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BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL SV-5A, SAN VICENTE GEOTHERMAL FIELD, EL SALVADOR, C.A.

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ABSTRACT

Well SV-5A is an exploration well located in El Salvador in the San Vicente geothermal field. It is a directional well, drilled to a depth of 1798.5 m. The drill cuttings of the well were analysed through a binocular microscope and through a petrographic microscope in thin sections. The lithology of Well SV-5A consists of andesite lava flows, basalt-andesite, dacite and three different types of tuffs: crystal tuff, lithic tuff and crystal-lithic tuff. The alteration minerals show that temperature increases with depth. Mineralogical assemblages reflect five zones of alteration: a smectite-zeolite zone at 386-750 m, a mixed layer clay zone at 750-920 m, a chlorite zone at 920-1200 m, a chlorite-epidote zone at 1200-1242 m, and an epidote-actinolite zone at 1500-1798.5 m. Four aquifers were identified in the production section of the well, based on the temperature profiles and circulation losses during drilling. When the first appearance of alteration minerals and the results of the analysis of fluid inclusions were compared, equilibrium was observed, reflecting a temperature of 280°C at 1500 m depth. The formation temperature estimated at that same depth in the well is 240°C. By comparing the formation temperature with fluid inclusions and the alteration mineralogy, a cooling of about 40°C has occurred in the geothermal system. According to the calculated Horner temperature, the well was still in a thermal recovery process during the last temperature log, which showed an increase of 5°C, which means that the formation temperature of the well could possibly reach 245°C.

1. INTRODUCTION

El Salvador is located in Central America, has a territorial extension of 20,742 km^2 and a population of 6.2 million. Geologically the country is part of the Pacific Ring of Fire and is situated in an environment of convergent tectonic plate boundaries, which promotes the formation of volcanic arcs and active geothermal systems.

El Salvador has significant geothermal potential and since the early 1960s many areas have been studied with geothermal interest. The geothermal power generation in El Salvador started in 1975 and has been increasing steadily since. Currently, there are two developed fields, Berlin and Ahuachapán, with an installed electrical capacity of 204.4 MW. The geothermal power station in Ahuachapán has three units and a total installed capacity of 95 MW; the total installed capacity in Berlin (four units) is 109.4 MW.

El Salvador has an estimated geothermal resource of 791 MW in areas of high and low enthalpy, so the use of this energy is only 25%. Recent studies have shown that geothermal energy is the best option to meet future demands and to diversify the country's energy matrix, as this would greatly reduce the energy dependence based on fossil fuels and, thus, the vulnerability induced by high oil prices that the country has had to face since the last oil crisis.

The geothermal field of San Vicente is located in the central part of El Salvador (Figure 1), about 60 km from the capital, San Salvador. This field is located by the San Vicente volcano (Chichontepeque), with no history of recent volcanic activity. Indications of an active geothermal system are found in three active fumaroles located on the northern flank of the volcano.

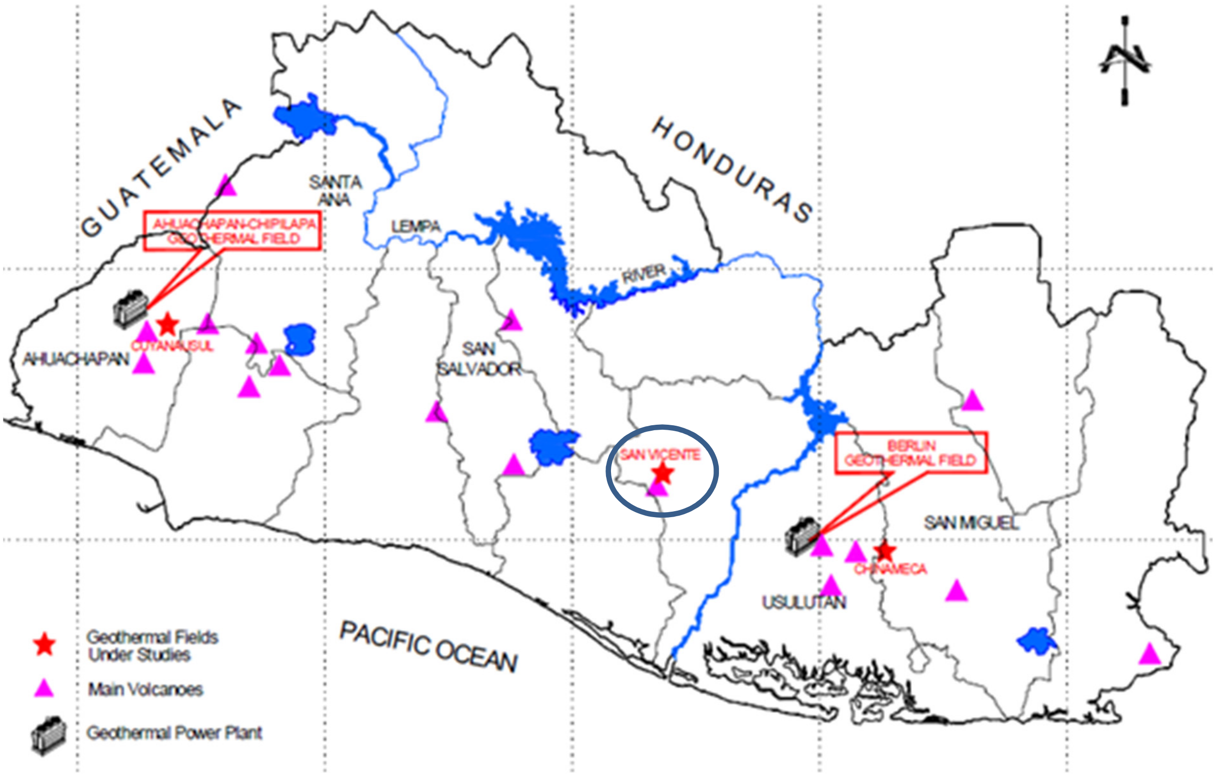

FIGURE 1: Location map of the geothermal fields and exploration fields of El Salvador (CNE, 2012). San Vincente is shown within the circle.

The geothermal area of San Vicente volcano has been the subject of several studies since the early sixties, when PNUD assessed the major geothermal areas of El Salvador. At the end of the 1970s, the Comisión Ejecutiva Hidroélectrica Del Rio Lempa de El Salvador, CEL (CEL, 1992), carried out the first geophysical exploration studies in the San Vicente area. Based on their results, it was proposed that exploration drilling should be conducted to confirm the existence of a geothermal reservoir in the San Vicente volcano.

Following the first exploration drilling (which did not show good results), the project was put on hold and it was not until the year 2004 that LaGeo S.A de C.V. obtained the concession field and continued with superficial exploration studies and exploratory drilling. During the years 2006-2007 three exploration Wells SV-1A, SV-2A and SV-3 were drilled (Figure 2); of the three, only the first confirmed the existence of a geothermal reservoir, but with low permeability. Consequently, LaGeo decided to drill exploration Well SV-5A to the southwest of well SV-1 with the aim of finding better permeability.

This report is focused on the characterization of the geology of Well SV-5A, which was drilled from October 2012 until January 2013, based on the analysis of the cuttings and the two cores obtained during drilling.

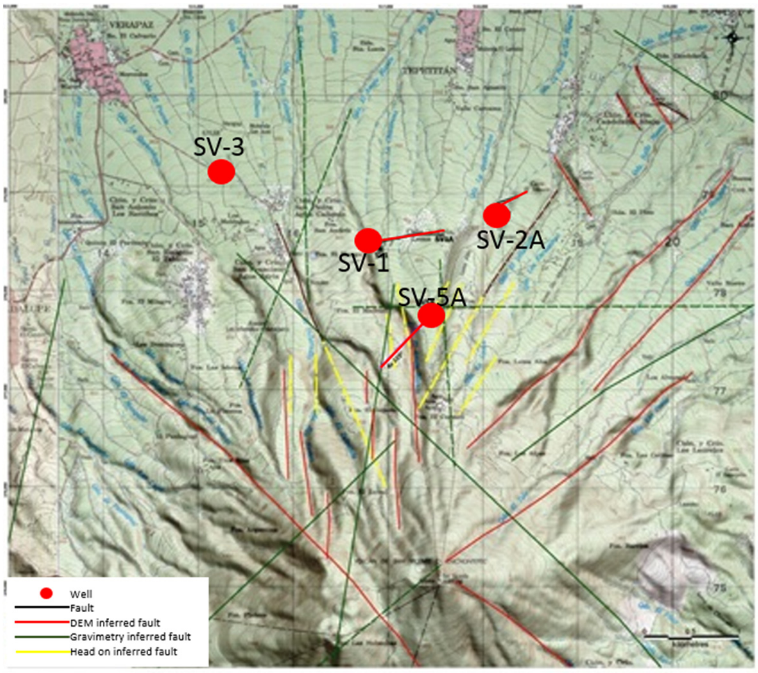

FIGURE 2: Map location of the wells drilled in the geothermal field of San Vicente (modified from LaGeo, 2013b)

1.1 Tectonic setting of El Salvador

The study area is located in the central-eastern Salvadoran territory, which, from the point of view of plate tectonics, is within the Caribbean Plate. The main morpho-tectonic features are produced by the subduction of the Cocos Plate under the Caribbean Plate (Middle America Trench) and the interaction of the Caribbean Plate with the North American Plate (System-Polochic-Motagua fault) (Figure 3).

The Salvadoran territory is bound to the north by a regional structure called the Central Graben, which runs through the country and extends from Guatemala to Nicaragua, where it is known as the "Depression of Nicaragua". This structure is the largest and most influential in the surface geology of the region. In fact, much of the recent volcanic edifices are arranged through this structure.

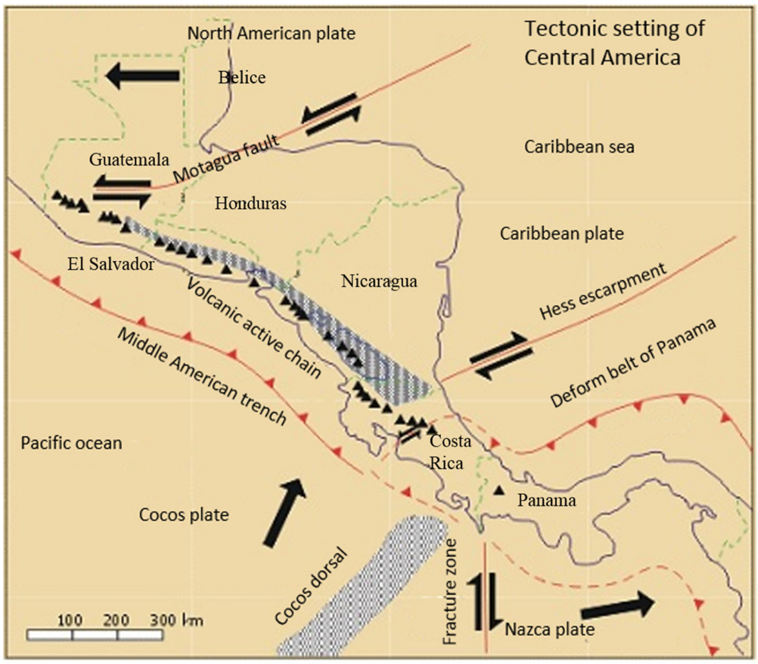

FIGURE 3: Regional tectonic framework of Central America (modified from LaGeo, 2005)

The transcurrent component of the movement between the Cocos and the Caribbean plates is probably accommodated on land by a slip along a major E–W trending dextral transcurrent fault system (El Salvador Fault Zone, ESFZ) (Martínez-Díaz et al., 2004) which runs along the volcanic front and represents the source of the strong strike-slip seismicity. Between the dextral ESFZ and the sinistral Motagua fault system, a series of N–S trending grabens testify to the existence of a broad zone of nearly E–W extension (Agostini et al., 2006).

The main structures belonging to the ESFZ have an approximate E–W strike, and are characterized by right-lateral kinematics. These faults, running sub-parallel to, and north of, the volcanic front, affect late Pleistocene and Holocene deposits and present a strong morpho-tectonic signature, testifying to very recent activity (Corti et al., 2005). The active tectonics of the ESFZ are further corroborated by the strong transcurrent crustal seismicity associated with this fault zone (Martínez-Díaz et al., 2004). In particular, the major upper crustal seismic events that have taken place since 1912 in El Salvador occur parallel to, and north of, the volcanic front (Martínez-Díaz et al., 2004). Reliable focal mechanisms indicate strike-slip events with one of the planes oriented E–W. At least six of the major destructive earthquakes (M≥6) along the volcanic front seem to be related to a slip along the ESFZ segment located between River Lempa and Lake Ilopango (Martínez-Díaz et al., 2004; Agostini et al., 2006).

1.2 Regional geology

El Salvador is very active tectonically, as it lies within the area of an interaction between the Cocos Plate and the Caribbean Plate, where the former is subducted beneath the latter. Geologically, El Salvador is a very young country, mainly composed of rocks of Quaternary and Tertiary age, in addition to a small portion of Cretaceous age rocks (Figure 4).

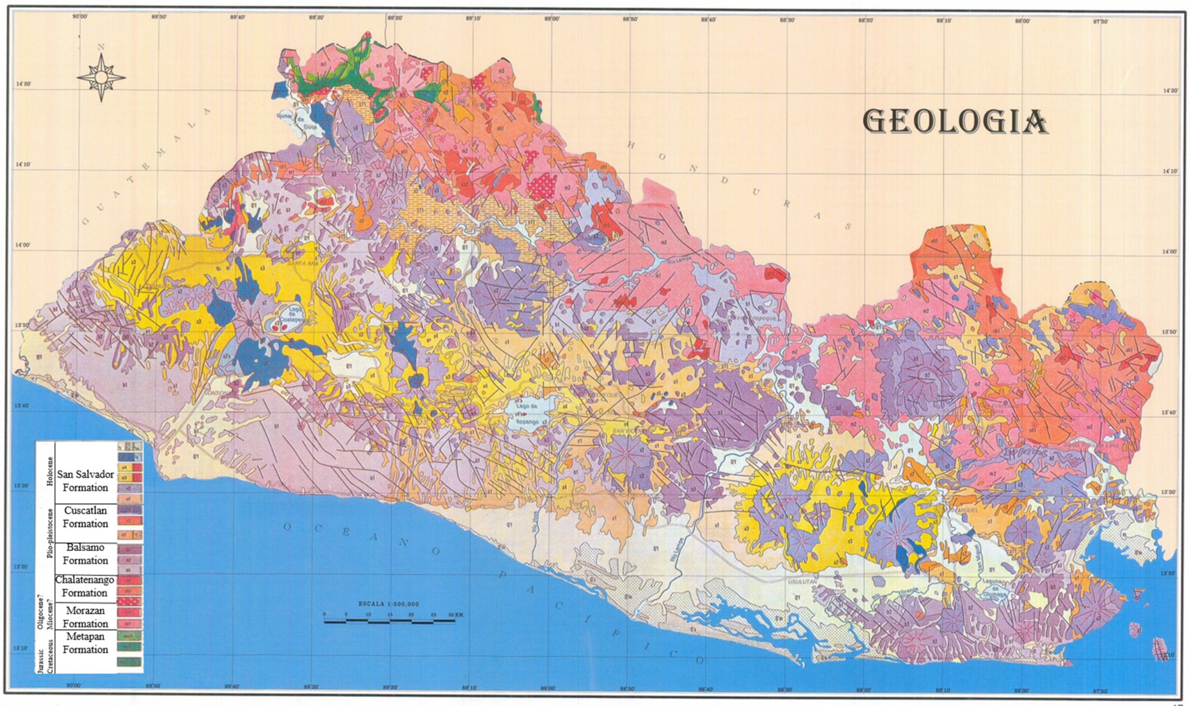

FIGURE 4: Geological map of El Salvador (modified from German Geological Mission, 1970)

The oldest rocks of El Salvador are sedimentary rocks corresponding to the Metapan formation, where limestone, marl and shale are intercalated. These rocks outcrop in the northwest part of El Salvador. The Tertiary rocks are of volcanic origin and are located in the north, as they belong to an ancient volcanic system. They are mainly composed of basalts, andesites, rhyolites and extensive ignimbritic flows. Intrusives of acid composition, related to the old volcanic structure, are also found. Many hot springs, as well as hydrothermal alteration in this area (Figure 5), are associated with the old magmatic chamber and possibly with the last intrusions of this extinct volcanic arc. The geothermal fields in this area are medium to low temperature (<180°C).

The Quaternary rocks owe their origin to the great structure that crosses the country parallel to the coastline of El Salvador, the central graben, where volcanic activity has emerged recently. The present active volcanic arc of El Salvador is located in this structure, which has given rise to many volcanoes, mainly of basaltic and andesitic composition. Additionally, it has given rise to large calderas, evidenced by dense ignimbritic flows. Currently all high-temperature geothermal fields (>200°C) are related to the active volcanic arc and many hot springs and hydrothermal manifestations can be observed along this structure.

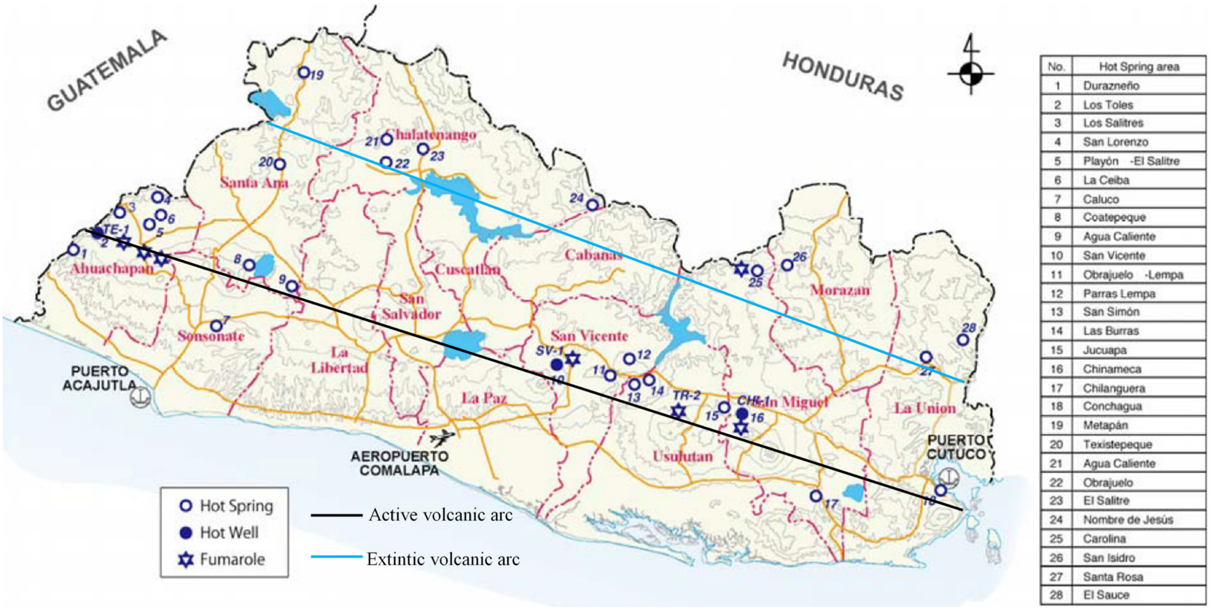

FIGURE 5: Location of volcanic systems in El Salvador (modified from CNE, 2012)

2. LOCAL GEOLOGY

2.1 San Vicente geothermal field

The San Vicente geothermal field is located in the central part of El Salvador, almost 5 km away from the city of San Vicente and approximately 60 km from the capital, San Salvador. Interest in the geothermal potential in the San Vicente volcano has been demonstrated since the 1960s when PNUD included the area in its campaign to assess the various geothermal prospects in El Salvador. The total area of concession, which was granted by the General Superintendence of Electricity and Telecommunications (SIGET), was approximately 100 km^2 (Figure 6). The project is currently at a prefeasibility stage, which includes the drilling of two more exploration wells.

2.2 Background of the San Vicente geothermal field

The geothermal area of the San Vicente volcano has been the subject of several studies since the early 1960s, when PNUD assessed the major geothermal areas of El Salvador. In the years 1977 to 1979, CEL conducted the first geophysical exploration study in the San Vicente, consisting of vertical electrical soundings AB / 2 = 1500. The penetration of these soundings was limited to the first 500 m. The results of these studies became the basis for delimiting the area for future investigations.

In 1978-79, exploration Wells SV-1, PSV-1 and PESV-2 were drilled, reaching depths of 1346.5, 551 and 506.5 m, respectively. SV-1 penetrated a permeable zone that can be considered part of a potential geothermal reservoir. In 1992-1993, CEL conducted a second exploration campaign with a suite of geoscientific studies including surface geological mapping, gravity and Schlumberger surveys and geochemical sampling of surface waters.

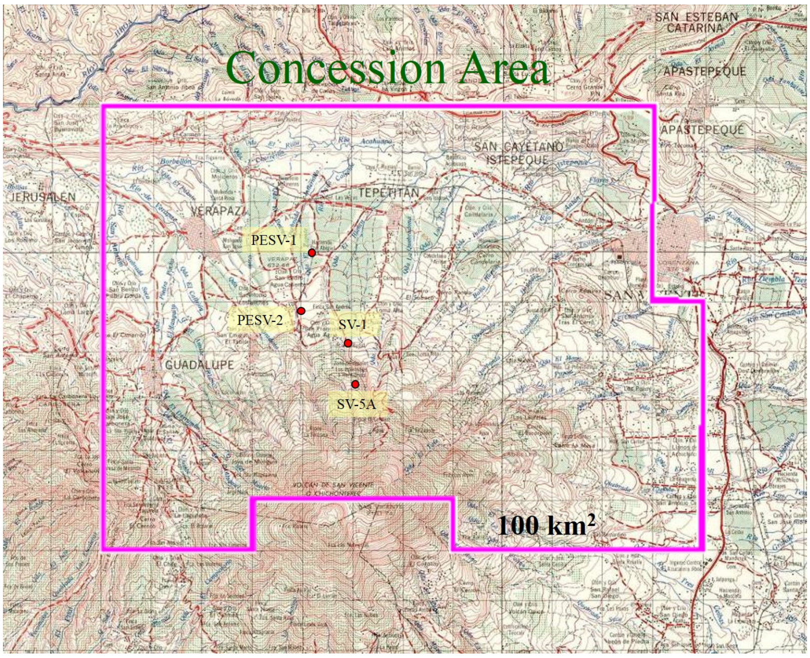

FIGURE 6: Concession map of San Vicente geothermal field (modified from LaGeo, 2005)

In late 2004, LaGeo SA de CV acquired the concession for studies of the San Vicente geothermal area. Until the beginning of 2005, LaGeo performed complementary studies of geology, geochemistry and geophysics. Based on their results, it was proposed that three exploration wells be drilled, two directional (Wells SV-1A and SV-2A) and one vertical (Well SV-3).

During the years 2006 and 2007, Wells SV-1A, SV-2A and SV-3 were drilled. However, the results were not as expected and in November of 2009, LaGeo engaged Iceland GeoSurvey (ISOR) in reviewing and evaluating the conceptual model of the San Vicente geothermal field and the results of the deep exploration drilling. Included was an estimate of the electric potential of the field and a feasibility assessment of continuing with further deep exploration drilling and the identification of new drilling targets. In the year 2012, LaGeo proposed the drilling of exploration Well SV-5A.

2.3 Geology of the San Vicente Volcano

The San Vicente volcano is an andesitic, composite volcano, the second most voluminous in El Salvador, covering 130 km^3 (Carr et al., 1981). It is located approximately 60 km east of the capital city, San Salvador.

Chichontepec is a paired volcano whose eastern crater (elevation: 2180 m) appears to be morphologically younger while the western crater (elevation 2105 m) seems older. The remnants of an older volcanic centre lie immediately west of the main volcanic edifice (Figure 7) which consist of a series of pronounced hills arranged in a semicircle (La Carbonera hills).

The beginning of La Carbonera volcano's activity is poorly defined according to Rotolo and Castorina (1998), but the onset is considered to be 2.2±0.4 and 1.2±0.2 Ma. La Carbonera volcano experienced a pyroclastic eruption that led to the collapse of the edifice, thereby giving rise to a caldera, which is referred to as the La Carbonera caldera (CEL, 1992). From this caldera numerous pyroclastic events occurred, beginning with a deposit of ignimbrite and followed by a sequence of dacitic pumice falls. According to Rotolo and Castorina (1998), the isopach pattern of dacitic pumice deposits locates the vent's position inside the annular structure, which is outlined by the La Carbonera hills.

The renewed volcanic activity, following the pyroclastic stage, formed a considerable volume (130 km^3) of thick (~20 m) lava flows, which built up the Chichontepec edifice inside the La Carbonera caldera. Lavas on the northern and southern flanks of the volcano were probably emitted from a central vent, while those of the eastern flank were emitted from a parasitic vent, which is located to the east of the summit craters (Rotolo and Castorina, 1998).

The most recent activity of this complex is dominated by effusive volcanic eruptions, a moderately fluid magma and low gas content. The lava flows that formed the San Vicente volcano are mainly of intermediate composition, predominantly andesitic lava flows with some alternating basaltic lava flows. These lavas have a high content of xenoliths, mainly of basic and intermediate composition.

In 2005, LaGeo conducted rock sampling with the purpose of defining the surface rocks in more detail, resulting in the discovery of a dacitic dome which is located in the West cone (Figure 8). The discovery of this structure in the San Vicente volcano is of great importance since it suggests a magmatic differentiation and, therefore, the possibility of a shallow magmatic chamber.

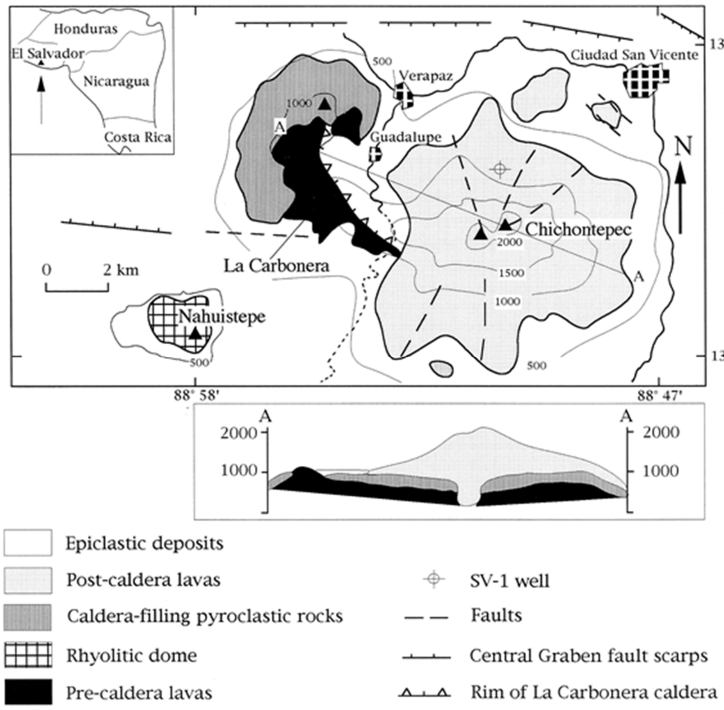

FIGURE 7: Generalized geological map of the Chichontepec volcanic centre (Rotolo and Castorina, 1998)

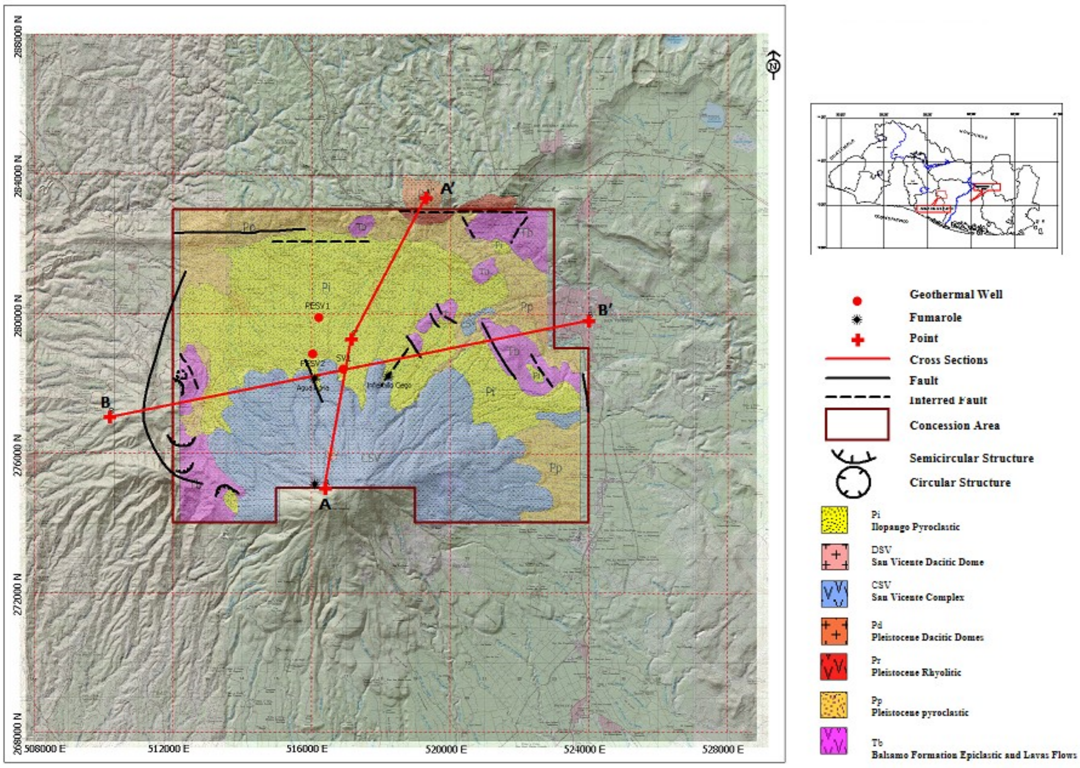

FIGURE 8: Geological map of San Vicente geothermal field (modified from LaGeo, 2005)

The age of this dome is uncertain, but the morphological characteristics and its location indicate that it may be the last event in the formation of the volcano. Furthermore, the fumaroles and hot springs of the geothermal system are close to the dome (LaGeo, 2005).

2.4 Geological structures

The study area is located within the most active areas of the country. The tectonics are related to regional forces associated with the subduction of the Cocos Plate beneath the Caribbean Plate. The area is dominated by a nearly E-W directional pattern, characterized by dominant right-lateral kinematics. This transcurrent movement is produced by horizontal stresses $\sigma1$ and $\sigma3$ oriented NNW-SSE and ENE-WSW, respectively (LaGeo, 2005).

The E-W fault system corresponds to the Central Graben system fault. The majority of the important structures in the San Vincente geothermal field have this orientation, and the most representative is the Agua Agria fault, which is directly related to the geothermal system. This fault is associated with the most fumarolic activity in the field.

The system of NW-SE faults is associated with an extension zone generated by the Central Graben. This pattern of faults is evident in the Infiernillo Ciego ravine and in the Agua Agria fumaroles. Many geological structures that cut San Vicente volcano have this orientation.

3. BOREHOLE GEOLOGY

This report is based on the borehole geology of exploration Well SV-5A in the San Vicente geothermal field. For the realization of this report, it was necessary to analyse drill cuttings and thin sections of selected cutting samples from the well.

Well SV-5A has the Lambert coordinates of 517.434N and 277.746E, situated at an elevation of 986.70 m a.s.l. on the northern flanks of the San Vicente volcano. The main objectives in drilling Well SV-5A were to confirm the existence of a geothermal reservoir and to find good permeable conditions.

The well was drilled from 4 m to 1798.50 m. In total, 600 samples were collected at 2 m intervals, from 4 m to 1242 m, after which the well experienced a total loss of circulation. Two cores were obtained, the first at a depth of 1500 m and the second at 1750 m.

3.1 Drilling history of Well SV-5A

Well SV-5A is a directional well with a final depth of 1798.50 m. The drilling company was Perforadora Santa Barbara (PSB), S.A. de C.V. using the drill rig, Massarenti 4000. The onset of drilling was October 13^{th}, 2012 and drilling finished on January 7^{th}, 2013.

This well was initially designed to be drilled in four sections. The first section was intended to be vertical and the second where deviation of the well took place. The third and the fourth sections were to be drilled directionally. However, during the progress of the well and due to early circulation losses, it was decided to continue to the fourth section of drilling with the same drilling diameter.

Drilling of Well SV-5A started with a vertical section with diameters of 26" and 17½" to 388 m, followed by deviation to the southwest, which ended with an azimuth of 231° and an inclination of 30.5°, with a horizontal displacement of 614.06 m at the final depth of 1798.50 m MD (1636.33 m TVD). A short description of the drilling activities is presented below and can also be seen in Figure 9:

First section: Drilling from the surface to 109.3 m was done with a 26" bit followed by RIH (run in hole) of the 20" surface casing down to 107.22 m depth. Small circulation losses were recorded at the end of this stage, from 93 to 109.30 m; two cement plugs were placed to control the circulation losses.

Second section: The formation was drilled from 109.30 to 756.50 m with a 17½" bit; the 13⅜" casing was placed at 752.43 m. Many circulation losses occurred between 110 m and 250 m, and 10 cement plugs were placed to control them. These partial and total losses were associated with changes in the formation and fractures in the host rocks. The deviation of the well started at 388 m.

Third section: The formation was drilled from 956.50 to 1798.50 m with a 12¼" bit, followed by the run in of a 9⅝" slotted liner. Total loss of circulation occurred at 1094 m; at 1116 m there was partial loss of circulation, and at 1244 m total loss was associated with the geothermal reservoir. After drilling the well, the BOP was removed to install the master valve.

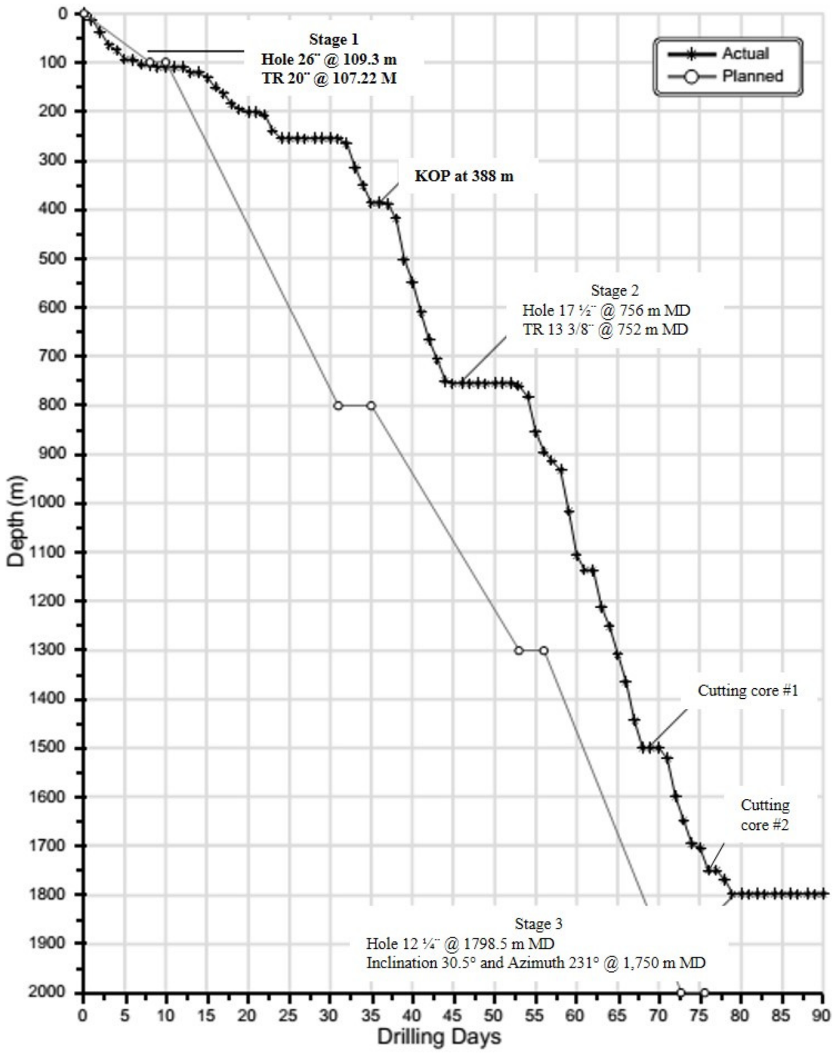

FIGURE 9: Drilling programme of Well SV-5A (modified from LaGeo, 2013a)

3.2 Analytical method

Four main techniques were employed to formulate the lithological and mineralogical descriptions of Well SV-5A:

Binocular microscope was used for the analysis of drill cuttings. The analysis consisted of identifying the properties of the rocks, mainly: rock type, grain size, primary mineralogy, texture, alteration mineralogy, vein fillings, and the intensity of hydrothermal alteration of the rocks. A total of 180 samples of drill cuttings were analysed by this technique, using an Olympus 12 binocular microscope.

Petrographic microscope was used to describe in more detail the properties of the rocks. It was helpful in identifying alteration minerals that could not be seen under the binocular microscope. It was also necessary to study the depositional sequence of secondary minerals by which it is possible to determine the state of the geothermal system from a mineralogical point of view. A total of 66 thin sections were analysed at intervals of 20 m with an Olympus SZ12 petrographic microscope.

X-ray diffractometer analysis: This technique is mainly used for detailed identification of the clay groups and to establish, with greater accuracy, the mineralogical boundaries between low and high temperature. Eighteen samples of clays were selected for this analysis, between 400 and 1242 m depths.

Fluid inclusion analysis provides us with the temperatures that the geothermal system has experienced through time. This technique involves heating the fluid inclusions trapped in the crystals (calcite, quartz or wairakite) and measuring the temperature of homogenization as the bubble within the fluid inclusion and the fluid itself merge. Microthermometric measurements were performed at one interval in the well (at 1500 m depth) using a Linkam THMSG-600 stage.

3.3 Stratigraphy

The stratigraphy of Well SV-5A is based on the analysis of the drill cuttings. The first stage consisted of binocular microscopic analysis and the second stage of the petrographic analysis, to confirm and define more precisely the types of rocks. As is common in volcanic environments, the well shows an intercalation of lava flows and tuffs. These lavas were classified as basaltic andesites, andesites and dacites, based on the contents of phenocrysts (pyroxene, plagioclase, olivine and hornblende), and on the texture, matrix type and degree of crystallisation of the rocks. The tuffs that were found were classified according to the matrix, crystal contents and lithic contents, and ranged from lithic tuffs to crystal tuffs and crystal lithic tuffs. A detailed description of the main formations is found below, but Figure 10 shows the stratigraphic column together with some drilling parameters.

Volcanoclastic deposits (6-18 m): Fine grained rock, sub-rounded to sub-angular grey-pink-yellow fragments composed of andesite, basaltic-andesite and oxidized fragments, crystals of plagioclase, pyroxene, magnetite and fresh glass. In the cuttings, limonite was observed in oxidized fragments.

Basaltic andesitic lava (18-30 m): Medium grained rock, dark grey, with vesicular porphyritic texture and phenocrysts of pyroxene, plagioclase, magnetite and some olivine. Petrographic analysis showed a hyalopilitic-porphyritic matrix. Fragments of xenoliths (dolerite) were also observed.

Andesitic lavas (30-260 m): Sequences of andesitic lavas interspersed with small amounts of generally oxidized scoria, due to contact between the flows. These lavas have a high content of xenoliths which, by means of petrographic analysis, were identified as two types: the most common is dolerite with phenocrysts of plagioclase, pyroxene, magnetite and small olivine. Diorite xenoliths were also observed with phenocrysts of plagioclase, pyroxene and opaque minerals which had been oxidized to hematite.

36-88 m: Andesitic lava, dark grey to light grey towards the bottom, with porphyritic texture, phenocrysts of pyroxene, plagioclase, magnetite and fresh glass.

88-146 m: Andesitic lava, grey to reddish grey towards the bottom, medium grained with porphyritic texture, phenocrysts of pyroxene, plagioclase, magnetite and fresh glass.

160-168 m: Andesitic scoreaceous, reddish grey, coarse grained, porphyritic texture, phenocrysts of pyroxene, plagioclase and magnetite. Some minerals of magnetite were replaced by hematite.

168-188 m: Andesitic lava, light grey, coarse to medium grained, porphyritic texture with phenocrysts of pyroxene, plagioclase and magnetite. Some minerals of magnetite had been replaced by hematite. Fresh glass was also observed.

202-270 m: Andesitic lava, reddish grey, medium grained, porphyritic texture, with phenocrysts of pyroxene, plagioclase and magnetite. Some magnetite minerals had been replaced by hematite. At the top and at the bottom, Fine grained and scoreaceous rock was seen.

Crystal tuff (270-278 m): Crystal tuff, beige with many crystals of plagioclase, pyroxene, yellow feldspar and magnetite. Fresh glass was observed.

Dacitic lavas (278-368 m): Sequence of dacitic lava flows, beige to light grey towards the bottom, coarse to medium grained and fine grained towards the bottom. The rock has porphyritic texture with

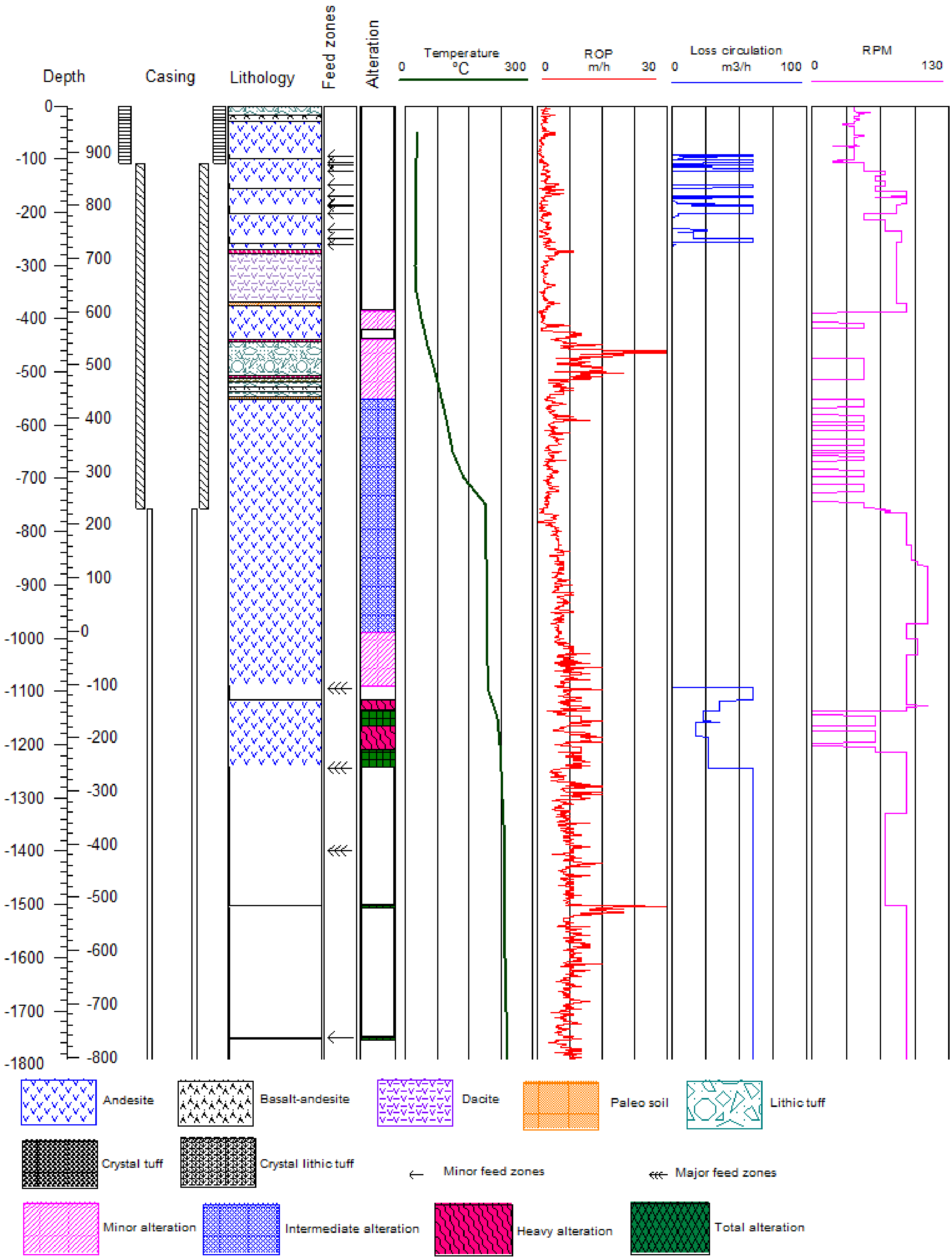

FIGURE 10: Stratigraphic section and drilling parameters in Well SV-5A

phenocrysts of plagioclase, pyroxene, hornblende and magnetite, some of which had been replaced by hematite. Dolerite and diorite xenoliths were observed.

Paleo soil (368-376 m): Fine rounded fragments, reworked. Opal and yellow clays were observed, considered to represent the beginning of low-temperature alteration.

Andesitic lavas (376-438 m): Andesitic lava, grey, medium to coarse grained, porphyritic texture, phenocrysts of plagioclase, pyroxene and magnetite. Some magnetite minerals had been replaced by hematite. Calcite, opal and smectite clays were observed. Small veins filled with opal and smectite clays were also noted. At the top and at the bottom, scoreaceous and fine grained rocks were seen.

Crystal tuff (438-450 m): Crystal tuff, dark grey, with some lithics of scoria and andesite and crystals of plagioclase, pyroxene and magnetite. Fresh glass was observed. Opal, calcite and smectite clays were noted.

Lithic tuff (450-506 m): Lithic tuff, grey-yellow, medium to coarse grained, with lithic andesite, dacite, pumice and scoria. There was some pyrite seen towards the bottom. Alteration minerals included calcite, opal and smectite clays.

Crystal tuff (506-512 m): Crystal tuff, dark grey, crystals of plagioclase, pyroxene and magnetite. Fresh glass was observed. Opal, calcite, smectite clays and some lithic pyrite were observed.

Crystal lithic tuff (512-518 m): Crystal lithic tuff, grey, medium grained with crystals of pyroxene, plagioclase and magnetite. Lithics of andesite were seen (very rounded) and some pyritized lithics. Opal, calcite and smectite clays were observed, representing alteration mineralogy.

Lithic tuff (518-528 m): Fine fragments, rounded, and crystals of plagioclase, pyroxene and magnetite. Opal, calcite and smectite clays were observed.

Andesitic lavas (528-538 m): Scoreaceous andesite, dark, coarse grained, with porphyritic texture, phenocrysts of plagioclase, pyroxene and magnetite. Calcite, opal and smectite clays were observed in pores.

Lithic tuff (538-546 m): Lithic tuff, dark grey, medium grained, with lithics of andesite and few crystals of plagioclase and pyroxene. Alteration minerals included calcite, smectite clays and opal.

Paleo soil (546- 552 m): Matrix of fine grained rocks of brown colour with some lithics of andesite and scoria. Calcite, opal, smectite clays and oxidation were observed.

Andesitic lavas (552-1242 m): Andesitic lava sequence with trachytic matrix. At the top, the formation is pink, and towards the bottom it is light grey.

552-740 m: Andesitic lavas, very altered, medium to coarse grained, displaying a scoreaceous texture and a trachyte matrix with phenocrysts of plagioclase and opaque minerals (magnetite) and a few crystals of pyroxene. Clays, calcite, opal and zeolites (heulandite) were observed in pores.

740-920 m: Andesitic lavas, grey to greenish grey, fine to medium grained, somewhat porphyritic with trachyte matrix and phenocrysts of plagioclase and opaque minerals (magnetite) and a few crystals of pyroxene. The mineralogy alteration consisted of mixed layer clays, calcite, tridymite, opal, oxidation, and smectite clays.

920-1090 m: Andesitic lavas, grey to greenish, grey at the top and some reddish grey grains towards the bottom. Fine to medium grained, somewhat porphyritic with a trachyte matrix and phenocrysts of plagioclase and opaque minerals (magnetite). The mineralogy alteration consisted of calcite, mixed layer clays, chlorite, quartz and sphene. Towards the bottom the amount of alteration minerals decreased and oxidation increased.

1116-1242 m: Andesitic lavas, much altered, light grey to greenish grey towards the bottom, fine grained, with a trachyte matrix. The amount of alteration minerals increased consisting of calcite, quartz, chlorite, epidote, sphene, illite, prehnite and wairakite.

4. HYDROTHERMAL ALTERATION

Hydrothermal alteration depicts changes in the mineralogy, texture and chemistry of the rocks, produced in the presence or movement of hydrothermal solutions.

Hydrothermal alteration minerals are secondary minerals deposited in vesicles (holes, cavities) and fractures and replace primary minerals.

Several hydrothermal alteration assemblages occur in the cuttings and cores from the San Vicente wells. In most cases, the alteration followed a pro grade trend of increasing rank and intensity with depth. At low temperatures, the subsurface mineral assemblages were characterised by various smectites and zeolites that, with increasing temperature, are replaced by e.g. chlorite, epidote, prehnite and actinolite. Alkali-feldspars, sulphides, quartz and calcite were found independent of temperature (Markússon and Stefánsson, 2011).

4.1 Primary rock minerals

The San Vicente hydrothermal system has altered the volcanic rocks in the area, resulting in the development of new mineral assemblages and a redistribution of certain elements through hydrothermal fluid circulation (Table 1). The primary minerals in the rocks are unstable at high temperature and pressure, leading to their replacement by new minerals that are stable in the new formation environment (Browne, 1978).

TABLE 1: Alteration of the primary rock minerals in Well SV-5A

Primary rock minerals	Alteration mineral products
Plagioclase	Clays, calcite, epidote, quartz, heulandite, wairakite, actinolite.
Pyroxene	Oxides, calcite, clays.
Opaque minerals	Sphene.
Olivine	Clays.

Different minerals have different susceptibilities to alteration, depending on the pressure and temperature conditions to which rocks are exposed. Primary minerals are present in all the rocks in Well SV-5A, being mainly plagioclase, pyroxene, opaque minerals and olivine, as well as hornblende in lower proportions.

Olivine is one of the basic rock forming minerals found in basaltic andesite lavas. Olivine was observed in two flows, the first at 20 m, where it had altered to iddingsite and the second at 528 m where small olivine crystals were completely replaced by smectite clays.

The plagioclases are the most common minerals in the rocks, and are mainly observed as phenocrysts in andesitic lava flows and the basaltic andesite. Plagioclases are also common in crystal rich tuffs, where they have been partly replaced by calcite, clays and opal from 400 to 750 m, and by chlorite, quartz, calcite, epidote and wairakite below 750 m and towards the bottom. The matrix of the lavas is mainly composed of feldspars which are slightly albitized in the lower part of the well.

The pyroxenes were found as phenocrysts in lava flows and crystal rich tuffs; through petrographic analysis, two types of alteration mineral replacements of pyroxene were identified. The first was noted at 20 m down to 400 m where pyroxenes were replaced by iron oxides, and the second at 400-1242 m where they were replaced by calcite, mixed layer clays and chlorite.

Opaque minerals were observed in large amounts in the lava flows, both as phenocrysts and as part of the matrix, primarily as magnetite which had, in many cases, been replaced by hematite. From 1000 m to 1242 m, the opaque minerals were partially replaced by sphene.

4.2 X-ray analysis

The X-ray analysis is used to quantify the proportions of different minerals, mainly in clay groups, and to identify different zones of clay minerals.

A total of 18 samples were analysed from 400 to 1242 m in Well SV-5A. The data is shown in Table 2 showing that, from 506 to 860 m, the clays correspond to the low temperature smectite group. At 880 to 920 m, the mixed layered clays appear.

From 1122 to 1242 m two types of high temperature clays were analysed: chlorite and illite. These clays are associated with high temperature minerals like epidote, actinolite and prehnite.

TABLE 2: Results of the XRD analysis of clay minerals in Well SV-5A;
Sm: smectite; MLC: mixed layer clay (smectite/chlorite); Chl: chlorite
Ill: illite; Chlunst: unstable chlorite

Sample #	Depth(m)	d(001) UNT	d(001) GLY	d(001) HIT	d(002)	Mineral	Type	Remarks	Other minerals	Depth(m)
#1	400					no clay				400
#2	506	15.9	17.9	10.1		Sm:sm	Sm			506
#3	528	15.9	17.9	10.1		Sm:sm	Sm			528
#4	564	15.6	17.9	10.1		Sm:sm	Sm			564
#5	600	13/15	17	10.1		Sm:sm	Sm			600
#6	640	15.9	16.8	10.1		Sm:sm	Sm			640
#7	740	15.5	17.9	10.1		Sm:sm	Sm			740
#8	800	12.8	13.5	10.1		Sm:sm	Sm			800
#9	860	14.9	15.7	10.1		Sm:sm	Sm			860
#10	880	32,5/14,9	34,7/16,1	11.8	~7,4	MLC: sm/chl	MLC			880
#11	920	30,8/14,8	33,0/16	11.7	7.3	MLC: sm/chl	MLC			920
#12	1000					No clay				1000
#13	1080					No clay				1080
#14	1122	~14,5/11	~14,5/11	~14/11	~7,2	Chl: ill.	Chl: ill	uncertain	Illite	1122
#15	1160					No clay				1160
#16	1200					No clay				1200
#17	1220	14,6/10	14,6/10	~14/10	7,2 hit=0	Chl. Unst.	Chlunst.		Illite	1220
#18	1242	14,6/10	14,6/10	~14/10	7,2 hit=0	Chl. Unst.	Chlunst.		Illite	1242

4.3 Distribution of hydrothermal minerals

Figure 11 shows the distribution of the hydrothermal alteration in the well, but a detailed description of the occurrence of the various alteration minerals is given below.

Calcite started to appear at 386 m, gradually increasing down to 1090 m, and mainly replacing plagioclase. At 1116 and down to 1242 m a strong increase in calcite was presented, replacing plagioclase and pyroxene and filling small veins. In the two cores obtained at 1500 and 1750 m, excessive depositional calcite was observed, which could indicate that the fluid is probably in a state of boiling.

Opal was observed from 374 to 740 m, generally associated with clays, filling small veins and cavities of andesitic lavas.

Pyrite first appeared promptly at 500 m, only appearing again at 1116 m, persisting down to the bottom of the well. It is usually disseminated in the matrix, forming perfect cubic crystals, and in the cores it was also observed as vein fillings. Generally, the appearance of pyrite in large quantities indicates good permeability.

Zeolites: This group belongs to the sodium-calcium-alumina hydrosilicates which are generally found as secondary minerals in the cavities of igneous rocks, replacing plagioclase or through decomposition of volcanic glass. Two varieties of zeolites were found: heulandite and wairakite, which are described below:

> *Heulandite* was observed in the range from 620 to 700 m, as small acicular and feathery crystals. In thin section they were observed in fractures and some cavities.
>
> *Wairakite:* This high temperature zeolite (200°C) was identified through thin sections, from 1220 m to the bottom of the well, usually associated with calcite, replacing plagioclase and filling cavities. In the cores obtained in the well, the wairakite was associated with quartz and epidote filling the fractures. This zeolite is indicative of good permeability.

Smectites clays: This group of clays (associated with temperatures less than 200°C) started to appear at 400 m and was seen down to 740 m, mainly associated with opal. It was also found in the matrix of the tuffs and replacing plagioclase in the matrix lava flows.

Mixed layer clays were observed continuously from 740 to 1040 m, mainly filling cavities and associated with calcite crystals. These minerals are a transition between the group of smectites and chlorites, indicating 200-230°C temperatures.

Chlorite (230°C) began to appear at 920 m and persisted down to the bottom of the well, replacing primary minerals such as plagioclase and pyroxene and also filling cavities and small veins. In thin section it was observed as grey coloured with feathery and fibrous appearance. In the cores it was seen pervasively substituting the matrix.

Quartz (180°C) was observed from 900 m down to the bottom of the well, beginning as deposits in small veins and some cavities in the lava flows. In the two cores, microcrystalline quartz was observed. In the second core the highest amount was found where the matrix was entirely replaced by quartz.

Sphene first appeared at 1000 m and was seen down to 1240 m. It was recognized through thin sections and found disseminated in the rock matrix replacing the iron oxides.

Epidote (230-250°C) began to appear at 1180 m and was seen all the way to the bottom of the well. At the beginning it was pale yellow in colour and was observed replacing plagioclase crystals, associated

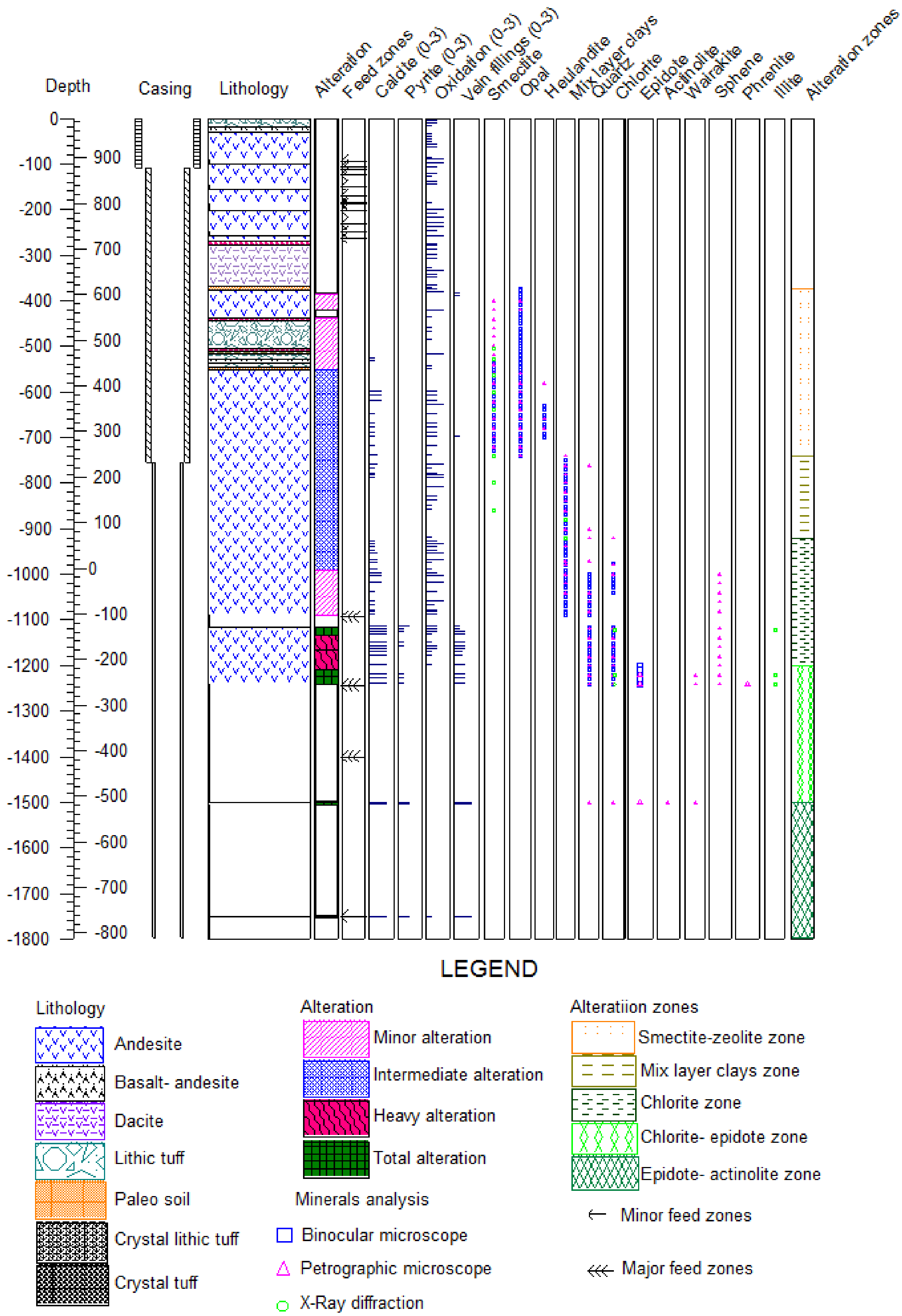

FIGURE 11: Distribution of hydrothermal alteration minerals in Well SV-5A

with prehnite, chlorite and wairakite. In the cores it exhibited yellow-green colours, with fibrous and radial forms, filling veins associated with calcite, wairakite and actinolite.

Prehnite (240°C) appeared only at 1240 and 1242 m, just before the loss of circulation. Tiny crystals were associated with epidote and it was only identified in thin section. It is characterized by high interference colours.

Actinolite appeared at 1500 m in the core obtained at this depth. The crystals were fibrous, with high relief and high interference colours. This amphibole mineral is associated with high temperature of more than 280°C in geothermal fields.

Illite (230°C) appeared first at 1220 m depth according to XRD analyses. It is the product of alteration of feldspar minerals and could be found in the groundmass in andesitic lavas flows.

4.4 Vein fillings

At the top of the well, no vein or vesicle fillings were observed. From 386 m it was possible to see small veins in lava flows that were filled with low-temperature minerals such as opal and clays of the smectite group.

From 560 m there was an increase in the deposition of low-temperature minerals, mainly in vesicles, most of them filled by opal, clays of the smectite group, calcite and zeolites of the heulandite type. Small veins filled with heulandite were also seen between 620 and 700 m.

Below 750 m there was a decrease in depositional alteration minerals both in vesicles and in veins. Small vesicles were filled with mixed layer clays and some veins with calcite. Then at 900 m the deposition increased again in vesicles and small veins which were filled with quartz, calcite and mixed layer clays. At 1000 m, the deposition of chlorite as vesicle fillings was observed. However, from 1040 to 1090 m deposition in veins and vesicles decreased again.

Between 1116 and 1242 m, a steady increase of high temperature alteration minerals was observed in small veins and vesicles, mainly calcite, pyrite and quartz. At 1240 m tiny vein fillings with wairakite and epidote were noted.

In core # 1 at 1501 m, most of the veins were filled with calcite, epidote, actinolite, wairakite, pyrite, and quartz. However, in core # 2 at 1750 m, there was a slight decrease in vein fillings compared to core # 1. The main veins were filled with calcite, quartz and iron oxides, which may infer cold water inlet into the geothermal system.

4.5 Alteration mineral zones

The mineralogical facies of Well SV-5A were determined through the hydrothermal alteration minerals observed by the three techniques (macroscopic, petrographic and x-ray diffraction) used for identification.

It is known that secondary minerals produced in a geothermal system are stable at certain pressures and temperatures (e.g. Browne, 1978; Franzson, 2013). That is why it is possible to determine the mineralogical facies that occur in a geothermal well and to estimate, according to the mineralogy assemblage, the temperature of the well.

The smectite-zeolite zone begins at 376 m and extends down to 750 m. This area is characterized by the presence of low-temperature minerals such as opal, clays of the smectite group, calcite and, towards the bottom of that interval, by the appearance of low-temperature zeolites of the heulandite type. This assemblage of minerals suggests a temperature of approximately 40-180°C.

The mixed layer clay zone starts at 750 m and extends to 920 m. in this section we observe the development of the mixed layer clays together with calcite and, from 780 m, the appearance of quartz. The development of this assemblage of minerals indicates a temperature of >180°C.

The chlorite zone is characterized mainly by the appearance and development of chlorite, which begins to appear at 920 m according to the petrographic analysis. This is slightly higher than the X-ray diffraction analysis of chlorite, reflecting the details accounted for in the thin sections, which can be missed from the XRD. From 1000 m, sphene began to develop. A good association of the minerals chlorite, calcite, quartz, pyrite, sphene, and illite was observed. This association of minerals indicates a temperature of around 230°C.

The chlorite-epidote zone developed from 1200 to 1242 m (due to loss of circulation, it cannot be determined further down) and was characterized by the appearance of epidote, which is associated with chlorite, sphene, calcite, quartz, illite, wairakite, prehnite, and pyrite. According to this association of minerals, the estimated temperature should be around 240°C.

The epidote-actinolite zone was observed in core # 1 at 1501-1507 m, characterized by the appearance of well developed actinolite filling fractures. At this depth, the association of epidote, actinolite, wairakite, pyrite, quartz, calcite, and chlorite was found, which indicates a temperature of at least 280°C.

4.6 Mineral deposition sequence

The deposition of secondary minerals produced by hydrothermal alteration, induced by geothermal systems, depends largely on the fluid temperature. However, we know that during the development of a geothermal system, the chemical and physical properties of the fluid can vary with time; this is evidenced in the depositional sequence of the secondary minerals, which in turn is of great importance for recognising the current status of the system.

The analysis of the depositional sequence of secondary minerals from Well SV-5A was carried out by means of petrographic analysis and binocular analysis of the cuttings (Table 3).

TABLE 3: Depositional sequences of hydrothermal alteration minerals in Well SV-5A

Depth (m)	Depositional sequence	Filling type
400	Smectite-opal	Vein
460	Iron oxides-smectite-calcite	Vesicle
760	Iron oxides-mixed layer clays	Vesicle
760	Calcite-mixed layer clays	Vesicle
780	Smectite-mixed layer clays	Vein
970	Iron oxides-calcite-chlorite	Vesicles
1220	Chlorite-epidote	Vesicle
1240	Prehnite-epidote	Vesicle
1501	Calcite-quartz	Vein
1501	Calcite-wairakite-epidote	Vein
1501	Wairakite-epidote-actinolite	Vein

At the top of the well, where deposition of secondary minerals starts, vein fillings were observed with clays of the smectite group and opal, suggesting a sequence of low temperature minerals. In the intermediate part of the well, a relative evolution in the mineralogy was observed. In some vesicles deposition of calcite followed by mixed layer clays was noted, as well as iron oxides followed by mixed layer clays. At 780 m the deposition of smectite before mixed layer clay suggests increasing temperature.

At 970 m other mineral sequences could be seen which evidenced an increase in temperature, where some vesicles presented a deposition from iron oxides to calcite and finally chlorite. At 1240 m deposition of prehnite, followed by epidote, was noted in vesicles, both high-temperature minerals reflecting a stable depositional system.

In core # 1 is an excellent deposition evidence of high-temperature minerals in the veins. At this depth, three main sequences were identified: the first with a deposition of calcite followed by quartz, the second deposition with calcite followed by wairakite and then epidote, and the third with deposition of wairakite followed by epidote and lastly actinolite. These depositions evidence a stable behaviour within the current geothermal system.

5. AQUIFERS

Well SV-5A crossed high permeability zones during drilling (Table 4). These total and partial losses were due to formation changes, fractures in the host rocks and were also associated with the geothermal reservoir (e.g. increased alteration and major faults). Figure 12 shows the lithology together with the experienced permeable zones in the well.

TABLE 4: Loss of circulation during the drilling of Well SV-5A

Stage	Depth (m)	Type of loss	Geological description
26”	93-94	PPC	Andesite scoreaceous oxidized
	95-96.5	PPT	Andesite scoreaceous oxidized
	96.5-100	PPC:	Andesite partially oxidized
	106.5-109.3	PTI	Andesite partially oxidized
17 ½”	112.5-122	PTC	Andesite
	123	PPC	Andesite
	149-154.5	PTC	Andesite
	170-185	PTI	Andesite
	185.5-188	PPC	Andesite
	189-202	PTC	Andesite scoreaceous oxidized
	203-208	PPC	Andesite scoreaceous oxidized
	232-250	PPC:	Andesite scoreaceous oxidized
	250-256	PTC	Andesite
	262	PPC:	Andesite scoreaceous
12 ¼”	1094-1115	PTC	Andesite
	1116-1244	PPC:	Andesite
	1245-1798.5	PTC	Andesite

PTC: Total loss of circulation, PTI: total losses intermittent, PPC: Partial loss of circulation

In the first section of the 26" width, partial and total losses were associated with change in the lithology (e.g. scoria between lava flows). In the second section of the 17½" width, partial losses were associated with formation changes and total losses were associated with fractures in the host rock. In the 12¼" production part of the well, total losses of circulation were associated with the geothermal reservoir.

For the determination of aquifers, temperature profiles from the well were used, from 7 to 81 days of thermal recovery (Figure 11). Based on the logs, it was concluded that the well crosses four hot aquifers, the first at 1100 m where there was total loss of circulation, coinciding with a sharp increase in the hydrothermal alteration.

At 1250 m there is another hot aquifer which coincides with total loss in circulation and, just before the loss of circulation, wairakite crystals were observed. Wairakite is associated with good permeability zones and aquifers (Reyes, 2000).

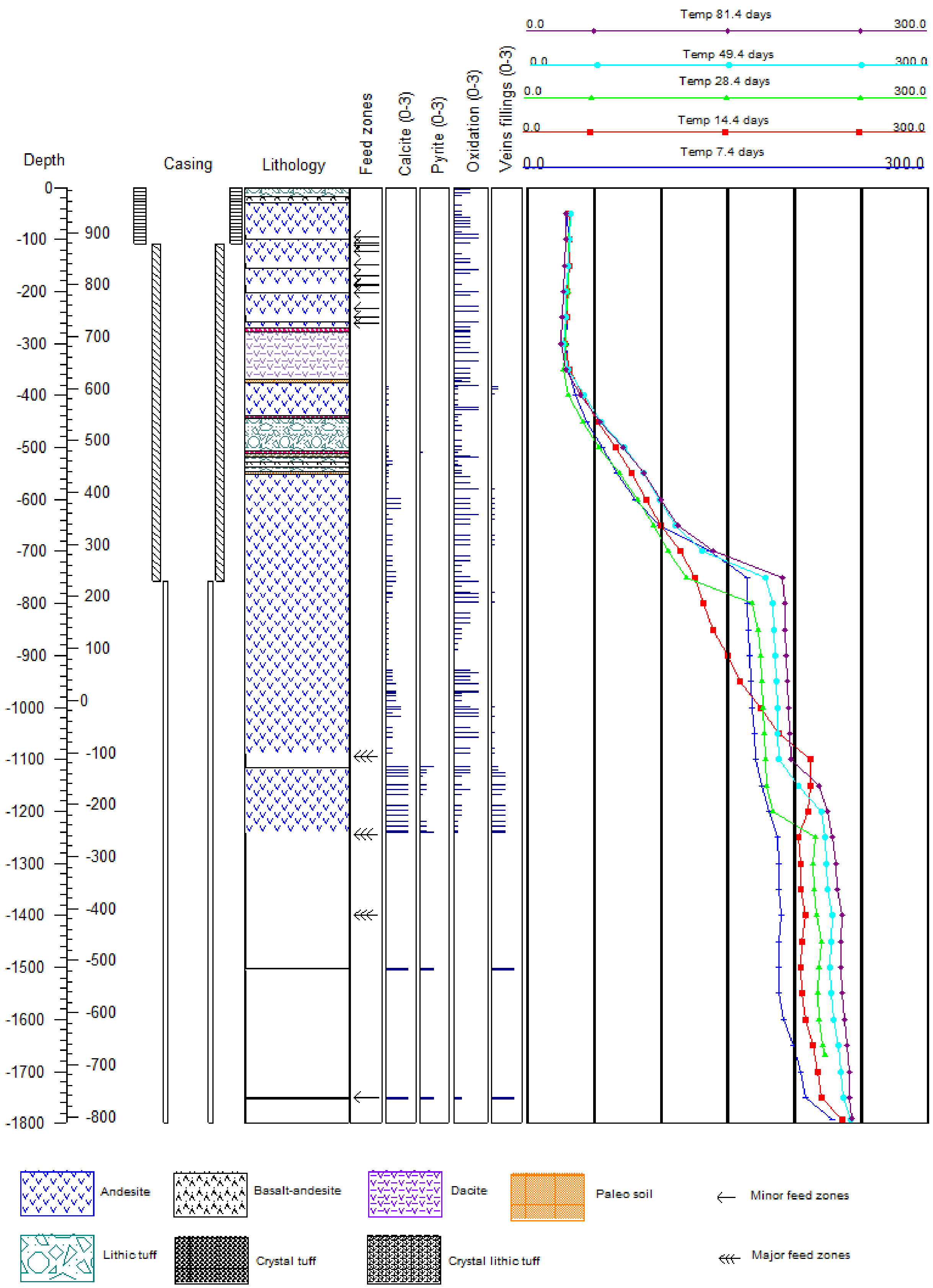

FIGURE 12: Lithology and permeable zones in Well SV-5A

At 1400 m another hot aquifer was observed, identified by means of temperature logs, where there is an input zone that continues to heat up. In this area, it was not possible to correlate with the alteration mineralogy because there were no cutting samples at this depth.

Towards the bottom of the well at 1750 m, yet another aquifer was observed in the temperature logs, which is evidenced in core # 2 by a breccia of faults. There are also many fractures found filled with high temperature minerals and with iron oxide of the hematite type as a last deposition.

The deposition of hematite in the fractures could indicate the presence of cold water. Cold water contains more oxygen than hot water and, upon contact with rocks, the process of oxidation between minerals and oxygen occurs, forming hematite in the fractures.

6. FLUID INCLUSIONS AND FORMATION TEMPERATURE

Fluid inclusions, trapped during the growth of minerals, provide important information on the temperature conditions in a geothermal system. Two main types of fluid inclusions from hydrothermal fluids exist: primary inclusions and secondary inclusions.

The primary inclusions are vapour and liquid portions trapped in the fluid during the crystallization of minerals, representing a small sample of the original hydrothermal solution of the geothermal system. The secondary inclusions were trapped after the growth of the crystal and formed in micro fractures and crystal imperfections. This type of inclusions is very important because it shows the current state of the geothermal system. When steam inclusions are heated and observed through a microscope, the vapour bubbles merge with the fluid (disappear) at a certain temperature and when this happens, the homogenization temperature has been obtained, giving information about the temperature at which the fluid was captured.

Fluid inclusions were analysed in two calcite crystals from core # 1 at 1501 m. A total of 70 fluid inclusions were analysed (Figure 13). The type of fluid inclusions in the crystals could, however, not be determined. It was not possible to analyse the crystals from the cuttings since the grains were too fine.

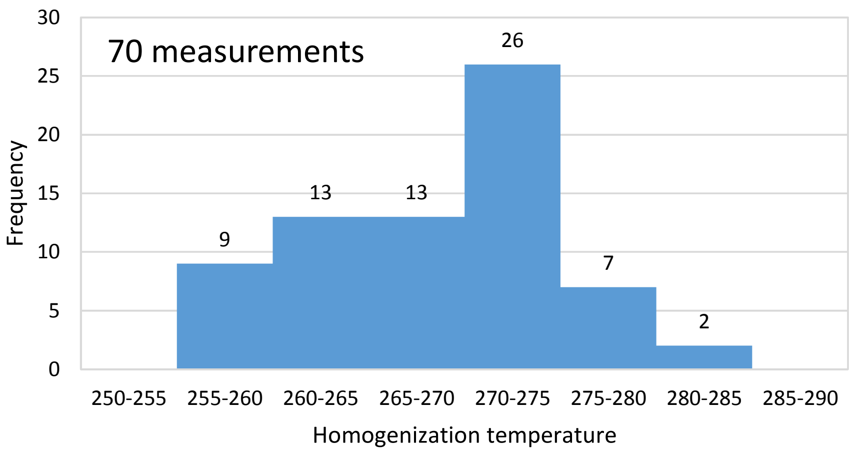

FIGURE 13: Fluid inclusion measurementsfrom 1501 m depth in Well SV-5A

The homogenization temperature of the fluid inclusions ranged between 255 and 285°C. The highest concentration of measurements was in the range 270-275°C. Tempe-ratures up to 285°C were measured, possibly indicating the initial fluid temperature, which is also supported by the appearance of actinolite, which forms at temperatures of 280°C. Furthermore, many inclusions were measured ranging between 255 and 270°C, possibly reflecting a conductive cooling within the geothermal system. However, the homogenization temperature seems to be in balance with the deposition of alteration minerals, further suggesting that some cooling of up to 40°C has occurred in the system since the estimated formation temperature at that depth is somewhat lower than the alteration temperature (see Section 7).

7. DISCUSSION

The stratigraphy of Well SV-5A is based on the analysis of drill cuttings, consisting primarily of lava flows and some pyroclastic sequences. The identified rocks vary in composition from basaltic andesite, andesite, dacite and a variety of lithic tuffs, crystal tuffs and a combination of the two. This variety of rocks reflects an evolved magma chamber under the volcanic complex of San Vicente.

However, from 556 to 1800 m, a thick series of andesitic flows were observed, all very similar chemically and texturally. At 438-556 m there is a sequence of tuffs that possibly originated from the collapse of the old volcanic structure of San Vicente and, from 4 m down to 438 m, there are sequences of dacite lava flows. In the lower part of that depth interval, a lot of andesites with xenoliths of basic composition could be seen, possibly meaning that beneath the San Vicente volcano lies a large intrusive of basic composition that may have been emplaced just after the volcano collapsed.

Aquifers and feed zones were identified by means of temperature logs, an abundance of alteration minerals and circulation losses experienced during drilling. The aquifers found in Well SV-5A at the top are related to changes in the formation and with natural fractures in the lava flows. By contrast, the aquifers within the geothermal reservoir are associated with large faults, indicated by the loss of circulation at 1094 m which is associated with a fault zone identified at the surface by a digital elevation model. The aquifer is also associated with the abrupt change in alteration mineralogy observed at that depth. Furthermore, at 1750 m in core # 2, a highly faulted and fractured area was noted which corresponds to an aquifer identified by means of the temperature logs. In both zones, a large amount of wairakite was identified, which is associated with good permeability zones.

Evidence of hydrothermal alteration started at 400 m, where mainly low temperature minerals such as opal, clays of the smectite group and calcite were deposited and at 620 m the low temperature zeolite heulandite was observed. Below 750 m there was a change in the mineralogical temperature, with the appearance of mixed layer clays and quartz and, at 920 m, another change was seen with the appearance of chlorite and sphene. However, the most drastic change in the alteration occurred below 1094 m where a high temperature mineral association was observed with pyrite, calcite, quartz, chlorite, epidote, wairakite, prehnite, and sphene. The maximum alteration associated with the geothermal reservoir was found at 1500 m where core # 1 was obtained, where a mineral assemblage of 280°C was found with the appearance of actinolite together with epidote, wairakite, quartz, chlorite, calcite, and pyrite. This distribution of alteration minerals, from low temperature minerals increasing with depth to high temperature minerals which appeared towards the bottom of the well, indicates a progressive increase in the deposition of these minerals.

In accordance with the mineralogical assemblage and the first appearance of certain temperature dependent minerals such as quartz, chlorite, epidote, and actinolite, it was possible to define five alteration zones: from 376 to 750 m the smectite-zeolite zone; from 750 to 920 m the mixed layer clay zone; from 920 to 1200 m the chlorite zone; at 1200 m the chlorite-epidote zone appeared; and at 1500 m the epidote-actinolite zone. These alteration zones reflect a normal deposition in the geothermal system, and the occurrence of high temperature minerals such as epidote, actinolite, wairakite, and prehnite suggest temperatures up to 280°C.

The analysis of fluid inclusions suggested temperatures up to 280°C, which is consistent with the alteration minerals found in the well, specifically in core # 1, where actinolite was identified. However, when these results are compared with the 240°C formation temperature measured in the well, a cooling of around ~40°C was noted. Figure 14 suggests that the temperature is at equilibrium down to 750 m and, below this depth, an imbalance between the alteration mineralogy and the formation temperature can be seen.

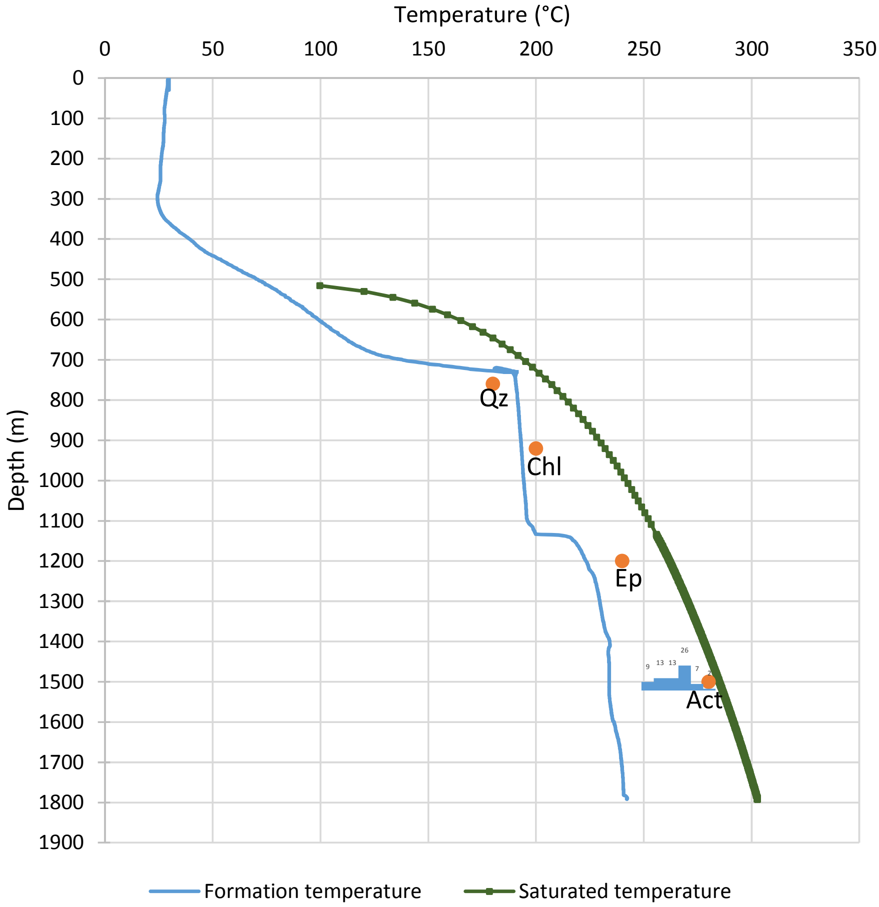

FIGURE 14: Comparison of the fluid inclusion, formation temperature, boiling curve and alteration minerals of Well SV-5A

8. CONCLUSIONS

- The lithology of Well SV-5A is composed of lithic tuff, crystal tuff, crystal lithic tuff, andesite, basalt-andesite, and dacite.
- According to binocular and petrographic analyses, the depositional sequence of alteration minerals in vesicles and veins show a normal gradation of hydrothermal alteration minerals from low- to high-temperature.
- Five alteration zones were identified, based on the hydrothermal mineral assemblages: from 376 to 750 m, the smectite-zeolite zone; from 750 to 920 m, the mixed layer clay zone; from 920 to 1200 m, the chlorite zone; from 1200 to 1242 m, the chlorite-epidote zone; and from 1500 m, the epidote-actinolite zone.
- The permeability at the top is controlled by fractured formations and lithological contacts between formations.
- The permeability within the geothermal reservoir is mainly associated with fractures and fault zones, where an increase in high temperature alteration mineralogy was observed as well as with a general high abundance of pyrite and calcite.
- The fluid inclusions at 1501 m depth reflect temperatures between 255 and 280°C, which are in concordance with the alteration mineralogy, reflecting temperatures of 280°C as seen by the appearance of actinolite.
- According to the calculated Horner temperature, the well should reach a temperature of 245°C, reflecting a cooling of ~40°C in the geothermal system.

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APPENDIX I: Characteristic XRD patterns for the clay minerals of Well SV-5A

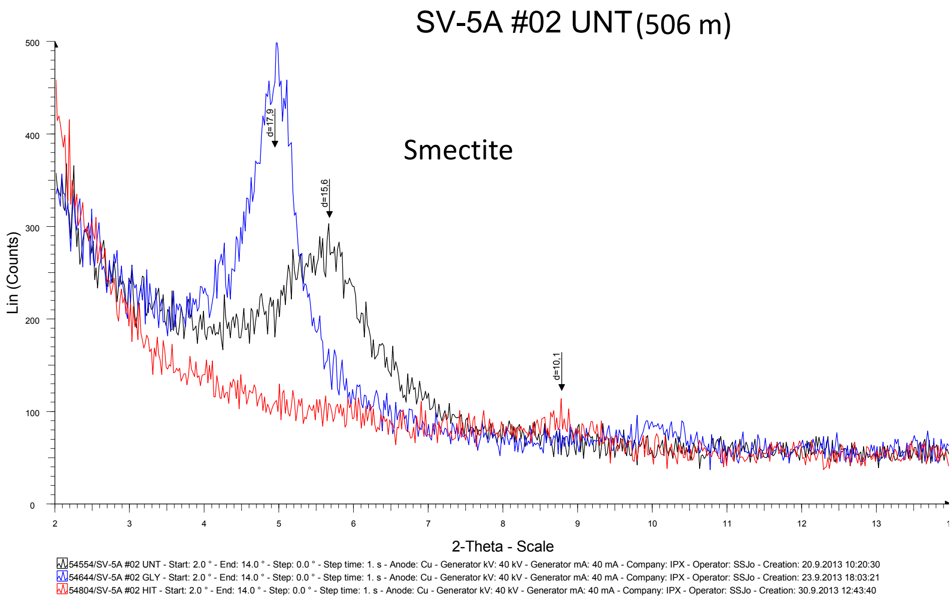

FIGURE 1: XRD analysis showing presence of smectite

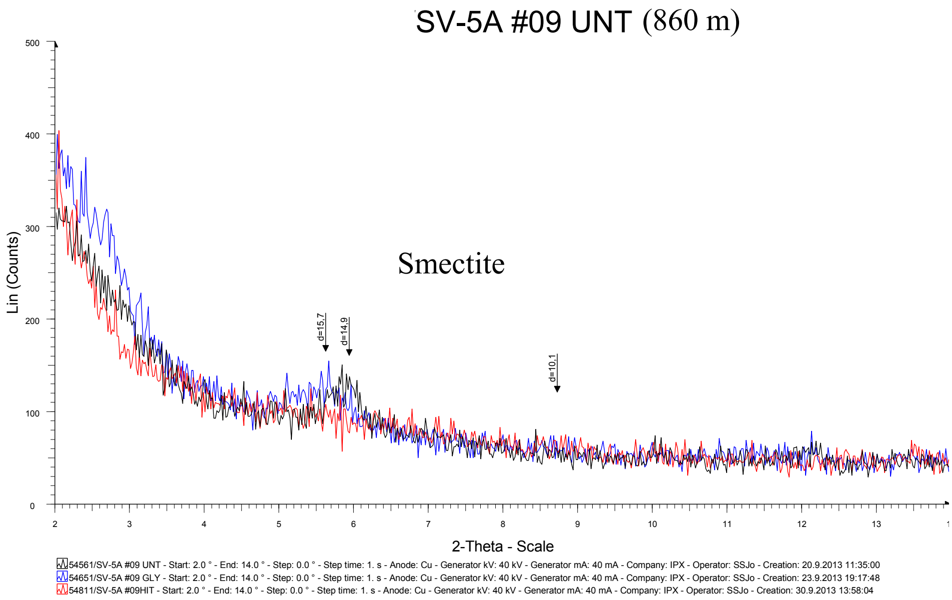

FIGURE 2: XRD analysis showing presence of smectite

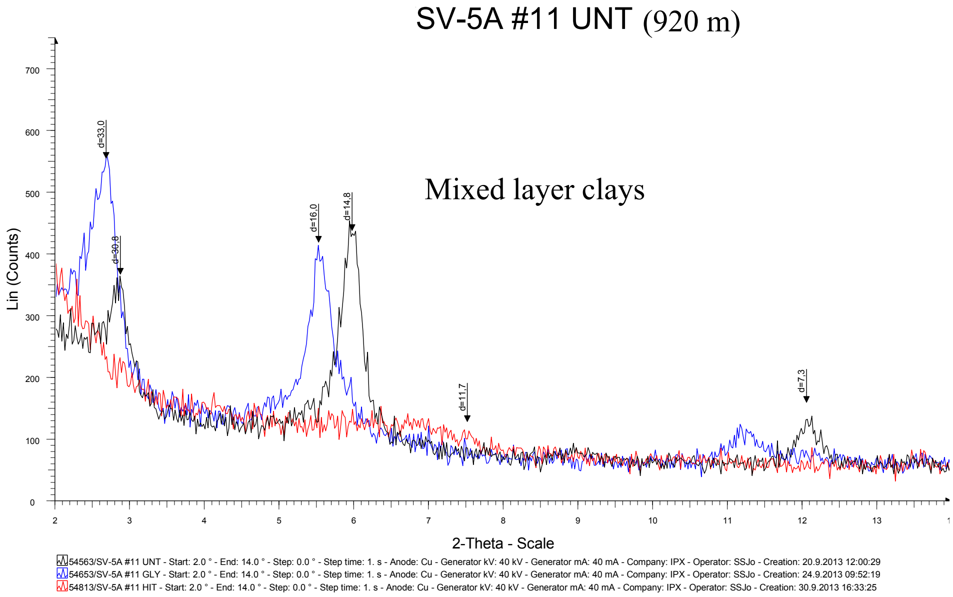

FIGURE 3: XRD analysis showing presence of mixed layered clays

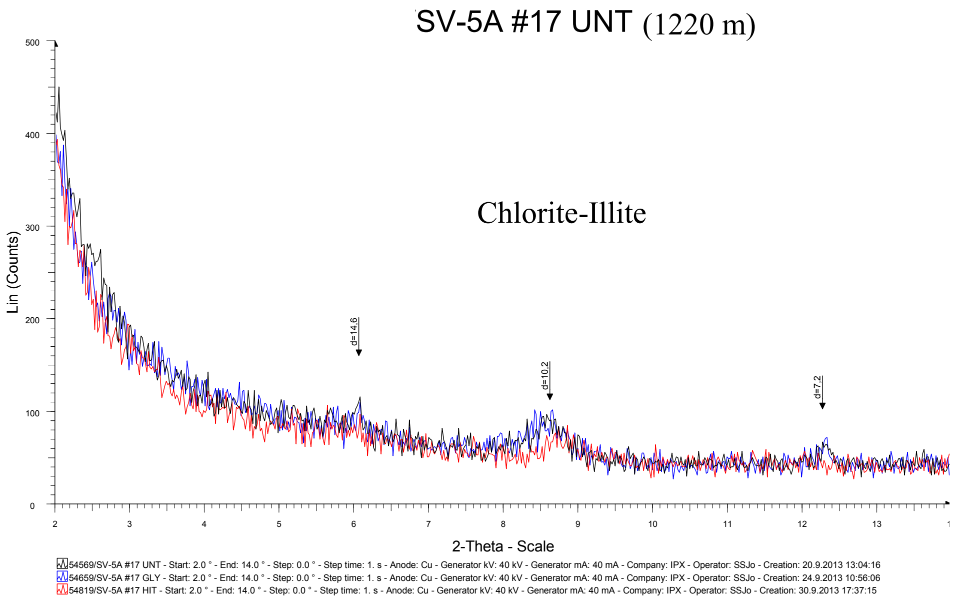

FIGURE 4: XRD analysis showing presence of chlorite and illite