Strengthening Geological Interpretation using Fluid Inclusion Studies in Geothermal Fields of El Salvador

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ABSTRACT

Microthermometry is an analytical technique to determine the physical - chemical changes (mostly phase transitions) that occur within the fluid inclusions in a crystal. This technique has been a valuable tool in strengthening geological and geochemical interpretations in El Salvador's geothermal projects.

The Geology laboratory of LaGeo acquired for the first time the fluid inclusion system in 2012, where several samples from different geothermal fields in the country have been analyzed to determine the thermal evolution of the geothermal system, as well as to support in updating the conceptual models of different geothermal fields. Likewise, the equipment serves as an educational support to the regional diploma course for Latin America held yearly in El Salvador.

Homogenization temperatures (Th) and melting temperatures (Tm) were measured in fluid inclusions of crystals present as vein minerals in core samples of wells at reservoir depths. Quartz and calcite crystals were usually the host minerals of fluid inclusions in samples that were analyzed.

Most of the Th measurements were in equilibrium with the reservoir temperatures of the wells and the mineralogical facies established during drilling of the wells. Furthermore, different geochemical processes were observed within the geothermal system such as boiling, conductive cooling and dilution.

At present, fluid inclusion studies are being undertaken in core samples obtained during the first few years (1980s – 1990s) of development of Ahuachapan and Berlin geothermal fields, as part of geological and geochemical investigations and to help update the conceptual models, as well as a tool in deep exploration especially during drilling in new areas in El Salvador.

1. INTRODUCTION

El Salvador is a small country in the heart of Central America bounded by numerous volcanoes, which makes geothermal energy viable to the country. LaGeo took the lead in exploring and developing the geothermal energy resources to address the growing energy demand of the country. The electricity growth went hand in hand with the country's economic development.

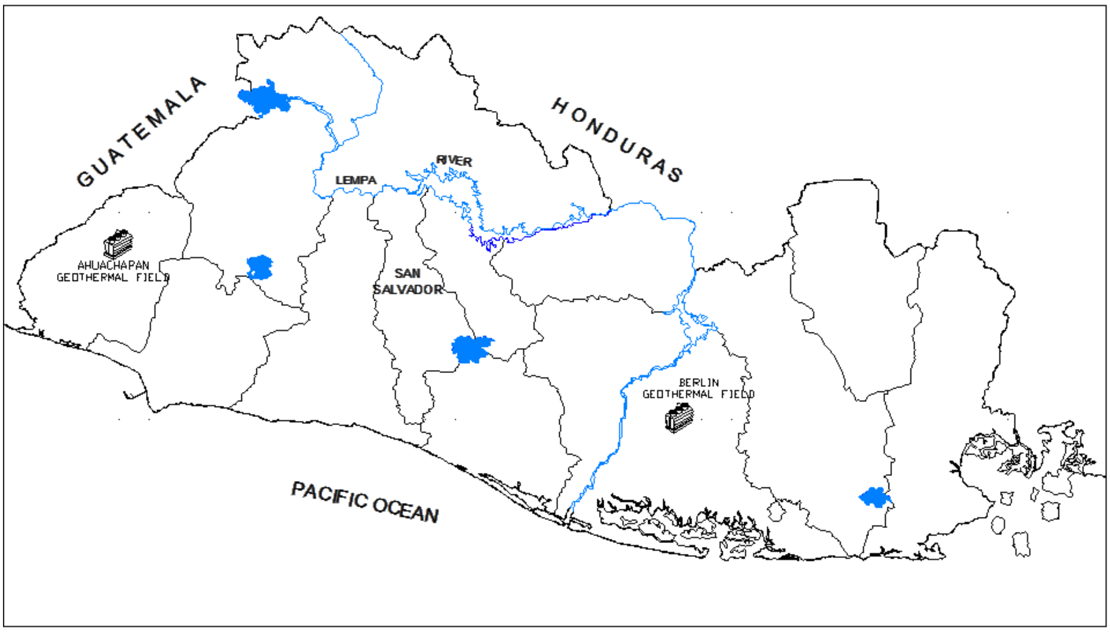

Figure 1: Location map of Ahuachapán and Berlin Geothermal Fields

LaGeo has two geothermal fields in El Salvador: Ahuachapán geothermal field at the western part of the country, and Berlin geothermal field at the eastern part (Figure 1), contributing almost 25% of the total electrical generation of the country. At present, there are two geothermal areas under exploration: San Vicente and Chinameca.

Geothermal energy exploration in El Salvador started in the 1970s, where scientific investigations have increased and have aided in understanding the geothermal system. The rapid pace of geothermal exploration and development in the country finally brought the creation of the laboratory of chemistry and geology.

The laboratory of Geology in LaGeo is responsible for interpreting, analyzing and evaluating the physical, mineralogical, and thermodynamic characteristics of the lithological formations, and all solid materials encountered during the exploration and development of geothermal areas. It started with Petrography and X-ray Diffraction (XRD) and in 2012; it acquired its Fluid Inclusion (FI) equipment for the first time as part of upgrading the laboratory, thereby contributing more information to evaluate the resource.

2. HISTORY OF ACQUIRING FLUID INCLUSION SYSTEM

In 2001, FI training was given in the Philippines under the IAEA project, an effort to open doors for learning the importance of its application and thereby, leading to the acquisition of FI system. Temperature of homogenization (Th) and melting temperature (Tm) measurements were undertaken in core samples of wells in Berlín geothermal field in El Salvador. Furthermore, a joint technical paper written together with the Filipino expert in FI was submitted to the Geothermal Resources Council (GRC) and was presented in Morelia, Mexico during the GRC workshop in 2003. This was the beginning of the interest in FI.

In 2006, exploration drilling of wells was carried out in San Vicente geothermal area and in 2009-2010, drilling was intense in Chinameca geothermal area. To update the conceptual model and the thermal evolution not only by alteration mineralogy and reservoir temperature measurement, crystals from vein minerals in core samples were selected to be analyzed using fluid inclusion studies. Samples were sent to a laboratory in Mexico, however, the results were a little bit delayed as wells were already finished and no FI data available upon well evaluation.

In 2011, the management authorized the purchase of FI system, with proper justification and insistence (delayed results, reservoir input, etc). By 2012, the new FI equipment was installed (Figure 2) and it started analyzing core samples in Chinameca and San Vicente geothermal areas in El Salvador.

Figure 2: Fluid inclusion equipment at LaGeo

From 2013 up to the present, FI technique was incorporated as one of the subjects given to the Latin American diploma course held in El Salvador. Six graduates of the diploma course from Colombia, Guatemala, Mexico and El Salvador did their project work on Fluid Inclusion.

No samples from external clients are being accepted yet at the moment, as there are numerous samples from the geothermal fields in El Salvador still to be analyzed.

2.1 Training

Some of the trainings given by different institutions were undertaken to strengthen the use of the equipment, preparation of samples, analysis and interpretation of FI data.

In 2001, training was given under the International Atomic Energy Agency (IAEA) project as an introduction to FI world at PNOC-EDC, Philippines under the guidance of Ms. Maribel Zaide-Delfin.

In 2008, training was provided by Consiglio Nazionale delle Ricerche (CNR), Pisa, Italy under the guidance of Dr. Giovanni Ruggieri and Dr. Giovanni Gianelli for the operation of equipment and introduction on interpretation of FI data.

In 2010, two personnel (geologist and technician) were sent to the University of Chile to learn the process of double polished sections for fluid inclusion studies.

In 2014, training was done at the Energy Geoscience Institute (EGI) at the University of Utah under the guidance of Dr. Joseph Moore for more analysis and interpretation of FI data.

3. FLUID INCLUSION STUDIES

Fluid inclusions are small volumes of fluid trapped within a crystal during its original growth, or during subsequent healing of fractures in the presence of fluid. Inclusions are generally very small, mostly < 10µm. Fluids trapped as inclusions during hydrothermal mineral growth is the only sample available of the fluid actually present during formation of mineral deposits.

The most common use is to obtain a measure of the temperature of past events, also known as microthermometry. Microthermometry is an analytical technique to determine the physical - chemical changes (mostly phase transitions) that occur within the fluid inclusions in a crystal; which provides reliable information on temperature, composition of fluids and pressure, attending various geological and geochemical processes, and relating to thermal evolution of fluids in time.

Homogenization temperature (Th) is the temperature at which a fluid inclusion transforms from a multi-phase (heterogeneous) to a single phase (homogeneous) state. Melting temperature (Tm) is the temperature at which ice is observed to melt or dissolve completely upon progressive heating of a fluid inclusion.

Homogenization temperatures (T_h) can indicate the spatial and temporal evolution of a system, the relation between relief, water table and temperature constraints, thus assisting geological interpretations. Ice melting temperatures (T_m) can indicate salinity (and potentially the gas concentrations), particularly where trends in T_m and T_h data for individual inclusions are available; these data may also provide evidence for boiling and mixing in the system (Hedenquist, J.W. et al., 1992).

In geothermal, fluid inclusion technique plays an important role on the thermal evolution of the reservoir (fossil or active), determination of origin of fluids through its salinity, location of upflow and outflow zones, determination of geochemical processes: boiling, cooling, heating and dilution and reconstruction of conceptual model of geothermal field.

4. CHALLENGES

4.1 Sample preparation

Two personnel from the Geology department (a geologist and a technician) were sent to the University of Chile in October 2010 to learn the process of making double polished section of samples. However, few problems were encountered later on during the preparation of sections at the Laboratory of Geology such as the use of Canada balsam (at present, samples are mounted using superglue); where at higher temperatures samples are burned and making it impossible to see the inclusions. Likewise, the selection of transparent minerals, too much polishing, poor sample polishing, crystals too thick, too tiny cuttings, too much bubbles in cementing material were part of the technical problems during preparation.

4.2 Measurement

Some of the fluid inclusions in samples are too small or very few, so it is harder to conduct microthermometry and usually can be part of the source of error. Sometimes it is difficult to recognize the type of inclusions, whether it is secondary or pseudosecondary or even primary inclusions. Relocating the inclusions for microthermometry (Th or Tm) is a little bit tedious or can be unsuccessful.

Nowadays, for better presentation of the dynamics of inclusions during measurement, cameras and videos are part of the equipment for the record of the inclusions. Furthermore, one can program the speed and delays of inclusions for better visualization and disappearance of bubbles and melting of ice in the inclusions.

The availability of liquid nitrogen is one of the difficulties at the laboratory of Geology during measurement, as it has to be bought and consumed at once, however, with the given problems such as relocating inclusions or less number of inclusions, the amount of liquid nitrogen to be bought needs to be less.

4.3 Interpretation

Some of the Th measurements have wide range of data probably due to necking, decrepitation, reequlibration after trapping or due to human error in measuring, thus may lead to erroneous geochemical process interpretation. Fluid inclusion assemblage (FIA) method should be done to represent and validate microthermometric data, however, not all samples can have group of inclusions.

After searching for inclusions, sometimes they are not useful for microthermometry, making it very tedious and time-consuming, hence a lot of patience and a little bit of luck are needed.

Through time and practice, these challenges are still being addressed and will eventually be overcome, as the laboratory wants to assure that data obtained are reliable.

5. FI DATA IN EL SALVADOR

Homogenization temperatures (Th) and melting temperatures (Tm) were measured in crystals present as vein minerals in core samples of wells at reservoir depths. Quartz and calcite crystals were usually the host minerals of fluid inclusions in samples that were analyzed.

Most of the Th measurements were in equilibrium with the reservoir temperatures of the wells and the mineralogical facies established during drilling of the wells in some of the geothermal fields and areas in El Salvador. Furthermore, different geochemical processes were observed within the geothermal system such as boiling, conductive cooling and dilution.

At present, fluid inclusion studies are being undertaken in core samples obtained during the first few years (1980s – 1990s) of development of Ahuachapán and Berlín geothermal fields. A summary of FI data are presented in Figure 3.

Fluid inclusion technique has been a valuable tool together with alteration mineralogy in strengthening geological and geochemical interpretations in El Salvador’s geothermal fields. It has provided information on the thermal evolution of the reservoir of the geothermal system, in updating conceptual model, drilling strategy, geological and geochemical processes such as boiling, cooling, etc.

Geothermal field	Well	Depth (m)	Mean Th (°C)	Measured T (°C)	Tm (°C)	Comments
Ahuachapán	Well1	153	110	107	0-0.7 to 2.2	Fluid has occasionally boiled Presence of primary steam and two-phase fluid inclusions.
		1953	286			
		2700	244			
	Well2	390	226-262	203	-0.5 to 0.0	
Berlín	Well1	1426	238	271	-0.2 to -0.4	Well1 cooling of deep aquifer fluids by conduction and mixing with cooler waters at higher depth
		1570	276	293		
		1654	299	289	-0.3 to -0.5	
		2281	258	276	-0.1 to -0.4	
	Well2	1700	322	278		
		2000	323	303		
	Well2B	1568.2	248	273		
		2000	282	292		
	Well3	1340-1410	261	214	-0.1 to -0.2	High T fluids around 300°C temperature reversals in the deep aquifer, thermal stability
		1620-1650	285	247		
	Well3B	1765-1771	295	297	-0.5 to -0.8	
	Well3C	1591-1595	286	264	-0.4	
	Well4	1195-1199	247	211	0.0 to -0.5	Relict hydrothermal system with deep fluid temperature of 330°C
		1890-1934	224	246		
		1940	276	243	0.2 to -0.3	
		1950	232	243	-0.2 to -0.5	
		2015	216	244	-0.2 to -0.3	
		2020	255	258	-0.1	
	Well5	1501-1504.5	267	248		Well5A: General cooling trend of mineralization at depth
		1750-1752.2	285	252		
		2000-2005	307	253		
		2417-2422	290	256		
	Well5A	2080-2082.10	300-310	272		
		2628-2629.20	270-330	223		
	Well6	1053-1057	Qz: 291	256		
			Ca: 218			
		2050 – 2055	Qz: 314			
			Alb: 272	258		
		2600 – 2603	Qz: 328			
			Alb: 258			
				262		
Chinameca	Well1	1028	230		-0.3	Tmed < Th
		1474	225	203	-0.4	Tmed < Th
		1657	254	187	-0.5	Tmed < Th
	Well1A	1277	223	234	-0.2	Tmed > Th
		1474	229	231	-0.6	Tmed = Th
	Well2A	1387	254	232		Tmed < Th
San Vicente	Well1A	1450	221	232	-0.4	Boiling process still occurring at the reservoir
		2061	222	222	-0.45	
		2209	225	215	-0.1	
		2400	201	215	-0.5	
	Well2A	844	212	140	-0.75	
		980	201	145	-0.56	
	Well3A	1505	265.8	235	-0.4	

Figure 3: FI data in different geothermal fields

5.1 Comparison of Th with measured temperature

Generally Th data is superimposed on temperature profile of the well, to see the thermal evolution of the geothermal system. In Figure 4, fluid inclusion temperature (Th = 233°C) and hydrothermal alteration minerals (phyllitic facies – 180-220°C) indicate higher temperatures than the measured temperature of the well (140°C) at 840 m depth. Furthermore, part of the reservoir has cooled down and the activity has declined since the alteration was formed.

This well was drilled to a depth of 1324 m MD and was programmed to be a production well during deep exploration of the geothermal area; however, with the results of fluid inclusion studies compared to the measured temperature, and the presence of quartz vein as the whole core sample, it was reclassified as a reinjection well. Fortunately, the well has high permeability.

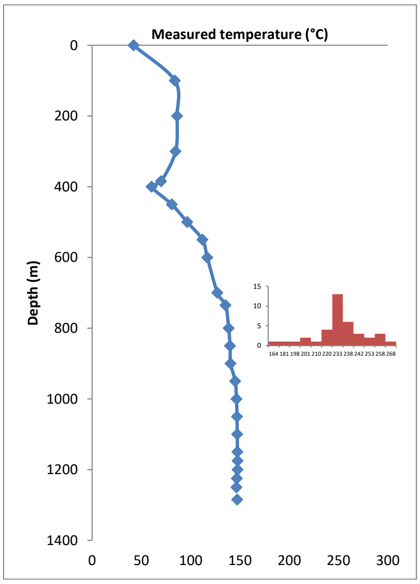

Figure 4: Th and measured temperature

5.2 Petrological model

Based on alteration minerals and fluid inclusion studies, a general petrologic model (Figure 5) was constructed with all the data of the wells drilled during deep exploration in one of the geothermal areas in El Salvador. High temperature of homogenization of 257 – 283°C coincided with the presence of epidote, total loss of circulation of the wells and the highest measured temperature of 235°C. Salinity of the wells was also determined, which supported the preliminary model.

The highest temperatures (Th and measured T) were correlated with the inferred upflow of the geothermal system, based on the conceptual model. More wells are programmed to be drilled in this high temperature area to provide the necessary steam for the future power plant.

Fluid inclusion data and alteration mineralization provided information of the physical, thermal and geochemical evolution of the hydrothermal system.

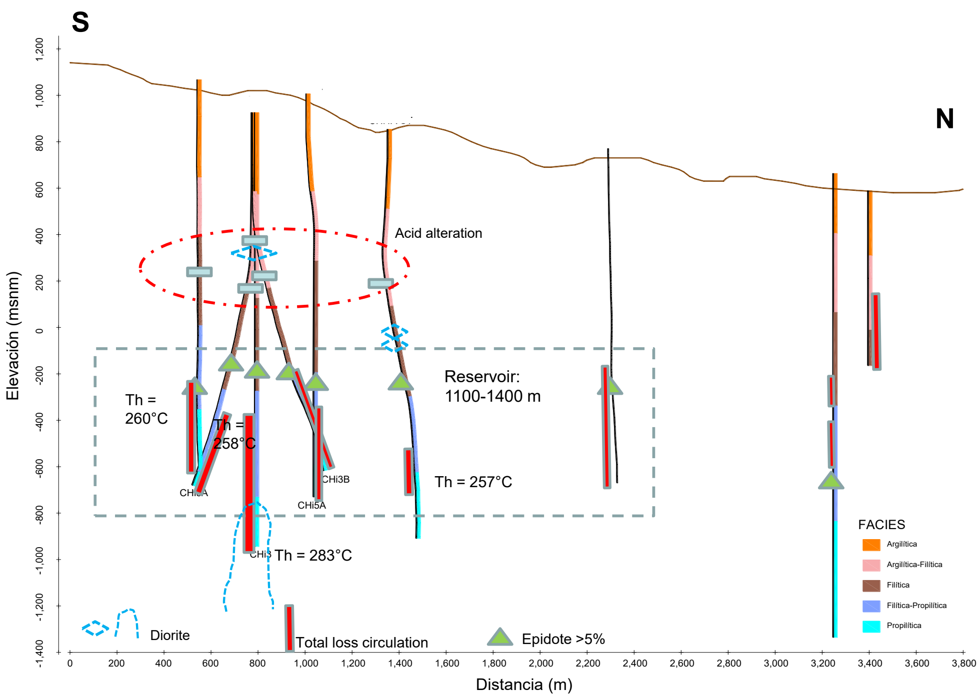

Figure 5: Petrological model

5.3 Relict heat source

Fluid inclusion studies of one of the wells at the outflow zone in a geothermal field in El Salvador revealed a relict hydrothermal system with deep fluid temperature of ~330°C and salinity of ~2,100-3,200 ppm chloride, not related to the present geothermal system. FI data probably correspond to hotter fluids that once existed in this part of the field, which maybe the intrusive rocks (granite and granodiorite) evidenced by seismic tomography and core samples obtained in some of the wells drilled. The old hydrothermal system was postulated by FI data even before the seismic tomography was conducted.

5.4 Drilling strategy

Geothermal wells which have been drilled provide data on measured temperature and pressure profiles; however where data are not available fluid inclusions T_h and T_m data can assist in exploration drilling (Reyes, 1990).

In one of the geothermal fields in El Salvador, fluid inclusion studies confirm wells which are near the present location of the upflow region, where approximately 300°C fluids are ascending through permeable caldera fault zones. These wells did not show temperature reversals in the deep aquifer.

One well drilled within the graben, near the eastern boundary of the geothermal system showed that 300°C brines flow laterally along lithological contacts towards the northwest, between -800 and -1000 m (msl). Below –1000 m (msl), however, cooler temperatures (<270°C) prevail based on fluid inclusion and borehole data. The temperature reversal is attributed to cooling of deep aquifer fluids either by conduction or mixing with cooler waters descending along permeable fault zones within the graben.

With these data, it was concluded that fluid inclusion can assist in future production drilling, focusing on the location of the postulated upflow zone. Wells should be designed to target permeable faults which channel ~300°C brine at –1000 m (msl). On the other hand, near the eastern boundary of the geothermal resource wells may be drilled to tap hot brine flowing between –800 and –1000 m (msl). In addition, the production casing shoe should be set deeper than –700 m (msl) to isolate the well from shallow groundwater aquifers.

5.5 Stages of hydrothermal alteration

Fluid inclusions studies showed two stages of hydrothermal circulation which affected one of the geothermal fields in El Salvador (Figure 6) with distinct levels of water table of the wells under study. The first stage was developed only at depth < 1100 m and was characterized by a water table 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 similar to present-day level. At the beginning of the second stage the system was characterized by the rise of hot boiling fluids (Th up to 344°C). Later, a decrease of the temperature down to present-day values, recorded by variations of fluid inclusion Th, affected the examined wells (Ruggieri et al., 2006).

Fluid inclusions also showed 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 (Rugierri et al., 2006).

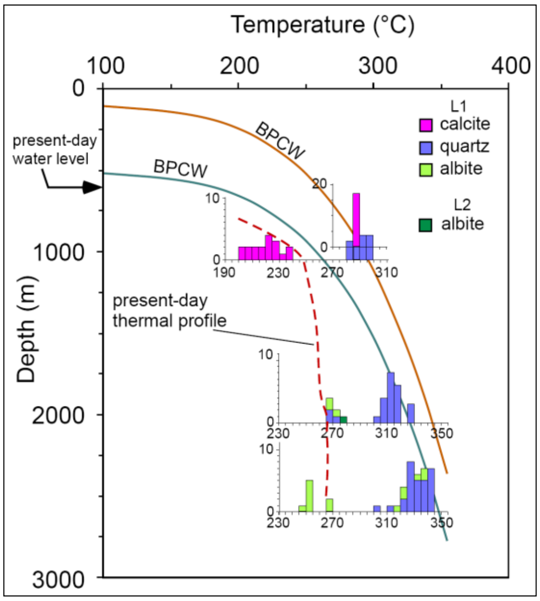

Figure 5: Fluid inclusion and boiling point curve (From Ruggieri et al, 2006)

6. CONCLUSIONS

The Geology laboratory of LaGeo acquired for the first time a fluid inclusion system in 2012. Double polished sections in most core samples of the geothermal fields and geothermal areas in El Salvador were prepared and analyzed, and later contributed in updating conceptual models. The equipment also serves as an educational support to the Latin American diploma course held yearly in El Salvador. Problems and challenges were faced, and with the help of fluid inclusion specialists who supported the laboratory, these were addressed by training, discussions and open communication.

Fluid inclusion technique has been a valuable tool together with alteration mineralogy in strengthening geological and geochemical interpretations in El Salvador's geothermal fields. It has provided information on the thermal evolution of the reservoir of the geothermal system, in updating conceptual model, drilling strategy, geological and geochemical processes such as boiling, cooling, etc.

Fluid inclusions deal with temperature and salinity, thus past thermal and chemical characteristics of a geothermal system are recorded, which maybe compared to the present conditions. Fluids trapped as inclusions during hydrothermal mineral growth are the only samples available of the fluid actually present during formation of mineral deposits.

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