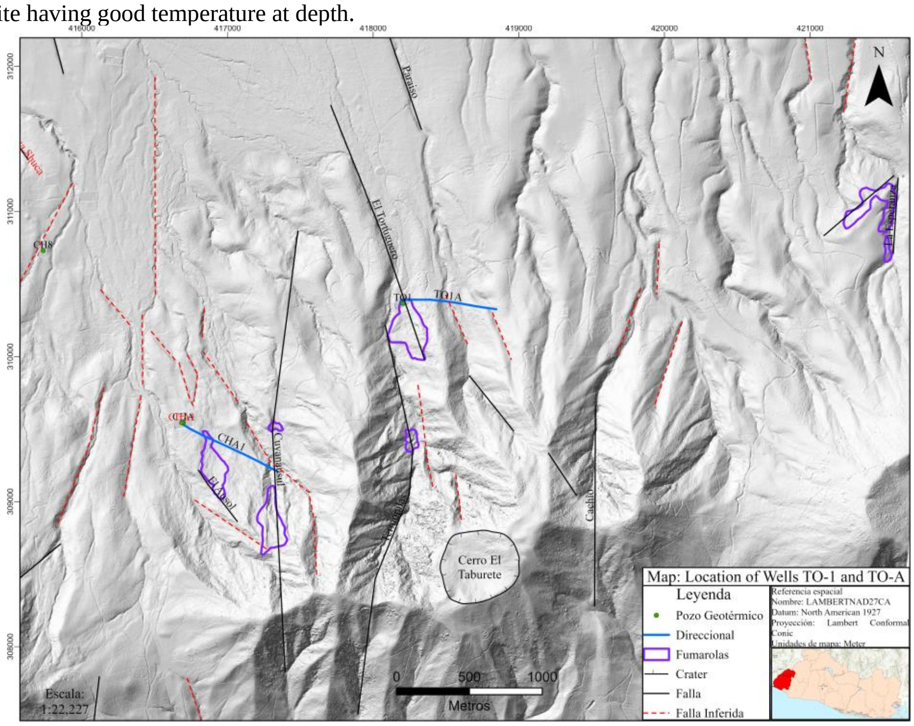

Figure 1: Location of wells TO-1 and TO-1A

Table 1 shows a summary of the technical completion, temperature, and permeability characteristics of the TO-1 and TO-1A exploratory wells drilled in the Cuyanausul geothermal area in 2005.

Well	Drlling date	Well design	Final depth (m)	Well characteristics
TO-1	07/03/05 – 21/06/05	4 stages - Cased down to 690 m with 9 $^5/_8$" casing - 704 to 2334.5 m: Open hole - 2147 to 2334.5 m: Total loss of circulation (TLC)	2334.5	Vertical T = 270°C (2000 m MD) Injectivity: 0.8 m3/h/bar Poor permeability Formation collapses at 735 m
TO-1A	28/06/05 – 29/10/05	5 stages - Cased down to 1780 m with 9 $^5/_8$" casing	2839 m MD (2721.35 m TVD)	Direction: N95° T = 247°C (1832 m MD, 1784 m TVD) Injectivity 0.6 m^3/h/bar Poor permeability Conductive zone below 1800 m TVD No significant fractures

Table 1: Characteristics of wells TO-1 and TO-1A

In 2020, a geoscientific re-evaluation was programmed to be undertaken to construct a more detailed conceptual model in Cuyanausul, however, due to the COVID pandemic, all studies were suspended. In 2021, some geoscientific studies were carried out such as geophysical survey, structural geology, fluid inclusion studies and detailed petrography.

This paper presents the results of petrography, hydrothermal alteration, and fluid inclusion studies.

2. ALTERATION MINERALS

Thin sections of cuttings and core samples of the Tortuguero wells were analyzed by microscopy and X-ray diffraction. A preliminary stratigraphy was proposed, where the first unit, Unit 1, is composed of andesitic lavas and vesicular lavas from 0 to 300 m; Unit 2 with tuff and andesites at the base from 300 to 800 m, Unit 3 with alternating layers of andesites and tuffs from 800 to 1500 m, and Unit 4 mostly with andesitic lavas and breccias from 1500 to final depth (Figure 2).

Most of the alteration minerals are found in the voids and matrix of the rocks, and few are observed filling the veinlets (Henriquez, 2005). Hydrothermal alteration increases slowly throughout the whole section of the well. Clay minerals (smectite) are abundant in the first 400 m. In some sections (1120 - 1235 m), calcite and quartz decrease, while other alteration minerals such as illite, some anhydrite minerals and wairakite appear. Epidote is found in smaller quantities either in cavities, in the matrix or replacing plagioclase. At 1410 to 1465 m, epidote occurs more with 1 - 2%. Most of the high temperature minerals (wairakite and epidote) at depth are found in vesicles and replacing the matrix. Fractures are rare where vein minerals can be observed.

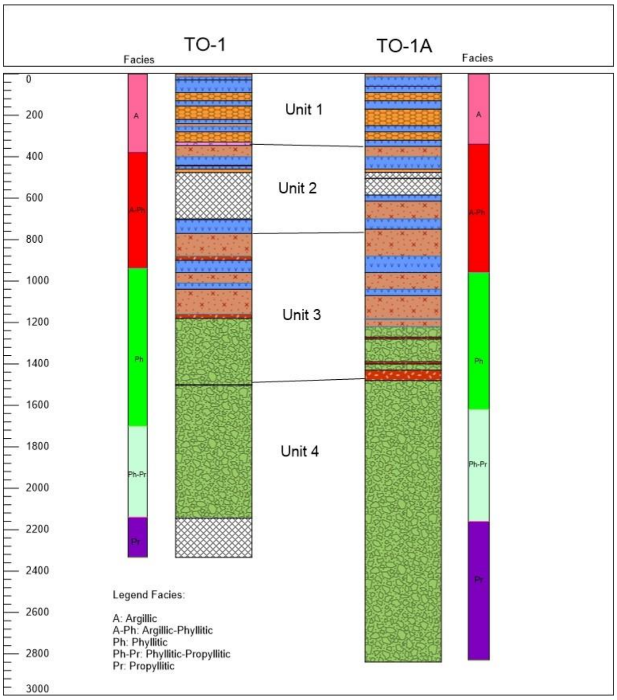

Figure 2: Preliminary stratigraphy and facies of Tortuguero wells

Mineralogical facies with corresponding temperature and depths of wells TO-1 y TO-1A are summarized in Table 2 (Henriquez, 2005; Henriquez & García, 2005). Some high temperature minerals (wairakite, epidote) are found at the upper part at 800 - 900 m depth.

Facies	Key minerals	Temp. (°C)	TO-1 Depth (m)	TO-1A Depth (m MD)
Argillic (A)	Smectite, Corrensite, Quartz, Cristobalite, Calcite, Stilbite, Clinoptilolite, Pyrite, Caolinite, Halloysite, Hematite	50 - 120	0 - 360	0 - 360
Argillic-Phyllitic (A-Ph)	Smectite, Corrensite, Chlorite, Quartz, Calcite, <Wairakite, tz Epidote, Pyrite, Hematite	120 - 200	360 - 940	360 - 940
Phylliic (Ph)	Chlorite, Quartz, Calcite, <Anhydrite, <Wairakite, <Epidote, Hematite	200 - 220	940 - 1600	940 - 1600
Phyllitic-Propyllitic (Ph-Pr)	Chlorite, Quartz, Calcite, <Anhydrite, <Wairakte, Epidote, Ilite, Hematite	220 - 240	1600 - 2140	1600-2160
Propyllitic (Pr)	Chlorite, Quartz, Calcite, <Anhydrite, <Wairakite, Epidote, Ilite, Albite, Hematite	240 - 260		2160 - (2832?)

Table 2: Characteristics of wells TO-1 and TO-1A

3. FLUID INCLUSIONS STUDIES (MICROTHERMOMETRY)

3.1 Fluid inclusion measurement by CNR, Italy

The first fluid inclusions studies in well TO-1 were carried out in IGG-CNR, Pisa, Italy in 2005 on the third core sample at a depth of 1500 - 1503 m, to help provide the formation temperature estimation of the well.

Nineteen homogenization temperature measurements were carried out on calcite crystals, giving a range of temperature from 205° to 265°C, and 18 melting temperature measurements with values from -1.0° to -0.3°C. The inclusions were found to be mostly vapor-rich inclusions.

Likewise, four homogenization temperatures were measured in quartz crystals giving a temperature range of 258° to 262°C and melting temperature of -0.6° to -0.5°C.

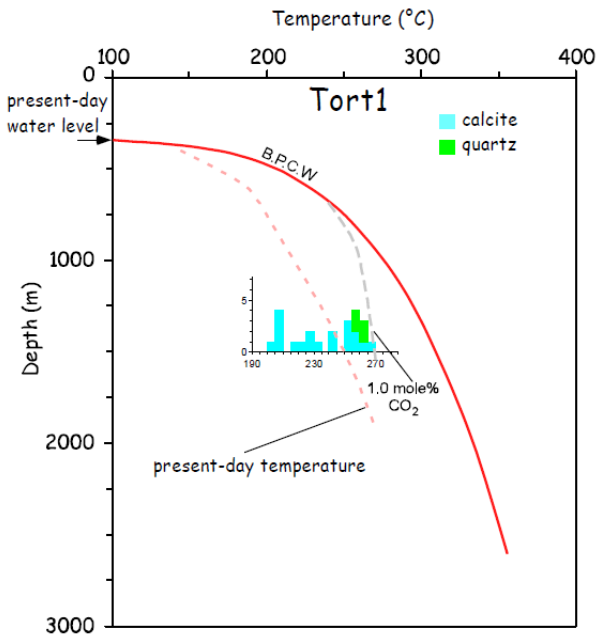

Figure 3: Graph of temperature versus depth with homogenization temperature. (Source: ENEL, 2005)

Figure 3 shows that the homogenization (Th) of fluid inclusions in quartz crystals (green color) are higher (258°-262°C) than the present day temperature (red dotted lines); while fluid inclusions in calcite crystals (blue color) have a wider Th range (205°-265°C), which could be related to the thermal variation of hydrothermal fluids, two-phase trapping during the boiling process or probably necking down (where it induces partitioning of inclusions). The high Th values could indicate that the past temperature was higher than the present measured temperature.

Considering the highest Th and the presence of vapour-rich inclusions, water table might have been lower that the present-day level and might have contained higher amount of CO_2 (ENEL, 2005).

In Figure 4, the graph of Th vs. Tm shows two geochemical processes during trapping of fluid inclusion:

(a) fluid cooling or dilution probably due to infiltration of meteoric water

b) boiling due to the presence of vapor-rich inclusions together with liquid-rich inclusions.

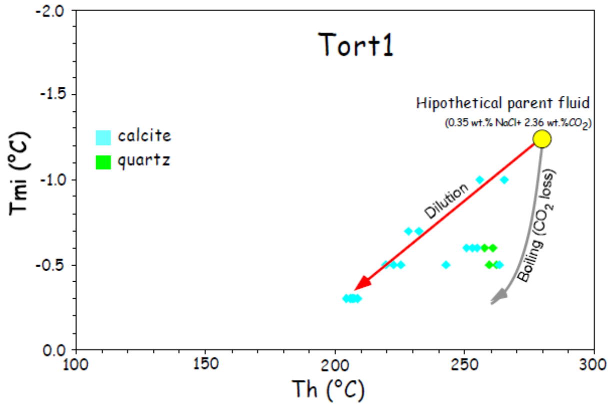

Figure 4: Graph of Th vs Tm (Source: ENEL, 2005)

3.2 Fluid inclusion measurement by LAGEO

As part of the complementary studies of fluid inclusions in Cuyanausul, homogenization and melting temperatures were measured by LAGEO on the same core sample used by CNR of well TO-1 (1500 - 1503 m, Photo 1). Core sample from well TO-1A (1182 - 1186 m, Photo 2) was also included to contribute new data in updating the conceptual model of Cuyanausul geothermal area.

Calcite crystals found in the voids and veins in the two core samples were selected.

Figure 5: Calcite in veins, TO-1 (1500-1503 m) **Figure 6: Calcite in vesicle, TO-1A (1182 – 1186 m)**

<u>3.2.1 Well TO-1</u>

Core sample #3 at 1500 - 1503 m is classified as a brecciated lava. Two tectonic events are observed based on the presence of fractures: a) the older one contains fractures mostly filled with Fe oxides, and b) the more recent one contains microfractures completely filled with calcite, quartz and chlorite (ENEL, 2005).

Twenty-nine inclusions were measured by LAGEO in calcite crystals where most of the inclusions are secondary inclusions, two-phase fluids, and a liquid-vapor ratio of 80%-20%.

Primary inclusions were also identified and gave a temperature range from 252.7°C to 281.2°C, with an average value of 267.8°C while the secondary inclusions gave a temperature range from 258.1°C to 280.6°C, with an average value of 265.8°C, almost similar to the temperatures of primary inclusions (Figure 7).

It can be assumed that the trapping of primary and secondary inclusions could be almost at the same time with a fluid temperature range of 265.8°C - 267.8°C.

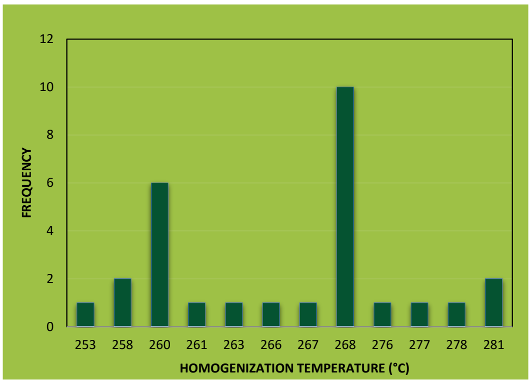

Figure 7: Histogram of homogenization temperature of well TO-1

In Figure 8, the histogram (yellowish) of the homogenization temperatures measured by LAGEO is shown. It can be seen that the highest temperatures of 260°C - 268°C are in the phyllitic facies, and are slightly higher than the 2005 temperature profile and the 200 - 220°C mineralogical temperature. However, the 268°C data coincides with the 1 mole% CO2 content, which confirms the presence of vapor-rich inclusions; also on the recent boiling curve. The cooling and boiling process is confirmed in the Tm vs Th plot in Figure 3. It is worth mentioning that the available temperature profile is only from 2005, since measurements could not be undertaken due to the plugging inside the well.

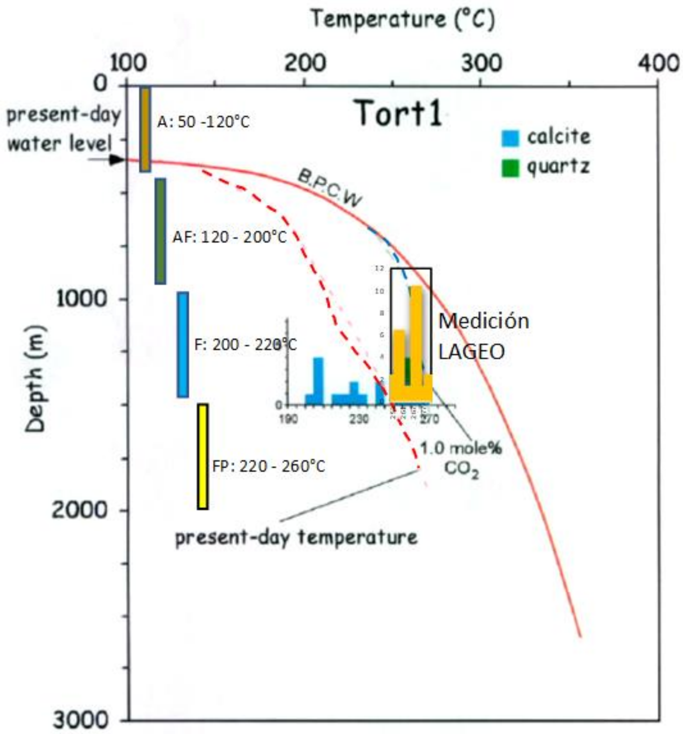

Figure 8: Temperature profile and homogenization temperature of well TO-1 (Modified: ENEL report, 2005)

3.2.1 Well TO-1A

Core sample #2 (1182 - 1186 m) of well TO-1A is classified as a pyroclastic rock with calcite-filled voids and fractures.

Most of the inclusions in the calcite crystals are primary with a homogenization temperature range of 242.8°C - 255.6°C (Figure 9) and an average of 250.7°C, which is higher than the temperature measured at this depth with 211.9°C in 2005 (Figure |10). However, measurement of reservoir temperature was undertaken in 2021 and has reached a temperature of 250°C, almost the same as the homogenization temperature of 250.7°C at this depth (Figure 10). The melting temperature provided temperature from -0.1°C to 0.2°C, with an average of -0.1°C equivalent to 1071 ppm Cl.

Most of the fluid inclusions are found in the phyllitic facies, which has mineralogical temperature of 200°C - 220°C.

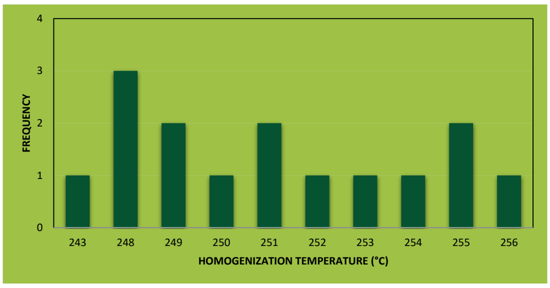

Figure 9: Histogram of homogenization temperature of well TO-1A

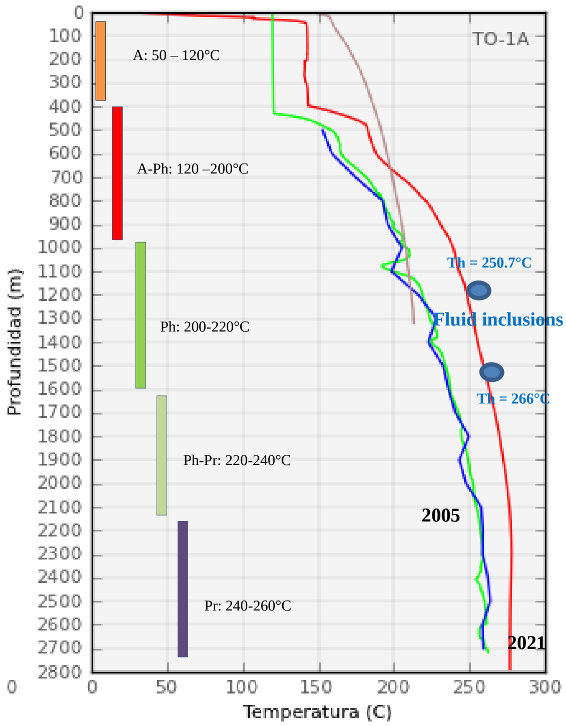

Figure 10: Temperature profiles 2005 and 2021; homogenization temperature and facies of well TO-1A

4. DISCUSSION

The different temperatures (measured temperature, homogenization temperature and mineralogical temperature) were correlated to evaluate the thermal evolution of the Tortuguero geothermal field reservoir (Figure 10).

Fluid inclusions in well TO-1 at 1500 - 1503 m depth has an average homogenization temperature of 267.8°C in primary inclusions and 265.8°C in secondary inclusions, which is slightly higher (approximately 15°C more) than the **2005** measured (static) temperature of 250°C and mineralogical temperature of 200°C -220°C in the phyllitic facies. However, using the temperature profile from well TO-1A in **2021** it is found to be around 260°C (Figure 10) at this depth, and almost 40°C higher than that of the 200 - 220°C mineralogical temperature in the phyllitic facies.

Most of the fluid inclusions in well TO-1A reach an average homogenization temperature of 250.7°C, which is in equilibrium with the measured temperature in 2021 of 250°C, according to the temperature profile at depth of 1182 - 1186 m. At this depth the phyllitic facies is found with a mineralogical temperature of 200 - 220°C, which is less than 30°C - 50°C of the measured temperature. Therefore, the original fluid (primary inclusions) of the reservoir at this depth, with homogenization temperature of 250.7°C is in equilibrium with the recent fluid, indicating that the calcite crystals trapped recent fluids during their growth.

In both wells, it is observed that the average homogenization temperatures (blue circle) are in equilibrium with the recently measured temperature. Below 1500 m, temperature is almost linear and isothermal.

Therefore, the fluids trapped in the calcite crystals have temperatures almost with the same value as the present measured temperature at both depths of 1182 m and 1500 m. Also, these temperatures verify the extension of the reservoir to the east of the area at 1500 m depth. Moreover, reservoir temperature may reach 250 – 270°C at 1500 m.

The hydrothermal alteration has lower temperature than the fluid inclusions temperature and measured temperature, which can be indicate that the alteration process of the minerals initially occurred. Subsequently, there was the fracturing of the rocks and calcite crystals were formed by the recent hydrothermal fluids.

Regarding the salinity of the fluid, according to the melting temperature at 1182 m, the Cl content is about 1071 ppm, which is a little lower than the geothermal water, indicating a dilution in the geochemical process.

Measurement on quartz crystals (ENEL, 2005) provided a homogenization temperature range of 258 to 262°C and melting temperature of -0.6 to -0.5°C, which was closer to the reservoir Cl value of approximately 5000 - 6000 ppm Cl. Therefore, the reservoir temperature is almost similar to the recent fluid temperature of 250 - 260°C.

5. CONCLUSIONS

1. In well TO-1, primary inclusions gave a temperature range from 252.7°C to 281.2°C, with an average value of 267.8°C. Secondary inclusions gave a temperature range from 258.1°C to 280.6°C, with an average value of 265.8°C, almost similar to the temperatures of primary inclusions. The trapping of primary and secondary inclusions could be almost at the same time with a fluid temperature range of 265.8°C - 267.8°C.

2. In well TO-1A, the inclusions in the calcite crystals are mainly primary, with a homogenization temperature range of 242.8 - 255.6°C and an average of 250.7°C, which is equal to the temperature measured at this depth at 250°C, according to the 2021 temperature log profile. The melting temperature provided the most temperature from -0.1°C to 0.2°C, with an average of -0.1°C equivalent to 1071 ppm Cl.

3. Fluids trapped in the 1182 m and 1500 m calcite crystals have homogenization temperatures in equilibrium with the present temperature measured in according to the 2021 profile. According to the geochemical process, these fluids have undergone the process of dilution and boiling due to infiltration of cooler water probably meteoric water into a permeable zone.

4. Hydrothermal alteration in the phyllitic facies has lower temperature of 200 - 220°C than the temperature of fluid inclusions and measured temperature (250°C - 266°C), so hydrothermal alteration minerals have been formed before the present condition, where fluid temperatures are found higher than the mineralogical temperature.

5. In the measurement on quartz crystals (ENEL, 2005) provided a homogenization temperature range of 258 to 262°C and melting temperature of -0.6 to -0.5°C, which was closer to the reservoir Cl value of approximately 5000 - 6000 ppm Cl. Thus, the reservoir temperature is almost similar to the recent fluid temperature of 250 - 260°C.

6. The fluids trapped in the calcite crystals have temperatures almost with the same value as the present measured temperature at both depths of 1182 m (TO-1A) and 1500 m (TO-1). Also, these temperatures verify the extension of the reservoir to the east of the area at 1500 m depth. Moreover, reservoir temperature may reach 250 – 270°C at 1500 m.

7. Summary of fluid inclusion data shown in Table 3.

Well	Depth (m)	Th (°C)	Tm (°C)	Comments
TO-1	1500 1503	CNR (Italy): 205 – 265°C	CNR (Italy): -1.0 to -0.3	Calcite crystals: 205 – 265°C Quartz crystals: 258 – 262°C
		LAGEO: 252.7°C – 281.2°C		Calcite crystals: Ave. Th 265.8 – 267.8°C Facies: Phyllitic (200 – 220°C) Th>Tmin
TO-1A	1182-1186	LAGEO: 242 – 255.6°C	LAGEO: -0.1	Temp. profile (2021): 250°C at this depth Ave. Th = 250.7°C Th = Tmeas In equilibrium

REFERENCES

ENEL: Exploration of the Cuyanausul Geothermal Area, Results of the Exploration Activities, 2005.

ENEL: Exploration of the Cuyanausul Geothermal Area, Summary and Integration of the Geoscientific Data, 2005.

ENEL: Tortuguero-1 Well, Cuyanausul Geothermal Exploration, Final Report, 2005.

ENEL: Tortuguero-1A Well, Cuyanausul Geothermal Exploration, Final Report, 2005.

Henriquez, E.: Análisis por la Técnica de Difracción de Rayos X Muestras de Recortes TO-1, Informe interno, LAGEO, 2005.

Henriquez, E.: Análisis por la Técnica de Difracción de Rayos X Muestras de Recortes TO-1A, Informe Interno, LAGEO, 2005.

Henriquez, E.: Análisis Petrográfico Pozo TO-1 desde 720 m hasta 1040 m, Informe Interno, LAGEO, 2005

Henriquez, E.: Informe Geológico del Pozo TO-1, Informe Interno, LAGEO, 2005.

Henriquez, E., and Garcia, m.o. (2005). Informe Geológico del Pozo TO-1A, Informe Interno, LAGEO, 2005.