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Thermal Characterization of a Geothermal Reservoir in a Volcanic Zone in Central America

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ABSTRACT

Within the framework of the Regional Training Program (PREG), along with the technical and logistical support of LaGeo SA de CV, the thermal characterization of a geothermal reservoir located within an active volcanic system was made through the application of laboratory techniques. It was done using optical microscopy for the identification of hydrothermal alteration minerals and Fluid Inclusion Assemblage (FIA) microthermometry to know the temperature and salinity of the original rock-forming fluids. In addition, along with the comparison of the temperature ranges obtained by mineralogy and FIA and the stabilized temperature records of the wells, it is possible to know the thermal evolution of the reservoir. Thus, contributing to the updating of the conceptual model of a geothermal field.

The samples analyzed correspond to cores of rocks of a reservoir area of three deep geothermal wells. Five samples of calcite and anhydrite veins were considered to perform doubly polished sections and subsequently microthermometry, and thin section samples for the identification of mineral temperature indicators. With them, reservoir temperature ranges were obtained for the depth intervals of the analyzed samples and compared with the stabilized temperature profiles of the well logs. All of them were to understand and know the evolution and thermal state of the reservoir.

1. INTRODUCTION

This study involves the analysis and interpretation of a geothermal reservoir using petrography and fluid inclusion studies, as part of the final work in PREG (Geothermal training program in El Salvador) and LAGEO S.A de C.V. Results were obtained by petrographic analysis of core samples in the reservoir zone of three wells located in one of the geothermal areas in El Salvador (identity of wells not mentioned due to confidentiality). The mineralogical assemblage of alteration facies and mineralogical temperature range (Tm) through petrography were estimated. Microthermometry of fluid inclusions in calcite and quartz was used to determine the homogenization temperature or minimum entrapment temperature (Th) and melting temperature (Tm) to calculate salinity content in the system (% NaCl). It was estimated the mineralogical temperature.

2. REGIONAL STRUCTURAL SETTINGS

This study was developed in an active volcanic zone, as part of the Volcanic Arc that crosses Central America, as result of the subduction of the Cocos plate beneath the Caribe plate (Fig. 1). This subduction environment produced compressional strains and large longitudinal fractures developing graben structures. This allows the up-flow of subcortical magma and location of magmatic chambers at shallow depth, probably of the order of 10 km.

These chambers have been, as of the Tertiary Superior, the power source of the Quaternary volcanism and continue to be the current volcanic activity.

These chambers are the origin of the strong geothermal anomalies associated with volcanism, in such a way that both volcanoes and geothermal areas have the same origin, but their formation is different. Volcanoes receive a direct feed of high-temperature magmatic material (around 1000 ° C), while geothermal areas are formed from a heat flow that is transmitted through the rocks that enclose the magma chamber.

Stratigraphic sequence in the geothermal area studied is composed of effusive basic to intermediates lavas from Pleistocene. Above them, there are pyroclastic, lapilli tuff, volcanic ash, and finally, sediment deposits from Holocene (Fig. 1). The structural geology of the area is directly influenced by the subduction of the Cocos and Caribbean plates, as in most of the geothermal fields of Central America. In the study area, the predominant regional structure is the Central tectonic trench of El Salvador with an EW preferential trend. There are at least two fault systems in the area. The first system corresponds to the Central Graben with preferential trend EW and the second system has a preferential trend NS, which is quite evident in the area. N-S and NNW-SSE lineaments are predominants in the study area and correspond to the local fault systems (Matus, 2009).

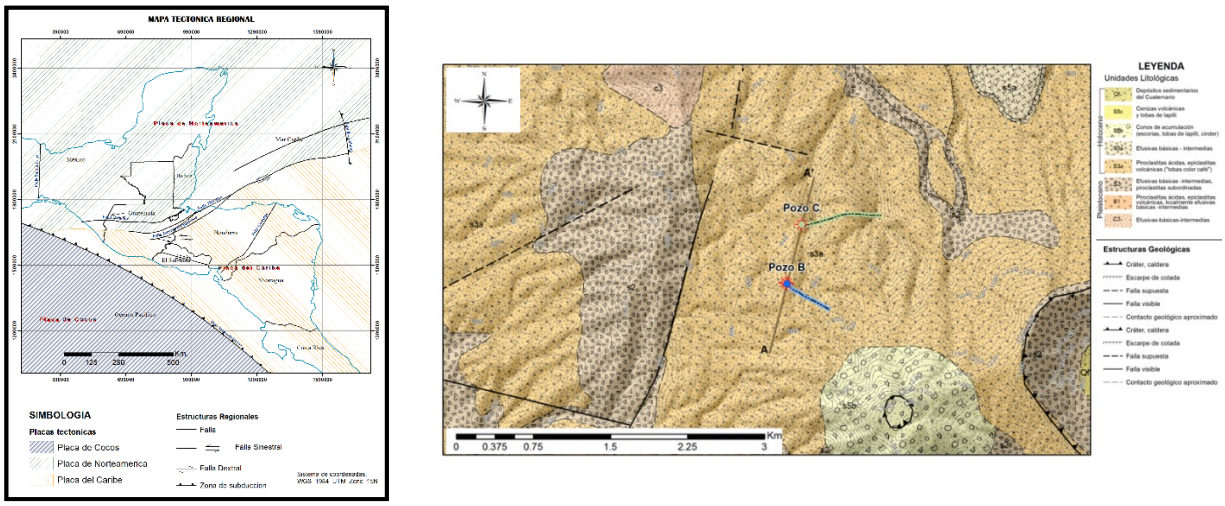


Figure 1. Regional tectonic setting (left) and geological map (right). Identity of wells and geographic coordinates not mentioned due to confidentiality rights.

3. METHODOLOGY

Thin sections were selected at different depths in located reservoir zones of the core rock of the geothermal wells in which hydrothermal alteration of high temperature was evidenced (Fig. 2). Thanks to the petrography of these thin sections, temperature indicator minerals were identified, establishing mineralogical facies and thus temperature ranges of the geothermal reservoir.

Additionally, veins samples were taken from the rock cores in reservoir areas of the three deep wells for microthermometry measurements. The selection of the samples to carry out the preparation and, subsequently the microthermometry, was made considering that they represented secondary events in the formation of the rock and that they have become elements of the high-temperature alteration. The petrography of fluid inclusions consisted of the identification of the FIA (Fluid Inclusion Assemblage), the geometry of the fluid inclusions, their location in the crystals and the type of inclusions.

The microthermometric analysis was made in LINKHAM MSDG 600 cooling and heating platform and a Nikon microscope with 4X, 10X, 20X and 50X lenses (Fig. 2). The procedure consisted of cooling the sample (chip) with liquid nitrogen to -60°C (approximately) and gradually heating until the final melting of the ice. This melting indicates the salinity of the trapped fluid and homogenization of the fluid inclusion, indicating the temperature of the reservoir. During the heating, changes in the phases of interest are mainly observed: final melting temperature (Tm) and homogenization or minimum entrapment temperature (Th).

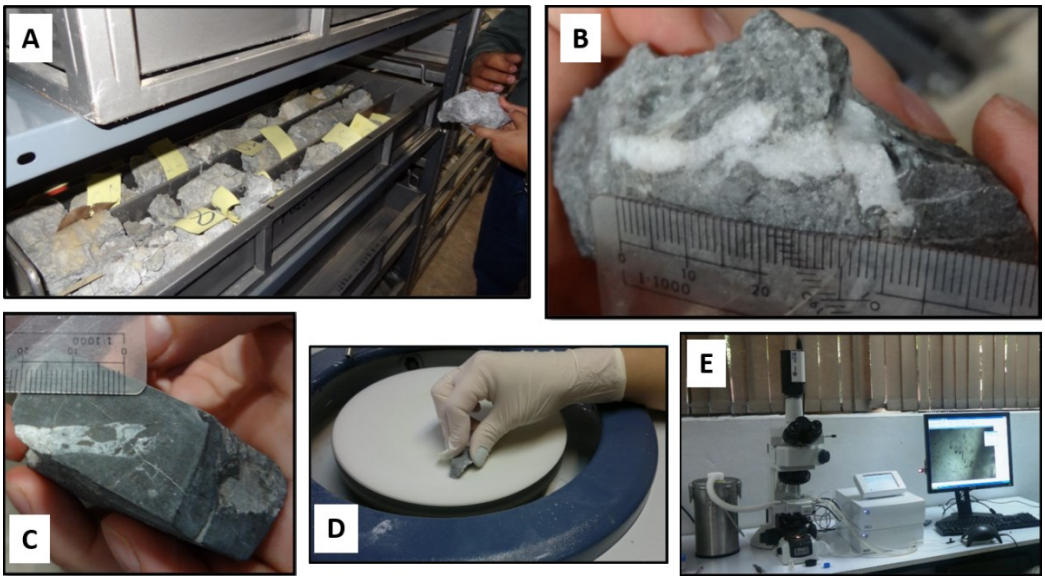


Figure 2. A. One of the core rocks with hydrothermal alteration. B and C. Samples with hydrothermal mineralization in veins used for microthermometry. D. Preparation of a doubly polished thin section for microthermometry. E. Microthermometry equipment.

4. RESULTS AND DISCUSSION

4.1 Hydrothermal alteration mineralogy

In the studied wells of this geothermal field, alteration minerals appear as a replacement for primary minerals, filling veins and fractures, and occasionally cavities. The abundance of the alteration minerals identification was carried out through the petrographic analysis of rock witnesses from the geothermal wells.

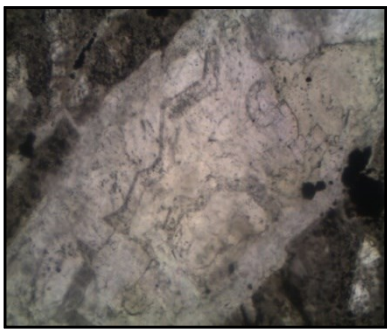
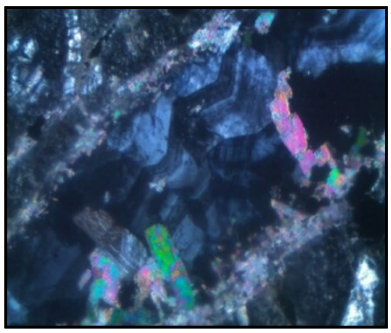
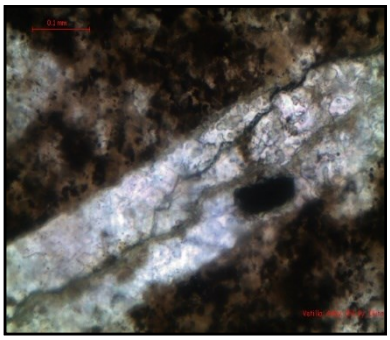
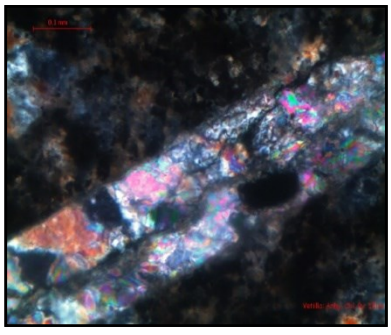
The alteration mineral present in all wells and with a greater proportion corresponds to anhydrite. Other minerals were found but their presence and abundance vary according to the well and the depth. These minerals are calcite, actinolite, wairakite, chlorite, pyrite and quartz. Table 1 shows the percentages of minerals of alteration indicators of temperature and Table 2 shows the microphotography of the samples with hydrothermal mineralogy alteration.

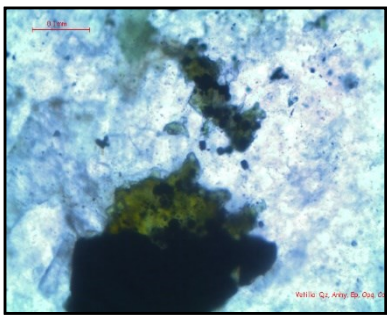
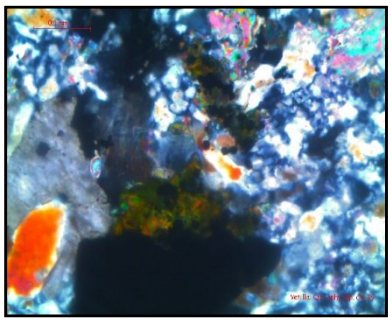
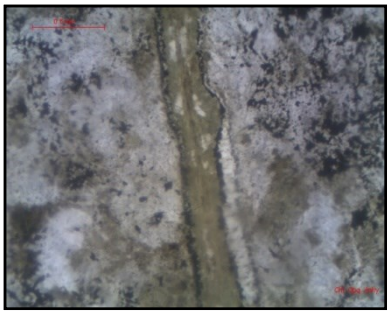
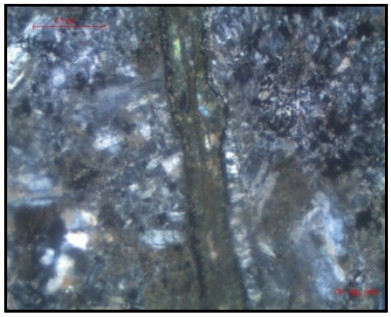
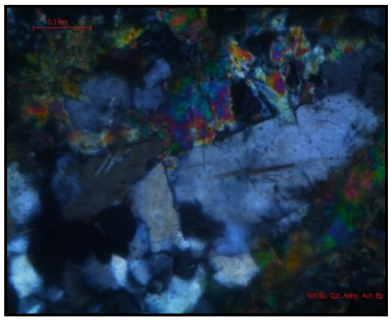
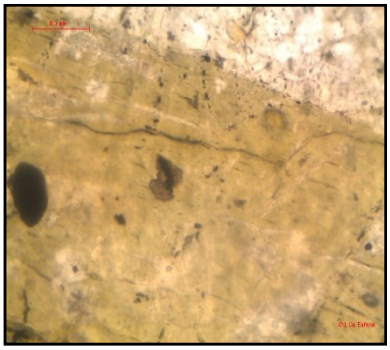
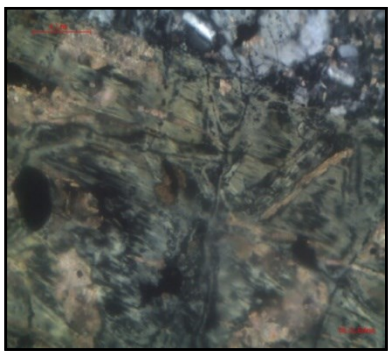
Table 1. Shows the percentages of minerals of alteration indicators of temperature.

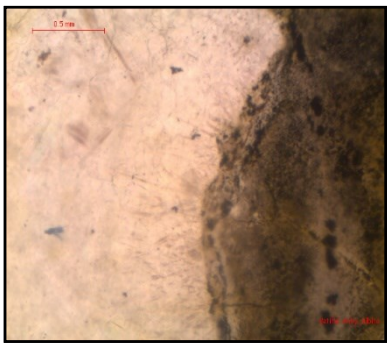
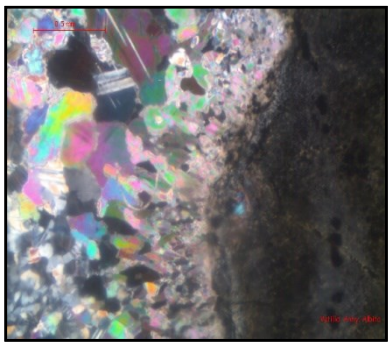
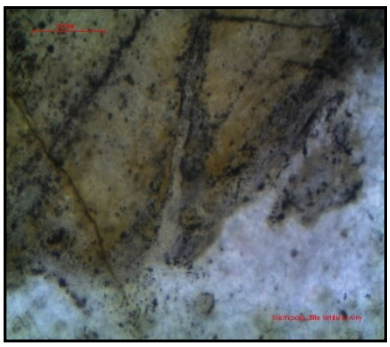
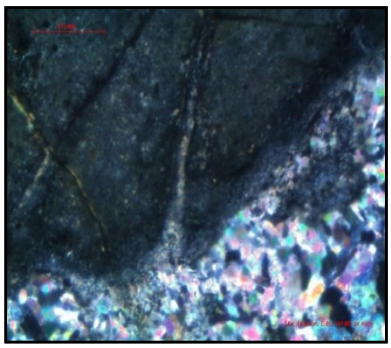
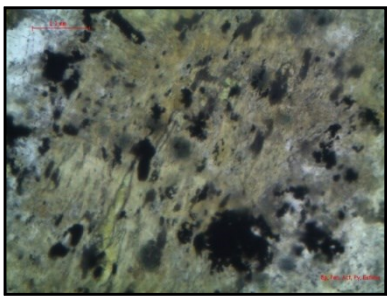
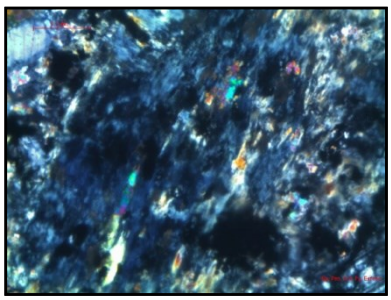
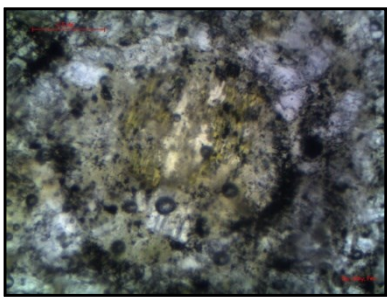
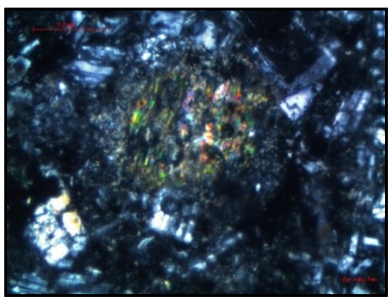
Well / Core	Depth (m)	% Anh	% Wai	% Ca	% Ep	% Chl	% Pen	% Act	% Qz	% Bt	% Py	% Ilt	% Spn	% Ab
A/1	1474-1478	4-2	9-1	1	-	1	-	-	1	-	25-1	10-1	-	-
A/2	1657-1661	7-1	1	2	6-3	17-3	-	15-1	21-5	7-3	12-2	-	-	-
B/1	1277-1279	15-2	-	15-7	-	20-5	-	-	35-5		13-7	-	10-1	10-1
B/2	1474-1478	18-3	-	-	-	5-1	-	-	40-8	-	25-5	30-10	-	-
C/1	2002-2004	7-3	-	-	10-3	-	15-1	7-1	12-4	-	-	-	3	-

Abbreviation: Anhydrite (Anh), Wairakite (Wai), Calcite (Ca), Epidote (Ep), Chlorite (Chl), Pennine (Pen), Actinolite (Act), Quartz (Qz), Biotite (Bt), Pyrite (Py), Illite (Ilt), Sphene (Spn), Albite (Ab).

Table 2. Microphotography of the samples with hydrothermal mineralogy alteration.

Well/Core (Depth in TVD)	Microphotography in PPL	Microphotography in XPL	Description
A/1 (1474-1479)			Vein fill with Wai and Anh, matrix altered by Ilt
A/1 (1474-1479)			Vein fill with Anh and Py, matrix altered by Chl and Ilt

Well/Core (Depth in TVD)	Microphotography in PPL	Microphotography in XPL	Description
A/2 (1657-1661)			Vein filled with Qz, Ep, Ca, Anh and Py
A/2 (1657-1661)			Vein filled with Chl, Anh, and Qz. Py in edges
A/2 (1657-1661)			Vein filled with Qz, Ep, Anh, Ca, and Act
B/1 (1229-1231)			Pseudomorph of piroxen altered by Chl, Spn and Ca

Well/Core (Depth in TVD)	Microphotography in PPL	Microphotography in XPL	Description
B/1 (1229-1231)			Vein of Anhand Ab
B/2 (1396-1400)			Vein with Anh, Ilt, Qz, and Py
C/1 (1856-1858)			Pseudomorph of piroxen altered by Ep, Act, Penn, Spn, and Py
C/1 (1856-1858)			Pseudomorph of piroxen reemplaced by Ep, Anh, and Penn

4.2 Temperature ranges according to mineralogy

Temperature ranges interpreted for each well in areas of geothermal reservoir are presented below according to occurrence of minerals and their abundance in each of the wells and their cores, the stabilized temperature ranges for each mineral, and the assembles of minerals used as temperature indicators. Ranges, where a mineral is in thermodynamic equilibrium, are represented as a red line, dashed lines meaning a range of temperature where the mineral is not in equilibrium. So, ranges, where assemblage of minerals in each core samples are in equilibrium between them, are shown using a polygon with dashed gray lines in Figure 3. These ranges indicate the temperature at which the minerals present in the rock have formed and remain in equilibrium, implying the temperature of the reservoir.



Figure 3. Ranges of interpreted temperature in the reservoir zone from mineralogy.

According to Table 3 for each well and its depth, the mineralogical assemblage is assigned. In Table 3, these assemblages are summarized:

Table 3. Mineralogical temperature ranges from wells analyzed of a geothermal reservoir.

Well/Core	Depth (TVD)	Ranges of temperature in reservoir zone according to petrography of mineralization (°C)	Minerals indicators of temperature	Mineralogical assemblage	Temperature range for assemblage (°C)
A / 1	1474-1479	200-240	Ilt, Anh, Wai	Phyllic-Propylitic	220-260
A / 2	1657-1661	Above a 280	Act, Bt, Ep	Propylitic	>260
B / 1	1229-1231	200-220	Spn, Ab	Phyllic-Propylitic	220-260
B / 2	1396-1400	220-240	Ilt, Anh	Phyllic-Propylitic	220-260
C	1856-1858	Above 280	Act, Ep	Propylitic	>260

4.3 Microthermometry of Fluid Inclusions Assemblages

Fluid inclusions were found in colorless and translucent crystals of calcite and anhydrite. They are of two phases of the type L-S (liquid-steam) with a higher liquid ratio, a relative proportion of the vapor phase of approximately 15% to 20% is calculated with respect to the total size of the inclusion.

The values obtained from homogenization temperatures (Th), after heating sequences (Fig. 4) of the fluid inclusions assemblages for each sample, were grouped in frequency histograms to know the temperature of the hydrothermal were trapped in these inclusions.

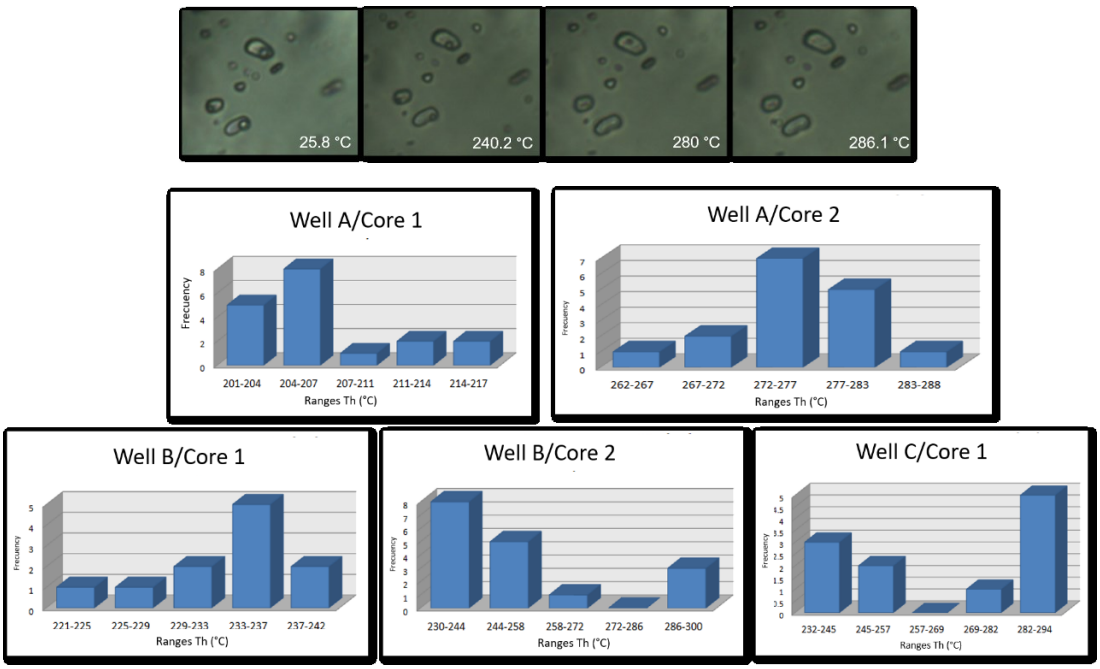


Figure 4. Heating sequence to determinate the Th in FIA and histograms of Th of Wells A, B, and C.

The melting temperature (Tm) of the ice was measured at the same FIA in which homogenization temperature (Th) was determined. In order to estimate the salinity of the hydrothermal fluid that reacted with the rock and which in turn was trapped as a fluid inclusion.

Considering all the information of temperatures obtained by mineralogical assemblages determined with petrography, Th and Tm of the fluid inclusions and stabilized temperature of wells (Ts), the comparison of these ranges of the temperature of the reservoir is made and helps to know reservoir behavior in nowadays (Table 4, Figure 5).

Table 4. Mineralogical temperature, Th, Tm of FIA, and Wells measured temperatures in the Three Wells A, B, and C.

Well/ Core	Depth (TVD)	Mineralogical temperature (°C)	Minerals indicators of temperature	Mineralogical assemblage	Th (°C)	Tm (°C)	Wt. % NaCl	Stabilized temperature of wells (Ts)	Reservoir Behavior
A / 1	1474-1479	200-240	Ilt, Anh, Wai	Phyllic-Propylitc	201-207	0.1	0.205	203	In thermal equilibrium with geothermal fluid
A / 2	1657-1661	Above a 280	Act, Bt, Ep	Propylitc	272-283	0.3	0.559	187	Cooling or thermal inversion
B / 1	1229-1231	200-220	Spn, Ab	Phyllic-Propylitc	233-237	0.3	0.559	234	In thermal equilibrium with geothermal fluid
B / 2	1396-1400	220-240	Ilt, Anh	Phyllic-Propylitc	230-258	0.3	0.559	231	In thermal equilibrium with geothermal fluid
C	1856-1858	Above 280	Act, Ep	Propylitc	232-257 >282	0.2	0.382	184	Cooling or thermal inversion

The correlation of mineralogical temperature, microthermometry data, and temperature measured in wells A, B, and C are presented in Figure 6. Well C contains actinolite below, almost to the bottom of the well, while wells A and B are identified higher at 1660 m. The presence of actinolite indicates a temperature above 280 ° C, which coincides with the micro-thermometry of fluid inclusions. However, at the bottom of well C, the measured temperature is almost 100°C lower than the mineralogical temperature, so this well is probably more distant from the heat source.

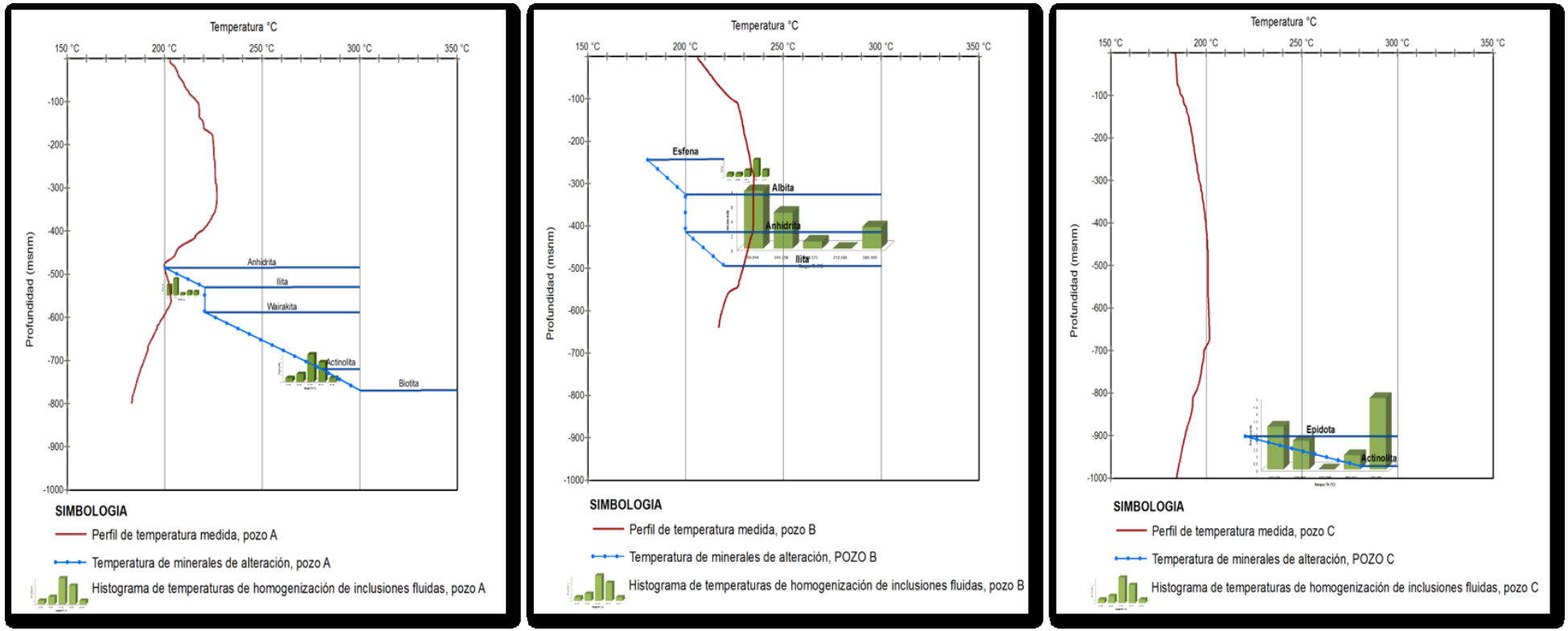


Figure 5. Correlation of stabilized temperature well, mineralogical, and IF homogenization of wells A, B, and C.

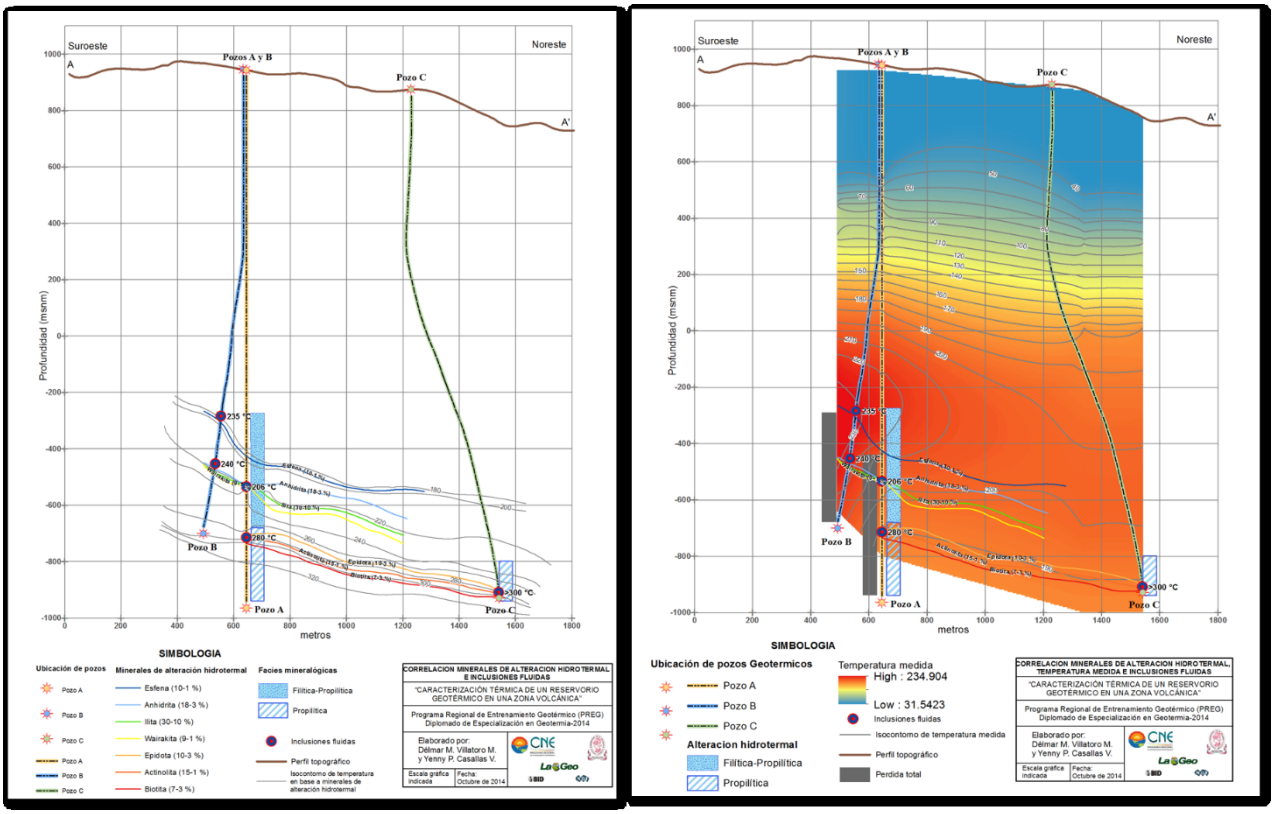


Figure 6. Correlation profile between measured temperatures, inferred temperatures from alteration mineralogy, and homogenization temperature of fluid inclusions.

CONCLUSIONS

Wells located at the southwestern part of the volcano named A and B, have phyllic-propylitic mineralogical facies with temperature from 200°C to 240°C increasing in depth to propylitic facies with a temperature of more than 280°C. These mineralogical temperatures match with Th, with a temperature range from 201°C to 258°C and 0.2 to 0.599 %NaCl. However, the Ts of well A in-depth is lower than the temperatures obtained using mineralogy and micro-thermometry. This probably indicates a cooling process in-depth, while in well B the three temperatures (Th, Tm, Ts) are within the same range, indicating thermal equilibrium. Well C is located in the northeast and has mineralogical facies of propylitic, with temperature over 260°C. Results of Th show two thermal events, one of them with temperatures between 232°C to 257°C, and other hotter one from 282°C and 0.382 de %NaCl. However, Ts is lower than Th and Tm, which could indicate a thermal inversion.

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