Petrologic Evaluation of the Southern Part of Berlin Geothermal Field, El Salvador

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ABSTRACT

Petrologic data has been used to determine the stratigraphical changes, mineral zoning, thermal history and permeability in Berlin geothermal field.

Petrographic and mineralogical analyses showed that the caprock at wells TR-17 and TR-18 is found at higher elevation (500 masl to sea level), composed of altered fine tuff and ignimbritic deposits, confirming the vertical displacement of the Berlín caldera.

Past and present thermal regimes were identified using microthermometry of fluid inclusions in different crystals. Measurement at depths indicated a temperature reversal of 256 – 258°C in wells TR-17 and TR-18, where temperature of homogenization (Th) obtained a maximum temperature of 346°C.

Geochemical data was plotted in variation diagrams to see the trend of the major oxides and relate to the hydrothermal alteration processes.

This paper will focus on the five production wells (TR-17, TR-17A, TR-17B, TR-18 and TR-18A) at the southern part of the field.

1. INTRODUCTION

The Berlin geothermal field is located 110 km ESE of the city of San Salvador, El Salvador (Figure 1). The first exploratory well, TR-1 was drilled in 1968 and intercepted the geothermal reservoir at 1400m depth, with a reservoir temperature of 230ºC. Exploratory drilling continued in 1978 and with the aid of Interamerican Development Bank (IDB) and Electroconsult (ELC), feasibility studies were carried out for a possible exploration and development of the area.

In 1992, two 5 MW back-pressure units were commissioned in Berlín. Expansion of the geothermal field was a priority to address the growing demand of electrical energy of the country. In 1999, two 27.5 MW condensing units went on-line, contributing to the 22% of the total geothermal electricity generation.

At present, a 40 MW plant constructed by ENEL Produzione S.p.A, the company's strategic partner of Lageo, is in operation making a total of 109 MWe.

2. GEOLOGY OF BERLÍN GEOTHERMAL FIELD

The Berlin geothermal field is found at the southern part of the Central American graben (with E-W trend), produced by the subduction of the Cocos plate and the Carribean plate.

It is located at the northern flank of the Berlin-Tecapa Quaternary volcanic complex, which is characterized by basaltic to andesitic lava flows, lithic tuffs and scoria, and andesitic to dacitic ignimbrites

Volcanic-tectonic activities started 1.4 million years ago. Recent volcanic activities (0.1 million years ago) brought large amounts of ignimbritic products produced by the collapse of the volcano and consequently forming the Berlín caldera. A smaller caldera, Blanca Rosa, was formed 75,000 years ago within the Berlín caldera. Subsequent volcanic activities gave origin to the actual Berlín-Tecapa volcanic complex. The last event (700 years ago) is represented by the "El Hoyon" phreatic explosion.

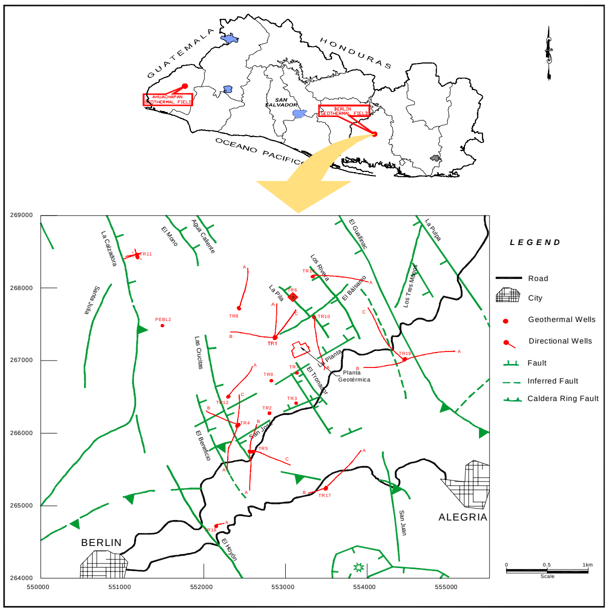

Figure 1: Location map of Berlin Geothermal Field, El Salvador

Four basic lithological units were identified based on drilling of wells and are presented in Table 1.

Nine wells have been drilled at the southern and eastern parts of Berlin geothermal field, five production wells along the northern flanks of the Berlin-Tecapa volcanic- complex (TR-17, TR-17A, TR-17B, TR-18 and TR-18A), within the Berlin caldera and four reinjection wells at the eastern margin of the field (TR-19, TR-19A, TR-19B and TR-19C) in 2003-2006, for the Third Condensing Unit under the ENEL project.

Table 1. Shows a Brief Description of the Lithological Units Found in Berlín Geothermal Field.

Unit	Lithology	Charactersitics	Thickness (m)
1	Andesite to basaltic andesite	Recent deposits	600 to 800
2	Ignimbrite intercalated with scoria and thin layers of andesite	Where intermediate aquifer is located	570 to 850
3	Fine silicified lithic tuff	Serves as the caprock	105 to 345
4	Andesite to basaltic andesite with intercalation of lithic tuff and presence of volcanic dykes	Where reservoir is located	370 to 920

Table 2. Characteristics of Production Wells at the Southern Part of the Field.

Well	Depth (m TVD)	Main Feed Zone (m TVD) (Rodriguez, 2006)	Reservoir temp. (°C)
TR-17	2600	1375, 2000, 2400	245-270
TR-17A	2530	2050, 2350 2530 (2nd feedzone)	280 230
TR-17B	1809	1545	252
TR-18	2600	1900	265
TR-18A	1073	1000	248

3. METHODS OF EVALUATION

Cores and cuttings were examined using petrographic and stereographic microscope to recognize the sequence of the hydrothermal minerals, texture and microstructures. Clay minerals and other hydrothermal alteration minerals were identified through X-ray diffraction method. Preliminary results of the fluid inclusion microthermometry were included to delineate the thermal history of the field.

4. RESULTS AND DISCUSSION

4.1 Petrography

4.1.1 Caprock

Petrographic analysis revealed the presence of caprock (Unit 3) at higher elevation in wells TR-17 and TR-18 than the rest of the wells of the geothermal field (Figure 2).

The presence of fine tuff and ignimbritic deposits in wells TR-17, TR-17A and TR-17B indicates the caprock at 1040 m up to 1300 m, while in TR-18 at 1080 m up to 1360 m, within the boundary of the phyllitic/phyllitic-propylitic facies.

Stratigraphic difference may be due to the vertical displacement of the collapse of the Berlín caldera at the southern part (Área de Geología, 2008), which now confirmed the border of the caldera (previously unknown).

3.1.2 Intrusive Rocks

The first intrusive rock in the Berlin geothermal field was found in well TR-14A, which belongs to a fine-grained, partially altered granodiorite.

Drilling of wells at the NE part of the field (TR-19) showed the presence of almost fresh granite and some hornfels (Figure 3). Moreover, well TR-17A (deviated at N45E) also encountered granite at 2530 m.

Revision of cuttings in well TR-5A showed the presence of biotite and fresh quartz at 1960 m to 2120 m, which indicates the appearance of intrusive rocks.

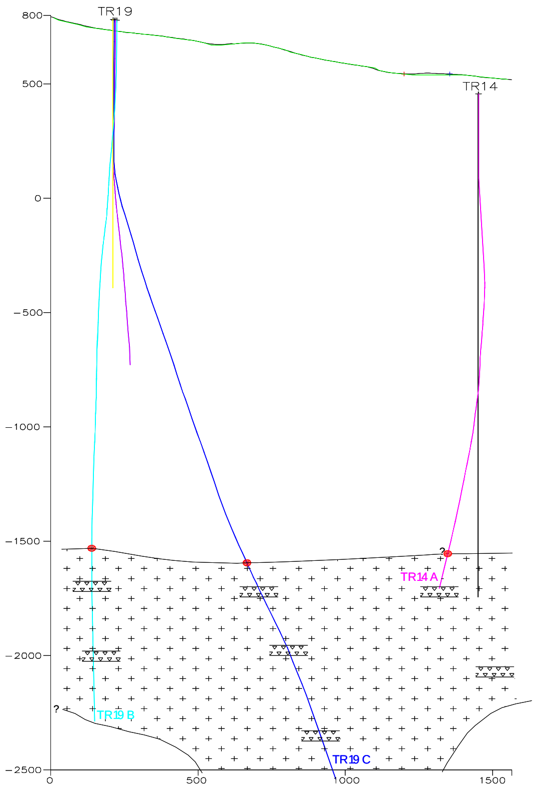

Figure 3: N-S profile showing the intrusive rocks intercepted by wells TR-14A, TR-19B and TR-19C

The presence of intrusive rocks was also evidenced by seismic tomography where anomalies of Vp/Vs delineated a dense body of rock.

4.2 Microstructures

The presence of mylonites and shearing, abundance of veins and alteration intensity can help in predicting permeability especially during drilling.

Petrographic analysis identified the presence of shearing at 1240 – 1400 m depths in well TR-17, 1815-2045 m and 2120 – 2160 m depths in well TR-17A, which could indicate possible permeable zones.

The principal fractures in these wells are generally filled with well-formed crystals of epidote, wairakite and occasionally with prehnite.

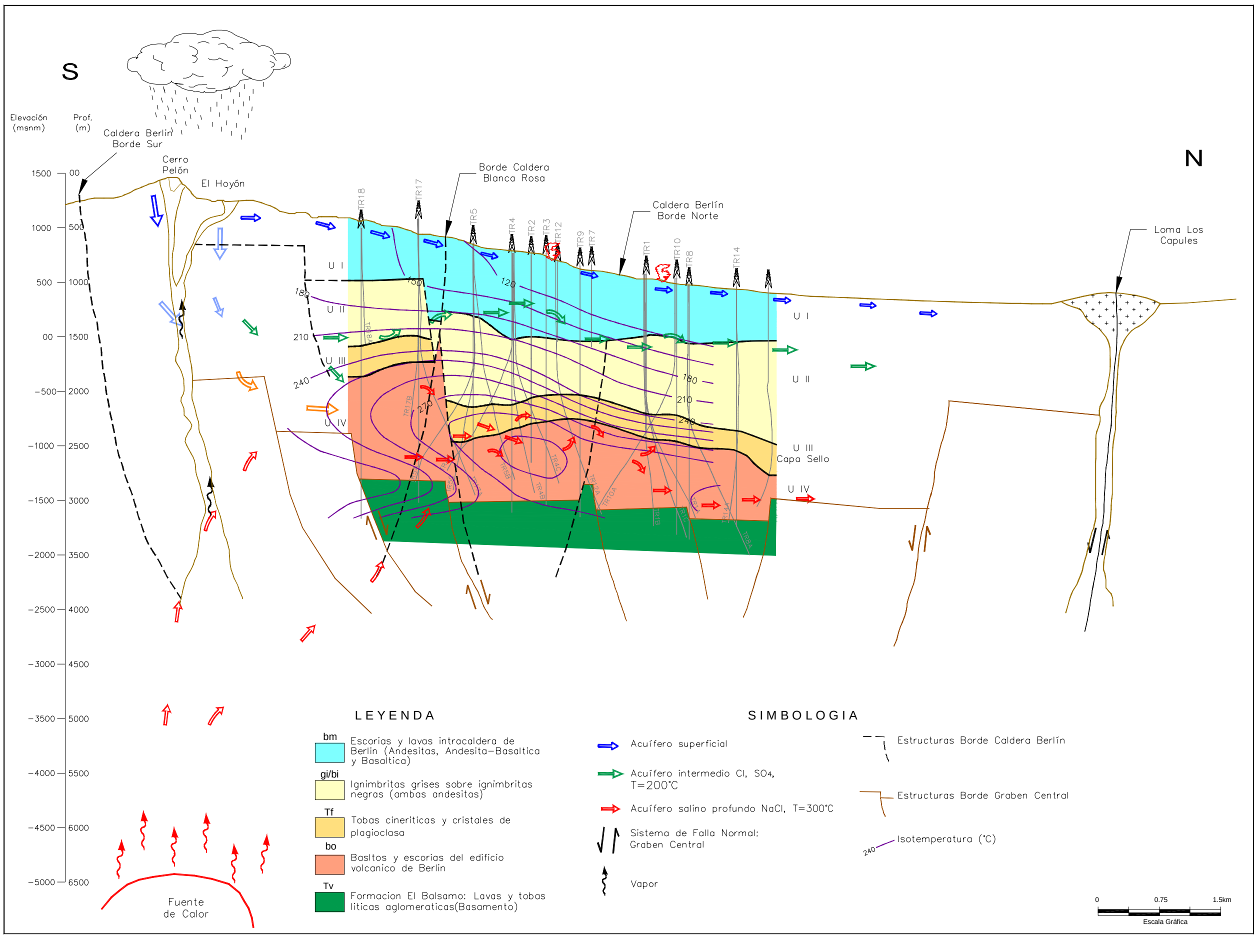

Figure 2: Cross-section of wells in Berlín. Caprock at lower elevation (dark yellow, Unit 3)

Table 3. Presents Permeable Zones Observed in Petrography and Production Test.

Characteristics	TR-17	TR-18
Total Loss Circulation	1345-1355 m 1400-2600 m	998-1060 m 1125-1155 m 1215-1240 m 1404-1820 m 1880-2660 m
Shearing based on petrography	1240-1400 m	875, 965-1070 m 1100-1110 m 1270-1300 m 1835-1845 m
Fracture identified during production test	1430 m 2070 m	
Total alteration at depths with shearing	22-44%	11-74%

Table 4. Presents the General Mineralogical Zones of Wells TR-17's and TR-18's.

Facies	Key minerals	Depth (m) TR-17	Depth (m) TR-18	Temp (°C)
Argillic	Smectite, Hematite, <Calcite, Silica, >>Quartz, < Corrensite, Heulandite, Clinoptilolite, Epistilbite	0-350	0-240	50-120
Argillic-phyllic	Smectite, Hematite, Corrensite, Calcite, <Chlorite, < Quartz	350-690	240-620	120-180
Phyllic	Calcite, Chlorite, <Illite, <Penninite, Quartz, <Epidote, Prehnite, Anhydrite, Wairakite	690-1040	620-1300	180-220
Phyllic-propylitic	Calcite, Chlorite, Penninite, Quartz, Wairakite, Epidote, Prehnite, Illite	1040-1550 ?	1300- ? (TLC)	220-260
Propylitic	Chlorite, Penninite, >Calcite, Wairakite, Epidote, Illite	1550-2690	?-2600	>260

4.3 Mineralogy

Well TR-17 has measured reservoir temperature of 280°C at depths 1800 – 2300m, which coincides with mineralogical temperature of the propylitic facies. Below 2300 m depth, measured reservoir temperature gave a temperature inversion of 256°C.

4.4 Chemical Compositions of Rock

Harker variation diagrams of chemically analyzed rocks of some wells were plotted and showed different trends. Data was obtained from Ruggieri et al, (2006) for samples of hydrothermally altered rocks.

Legends are shown for the following Harker diagrams and are given by:

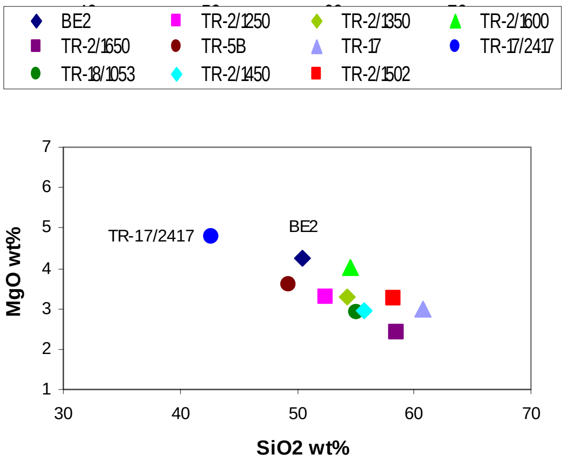

Figure 4: Plot showing tendency of MgO vs SiO_2

In Figure 4, the plot of MgO vs SiO_2 shows an inverse trend where SiO_2 increases with decreasing MgO. Sample from well TR-17 at 2417 m depth belongs to an andesite and not basalt. Increase in MgO content is probably due to an increase of penninite and epidote, which contains high Mg.

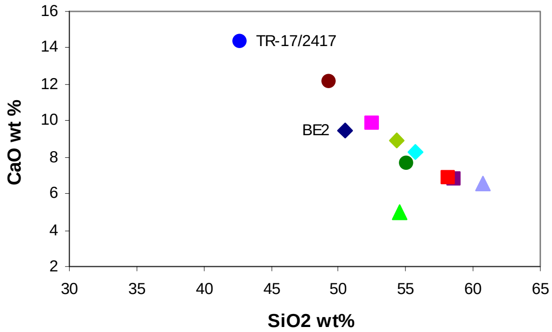

Figure 5: Plot showing tendency of CaO vs SiO_2

The plot of CaO vs SiO_2 in Figure 5 shows the same trend as MgO where there is an increasing SiO_2 with decreasing CaO. Sample of well TR-17 (2417 m) has the highest CaO content, probably due to the presence of Ca-silicate mineral (Epidote).

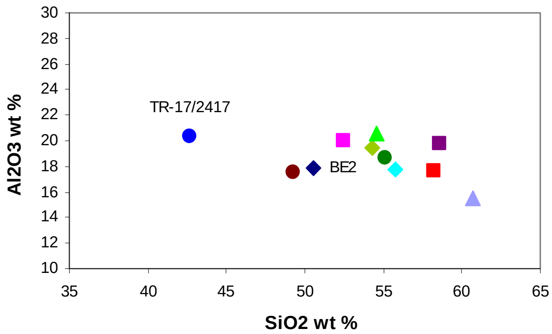

Figure 6: Plot showing tendency of AlO_2 vs SiO_2

The content of AlO_2 in Figure 6 is nearly constant with increasing SiO_2.

The Fe content in Figure 7 is high in sample TR-17 (2417 m), with decreasing Fe at increasing SiO_2. The enrichment of Fe may be due to the presence of chlorite (Fe-Mg silicate), epidote and pyrite.

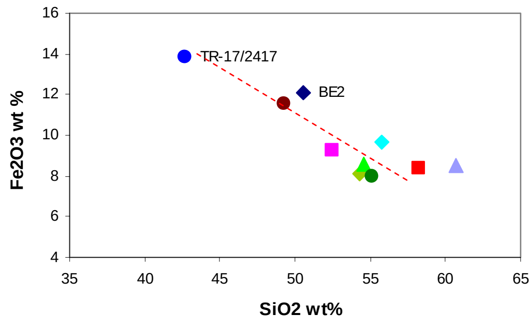

Figure 7: Plot showing tendency of Fe_2O_3 vs SiO_2

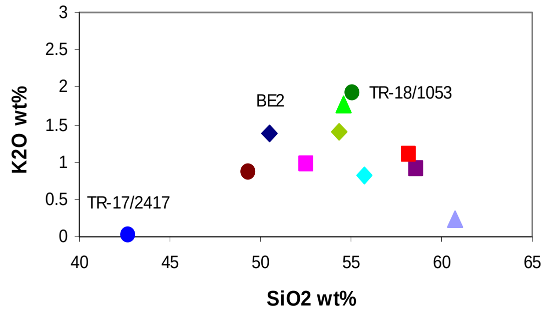

Figure 8: Plot showing tendency of K_2O vs SiO_2.

Scattered data was observed in the plot K_2O vs SiO_2 in Figure 8, where TR-17 (2417 m) has the least K, probably due to the leaching of K in the rock.TR-18 has the highest K content due to the presence of illite and sericite.

It can be observed that the rocks in wells TR-17 at 2417 m depth and TR-5B at 1765 m depth are the most intense hydrothermally altered rocks, giving a record of a past natural state condition.

4.5 Fluid Inclusion Studies

Thermometric measurements in 2008 were carried out using LINKAM equipment with Linksys software at the Laboratory in CNR, Pisa, Italy.

Most inclusions are secondary inclusions, and only few are primary. Tm and Th were measured mostly in quartz and calcite crystals. Some of the measurements presented were obtained from papers of Ruggieri et al, (2006) and Henriquez and Zaide-Delfin (2003).

Summary of the results of microthermometric analysis of fluid inclusions of wells in the southern part of the field is presented in Table 5. Two-phase liquid was observed with more liquid-rich inclusions (70 – 80%) and few vapor-rich inclusions (20%).

Maximum temperature of homogenization (Th) in wells TR-4 and TR-17 gave values ranging from 340.9 – 346.2 °C, which could be considered the temperature of the original fluid of the geothermal reservoir. High Th values > 300°C were found at the southern part in wells TR-4, TR-5A, TR-5B, TR-5C, TR-17 and TR-18, which could indicate the near source of the hot fluids (or the upflow zone).

Measured reservoir temperature at the bottom of the wells TR-17 and TR-18 gave lower temperatures of 248 – 258 °C as compared with the Th measured by fluid inclusion studies of >300°C, which could indicate that recent fluids were diluted by the incursion of cooler, meteoric waters, through permeable structures. This was also evidenced in some calcite crystals, which are in equilibrium with the measured temperature, indicating recent fluids trapped in these crystals.

The salinity data (wt% NaCl) in Table 5 shows that wells TR-4B, TR-5A and TR-17 indicate that inclusions are too saline (1.05 – 2.2 wt% NaCl) to have been produced by modern geothermal system.

Figure 9 shows the temperature contours using mean homogenization temperature (Table 5) from top to bottom of reservoir. Figure 10 shows the temperature contours based on measured reservoir temperature.

Table 5. Shows the Summary of Fluid Inclusion Data in Wells at the Southern Part of the Field.

Well	Depth (m) TVD	T_h (°C)	Mean T_h (°C)	Salinity wt% NaCl	Crystal	Stable meas. T (°C)	Comments (Mean T_h & T meas)
TR-4	1700	301-342.9	322	0.53	Quartz	278.3	Th > Tmeas
TR-4	2000	299.2-346.2	323	0.32-0.71	Quartz	303.4	Th > Tmeas
TR-4B	1520	231-264.9	248	0.32-0.88	Calcite	273	Th > Tmeas
TR-4B	1936	278.4-284.8	282	0.32-1.05	Quartz	292	Th < Tmeas
TR-5	1410	220-272	245		Anhydrite	214	Th > Tmeas
TR-5	1600	255.8-260.2	258	0.53-0.71	Calcite	247	Th > Tmeas
TR-5A	1500	198.4-236.9	218	0.53-1.05	Quartz	276	Th < Tmeas
TR-5A	1970	269-327.4	298	0.32-0.71	Calcite	301.43	Th < Tmeas
TR-5B	1750	286-309	297		Calcite	297.6	Th = Tmeas
TR-5C	1550	266-311	288		Calcite	264	Th > Tmeas
TR-17	1501	255.3-274.1	265	0.4-1.4	Albite?	248	Th > Tmeas
TR-17	1750	275.1-293.9	285	0.4-1.9	Quartz/Adularia	252	Th > Tmeas
TR-17	2000	294.6-321.0	308	0.4	Quartz	253	Th > Tmeas
TR-17	2080	275.1-293.9	285	0.4-1.9	Albite?	254	Th > Tmeas
TR-17	2417	2857.5-292.5	290	0.9-1.7	Quartz	256	Th > Tmeas
TR-17	2600	276.5-340.9	309	0.4-2.2	Quartz	256	Th > Tmeas
TR-18	1054	283.1-297.6	290	0.2-0.4	Quartz	256	Th > Tmeas
TR-18	2050	267.7-276.9	272	0.4	Albite?	258	Th > Tmeas

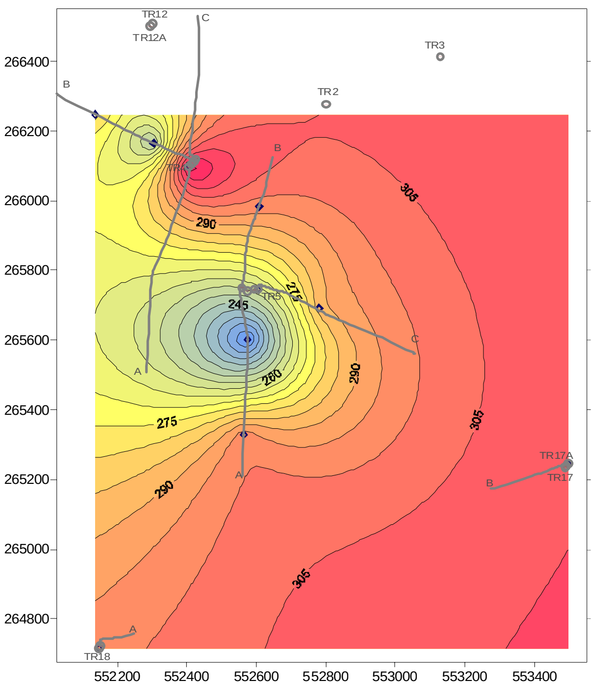

Figure 9: Isotherms using temperature of homogenization, fluid inclusion studies

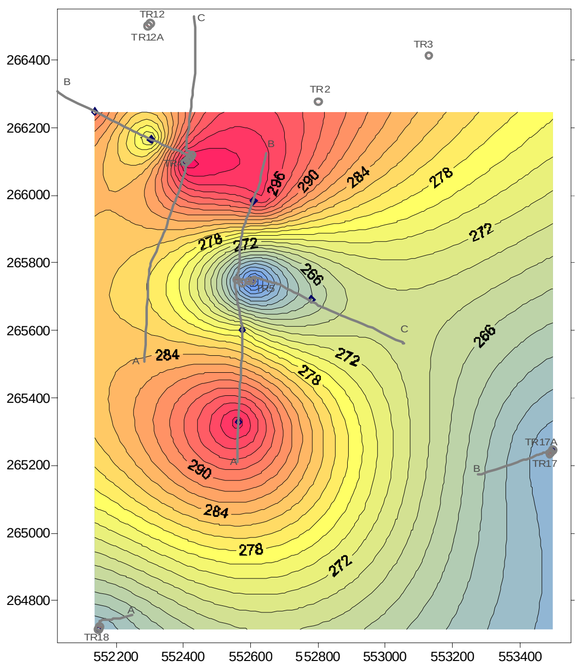

Figure 10: Isotherms using measured reservoir temperature

It can be seen that the original fluids of high temperature > 300°C are mostly at the southeastern part of the field. Recent fluids based on measured reservoir temperature show a decrease of at least 50°C at the southeastern part probably due to the percolation of cooler (meteoric) waters at the Berlín –Tecapa volcanic complex.

CONCLUSIONS

The stratigraphy of the new production wells (TR-17, TR-17A, TR-17B, TR-18 and TR-18A) at the southern part of the field revealed the collapse of the Berlin caldera, where the caprock is found at a higher elevation (500 msl to sea level) than the rest of the wells. Mineralogical facies also supports the vertical displacement in this area. Several shearing and veins are observed proving the presence of some permeable zones.

Drilling of new wells revealed the presence of intrusive rocks (granite) at TR-14A, and wells TR-19, TR-19B and TR-19C, which was also evidenced by seismic tomography.

High temperature original reservoir fluids of > 300°C were once present at the southern part of the field; however, measured reservoir temperature gave lower values of 253 - 258°C, probably due to the percolation of the meteoric water at the southern part of the field. This was also evidenced in some calcite crystals, which are in equilibrium with the measured temperature, indicating recent fluids trapped in these crystals.

The salinity data (wt% NaCl) in Table 5 shows that wells TR-4B, TR-5A and TR-17 indicate that inclusions are too saline (1.05 – 2.2 wt% NaCl) to have been produced by modern geothermal system.

Intense hydrothermal alteration of rocks in wells TR-17 and TR-5B as seen in Harker diagrams indicates the past natural condition of the hydrothermal system, where there is an increase in Mg, Fe and Ca content and decrease in K content.

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