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Thermo-Chemical Variations of the Hydrothermal Fluids in the Berlin Geothermal Field (El Salvador)

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ABSTRACT

Fluid inclusion and epidote isotopic studies have been carried out on core-samples drilled in the liquid-dominated Berlin geothermal field (El Salvador) in order to obtain information on the thermo-chemical evolution of the geothermal fluids. Fluid inclusions microthermometry was performed on inclusions hosted in hydrothermal minerals (quartz, albite, adularia, calcite, anhydrite and prehnite) and igneous quartz. Homogenization temperatures of liquid-rich inclusions are between 191 and 344°C. Final ice melting temperatures of fluid inclusions are mostly from -3.7 to -0.1°C, corresponding to maximum salinities between 0.2 and 6.0 wt% NaCl eq. Few liquid-rich inclusions show lower final ice melting temperatures between -13.1 and -26.3°C, with calculated maximum salinities from 17.0 to 21.2 wt% NaCl eq.. Vapor-rich inclusions also occur in the some of the examined samples, in one case they coexist with liquid-rich inclusions suggesting boiling processes. A single three-phase (liquid-vapor-halite) hypersaline (38.5 wt% NalCl eq.) inclusion was also found.

Isotopic analyses on hydrothermal epidote showed δD values from about -79 to -90‰. The δD of water (δD_{H2O}) in equilibrium with epidote, computed using temperatures derived from fluid inclusions, are between -42 and -56‰.

Comparison between homogenization temperatures and boiling point curves suggests that two stages of hydrothermal flow characterized the study area: a) the first stage was restricted at depths <1100 m below the ground level (b.g.l.); and b) the second stage occurred also in the deepest part of the present-day system. During this stage, fluid inclusions with the highest homogenization temperatures documented the upflow of a hot boiling fluid. Later, a significant temperature decrease down to present-day value, testified by homogenization temperature variation, affected the system.

Salinity and δD_{H2O} variation can be explained by the introduction and mixing of magmatic derived fluid and meteoric waters. In particular, relatively high-salinity values displayed by some liquid-rich fluid inclusions, the occurrence of a hypersaline inclusion and the highest δD_{H2O} value indicates a contribution of magmatic derived fluid to geothermal circulation. Whereas, the very low-salinity values displayed by other fluid inclusions, combined with the lowest δD_{H2O} values, testify the infiltration of meteoric fluids.

1. INTRODUCTION

The Berlin geothermal field is a liquid-dominated system located at the eastern part of El Salvador, about 110 km ESE of the capital city of San Salvador (Figure 1).

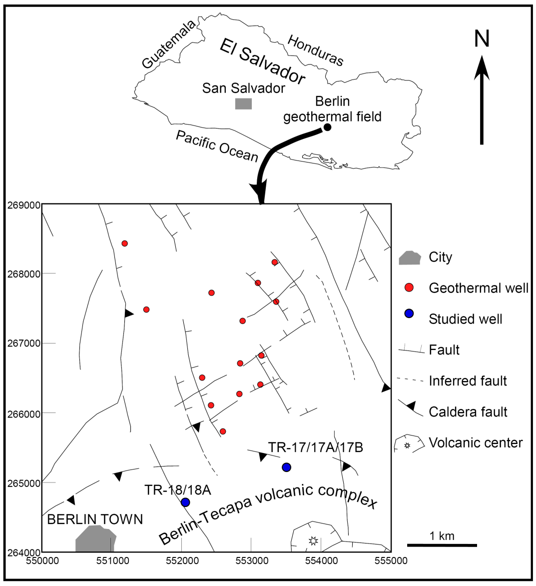

Figure 1: Schematic map showing the location of the studied wells of the Berlin geothermal field and the main tectonic structures and volcanic centers.

Geothermal exploration in Berlin area started in the '60s. A recent exploration project was carried out under the Share Holder Agreement Enel–GESAL (now LaGeo) in the frame of exploring the southern part of the field. As part of its objectives, new vertical (TR-17, TR-18) and directional wells (TR-18A, TR-17A and TR-17B) were drilled.

During the recent drilling activities 10 samples have been cored from depths between about 400 to 2600 b.g.l. in the new wells. This paper presents the results of fluid inclusion studies carried out on core samples from the drilled wells. Moreover, the δD isotopic compositions were determined on hydrothermal epidote found in six of the samples examined for fluid inclusions.

Since fluid inclusions record very local fluid circulation conditions, physical-chemical information on the fluids that circulated in particular areas of the reservoir can be obtained from their study (Hedenquist et al., 1992; Cathelineau and Marignac, 1994).

The new data allow us to reconstruct some of the physical-chemical parameters (i.e. temperature, salinity, CO_2 content) of the past geothermal fluids circulating at different depths. The variation of these parameters, the origin of the fluids and the processes that may have affected the geothermal fluids are discussed also by comparing fluid inclusions data with present-day reservoir features. Such information, and remarkably the thermal data obtained from fluid inclusions, can help the exploration strategy of the area intercepted by the new wells.

2. THE BERLIN GEOTHERMAL SYSTEM

The Berlin area is located south of the Central American graben, produced by the subduction of the Cocos plate and the Caribbean plate.

The tectonic setting in the Berlin area is characterized by one of the two main active fault segments (E-W and NW-SE trending fault systems) recognized in the eastern part of El Salvador. In particular, the fault system, running NW-SE, is the most representative in the Berlin area.

The Berlin geothermal field is situated at the northern slope of the Berlín-Tecapa volcanic complex (Figure 1). The volcanic complex is characterized by basaltic to andesitic lava flows and scoria, and andesitic to dacitic ingimbrites, which were produced during major eruptions (Raymond et al., 2005). The basaltic rocks date 1.4 Ma, whereas the andesitic-dacitic ignimbrites date from 0.1 to 0.075 Ma. The productive wells, located at the central part of the geothermal field, show an average temperature close to 300°C at -1100 m above the sea level (a.s.l.), while lower temperature characterizes the northern domain where the reinjection wells are located (Figure 1).

The heat source of the geothermal system is believed to be a cooling magma body associated with the most recent volcanism located south of the geothermal wells.

2.1 Geothermal Fluid Characteristics

Geothermal fluid enthalpies vary between 1200 and 1400 kJ/kg. These fluids are typical NaCl waters with approximately 5000-11000 mg/kg of total dissolved solids (TDS), 3000 to 6000 mg/kg of chloride, and 600 to 900 mg/kg of silica (D'Amore and Mejia, 1999; Matus et al., 1997; Montalvo and Axelsson, 2000). The non-condensable gases in the steam are in the range of 0.25-0.50%. CO_2 concentration in the present-day reservoir fluids is usually between 200 and 1900 mg/kg. The $\delta^{18}O$ and δD values of the fluid from different wells are in the range of -2.50/-3.80‰ and of -41.10/-45.13‰, respectively (Mejia et al., 1997; Renderos 2002).

For the TR-17 and TR-18 wells, considered in the present study, preliminary geochemical data indicate that the TDS in the reservoir fluids are around 5000 and 10000 mg/kg respectively, whereas the total CO_2 content is close 500 mg/kg in both wells.

2.2 Hydrothermal Alteration

Drilling data reveal that the deep reservoir-rocks at Berlin prevalently consist of interlayering andesite to basaltic-andesite lava flows with lithic tuffs, andesitic dykes and more rarely, acidic intrusive rocks (Henríquez, 2007). The thickness of the reservoir is at least 1000 m, while its elevation is approximately -1100 m a.s.l. (Arias et al., 2003; Ruggieri et al., 2006). The cap-rock of the deep reservoir is mainly composed of fine silicified lithic tuff. Underlying the tuff there is a complex sequence of lava and tuffs which often accommodates the thermal aquifers.

All these rocks are affected by variable degree of hydrothermal alteration. The volcanic rocks intersected by geothermal wells are always affected by variable degree of hydrothermal alteration. The hydrothermal minerals occur either as replacement of primary magmatic minerals volcanic groundmass and glass, or as breccia cement, and fillings of small voids and micro-fractures.

Four hydrothermal alteration zones have been recognized from surface to increasing depth (Ruggieri et al., 2006; Henríquez, 2007):

1) from surface to 670-700 m b.g.l, a relatively low-temperature assemblage, consisting of clay minerals, heulandite, quartz and calcite occurs;

2) from 670-700 to 1100-1630 m b.g.l. the main hydrothermal phases are calcite, chlorite, quartz and lesser amount of wairakite, laumontite, anhydrite, illite and illite-montmorillonite mixed-layers;

3) from 1100-1630 to 1460-1840 m b.g.l. epidote and albite occur together with most of the minerals of the previous hydrothermal assemblage;

4) below 1460-1840 m b.g.l., epidote, quartz and albite are the main hydrothermal phase whereas, chlorite, actinolite, wairakite, adularia, prehnite, anhydrite and hydro-garnet occur in variable amounts.

3. SAMPLES

The studied core-samples for fluid inclusions were obtained from vertical (TR-17 and TR-18) and directional wells drilled at the same site of the vertical ones (TR-17A, one from TR-17B). The samples are constituted by hydrothermally altered volcanic rocks and breccias.

Eight samples (TR-17A/1702, TR-17A/1987, TR-17A/2475, TR-17/1501, TR-17/2000, TR-17/2417, TR-18/2050, TR-18/2600) belong to the two deepest hydrothermal assemblages. Two samples (TR-18/1054, TR-18A/960) came from the hydrothermal assemblage characterized by the occurrence of calcite, sometimes associated with quartz and chlorite, and by the absence of epidote. One sample was drilled in the shallow depth (TR-17B/401) hydrothermal alteration assemblage.

Fluid inclusions suitable for microthermometric analyses were found in hydrothermal and igneous quartz, calcite, and albite, and, more rarely, in prehnite, adularia and anhydrite (Table 1). Six samples selected for fluid inclusions were also used for δD isotope analyses on epidote (Table 2).

4. FLUID INCLUSION STUDIES

The studied fluid inclusions are mostly two-phase, liquid-rich inclusions (L). Vapor-rich inclusions (V) are rarer and occur as either two-phase (vapor plus minor liquid) or apparently single phase (vapor), although small amounts of liquid, not visible under the optical microscope, may be present. In few cases, L inclusions clearly coexist with vapor-rich inclusions. In one sample (TR-17A/2474) a single three-phase inclusion (liquid-vapor-halite: LVH) is also observed.

Several fluid inclusions hosted in hydrothermal quartz, adularia, prehnite and albite are considered of primary orgin according to Roedder's (1984) criteria. In most of the hydrothermal minerals, fluid inclusions can also occur along trails, but it could not be determined if they are of secondary or pseudosecondary origin. In igneous quartz the fluid inclusions usually occur within secondary healed fractures, an exception is represented by the isolated single LVH inclusion in the sample TR-17A/2474.

4.1 Microthermometric Results

Microthermometric measurements were performed at the Institute of Geosciences and Earth Resources (IGG) of CNR (Pisa-Italy), using a Linkam THMSG 600 stage, on chips cut by double polished sections. The stage was calibrated by means of synthetic fluid inclusions containing H_2O with critical density and H_2O-CO_2 fluids. Reproducibility is in the order of ± 0.1°C for the final ice melting temperature (T_m), and ± 1.5°C for the total homogenization temperature (T_h) and final halite melting temperature (T_{mh}).

Two main types of liquid-rich inclusions (L1 and L2) have been distinguished on the basis of T_m data. L1 inclusions show T_m in the -3.7/-0.1°C range corresponding to a salinity range 0.2/6.0 wt% NaCl eq. (calculated by using the equation of Bodnar and Vityk, 1994) (Table 1). Because of the possible presence of dissolved CO_2 in the inclusion fluid, which can depress the T_m value of up to 1.5°C (Hedenquist and Henley, 1985), these salinities must be considered as maximum values.

L2 inclusions, observed only in one magmatic quartz and one albite crystal, are very scarce and are characterized by T_m between -13.1 and -26.3°C. The calculated maximum salinities for L2 inclusions showing T_m above the eutectic temperature of the H_2O-NaCl, ranged from 17.0 to 21.2 wt% NaCl eq. (Table 1).

Table 1: Summary of the microthermometric results of the L1, L2 and V fluid inclusions of the Berlin geothermal system. Abbreviations: b.g.l.=below the ground level, F.I.=fluid inclusion, T_m=final ice melting temperature, T_h=homogenization temperature, H-qz=hydrothermal quartz, M-qz=magmatic quartz, ab=albite, pre=prehnite, anh=anhydrite, ad=adularia, cc=calcite.

Well	Depth (m b.g.l.)	Host mineral	F.I. type	T_m (°C) range	T_h (°C) range	Salinity (wt.% NaCl eq.)
TR-17A	1702	H-qz	L1	-1.1/-0.2	275/294	0.4/1.9
	1987	ab	L1	-0.5/-0.2	282/310	0.4/0.9
	2475	M-qz	L1	-1.3/-0.1	269/327	0.2/2.2
	2475	M-qz	L2	-18.3/-13.1	280/284	17.0/21.2
	2475	M-qz	V	-1.2/-0.9	319/>350	1.6/2.1
TR-17B	401	cc	L1	-0.4/-0.1	191/221	0.2/0.7
TR-17	1501	pre	L1	-0.7/-0.6	255/258	1.1/1.2
	1501	ab	L1	-1.5/-0.6	255/274	1.1/2.6
	1501	H-qz	L1	-0.8/-0.4	271/288	0.7/1.4
	1501	H-qz	V	n.d.	275/>320	n.c.
	1501	ad	L1	-0.6/-0.5	256/259	0.9/1.1
	2000	H-qz	L1	-0.6/-0.1	295/321	0.2/1.1
	2417	anh	L1	-0.8/-0.3	284/319	0.5/1.4
	2417	H-qz	L1	-1.0/-0.5	288/293	0.9/1.7
TR-18A	960	cc	L1	-0.3	286/289	0.5
TR-18	1054	cc	L1	-0.4/-0.1	201/240	0.2/0.7
	1054	H-qz	L1	-0.2/-0.1	283/298	0.2/0.4
	2050	ab	L1	-0.6	268/271	1.1
	2050	ab	L2	-26.3	277	n.c.
	2050	M-qz	L1	-0.3/-0.1	265/330	0.2/0.5
	2600	ab	L1	-3.7/-0.1	249/336	0.2/6.0
	2600	H-qz	L1	-2.6/-0.2	300/344	0.4/4.3

T_m on vapor-rich inclusions could be measured only on few inclusions containing an amount of liquid sufficient to form visible ice, which ranged from -0.1 to -1.2°C corresponding to maximum salinities between 0.2 and 2.1 wt% NaCl eq.

First melting temperature for L1 inclusions could be detected in only two L1 inclusions in quartz crystal of TR-18/2600 sample, which was observed at about -20°C indicating that the dissolved solids in the fluids are mostly Na^+ and Cl^-. Few large inclusions in anhydrite crystals of the TR-17/2417 sample showed first melting (around -35°C), suggesting that bivalent cations (probably Ca^{2+}) can be present in the trapped fluid in addition to Na^+ and Cl^- (Crawford, 1981). L2 inclusions in quartz and albite crystals are characterized by first melting around -45°C, also suggesting that Ca^{2+} can be present in the trapped fluid in addition to Na^+ and Cl^- (Crawford, 1981). During freezing experiment no phase transition was observed in LVH inclusion.

T_h histograms for each studied sample were reported in temperature versus depth diagrams and compared with present-day formation temperatures of the examined wells, as reported by Rodriguez (2005). Boiling point depth curves for pure water (BPCW) originating at selected depths were also reported. One of these diagrams for samples coming from the wells TR-18/18A is shown in Figure 2.

The minimum and maximum T_h values (191°C and 344°C) of L1 inclusions are recorded at the shallowest and deepest samples respectively (Table 1). Fluid inclusions in magmatic quartz (TR-18/2050 and TR-17A/2475 samples) are characterized by large Th variations (58-64°C) probably related to distinct thermal states of the system.

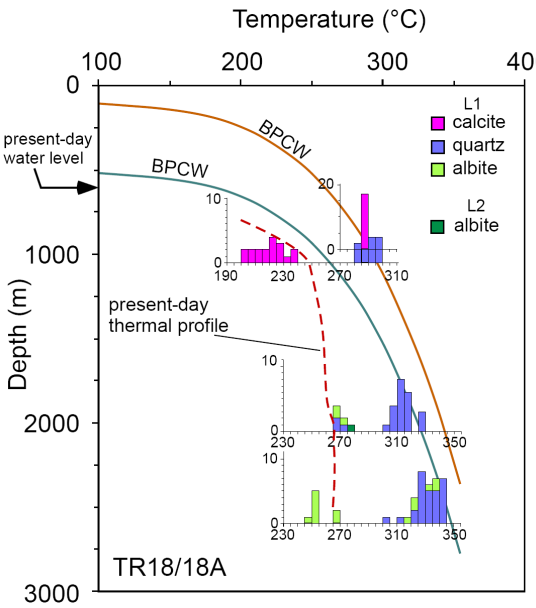

Figure 2: Temperature vs. depth diagram showing T_h histograms of the examined samples at the sampling depths, present-day thermal profile and two boiling point curve for pure water (BPCW) at different depths.

L2 inclusions show a restricted T_h range from 277 to 284°C. In the single LVH inclusion of TR-17A/2475 sample the vapor phase homogenized at 227°C, and T_{mh} was 305°C. The salinity of this inclusion computed from T_{mh} (calculated by using the equation of Bodnar and Vityk, 1994) is around 38.5 wt% NaCl eq.

V inclusions are characterized by variable T_h values (Table 1) from 273 to more than 330°C (at this temperature heating was stopped in order to prevent decrepitation of L1 inclusions, but many V inclusions were not yet homogenized). The variable T_h values of V inclusions are interpreted to be related to heterogeneous trapping process during boiling (Roedder, 1984; Bodnar et al. 1985).

L1 inclusions hosted within hydrothermal minerals from a single sample show a more limited T_h variation, in most of cases ≤30°C (Table 2). In some samples, the T_h ranges of L1 inclusions in the distinct hydrothermal minerals are different, which can also be related to temperature changes of the hydrothermal system.

5. EPIDOTE δD COMPOSITION

Hydrogen isotope composition of epidote was measured at the CNR–IGG applying the TC/EA method described in Sharp et al. (2001), using a ThermoFisher Delta XP IRMS. Epidote fragments were separated by hand picking under binocular microscope. Aliquots of 1.5 to 2.0 mg were used, and the measurements were at least duplicated and averaged. The δD values were compared with those of internal standards, calibrated relative to NBS-30 (δD = 67‰).

Epidote δD values vary from about -79 to -90‰ (Table 2). The δD of the hydrothermal fluid in equilibrium with epidote (Table 2) was calculated using the equation for the epidote-water equilibrium fractionation of Chacko et al. (1999). Equilibrium temperature for calculations were obtained from the T_h data of L1 inclusions trapped in minerals in equilibrium with epidote or in magmatic quartz. Equilibrium temperatures were assumed equal to the T_h means of the highest peaks for the sample showing a bi-modal or poly-modal of T_h, or equal to the T_h means of the whole data where only one frequency peak is present.

The computed δD values of the water in equilibrium with epidote are between -42 and -56‰ (Table 2).

Table 2: δD values of epidote and analytical errors (σ). δD_{H2O} values of the fluid in equilibrium with epidote were computed using an equilibrium temperature (Teq.) derived from fluid inclusions. See text for explanation.

Well	Depth (m b.g.l.)	δD_{ep} (‰)	±σ (‰)	δD_{H2O} (‰)	Teq. (°C)
TR-17A	1987	-80.22	0.07	-46.90	297
	2475	-81.63	0.85	-46.16	320
TR-17	2000	-89.70	1.60	-55.62	305
	2417	-85.18	0.85	-51.38	302
TR-18	2050	-86.56	0.04	-51.64	314
	2600	-78.84	0.73	-42.41	331

6. DISCUSSION

Information on the physical-chemical processes that occurred in the geothermal system and the origin of the fluids that circulated in the system are provided by fluid inclusions and isotopic data. In particular, comparison of fluid inclusions T_h values with geothermal wells thermal profiles and BPCW gives information on the thermal stability of the geothermal system, and can help determine possible boiling conditions and the level of the paleo-water table (if the system was at boiling) (Hedenquist et al., 1992).

BPCW and fluid inclusions T_h have been compared using temperature vs. depth diagrams (the diagram for TR18/18A wells is show in Figure 2). The effect of CO_2 and of salinity has been neglected for BPCW used in the present study, since salinities are low in most cases and preliminary crushing tests on fluid inclusions (cf. Roedder, 1984) also suggest that the CO_2 content in most inclusions is modest (≤0.40 wt%).

Temperature vs. depth diagrams evidenced that two stages of hydrothermal activity with distinct levels of the water-table characterized the examined wells. In most cases, the BPCW drawn from the present-day water-table depths encompass the T_h values of L1 inclusions of the samples drilled at depth >1500 m b.g.l., whereas the T_h of L1 inclusions from samples drilled at depths <1100 m b.g.l. plot inside the BPCW starting at shallow depths (100-140 m b.g.l.).

In well TR-18, T_h values of L1 inclusions in calcite crystals of TR-18/1054 sample are all encompassed by the BPCW starting al higher depth whereas the T_h values of L1 inclusions in quartz are within the BPCW starting at shallower depth (Figure 2). In these two minerals, L1 inclusions are mostly primary and textural relationships indicate that quartz crystallized before calcite, suggesting that the hydrothermal stage characterized by the shallowest water-table was likely developed before the stage with a water-table similar to the present-day one.

The absence of fluid inclusions related to the first stage of hydrothermal circulation below 1100 m b.g.l. is indicative of a lack of hydrothermal fluid flow below such depth. During this stage, therefore, the permeability was likely scarce at the level of present-day reservoir, probably because conductive thermal conditions and high geothermal gradient, due to the presence of a hot magma body, occurred at that time.

For most samples drilled at depth >1500 m b.g.l. the BPCW match or are very close to the maximum T_h values of L1 inclusions (Figure 2), indicating that the system was at or close to boiling conditions during the trapping of high-T_h L1 inclusions. In one case (sample TR-17/1501) boiling at the sampling site was observed by the coexistence of V and L1 inclusions and by the similar T_h of a V inclusion (273°C), not affected by heterogeneous trapping, and the T_h of the associated L1 inclusions (271-288°C).

In other samples, L1 and V inclusions do not coexist but the T_h range of V inclusions showing consistent data is similar to the highest T_h values of L1 inclusions, thus if boiling took place during inclusions trapping it could have occurred at relatively high temperatures in agreement with the BPCW.

Boiling, therefore, probably took place only during the upflow of high temperature fluids, afterwards the system underwent a significant cooling process towards the present-day temperatures (Figure 2). The thermal changes that occurred in the studied wells are reflected by the wide range of T_h of L1 inclusions in some samples (up to 65°C of variation) and by the distinct T_h ranges shown by different minerals from single core-samples (Table 1). For the samples drilled at depth >1500 m b.g.l. the minimum T_h values usually approach the present-day temperatures (Figure 2).

T_h vs. T_m (salinity) diagrams were also plotted in order to highlight the processes (e.g. boiling and/or mixing) that may have characterized the geothermal fluids and the fluid origin. One of these diagrams for the TR-18/TR-18A samples is shown in Figure 3. Present-day reservoir fluid salinities (expressed in NaCl wt%) are also reported for comparison. Since dissolved CO_2 contributes to fluid inclusion salinities computed from T_m, present-day salinities have been calculated by summing the total dissolved solid concentrations to the NaCl concentrations corresponding to the ice melting depression due to the CO_2 of the reservoir fluids. The depression of ice melting temperature caused by dissolved CO_2 was calculated by using the equation of Hedenquist and Henley (1985).

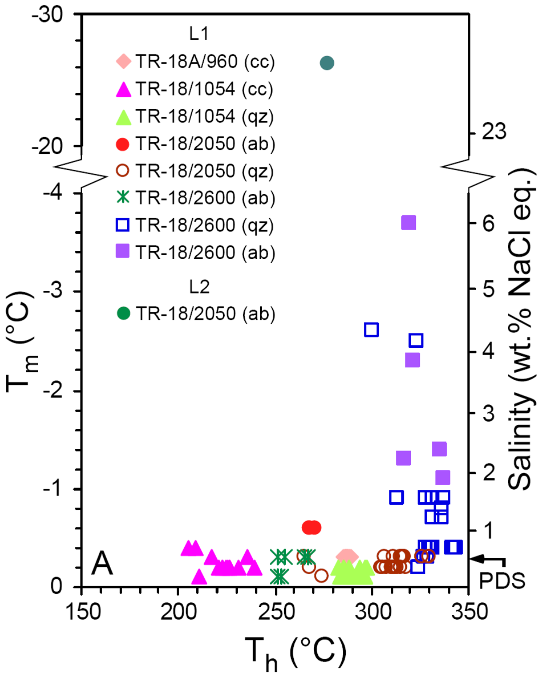

Figure 3: Homogenization temperature (T_h) vs. final ice melting temperature (T_m)/salinity diagram of samples coming from the wells TR-18 and TR-18A. Abbreviation: PDS=present-day fluid salinity (see text for explanation)

Although, many L1 inclusions show salinity values comparable to those of present-day fluids there are also several inclusions with higher and lower salinity than present-day fluids (Figure 3). CO_2 depletion in fluid inclusions caused by boiling could explain only part of the variation of the observed salinities. In fact, preliminary crushing tests suggest that the CO_2 concentration in L1 inclusions in the deep samples (>1500 m b.g.l.) is in many cases at maximum 0.40 wt%. The loss of such amount of CO_2 from the fluid would produce a reduction of the apparent salinities of 0.3 wt% NaCl eq. which is not sufficient to explain the difference between present-day salinity and the lowest salinity values of inclusions in the deep samples from TR-17 and TR-17A wells. At least in these samples, the circulation of liquids resulting from steam condensation and/or the infiltration of ground waters can explain the low-salinity values of the fluid inclusions.

The occurrence of numerous L1 inclusions, particularly in deep samples, showing significantly higher salinities (up to 6 wt% NaCl eq.) than present-day fluids, and of the saline L2 inclusions can be related to two processes: 1) open system fluid boiling with steam loss, or 2) injection of a high-salinity fluid in the system.

Prolonged open system boiling may produce high-salinity residual liquids but this process rarely occurs where fracture-dominated permeability allows the separation of liquid and steam, particularly if the liquid is immobilized in pores adjacent to the fracture as steam is lost (Simmons and Browne, 1997).

Saline fluids in geothermal fluids can be also related to the injection of brines exsolved from silicic magma, connate waters, and fluids resulting from evaporite-water interaction.

At Berlin, the sporadic input of saline fluids in the deep part of the hydrothermal system could explain the salinity increase of L1 inclusions and the occurrence of L2 inclusions. This hypothesis is based on two observations: 1) the combined δD_{H2O} and salinity values are not coherent with open system boiling, and 2) there are evidences that magmatic derived fluids circulated in the Berlin area.

During boiling, in fact, deuterium is preferentially partitioned in vapor phase at temperature above 220-230°C (Giggenbach, 1991). The T_h of all fluid inclusions in the deep samples is >240°C, therefore, if open-system boiling was the cause of the salinity increase, the saline boiling fluid would be depleted in deuterium. On the contrary, the highest maximum salinity value of L1 inclusions was observed in the TR-18/2600 sample which is characterized also by the highest δD_{H2O}. Whereas, the lowest δD_{H2O} values are found in the TR-17/2000 sample, showing a rather low maximum salinity value of L1 inclusions (Table 1).

Since brine sources such as evaporitic sequences or basins containing connate waters are absent in the Berlin geothermal area, the presence of magmatic derived fluids is most likely the source of the saline fluids. The LVH inclusion of sample TR-17A/2475 testifies that brines likely exsolved during the solidification of a silicic magma could be produced in the Berlin area. The occurrence of granite and granodiorite rocks in recently drilled wells (Henríquez, 2007) is coherent with this hypothesis.

Magnetotelluric data suggest that a residual magma body is still present at more than 4 km below the surface in the Berlin area (Anderson et al., 1994). Some fluids exsolved from this residual magma may have been episodically injected in the deep part of the geothermal system and mixed with low-salinity geothermal liquids producing the saline L1 and L2 inclusions.

The existence of magmatic fluids in the Berlin geothermal system is also indicated by Mejia et al. (1997). On the basis of stable isotope and geochemical data, it was suggested that the present-day upflowing geothermal waterin the Berlin geothermal field, characterized by δD_{H2O} = -43.4‰, is the result of the mixture between meteoric and isotopically heavy parent water, likely andesitic in composition. Analogous genetic processes of the past and present-day geothermal fluids are also suggested by the similarities between the less negative δD_{H2O} values of the two fluids.

However, fluids in equilibrium with epidote also show δD_{H2O} values lower than present-day fluids. These low values can be related to the infiltration of meteoric fluids which can eventually mixed with the fluid enriched with deuterium.

7. CONCLUSION

Fluid inclusion studies show that two stages of hydrothermal circulation affected the examined area of the

Berlin geothermal system: the first stage developed only at depth <1100 m b.g.l. and was characterized by a water table level close to the surface. During the second stage the hydrothermal circulation intercepted also the deep portion of the geothermal system and the depth of the water table was similar to present-day level. At the beginning of the second stage the system was characterized by the rise of hot boiling fluids (T_h up to 344°C). Later, a decrease of the temperature down to present-day values, recorded by variations of fluid inclusion T_h, affected the examined wells.

Fluid inclusions also show variable salinities (0.2-6.0 wt% NaCl eq. for L1 inclusions, 17.0.21.2 wt% NaCl eq. for L2 inclusions). The relatively high salinity showed by a number of L1 fluid inclusions can be related to the contribution of magmatic derived fluid to the geothermal liquid. The introduction of water exsolved from a magma is in agreement with the occurrence of saline L2 inclusions. The occurrence of a single hypersaline LVH inclusion, observed in one sample, also testifies that magmatic fluids were produced in the Berlin system.

In addition, the relatively high δD_{H2O} value (-42‰) of the fluid in equilibrium with epidote combined with the relatively high maximum salinity of L1 inclusions (6.0 wt% NaCl eq.) found in one sample (TR-18/2600) also support the contribution of magmatic fluid to the geothermal liquid.

This δD_{H2O} value is similar to the δD_{H2O} (=-43.4‰) composition of the reservoir fluid of well TR-5 (Mejia et al., 1997). This fluid is considered to represent the present-day upflowing water, and is interpreted to be the result of mixing between meteoric and “andesitic” fluids (Mejia et al., 1997).

On the other hand, inclusions with salinity lower than present-day values can be attributed to fluid produced by steam condensation and/or to the incursion of ground waters. The inflow of meteoric waters is supported by the relatively low δD_{H2O} values of the fluid in equilibrium with epidote (-56‰) shown by a sample (TR-17/2000) and characterized by relatively low maximum salinity value.

δD_{H2O} values in-between the above extreme values can be the result of mixing of the deep geothermal fluid and meteoric waters.

The studied of fluid inclusions and epidote isotopic composition allowed to reconstruct the physical-chemical changes that occurred in the examined area of the Berlin geothermal system. These information can help build conceptual models that will be used for the elaboration of numerical models showing the temporal evolution of the Berlin geothermal system.

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