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# STRATIGRAPHIC, TECTONIC AND THERMAL MAPPING THROUGH GEOLOGICAL WELL LOGGING IN EL SALVADOR

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**ABSTRACT**

Prefeasibility phase determines the most favorable site for drilling, with all the complementary geoscientific information such as geological mapping, geochemical analysis and geophysical surveys to allow a better understanding of the subsurface features of the geothermal resource.

The wells drilled provide geological information on fracturing, shearing evidence, porosity data, microfractures, hydrothermal alteration mineralogy; thermal gradient, permeable zones, thermal characteristics of the well which complement the construction of the conceptual model of the geothermal system.

This paper describes the procedures and considerations such as lithological units, hydrothermal alteration and structural features during geological well logging with a case study in Berlín geothermal field.

## 1. INTRODUCTION

From the geothermal exploration guidelines adopted by the Latin American countries (OLADE), the different stages on how to develop a geothermal project are: a) exploration and exploitation. Within the geothermal exploration stage, three phases are usually endorsed: a) reconnaissance, b) prefeasibility and c) feasibility.

After the reconnaissance phase, it is through the prefeasibility phase that the project determines the most favorable site for drilling, with all complementary geoscientific information such as geological mapping, geochemical analysis of fluids from surface manifestations, and geophysical surveys such as resistivity measurements, gravity and seismic profiling, to allow a better understanding of the subsurface features of the geothermal resource.

Wells are also drilled to obtain important information necessary to elaborate a conceptual model of the geothermal system, which includes the main features of geoscience: geology, geochemistry and geophysics.

Establishing the structural geological pattern of the area and differentiating recent and old faults are important to site a well because they are usually responsible for the direction and movement of geothermal hot fluids.

The availability of at least one geothermal gradient well, shallow or deep exploratory well, provides information about the stratigraphy, type of rock (by determining the cap rock and the host rock of the reservoir) as well as evidence of fracturing and porosity of the rocks. Data from hydrothermal alteration mineralogy, thermal gradient, permeable zones, thickness of permeable zones, thermal recovery data of wells, etc. provides complement in constructing the conceptual model.

With all of this information, an integration of the reservoir engineering aspects is possible for a conceptual reservoir model to be developed.

## 2. TYPES OF WELLS DRILLED IN A GEOTHERMAL AREA

Once a well site is determined, it is important to decide whether to drill thermal gradient wells, slim holes or shallow or deep exploratory wells

A brief summary of the different types of wells is given:

- Thermal gradient wells: usually drilled from 50-100 meter depth, with a borehole diameter less of 5 inches.
- Slim hole: of the smallest practicable size, drilled with less than normal diameter tools, used primarily as a seismic shothole and for structure tests and sometimes for stratigraphic tests. Traditionally, diamond-cored "slimholes" (usually 3-4 or 5 inches in diameter) have been used to measure temperature gradients while selecting sites for production size exploratory geothermal wells.
- Shallow exploratory wells: usually 50-300 m to measure temperature gradients in order to locate the up-flow zone of hot fluids in the geothermal reservoir in an attempt to conclusively determine the presence or absence of a geothermal resource. In the case of Berlin, 3 wells were drilled in the 70´s at a depth between 100-500 meters.
- Deep exploratory wells: drilled to test the presence of high temperature geothermal reservoir rocks for future exploration and development. The design is usually with conventional diameters in order to be tested and to allow the geothermal fluid to flow on surface.
- Commercially exploitable geothermal wells: depths between 500-2000 m where temperatures are around 150-300°C. Researchers recently believe it is possible to drill down to 10,000 m where temperatures can reach at least 374°C and water with a pressure of at least 220 bars.

Each of the mentioned wells provides geological information on fracturing, shearing evidence, porosity data, microfractures, hydrothermal alteration mineralogy present in the rock matrix, in microfractures and/or porosity, which can be used to determine the range of mineral stabilization temperature. This temperature is then compared with the stabilized temperature at the end of the thermal recovery of the well.

## 3. GEOLOGICAL LOGGING

Drilling is one of the principal tasks in the development of a geothermal resource, hence, it is important to have an appropriate design of the well as well as complete control of the subsurface lithology through cuttings and cores. Through the geological logging it is possible to know how the geological structures control the movement of geothermal fluids in the reservoir, as well as the relationship between the alteration minerals and the present-past conditions of the hydrothermal system.

Geological logging is the fine scale observation and recording of the sequence of rocks from cuttings as well as core samples obtained while drilling a geothermal well. All information obtained from surface geological mapping such as type of rock, chemistry of rocks, dating, structures and textures of the

outcrops described, correlation of rocks of different outcrops, etc, should be clear to the wellsite geologist who will perform the geological logging while the well is being drilled.
Information such as stratigraphy, tectonics and thermal mapping can be obtained from the wells and should correlate, as much as possible, with the information described on the geological map. If the geothermal field is in a volcanic environment, the evolution of the system should also be well understood.

### 3.1 Stratigraphy

Stratigraphy is a branch of the geology which studies rock layers and its sequence. It is primarily used in the study of sedimentary and layered volcanic rocks. It includes two related subfields: lithological stratigraphy or lithostratigraphy and biologic stratigraphy or biostratigraphy.

In this paper, the stratigraphy to study is mainly concerned with layered volcanic rocks. The type of volcanoes in El Salvador are mostly stratovolcanoes, therefore, it is common to find in the wells alternating layers of andesite – basaltic andesite lava flows with different types of volcanic tuffs.

The lithological information obtained from each of the wells drilled is useful to design the mechanical configuration of future injection or production wells. The setting of the casing shoes in stable formation with certain mechanical properties and hydrothermal mineralogy is the main purpose of the geological control during drilling.

To determine where to set the upper and production casings, a lithostratigraphic correlation of the lithological units encountered is definitely needed. These lithological units should have correspondence with the geological units mapped on surface, to be able to understand the volcanological evolution. The lithological units are defined through the geological analysis of cuttings and core samples obtained during drilling. Cutting samples are obtained when there is normal circulation of mud.

### 3.2 Lithological control

Cuttings are recovered from the circulated drilling fluid and are analysed to give a better overall picture of downhole changes in lithology and mineralogy. Cores, on the other hand, are extracted when the total circulation loss is encountered, which is mainly done in the production zone or the reservoir. Cutting samples are analysed every 2 meters and a lithological log is constructed where a small amount of representative cutting samples is placed in a wooden plate to be able to analyse it afterwards. When two or three deviated wells are placed in the same pad, the sampling is done every 4 meters as well as the macroscopic analysis, until the kick off point is reached. After this depth, the samples are then analyzed every 2 meters.

### 3.3 Methods of analysis

a) **Macroscopic Analysis:** The first study of cuttings is mainly done by a macroscopic analysis. It describes the color, texture and composition and it helps to determine the boundaries of the formations. A rock name is given to provide its origin as well as the mineral composition. This study is done using a binocular stereomicroscope. Drops of HCl acid (10% conc) is used to determine the presence of carbonate minerals.

   The clay content in cuttings is determined mainly to know if the formations encountered during drilling have swelling clay or content of shales that might react with water and cause blockage problems in the hole. The cutting sample is immersed in water to see the presence of swelling clays.

b) **Microscopic Analysis:** The microscopic study includes the description of the minerals (primary and secondary) and the classification of rock. A thin section is used to identify the rock texture and microstructural relationships of minerals. The optical characteristics observed under the microscope include color, color variation under plane polarized light (pleochroism) produced by the lower Nicol prism, or more recently polarizing films, fracture characteristics of the grains, refractive index (in comparison to the mounting adhesive, typically Canada balsam) and optical symmetry (birefringent or isotropic). These characteristics are sufficient to identify the mineral, and often to estimate its major element composition.

c) **Separation of components:**
- Separation of the fragments in cuttings is mainly done to obtain pure samples for analysis. It may be performed with a powerful, adjustable strength electromagnet to separate magnetite. A weak magnetic field attracts magnetite, then haematite and other iron ores. Finally, only the colorless, non-magnetic compounds, such as muscovite, calcite, quartz, and feldspar remain.
- Chemical methods also are useful: A weak acid dissolves calcite from crushed limestone, leaving only dolomite, silicates, or quartz. Hydrofluoric acid attacks feldspar before quartz and, if used cautiously, dissolves these and any glassy material in a rock powder before it dissolves augite or hypersthene.
- Methods of separation by specific gravity have a still wider application. This separation technique is applied when zeolites and clay analysis are to be achieved.

d) **X-Ray Diffraction Analysis**: X-ray diffraction (XRD) is a very useful technique to identify clay minerals and chlorite that are difficult to identify by other methods. It can also give quantitative information of the minerals present. Clay analysis by XRD is done in three stages: 1) untreated samples in a constant humidity with $CaCl_2$, 2) glycol saturated samples and 3) heating the samples to 550-600°C. The XRD analysis can be done every 10 meters or when a change in mineralogy is observed.

e) **Fluid inclusion analysis:** Fluid inclusions are microscopic bubbles of liquid and gas that are trapped within crystals. As minerals often form from a liquid or aqueous medium, tiny bubbles of liquid can become trapped within the crystal structure or in healed fractures within a crystal. These small inclusions range in size from 0.1-1 mm and are usually only visible in detail by microscopic study. The trapped fluid in an inclusion preserves a record of the composition, temperature and pressure of the geothermal fluids in the reservoir. An inclusion often contains two or more phases. If a vapor bubble is present in the inclusion along with a liquid phase, simple heating of the inclusion to the point of resorption of the vapor bubble gives a likely temperature of the original fluid. If minute crystals are present in the inclusion, such as halite, sylvite, hematite or sulfides are present, they provide direct clues as to the composition of the original fluid. The fluid inclusions can provide information if whether or not the geothermal fluids are in equilibrium with the geothermal system or not. It is useful to know if a geothermal field is active or fossil.

Once analyzed, cuttings can be grouped into formations with similar rock types, color, composition, textures, and structures. This group of formations must belong to the same sequence as in its volcanic evolution.

Grouping formations with similar characteristics allows correlations between wells, which is better applied when the geothermal system is situated in a volcanic environment. The correlation between lithological units is possible when dealing with a stratovolcano, where an interlayering of lava flows and tuffs either lithic, fine, crystal is present. Stratigraphic marker such as fine tuff with thickness of about 50-100 meters is very useful when correlating lithological units from one well to another with several hundreds of meters apart. Another marker to consider is the ignimbrite layering, a volcanic deposit and part of a caldera.

### 3.4 Information described during the geological control

#### 3.4.1 Type of rock:

Cuttings are analyzed macroscopically and microscopically with a petrographic microscope to determine the mineralogical composition, texture, microfractures, porosity and rock type. They are sampled only when drilling uses bentonitic mud as circulation fluid. When total loss is encountered, drilling fluid enters the microfractures/fractures of the formation. If these permeable zones are not of interest, they are usually sealed or cemented to further continue drilling.

Cuttings are still sampled several tenths to a hundreds of meters below the casing shoe. Upon encountering the total loss of circulation when cuttings do not return to surface, aerated fluids, diluted mud or water with polymers and viscous plug are used. However, cuttings can return to the surface if the permeability of the reservoir is not high enough, and the exact location and depth of the sample it is not anymore known. Therefore, a core sample is then considered from 100 to 200 meters below the depth of the first total loss of circulation. Two to three cores can be extracted within a perforated interval of 600-800 meters depth.

Usually, a daily report of analysis in the field is presented using the logging software (Strater).

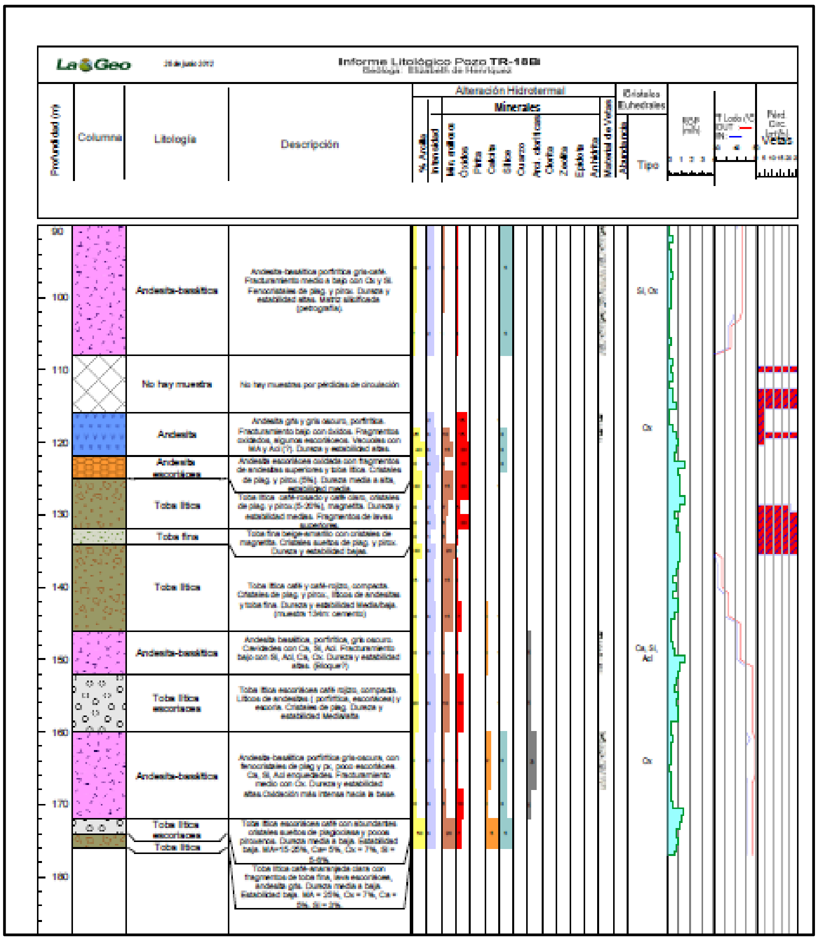


FIGURE 1: Schematic representation of a lithological log obtained from wells drilled

### 3.4.2 Hardness and stability of rock:

Hardness is a descriptive parameter to help define the strength and stability of the formation. It is usually done by exerting pressure on or squeezing fragments of cuttings using a metal tweezer. The hardness of a rock reflects the average hardness of the minerals present in them; therefore it is a relative description. Clay minerals tend to be soft, while rocks with abundant quartz can be very hard. It is usually described as low, medium and high.

The strength of a rock has an appreciable influence on drilling force required, as sufficient force is necessary to exceed the strength of the rock. Usually, the harder the rock, the higher the strength, however the existence fractures and bedding planes can destabilize the rock formation once drilling fluid enters the wellbore.

However, for descriptive purposes, stability of lava formation (or a solid rock) is considered high, rocks with few alteration or lithic tuff are medium and rocks with high content of clay minerals are considered low stability.

### 3.4.3 Hydrothermal alteration minerals:

Preliminary identification of hydrothermal minerals in the cutting samples is done at the wellsite during drilling to provide a first-hand information on the temperature and permeability of the well.

The detailed analysis of secondary minerals is usually based on microscopic analysis and the technique of X-ray diffraction. To complement the geologic information, fluid inclusion studies are currently undertaken.

Usually description of minerals include type of secondary minerals, occurrence (veins, replacing primary minerals, vesicles), abundance of veins and vesicles, and alteration intensity.

Primary minerals are mainly present in formations at shallow depth where the rock has not undergone great changes other than weathering. Secondary minerals start appearing when thermal gradient reveals higher temperatures at depth of 50-100°C. As the thermal gradient increases, primary minerals are transformed to secondary minerals, either by fluid rock interaction or by the influence of temperature itself (weak metamorphism).

Hydrothermal alteration of volcanic rocks involves the replacement of primary igneous glass and minerals (plagioclase, orthoclase, quartz, biotite, muscovite, amphibole and pyroxene) with alteration minerals stable at the conditions of alteration, generally in the temperate range of 50–400 °C. Alteration minerals where rock interaction has taken place ma y include quartz and other forms of silica (chalcedony, opal, amorphous silica), illite, sericite, smectite, chlorite, serpentine, albite, epidote, pyrite, carbonates, talc, kaolinite, pyrophyllite, sulfates (anhydrite, barite, alunite, jarosite), oxides (magnetite, hematite, goethite appear), and zeolites (chabasite, heulandite, laumontite, wairakite).

Alteration textures range from weak alteration of only some of the minerals or matrix in the host rocks, producing an earthy aspect to the overall rock, or to partially-altered phenocrysts. Such alteration may be difficult to distinguish from weathering in the field. Glassy rock matrix or fine-grained can be particularly susceptible to alteration and may be massively silicified or replaced by chlorite or sericite as alteration intensity increases. At high alteration intensity, rocks may be pervasively altered, in which all primary phases in the rock are altered to new hydrothermal minerals.

The degree and the amount of hydrothermal alteration or secondary minerals depend basically on the permeability of the rock, rock composition and temperature, chemical composition of the fluid and the age of the geothermal area.

Secondary minerals and mineral assemblages are defined in order to establish hydrothermal alteration zones or hydrothermal facies. The term "alteration zones" or "hydrothermal facies" are just two different ways of explaining the chemical processes a formation has suffered due to fluid-rock interactions within the geothermal system. The chemical and mineralogical distributions of hydrothermal alteration zones are generally the only direct evidence of fluid circulation pattern taking place in the system.

In Iceland for example, according to Kristmannsdottinr (1998), zonation of alteration minerals is the term currently used. Mineral chlorite becomes the dominant sheet silicate at rock temperatures of 230-

250°C and in geothermal areas where the maximum temperature does not exceed 240°C, chlorite is only found sporadically. The clay minerals such as smectitc are seldom recorded at rock temperatures above 200"C. Mixed layer clays of smectite and chlorite is dominant at 200-230°C.

According to Browne (1984) the minerals mostly used as geothermometers are the zeolites, clays, epidote and amphiboles. In Icelandic regions, most zeolites are common before 100°C and disappear before 200°C (stilbite, heulandite, mordenite). Laumontite replaces other zeolites at l00-120°C. Wairakite, just as in Cerro Prieto, Mexico, starts appearing at 180°C and is recorded up to 300°C (Kristmannsdottir, 1978; Elders, Cl al., 1979). On the other hand, in New Zealand wairakite is identified at temperatures between 200-250°C (Steiner, 1977).

Among the minerals that occur at higher temperatures (above 250°C), epidote seems to be the most reliable and consistent temperature guide. In Icelandic active geothermal fields, epidote occurs sporadically at 230-250°C, but it appears in high quantity at rock temperatures above 250"C. According to Browne, (1984), epidote first appears in many fields at 250°C and the lithology does not influence its formation. Variations regarding prehnite are seen in New Zealand, where it appears at temperatures more than 220°C. In Cerro Prieto, Mexico, it occurs, on the contrary, at higher temperature of 300°C. This is probably due to the difference in the pH and calcium contents of the geothermal fluids.

The intensity and type of alteration usually reveals the degree of permeability. Minerals such as adularia and albite are often related to permeable zones, especially if these are present individually in association with quartz and calcite, (Tongonan, Philippines and all New Zealand geothermal fields). This relationship can be used when these minerals are present in veins and fractures (Browne, 1984).

If they are, however, altering plagioclase, this relationship does not apply. A1bite is also a useful geothermometer only when it occurs in veins. Otherwise the albitization of plagioclase occurs within a wide range of temperatures (Reyes, 1990). It has been observed that in veins where both albite and adularia occur together, the permeability of the rock tends to decrease through self-sealing. Therefore, the former relationship should be used carefully. The original mineralogy of the rock seems to have a minor effect on the type of mineral assemblage in permeable zones. For instance the association of minerals such as albite, quartz, epidote, chlorite, adularia pyrite and illite (26O°C) occur in different geological environments. It is seen in andesitic rocks (Philippines and Indonesia), in rhyolites (New Zealand), alkaline lavas (Kenya) and sediments (Cerro Prieto). K-mica and K-feldspar is near absent in Icelandic geothermal fields and adularia less frequent than found elsewhere (e.g. Fridleifsson, 1984).

In all active geothermal fields, (New Zealand, Cerro Prieto, Iceland and Philippines), alteration zones were derived by empirical data found between rock temperatures and secondary minerals. For example, in Iceland, different alteration zones were obtained regarding the formation of smectites, mixed layer clays and chlorite than found elsewhere. The temperature ranges for these zones are 0-200°C, 200-230°C and 230-250°C respectively. In New Zealand other alteration zones concerning temperatures have been developed. For instance, smectites, mixed layer clays (smectite/illite) and illite give a temperature range of 0-140°C, 140-220°C and greater than 220°C respectively. These empirical relationships as well as the indicative minerals of temperature and permeability can be applied to other geothermal systems. Nevertheless, it is important, that each area develops its own local zonation of hydrothermal alteration mineralogy vs. temperature relationship.

Studies of alteration assemblages in El Salvador led to a series of commonly recognized alteration Facies: Argillic, Argillic-Phyllitic, Phyllitic, Phyllitic-Propylitic and Propylitic, with distinct mineralogy and increasing intensity of alteration when it’s close to the geothermal reservoir.

Typically, in geothermal fields in El Salvador, the abundance of wairakite, illite and pyrite indicate permeability, coinciding and occurring near the top of the reservoir, while epidote, wairakite, penninite and anhydrite describe the propylitic facies with temperatures greater than 250°C.

Mineralogical facies in the two fields in El Salvador show almost the same alteration minerals in each facies, with the only difference in depths. The Ahuachapán geothermal field has shallower reservoir from 800 – 1500m, while Berlín's reservoir is found at 1500 – 2500 m depth.

TABLE 1: Alteration minerals in Berlin geothermal field

| Facies | Alteration Minerals | Temp. (°C) |
|---|---|---|
| Argillic | Clay minerals, Hem, Si, OM, Ca | 50-120 |
| Argillitic-phyllitic | Ca, Cl, Qz, Hem, Cl clays, OM, Clay minerals | 120-180 |
| Phyllitic | Ca, Illite, Cl, OM, Qz, Pen | 180-220 |
| Phyllitic-Propyllitic | Wai, Ca, Qz, Ser, Cl, Anhy, Preh, Illite | 220-250 |
| Propyllitic | Ep, Qz, Preh, Wai, Cl, Qz, Anhy | 250-300 |

Thermometric measurements are carried out using LINKAM equipment with Linksys software. Temperature of melting (Tm) and temperature of homogenization (Th) are measured mostly in quartz and calcite crystals.

Summary of the results of microthermometric analysis of fluid inclusions of wells in Berlín geothermal field shows two-phase liquid with more liquid-rich inclusions (70 – 80%) and few vapor-rich inclusions (20%). It can also 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.

**I. Drilling parameters:**

A preliminary stratigraphic section is constructed by the analysis of cuttings which goes hand in hand with the drilling parameters such as drill bit weight of the load pressure on the drillstring, rate of penetration and mud temperature (in and out of the borehole), as they also affect the interpretation of all geological data collected at the wellsite.

One of the most useful "real time" geological tools is the rate of penetration, which depends upon formation porosity and rock matrix strength. Different bit types should also be taken into account; in general, longer toothed bits are used for softer formations.

The amount of weight on bit (WOB) that may be added on any bit is provided by and limited by bit size and the drillstring (especially the drill collars). Changes in the WOB, when not intentionally changed by the driller, often indicate changes in formation. Soft formations require little WOB, while hard formations require the maximum amount of WOB.

**II. Completion tests:**

After drilling a completion test is undertaken consisting of permeability assessment, temperature of formation and thermal recovery.

## 4. CASE STUDY BERLÍN

### 4.1 Regional tectonics – geology

The Berlin geothermal field is located 100 km east of San Salvador city, at the northern slope of the volcanic complex named Berlin-Tecapa. The area is influenced by a compressive stress due to the subduction of the Cocos plate under the Caribbean plate.

The subduction direction of the Cocos plate is to the NE, but due to the redistribution of stress in the on the back arc setting, the maximum horizontal stress in the vicinity of the Berlin field is NW-SE oriented. The evidence for this is from the earthquake focal mechanism shown on the present day stress map.

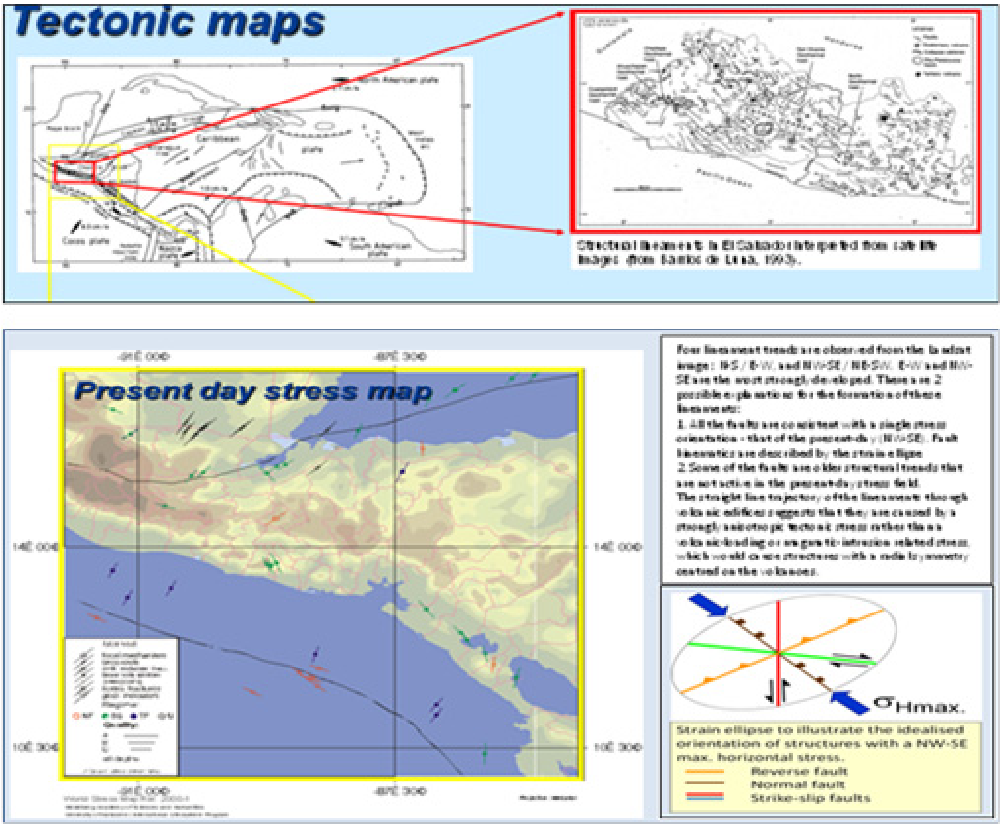


FIGURE 2: Present day stress map and tectonic map of El Salvador

This process originated a Caldera structure which is cut by the trending faulting E-W (Central America Graben), NW-SE faulting. The main lineament trends are running approximately at right angles. N-S/E-W, NW-SE and NE-SW. Of these trends, the E-W and NW-SE are strongly developed.

The intersections of several fault systems are potential drilling targets, therefore it is necessary to count on a reliable map to clearly see either the visible faulting sites on the ground, photo geological lineaments or discontinuities obtained either from Landsat images interpretation, aerial photographs or lineaments from a particular geophysical modelling (mainly electric, gravimetric). Digital model (DEM) of Berlin field is also important to locate structures, lineaments and morphological shapes.

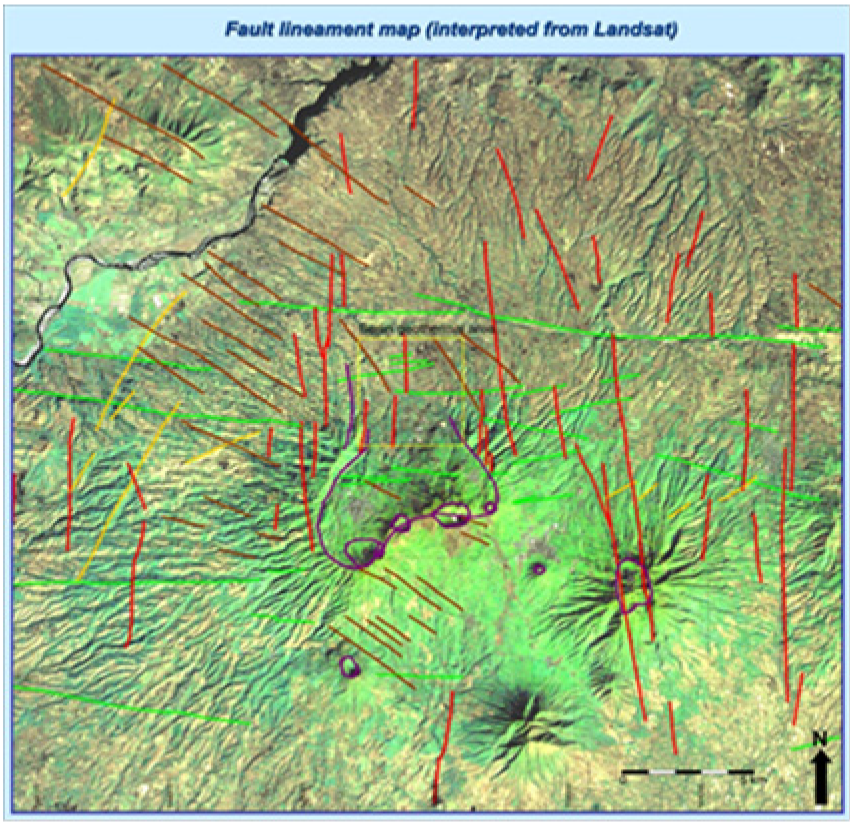


FIGURE 3: Structural lineaments gathered by
Landsat satellite images

The Berlin area is affected by a quaternary calc-alkaline volcanism, where effusive events alternate with explosive events generating an interlayering of lava flows and tuffs. Pumice a deposit that correspond to the Caldera Blanca Rosa, is the only evidence of differentiation which covers most of the surface near the Berlin city. This layer is used as a guideline and is mapped in the Berlin and Chinameca areas.

Andesitic grey and black ignimbrite deposits originated from the Berlin Caldera structure covering most of the northern and southern slope of the Berlin area are stratigraphically correlated with the Blanca Roca pumice.

The only dating of a well, the one at the bottom of well TR_3 (paleomagnetic method), is 4.5 Ma. If this **dating** was substantiated, the reservoir rocks could belong to an earlier stage of activity (MioPliocene), also known at Ahuachapán. Central-American volcanism seems to have had two stages of activity, separated by a long lull: one, dating back to > 3 Ma, that led to the formation of the so-called basement (Balsamo formation), and another which developed about 1 Ma and is still active.
The identification of dykes, linear intrusions along fractures and/or discontinuity surfaces provide structural information. Dykes are observed not only on the western part of the caldera border but also in the wells drilled. The dykes are not evenly distributed but appear mostly in the northern section of the field, where the wells are less permeable and hence less productive.

The mapped formations on surface and stratigraphy relationships in the Berlin Geothermal Field are, starting from the oldest to the recent ones:

TABLE 2: Geological Units in the Berlin Geothermal Area

| Geological Units | Description | Dating K/Ar | Regional formations |
|---|---|---|---|
| bo | Basaltic lavas and scorias that belong to the old Berlin Volcano | 1.4-0.9 Ma | Balsamo formation |
| bi-gi | Black ignimbrite and Grey Ignimbrite | 100 ka | San Salvador Formation |
| bm | Berlin intracaldera lava flows and scoria deposits | | |
| by | Lava and scoria's from the young quaternary volcano Berlin-Tecapa | 0.1 Ma | |
| ri | Blanca Rosa Ignimbrite | 0.075 Ma | |
| | Surge deposits from El Hoyon | 700 years | |
| | Distal Tefras from eruptive edifices | | |

### 4.2 Local Faulting systems

*Fault System WNW-ESE*
This fault system is the most important from the regional perspective, as it is responsible for the formation of the Central or Central graben and active volcanic chain and the country. Some of the more recent volcanoes such as Cerro Pelon, and Cerro Laguna de Alegría Alegría, are aligned in the same direction, indicating that this active tectonic system is not only found in the Berlin area, but throughout the country.

*Fault System NW-SE*
This system is considered the most recent and important asset, since allows the ascent of geothermal fluids from depth to the surface. Most demonstrations of hydrothermal in the geothermal field are found within this graben structure NNW-SSE.

*Fault System NNW-SSE*
It is a system of faults associated with NW-SE system and is responsible for the displacement of the north wall of the Berlin Caldera structure.

*Fault System NNE-SSW*
This fault system is not fully visible in the Berlin geothermal field, but its presence can be inferred based on the apparent alignment of fumaroles and small post-caldera volcanoes such as Cerro Las Palmas and Cerro Laguna Ciega.

*Berlin Caldera System*
It originated in the end stage of the ancient volcano eruption in Berlin, following the collapse of the largest volcanic structure. This structure was dislocated by normal faults trend NNW-SSE and NW-SE.

### 4.3 Lithostratigraphic units in wells

The lithological correlation is done using primary textures of rocks that differentiates between effusive and explosive products. Lithological columns constructed for each well using formation units obtained from macroscopic analysis and petrographic data do not change from wells drilled during the 70´s-80´s to wells drilled in the 90´s. The main differences are seen in depth of appearance and thickness for each unit, showing structural influence such as normal faulting and strike slip faulting.

Four geological units (I to IV) are defined by analyzing thin sections of cuttings and cores in a total of 27 wells drilled from the 70´s to the year 2003. The general description is in Table 3.

TABLE 3: Lithostratigraphic unit-Geological units in South and North sector of the geothermal field

| **Lithostratigraphic Unit/ /Gelogical unit** | **Lithology** | **South sector** | **North Sector** | **Average Thickness (m) North-South** |
|---|---|---|---|---|
| UNIT I<br>Surface Materials<br>Outcrop name: (by , ,bm) | Alternate secuence of pyroclastics with a predominance of andesitic and basaltic andesite lava flows. Several levels of fine tuffs and lithic tuff. | Mainly lavas in TR4´s/TR5´s Wells. In some levels of pyroclastic at the surface is seen.<br>No dykes observed | Thick pyroclastic deposits. At the top of this unit. Presence of sporadic dykes and sills. | 600 a 800<br>(410 a 435 in Wells TR-11´s) |
| UNIT II<br>Pyroclastic flows with thin layers of andesitic lava flows<br>Outcrop name: (gi,bi) | Pyroclastic flows of various types (variation of lithic and cristalline tuffs with scorias interlayering thin and thick basaltic andesite lava flows. | In most Wells, it begins with an ignimbrite deposit (banded textures). Thick layers of tuffs mainly scoriaceous. | Thick layers of Tuffs with various thicknesses layers of andesitic lavas. Minor levels of scoria. | 570 a 850<br>(985 in Wells TR-11) |
| UNIT III<br>No outcrop: (tf) | Guide level composed by cineritic tuff, Green color with Plagioclase with sporadic thin layers of andesitic lava flows.<br>Dykes are identified.<br>Defined as cap rock of the geothermal reservoir. | Presents the best characteristics of this unit. It is observed in every well of the sector. | Characteristics are not totally complete. Crystal are bigger in size and with less thickness. | 105 a 345<br>(365 in Wells TR-11) |
| UNIT IV<br>Outcrop name: (bo) | Mainly andesitic lavas interlayerd with basaltic andesite, andesitic brecias and a variety of tuffs with abundant dykes /sills. Granodiorite and Granite rocks are present in several wells showing high permeability. Silicified tuff is present in some wells. | Thick layers of lavas of different composition interlayerd with thin packages of tuffs. Dykes and sills, as wells as Granodiorite and diorite rocks are present. | Thick packages of lavas interlayered with thin tuff packages. Dykes and sills with the higher thickness are present in this sector. | 370 a 920<br>(210 a 730 in Wells TR-11) |

The lithostratigraphic columns and the corresponding correlation were done analyzing thin films every 20 meters. With the information available to date from wells TR-1, TR-3 and TR-4, no substantial differences in the number and type of unit and only found some differences related to the depth of appearance and thickness of each unit (I to IV), and that the review was conducted lithological smaller intervals.

Thin sections of cuttings and cores were analyzed by optical microscopy. Petrographic analyzes conducted on <50% of the samples referred to rock wells representative of major geological units and hydrothermal alteration zones. The main rock types are analyzed: a) • andesitic and / or basaltic-andesitic lava and b) • Rocks shaped pyroclastic tuffs and / or ignimbrites.

The volcanic rocks are often altered by hydrothermal fluid circulation, zoning exhibiting mineralogical paragenesis associated with typical temperatures that increase with depth (Argilítica, Filítica, propylitic). The succession of these alteration facies disagrees with the stratigraphic units grouped as dependent on fluid flow and temperature flowing through the rock fractures.

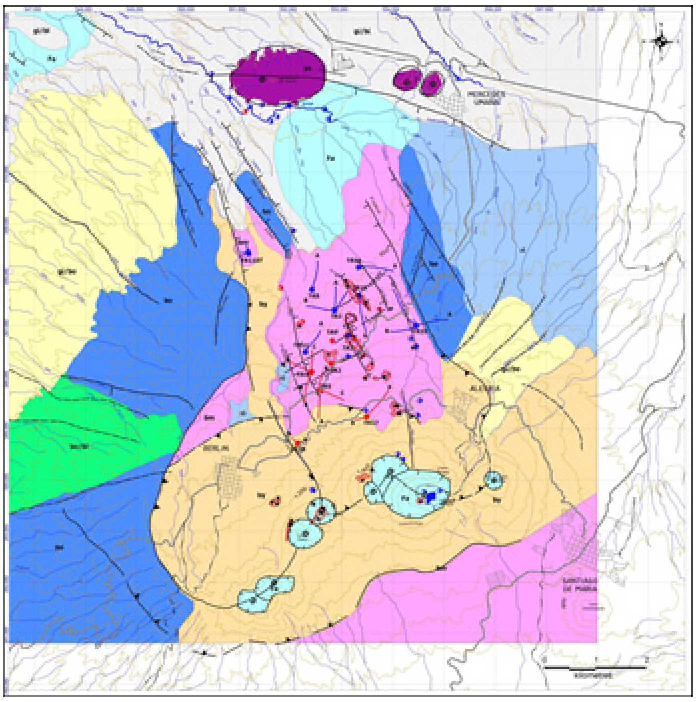

FIGURE 4: Berlin Structural and Geological map

## 4.4 Hydrothermal alteration minerals in Berlin

The alteration zones term used in Iceland, described in detail the type of minerals from chlorite clays found in depth. These are used as geothermometers as to identify possible cooling zones. In this description in addition to clay minerals, chlorite group, complete mineralogical association is considered. This report uses the term mineralogical facies, which then describes each: Facies: Argillic, Argillic-Phyllitic, Phyllitic, Phyllitic-Propylitic and Propylitic, with distinct mineralogy and increasing intensity of alteration.

*Argillitic facies*
It is characterized by the presence of the smectite clay minerals and zeolites low temperature, traces of quartz and calcite.Stabilization temperatures indicated generally between 50-150 ° C. South of the field lower limit of this facies are identified +500 m and north of the country to +150 m, with average thickness between 350-400 m.

*Argillitic-phylitic facies*
The characteristic minerals are clays, mixed layered clays. Minerals such as quartz, calcite and zeolite indicate stabilization temperatures between 150-180 ° C. South of the field the lower limit is identified between +100 m and to the north between the -100 m, showing an average thickness of 400 m.

*Phyllitic facies*
It is characterized by the appearance of chlorite mineral and mixed or interstratified layered clays decrease. Minerals such as calcite, quartz remain with the presence of zeolites of higher temperature The stabilization temperature is about 200-230°C. The lower limit of this facies is identified south of the field between -400 m and north between -700 meters, and has an average thickness of 600 m. Partial replacement of epidote + chlorite (propylitic zone before) with quartz, calcite, sericite and hematite. On average, this area is located at a depth of 500-1500 m.

Presence of epidote + chlorite and rocks partially replaced with quartz, calcite, hematite, show greater zones of fluid interaction in the reservoir rock. However, the appearance of epidote could be used to reconstruct the evolution of geothermal reservoir, which contributes to highlight the main volcano-tectonic structures responsible for the movement of geothermal fluids.

*Phyllitic-propylitic facies*
It begins the formation of epidote, full development of chlorite, presence of chlorite penninite type. The stabilization temperature in this zone is approximately 230-260°C. The lower limit of this facies is

identified south of the field between -950 m and north to -1200 m, showing an average thickness of 300 m.

*Propylitic facies*
It is characterized by the complete development of epidote and observed mineral are deposited mainly in fractures. It is also associated with minerals such as quartz, calcite and other minerals of high temperature. Stabilization temperatures are estimated between 260-300 ° C. No lower limit is identified and therefore its thickness is unknown. A wide presence of epidote, chlorite and adularia is generally at depths greater than 1500 m.

Advanced Argilítica alteration (combination of kaolin, alunite + S) is a fluid product which possess an acid pH (2-3). This disruption occurs at low temperatures of 100-130 ° C and is the result of condensation on the surface of H2S oxidation sulphate and acid sulphate final production fluids. In systems hydrothermal alteration prophylitic (generally have combinations of calcite + QZ + Ep + chlorite + adularia ± pyrite) is the result of the fluid circulation of sodium chloride at temperatures between 200 and 350 ° C.

The propylitic facies is defined as a variety of andesite strongly affected by volcanic gases. The dark green color of the rock is due to the formation of mineral abundant chlorite as alteration of primary minerals hornblende and biotite type.

### 4.5 Fluid inclusions

The data obtained from analyzes of fluid inclusions in core samples from wells in the center of the field, at depths greater than 1000 meters, show homogenization temperatures (Th) between 250 and 340 ° C and salinity of the fluid (Tm) between 2100 and 4300 ppm (Cl), which are consistent with the physicochemical properties of the produced geothermal fluids. The temperatures are always higher in the southern part of the field and decrease as it moves northward.

By correlating the information, from the petrographic analysis of well TR-17 did not observe minor minerals of temperature on the highest temperature, which may give information that lower temperatures can be found associated with a reservoir which may have occurred cooling by deep percolation in the intermediate aquifer as reservoir temperatures of wells TR17 sectors are 25-30 ° C lower than the temperatures of the wells TR4 / TR5.

TABLE 4: Summary of fluid inclusions wells TR4 and TR

| Well | Depth (m) | Homogenization Temperature Range (Th) °C | Mineral | Comment |
|---|---|---|---|---|
| TR4 | 1700 | 301.6-342.9 | Quartz | Th max > measured temperature |
| TR4 | 2000 | 299.2-346.2 | Quartz | Th max > measured temperature |
| TR4B | 1568.2 (MD) | 231-264.9 | Calcite | Th temperature similar with measured temperature |
| TR4B | 2000 (MD) | 278.4-284.8 | Quartz | Th temperature similar with measured temperature |
| TR5 | 1600 (MD) | 255.8-260.2 | Calcite | Th < measured temperatuere |
| TR5A | 1550 (MD) | 198.4-236.9 | Quartz | Th < measured temperatuere |
| TR5A | 2008 (MD) | 269-327.4 | Calcite | Th max > measured temperatuere |
| TR17A | 1750-1752.2 | 284 | Quartz | Fluid inclusions range 275-294°C |
| | 2050-2055 | 305 | Quartz | Fluid inclusions range 330-310 |
| TR18 | 1053-1057 | 291, 218 | Quartz/Calcite | Fluid inclusions range 195-298°C |
| | 2050-2055 | 314, 272 | Quartz /Calcite | Fluid inclusions range 268-330°C |
| | 2600-2603 | 328 , 258 | Quartz /Calcite | Fluid inclusions range 249-338°C |

### 4.6 Hydrogeology

At Berlin wells, four types of aquifers are identified with variations in temperature, host rock and permeability.

*Possible Cold Shallow aquifer:*
It does not have a freatic level and probably the total circulation losses are due to the presence of thick fractured andesitic lava flows. This is located between 10-50 m from the ground.

*Intermediate aquifer:*
It is located between 250 masl to -50 masl and has a temperature of 175-200°C. It is present in all wells in the field, but at the south sector it has the highest permeability. The aquifer is mainly located at the base of Unit I.

*Thermal aquifer:*
It is found only in the wells at the northern sector of the field, specifically in wells TR14´s and TR8´s at a depth between 85-150 m (+200 msnm y -300 msnm) and has a temperature of 90-100°C. Mainly located at top of Unit III:

*Deep Hot Saline aquifer:*
It is the reservoir of the field which is used for electrical generation. It has a temperature of 300°C at the south sector and 250°C at the north. The higher permeability of this aquifer is at the south sector and is located at -900-1200 masl.. Wells at the north sector (mainly injection Wells), encountered a less permeable well and at deeper elevations (-1300-1500 masl).

## 5. TEMPERATURE

All available temperature data (master logs, final well reports, temperature logs) were used to elaborate a temperature contour map.

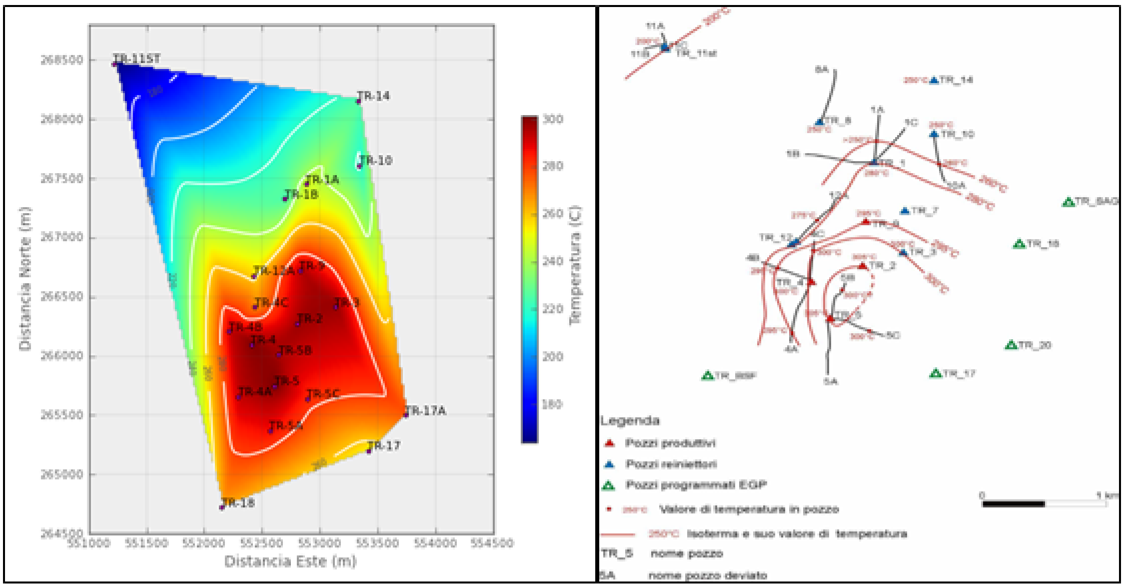


FIGURE 5: Areal temperature distribution of Berlin wells at -1200 masl and -1100 masl

## 6. CONCLUSIONS

1. The intersections of several fault systems are potential drilling targets, therefore it is necessary to count on a reliable map to clearly see either the visible faulting sites on the ground, photo geological lineaments or discontinuities obtained either from Landsat images interpretation, aerial photographs or lineaments from a particular geophysical modelling (mainly electric, gravimetric). Digital model (DEM) of Berlin field is also important to locate structures, lineaments and morphological shapes.

2. The degree and the amount of hydrothermal alteration or secondary minerals depend basically on the permeability of the rock, rock composition and temperature, chemical composition of the fluid and the age of the geothermal area.

3. Lithological columns constructed for each well using formation units are usually obtained from macroscopic analysis and petrographic analysis.

4. Microthermometric analysis by fluid inclusion studies can provide cooling or heating processes.

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