

Update of the Geologic Model at the Las Pailas Geothermal Field to the East of Unit 1

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ABSTRACT

The Las Pailas Geothermal Field (LPGF) is the second geothermal development in Costa Rica (Las Pailas Unit 1). The Geothermal Resources Service Center (GRSC) of the Costa Rican Electricity Company (ICE) is drilling deep directional wells in the eastern sector of LPGF, where Unit 2 will be installed. An integral analysis of lithostratigraphic and mineralogic data obtained from the wells drilled for Unit 1 (western sector) and for Unit 2 (eastern sector) shows that there is a geothermal reservoir similar to the one found for Pailas I. The limits of this reservoir are still unknown and the possible connection with Pailas 1 has still not been confirmed. The geologic model presented in this paper reveals recently obtained geological information in this sector of the field.

1. INTRODUCTION

The Las Pailas Geothermal Field is located 200 km northwest of San José Costa Rica on the southern flank of the Quaternary Rincón de la Vieja andesitic volcanic complex (Figure 1). Since July, 2011, Unit 1, a 35 MWe binary unit, has been supplying low cost base load power to the national grid. As part of the feasibility study for Unit 2 at Las Pailas Geothermal Field, and due to the nationwide initiative to generate electricity from clean energy sources in order to cover the increasing energy demand GRSC, ICE has continued drilling deviated wells in search of new permeable zones related to permeable lithostratigraphic levels and the local structural framework, in the eastern sector of the LPGF.

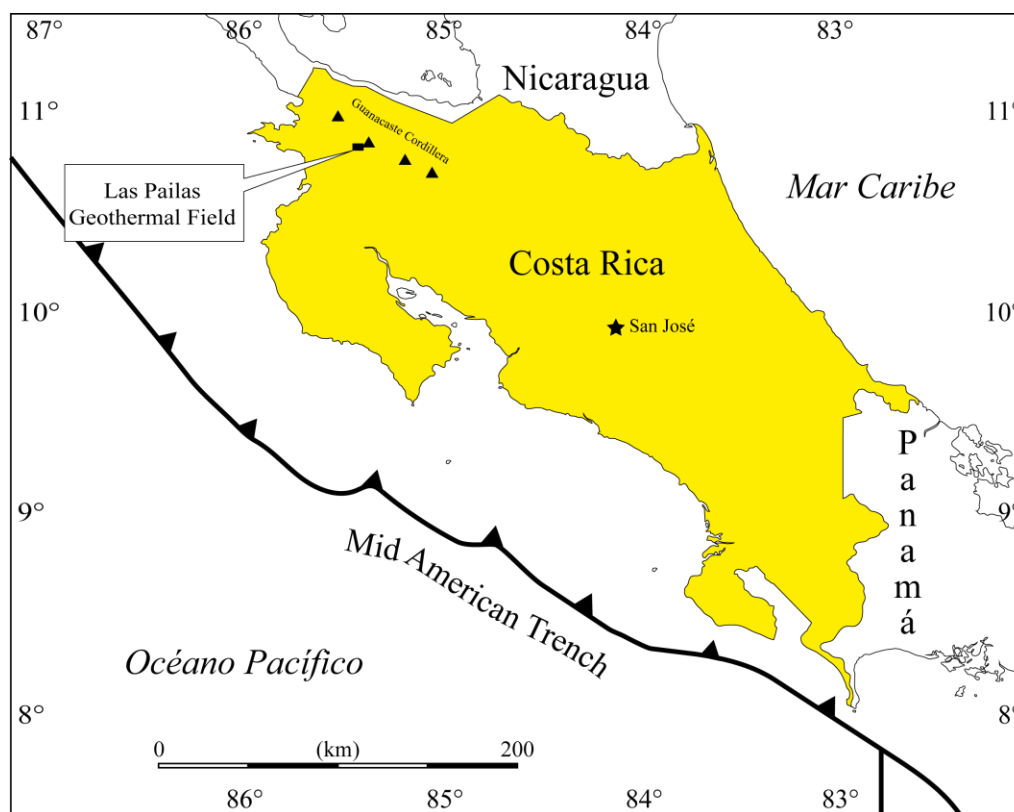


Figure 1: Location map of Costa Rica and the Las Pailas Geothermal Field.

To the east of Unit 1 a new drilling campaign has begun in an area of approximately 2.7 km² where six drill pads, from which multiple wells will be drilled, have been located (Figure 2). The northern wells will be for production while the southern wells will be for re-injection. To date only three wells have been drilled in the eastern sector (two production wells and one re-injection well) all of which are in the western-most part of this new area. Preliminary results (geology, production and reinjection tests) are promising and with the 15 additional wells that are to be drilled by 2018, there will be a sufficient number of production and reinjection wells to commission Unit 2, a 55 MWe flash power plant.

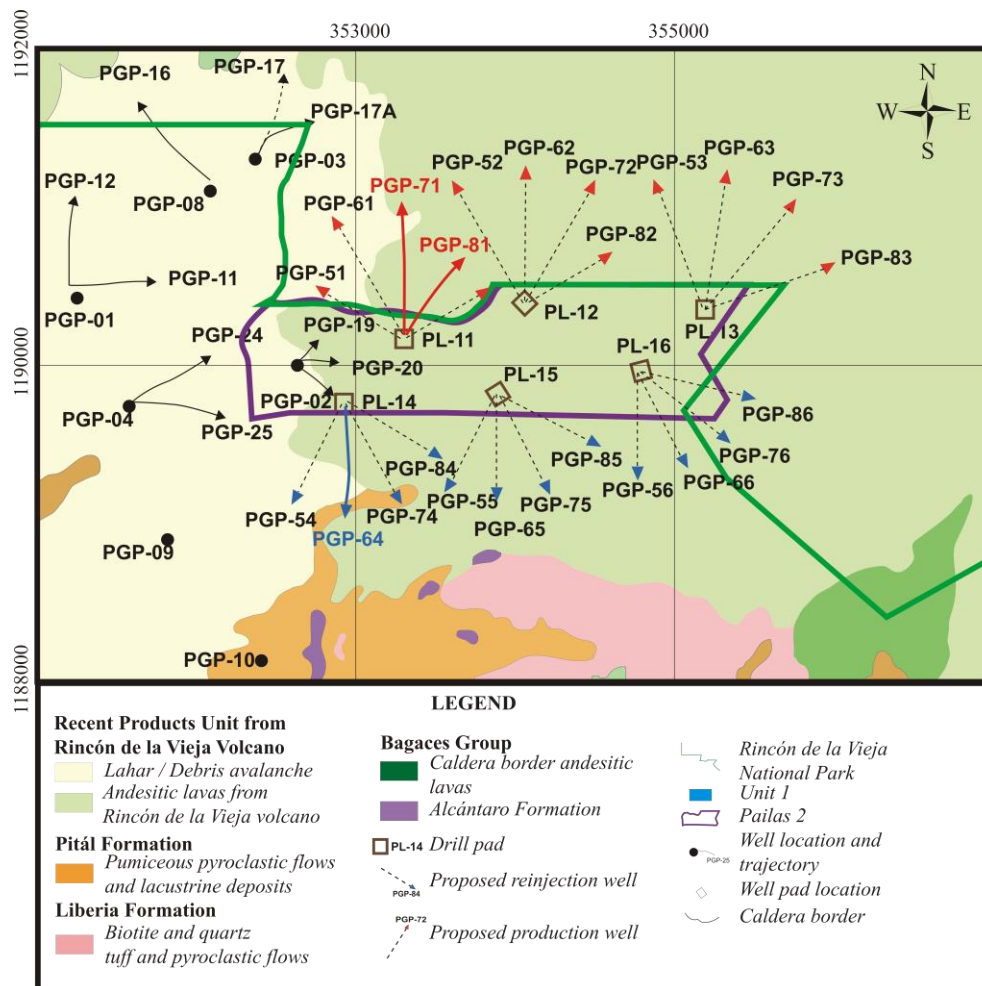


Figure 2: Location map of Pailas 2, showing proposed borehole path trajectories.

2. GEOLOGIC SETTING

The LPGF is located on the southern side of the andesitic Guanacaste volcanic mountain range within the Cañas Dulces caldera (figure 3) which is the most important tectonic structure in the area. It is a collapse caldera elongated NW-SE nearly parallel to the Mid-American trench and convex to the NE. The western and southwestern borders of are evidenced at the surface by the outcropping Alcántaro Formation while the southeastern and northern caldera rims have been buried by more recent pyroclastic flows and fall-out deposits as well as andesitic lava flows. Within the Cañas Dulces caldera is the Guachipelín caldera which is smaller in size and less well defined at the surface. It is within this smaller caldera where most all of the deep wells have been drilled at the LPGF (Figure 3).

In 2010 Chavarría, *et al.* presented a geologic model of the LPGF for Unit 1 based on information from 9 deep wells which suggested that the heat source is located towards the north- northeast and is associated with the Rincón de la Vieja volcanic complex, and declines towards the south-southwest.

The geology team at the CSRG, ICE has analyzed geo-scientific variables to determine the presence of a geothermal reservoir to the east of Pailas 1, which may or may not be an extension of the latter.

2.1 Structural Setting

The regional structural setting of the Guanacaste cordillera and the LPGF has been studied since the 1963 and in numerous internal reports at ICE dating back to 1976 in which both regional and local structures oriented NW-SE, N-S, NE-SW y E-W have been recognized based on aerial photo analysis and field checks.

In 2003, with just 5 deep wells drilled (PGP-01, PGP-02, PGP-03, PGP-04 and PGP-05), West Japan Engineering Consultants, Inc. (WJEC) presented a pre-feasibility report for the use of renewable energies under the Puebla-Panamá Plan and a preliminary conceptual model for the LPGF that showed five main structures. Later, in 2006 a geologic-structural model was prepared by GSRC, ICE and as part of the feasibility study for Pailas 1, a structural map and geothermal model were presented. During the period of 2012-2013 a structural model consisting of seven main faults was proposed for the possible extension of the LPGF to the east of Unit 1 (Figure 4). Directional drilling began at the LPGF in 2009 which permitted a more efficient use of the limited area available for drill pad construction to intersect structures that would be otherwise inaccessible with vertical wells. Directional drilling has also increased borehole permeability because a longer section of the well passes through the fractured zones than in vertical wells.

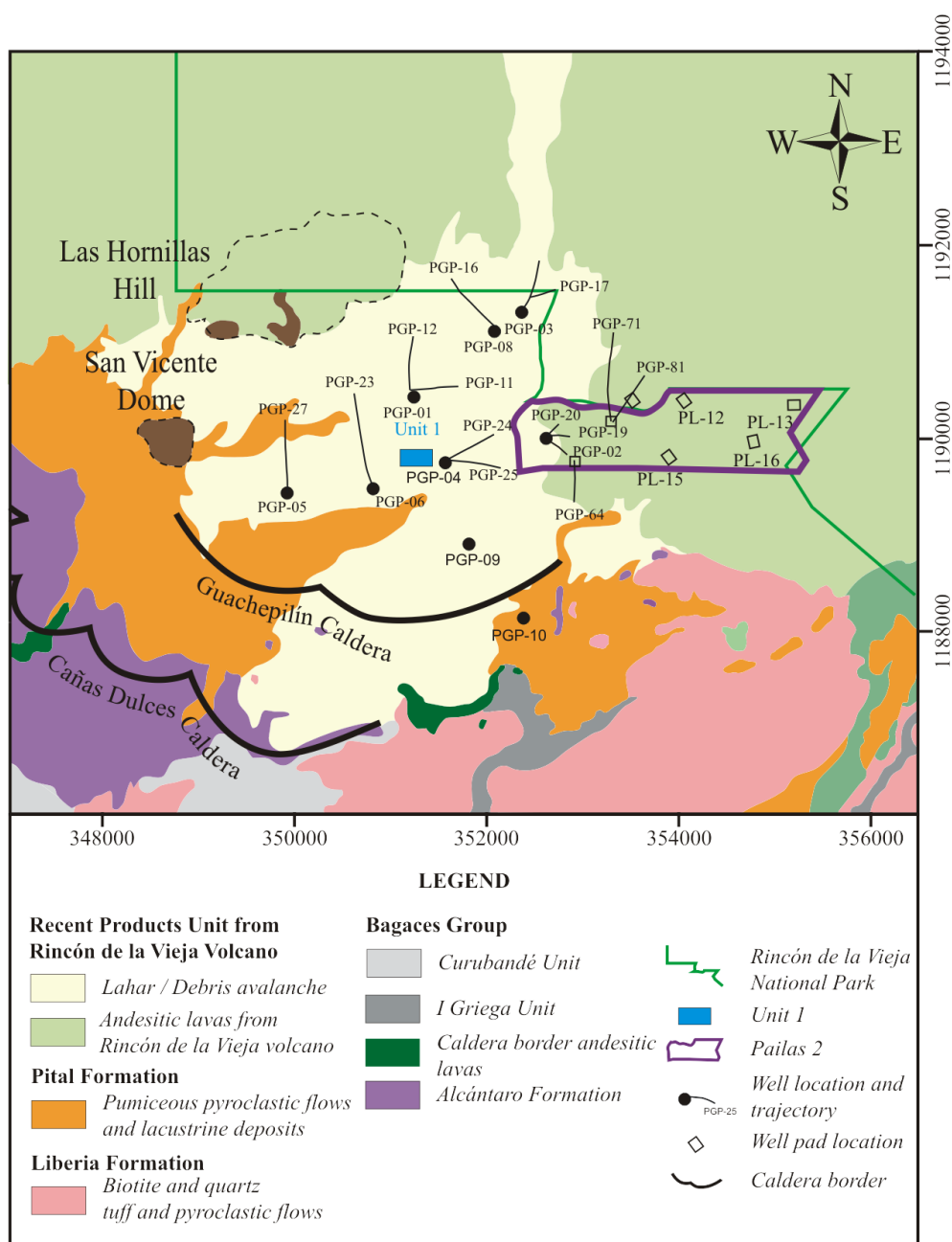


Figure 3: Local geology of the Las Pailas Geothermal Field showing the areas of Pailas 1 and Pailas 2 showing the traces of the Cañas Dulces and Guachipilín calderas.

With these deviated wells, lost circulation zones have been correlated with geologic structures and lineations associated with the fractures modeled at the surface. Geologic structures and lineations were correlated with lost circulation zones associated with the fractures present in the deep wells. Other lost circulation zones were associated to lithological contacts. The geologic structures defined for the area of Las Pailas identified through geological information, aerial photos, high spatial resolution satellite imagery and geophysical analyses¹ are described.

2.1.1 Volcano-tectonic structures and lineations

The main lineations and geologic structures in the LPGF were obtained from topographic information compiled from aerial photography and geophysical analysis of resistivity, gravimetric and magneto-telluric data in which the Cañas Dulces caldera is a semi-circular structure intercepted by lineations oriented NW-SE and NE-SW.

2.1.2 NW-SE and NNW-SSE System

These are the primary lineations in the area and affect all of the lithologic units in the area; they are parallel to the the Guanacaste volcanic belt (NF3) and also with the distribution of the main thermal manifestations (NF7). Lineations oblique to the NW-SE system are interpreted as secondary stress-related Riedel faults (WJEC 2013).

¹ West Japan Engineering Consultants, 2013.

2.1.3 NW-SE and NNW-SSE System

This system is present in the central part of the LPGF and to the south of PGP-10 (NF4).

2.1.4 E-W System

Lineations in this orientation are recognized in the central (NF2) and northern (NF1) parts of the LPGF.

2.1.5 N-S System

A lineation in this orientation is located to the east of PGP-02 (NF5).

3. BOREHOLE STRUCTURAL GEOLOGY

The structural setting of the LPGF is characterized by the presence of calderas and fault systems with different orientations. These faults have been re-modeled by WJEC (2009-2013) considering the geophysical information, information from deep wells, and geologic studies carried out during the geothermal project development. Some of the faults were interpreted by litho-stratigraphic analyses between wells, correlation of lost circulation zones and through alteration mineralogy analyses. As part of this process, seven faults have been determined for the LPGF (Figure 4).

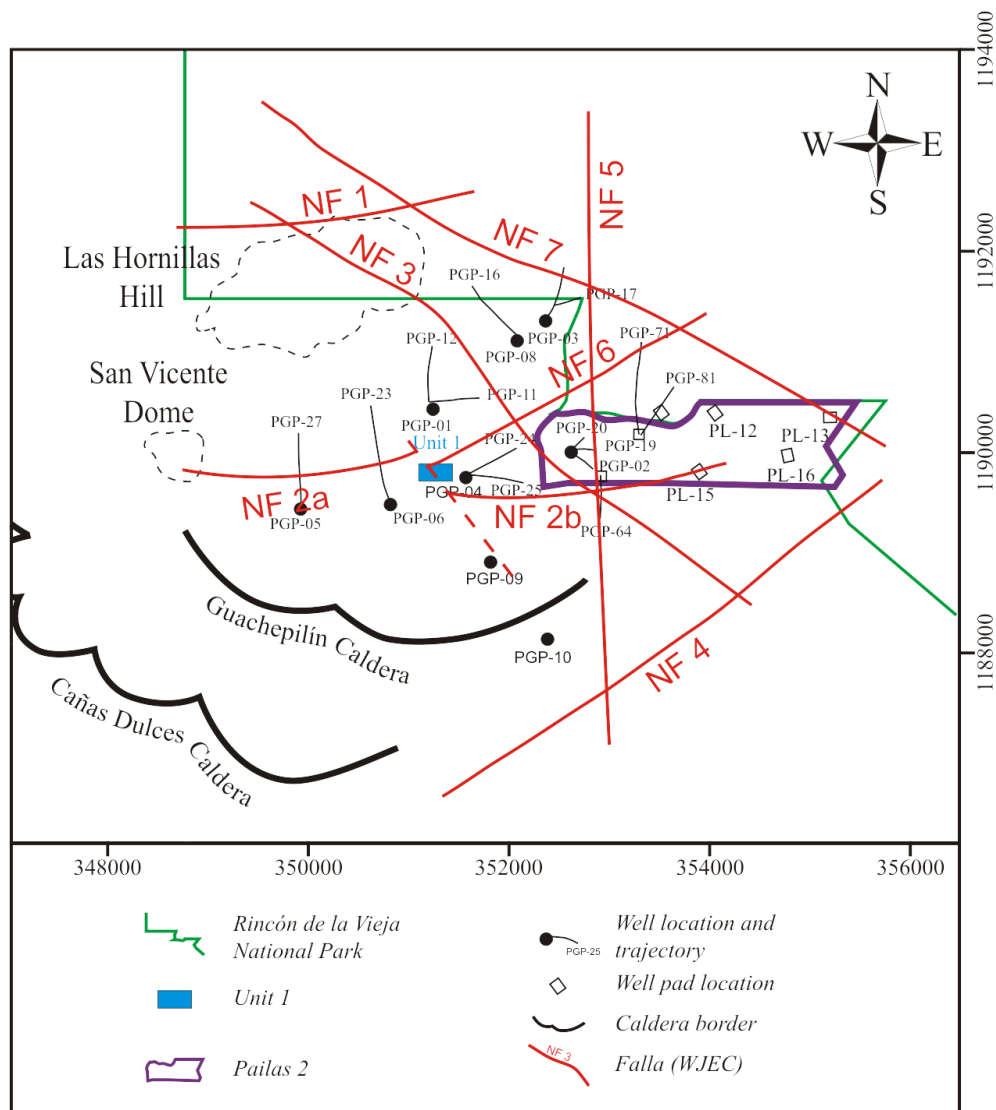


Figure 4: Structural map of the Las Pailas Geothermal Field, showing the areas of Pailas 1 and Pailas 2.

3.1 Fault NF-1 (E-W strike, dipping south)

This fault is near the Hornillas manifestation in the Rincón de la Vieja National Park and was determined by lineations and geophysical discontinuities. No wells have been drilled in this area.

3.2 Fault System NF2 (E-W strike, dipping north)

This fault system is composed of three segments denominated NF2a, NF2b and NF2c. Segment NF2a is located to the north of PGP-05 and PGP-06 and its orientation was determined by analysis of lineations and geophysical data. It may be associated with the lost circulation found in well PGP-23 at 1900 m depth and 855 m displacement. Segment NF2b is to the south of PGP-04 and is

associated with the lost circulation zone of this well at 1300 m depth. Segment NF2c is inferred by the apparent displacement of units in wells PGP-04 and PGP-06.

3.3 Fault NF3 (NW-SE strike, dipping southwest)

This fault extends from the north and passes near PGP-01, continuing to the southeast between PGP-02 and PGP-04. A southwest dip has been inferred due to low gravity anomalies to the south of this fault. This fault is associated with the permeability found in PGP-11.

3.4 Fault NF4 (NE-SW strike, dip unknown)

This fault was determined by resistivity distribution analyses and is modeled to extend from the Santa María Sector towards PGP-10 and the Cañas Dulces Caldera. No wells have been drilled in this area.

3.5 Fault NF5 (NNW-SSE strike, dipping west)

This fault was determined from Magneto-Teluric and Bouguer gravity analyses. It is located to the east of wells PGP-03 and PGP-02 and is associated with the presence of various thermal manifestations and alteration zones. This structure may have influenced in the formation the lahar / debris avalanche in Las Pailas. A western dip is interpreted based on low gravity anomalies to the west and has been confirmed by the association of lost circulation zones in PGP-17 (below 1075 m) and lost circulations in PGP-19 (650 m) and PGP-20 (640 m).

3.6 Fault NF6 (NE-SW strike, dipping north)

This fault is located to the south of wells drilled from platforms PGP-01, PGP-03 and PGP-08. Although there is little geophysical evidence for this fault, lost circulation in well PGP-03 (1240 m) and the permeable zone in PGP-71 at 2060 m depth are associated with this structure.

3.7 Fault NF7 (NW-SE strike, vertical, left lateral)

This is a regional fault located to the north of PGP-03 along various thermal manifestations in Pailas. Taylor (2004) has assigned it as a left lateral strike slip normal fault, with a downthrown southern block. The orientation of this fault is parallel to the orientation of the craters in the Rincón de la Vieja-Santa María volcanic complex and the Mid-American trench.

4. BOREHOLE GEOLOGY

The local geologic history of the LPGF is closely related with the evolution of the Cañas Dulces and Guachipelín collapse calderas in addition to the more recent volcanic activity at the Rincón de la Vieja volcanic complex. Dacitic to rhyo-dacitic domes have risen along fractures associated with the Cañas Dulces caldera and the majority of the deep wells drilled at the LPGF are within the Guachipelín caldera. The litho-stratigraphic column constructed from surface and borehole geology shows six units (Figures 5 and 6).

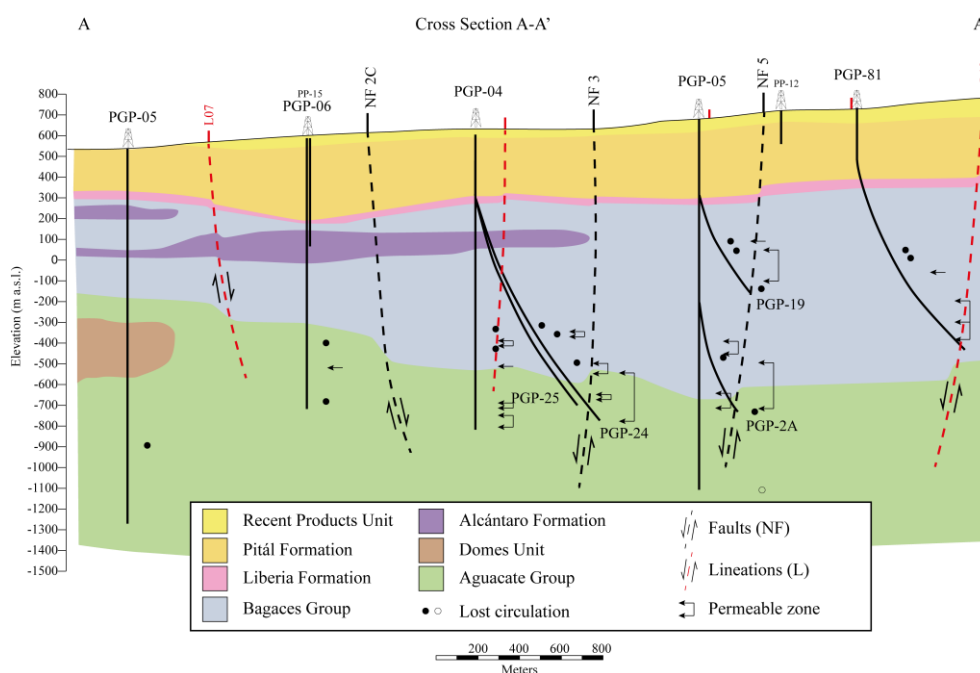


Figure 5: Geologic cross section A-A' oriented SSW-NNE from PGP-05 to PGP-81.

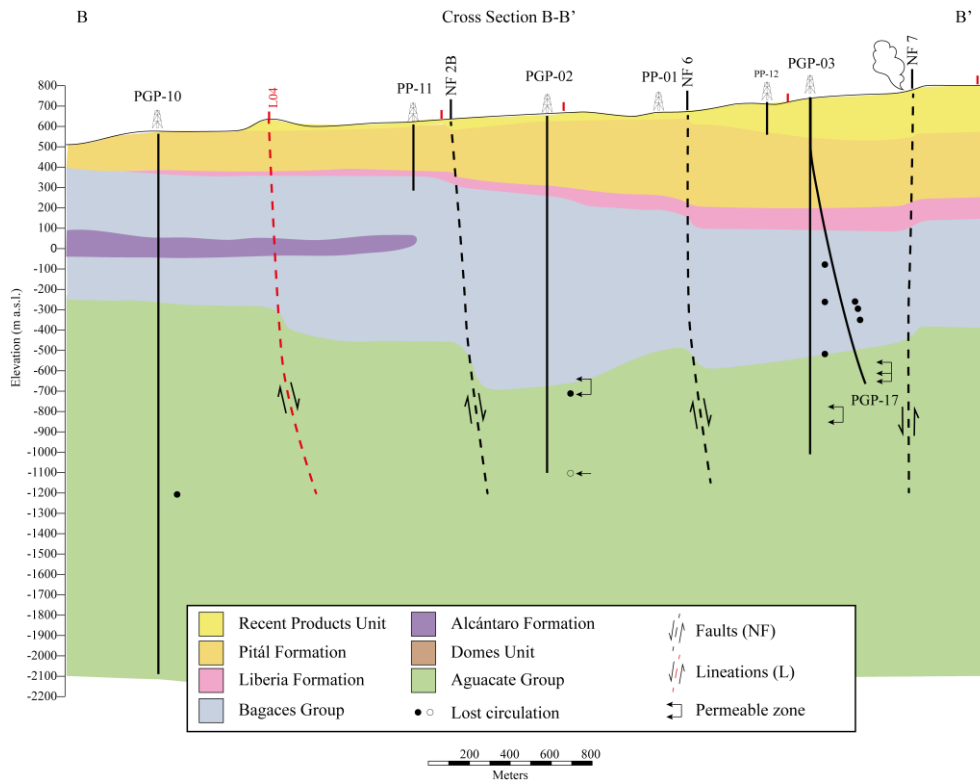


Figure 6: Geologic cross section B-B' oriented S-N from PGP-10 to PGP-03.

4.1 Recent Products Unit from Rincón de la Vieja Volcano

Within the field area, this unit is formed by two main types of deposits: lahar / debris avalanche and andesitic lava flows. Towards the peak of the Rincón de la Vieja volcano, fallout deposits are found intercalated with the andesitic lava. Lost circulation occurs within this unit in some wells, mostly due to unconsolidated materials. The thickness of this unit ranges from 0 to 200 meters, with the greatest thicknesses in wells PGP-03 and PGP-17.

4.2 Pital Formation

The lithologies of the Pital Formation found in the deep wells have been correlated to outcrops found to the east and south of the LPGF. It is composed mainly of: pyroclastic flows, lithic tuffs, largely pumiceous cristal-lithic tuffs and some lacustrine and epiclastic sedimentary rocks. Locally within this formation hornblende and biotite may be differentiated. Permeability commonly occurs in this formation due to lithologic contacts between pyroclastic events and the presence of paleosols. It is present in all of the deep wells as caldera fill material with a thickness that ranges from 180 m to 360 m in Pailas 1 while to the east thicknesses of 125 to 170 m have been drilled.

4.3 Liberia Formation

The Liberia Formation is a white to pink rhyolitic tuff, containing embayed quartz crystals, plagioclase and biotite. Due to its composition, it is considered as a marker level associated with the wide-spread pyroclastic sequence which crops out on the Santa Rosa ignimbrite plateau. In general, permeability is low and this formation is part of the geothermal system cap rock, although some permeability may be found at lithologic contacts or in paleosols. Within the caldera this formation thins out to the south and west (3-52 m) while towards the north and east thicknesses from 123-323 m have been observed. In the sector of Pailas 2 this formation is from 110 to 160 meters thick.

4.4 Dacitic Dome Unit

This unit is comprised of dacitic to rhyo-dacitic domes and dome flows. Within the field area, the San Vicente dome and a dome structure to the northwest of PGP-01 are shown. It was observed in wells PGP-05, PGP-11 y PGP-12 with a thickness ranging from 315 m (PGP-05) to 80 m (PGP-11). In this unit permeability has not been found, possibly because it is a massive intrusive rock. No rocks associated to this unit have been drilled in Pailas 2.

4.5 Bagaces Group

This group corresponds to pyroclastic flows and tuff sequences (lithic, lithic-pumice, and crystalline) with alternating lavas, lacustrine deposits and dikes. Some of these rocks crop out at the Cañas Dulces caldera border. Secondary permeability in the upper section is associated to lithologic contacts whereas the permeability in the basal section may be associated with fractures present in lavas and consolidated tuffs. It has been drilled in all of the deep wells at LPGF with thicknesses ranging from 370 m in the north, 1040 m in the center of the field and 700 m towards the south. Within this group the Alcántaro Formation, composed of vitreous lava and ignimbrites, is thicker to the west and south of the field and is associated with the Cañas Dulces caldera border.

4.6 Aguacate Group

At the regional level this group includes a sequence of andesitic lavas intercalated with pyroclastic and sedimentary rocks as well as reworked material and dikes. These rocks do not crop out in the LPGF, however in the deep wells they are correlated with thick intensely altered lava sequences in the northern and eastern sectors of the field. The secondary permeability is found along fractures and also lithologic contacts. The top of this unit is found at elevations between -150 and -700 m a.s.l., for which reason in some wells it was not reached (PGP-19, PGP-20, PGP-25 y PGP-81). The greatest thickness of the Aguacate Group was drilled at PGP-10 without reaching the base. The top of this unit has been modeled with indirect methods such as ROP and interpreted to be present in well PGP-71, the deepest well to date in the eastern sector.

5. BOREHOLE ALTERATION MINERALOGY

The minerals formed by hydrothermal alteration are used as indicators of past and present temperatures, as a guide to infer permeability in geologic units and also to define the cap rock and reservoir extension.

5.1 Clay Zonification

For the areas denominated as Pailas 1 and Unit 2 Las Pailas Geothermal Field, x-ray diffraction methods have been used to identify four clay zones based on the paragenesis of each one: kaolinite, smectite, illite/smectite and illite (with or without the presence of chlorite in the last three). Cross sections A-A' (figure 7) and B-B' (figure 8) show the distribution of these clay zones.

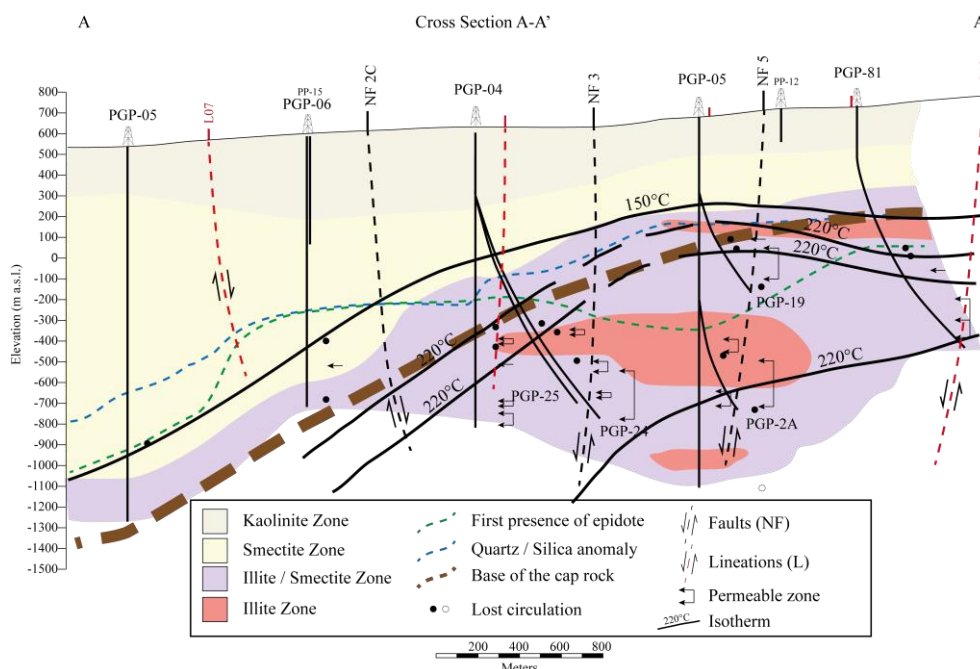


Figure 7: Alteration mineralogy cross section A-A' oriented SSW-NNE from PGP-05 to PGP-81 showing clay zones, the silicified zone top and the first continuous appearance of epidote as well as isotherms of measured downhole temperatures.

5.1.1 Kaolinite Zone

This is the shallowest zone and is characterized by moderate to high intensity and low grade alteration to kaolin clays with temperatures lower than 120°C, in association with oxides and/or silica. It is present in all of the wells and the base is located between 550 – 200 m a.s.l. The thickness of this zone is least in the north (200 m) and greatest to the southwest (425 m), affecting partially to totally the Recent Products Unit and Pital Formation. This zone is 180 meters thick in Pailas 2 (500 to 680 m a.s.l.).

5.1.2 Smectite Zone

The alteration in this zone is characterized as high intensity and low grade to smectite-type clays, stable at temperatures lower than 160°C, in addition to iron oxides, silica, pyrite and on occasion calcite and chlorite. Also included in this zone is the mixed layer clay chlorite / smectite.

It is present in all of the wells from 560 to 300 m a.s.l. to the north and from 460 to 300 m a.s.l. to the west and south. The greatest thicknesses (780-1480 m) are found to the west, southwest and south (areas of lower temperature) and affect partially to entirely the Recent Products Unit, Pital Formation, Liberia Formation, Bagaces Group and Aguacate Group. This zone pinches out to the north and northeast (40-550 total thickness) where it is present in the Recent Products Unit and Pital Formation. In Pailas 2, a thickness of 200 meters has been observed (500 to 300 m a.s.l.).

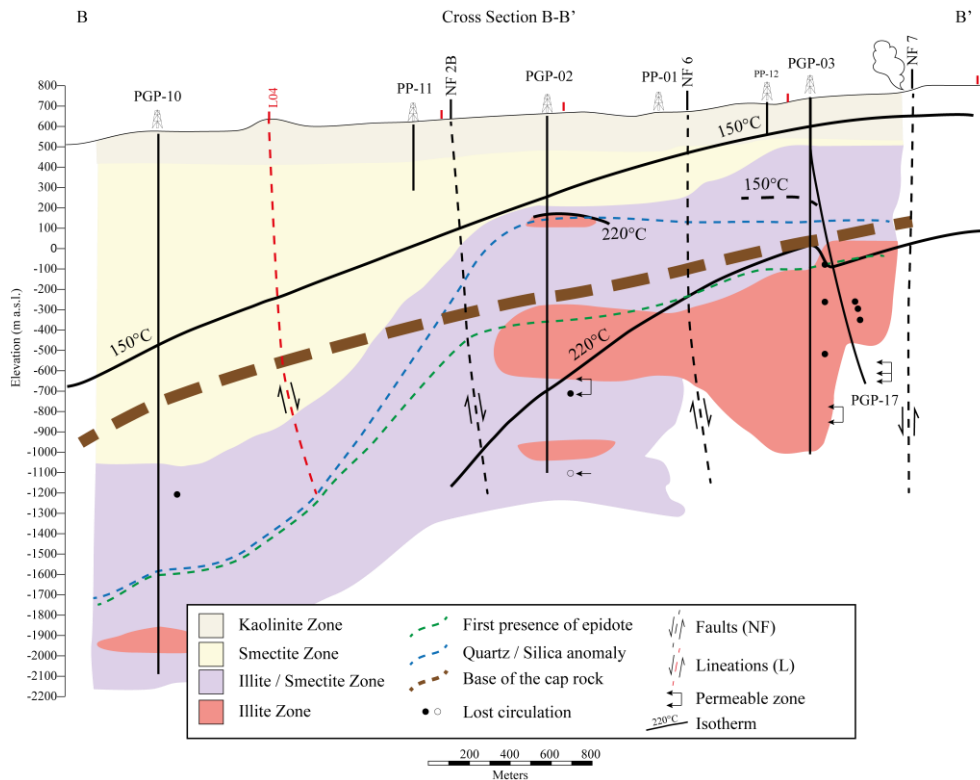


Figure 8: Alteration mineralogy cross section B-B' oriented S-N from PGP-10 to PGP-03 showing the base of the cap rock as interpreted from clay zones, the top of the anomalous quartz zone top, the first continuous appearance of epidote and the isotherms from measured downhole temperatures.

5.1.3 Illite / Esmeectite Zone (or Transition Zone)

This is a mixed-layer clay zone where illite and smectite occur in association with high intensity and high to moderate grade alteration representing a temperature range between 165°C and <220°C which varies in function of illite percent. It is associated with alteration minerals such as quartz, calcite, pyrite, chlorite, zeolites, sericite, leucoxene and epidote.

It is present in all of the wells of the field. To the north and east this zone starts from 450 to 300 m a.s.l. in the Pital Formation, Liberia Formation, Bagaces Group and Aguacate Group. To the west and south the top deepens to -1100 m a.s.l. (PGP-05 and PGP-10), affecting mainly the Bagaces and Aguacate Groups. In the west 200 m of this zone have been drilled and in the south 1000 meters have been drilled. To the central, northern and eastern parts of the field it is greater than 1000 meters thick. However, the thickness drilled varies in function of the depth of each well. Also, in some wells, pure illite is intercalated within this zone.

5.1.4 Illite Zone

This zone has higher than 95% illite and occurs with high grade and moderate to high intensity alteration that indicate formation temperatures $\geq 220^\circ\text{C}$ associated with sericite, calcite, quartz, chlorite, leucoxene, epidote and wairakite.

In the majority of the wells this zone is below 0 / 50 m a.s.l. and was not observed in the western or southern parts of the field except in well PGP-10. To the north and east it is found at an anomalously shallow level from 150 – 0 m a.s.l. possibly caused by a lateral heat flow. It is present mainly in the Bagaces Aguacate Groups.

5.2 Quartz / Silica Anomaly

In general, the quartz / silica anomaly is found within the cap rock of the geothermal reservoir with a trend that similar to the top of the illite / smectite zone and the base of the cap rock. In the central and northern parts of the field, where the geothermal gradient is higher, it is found within the illite / smectite zone. However, to the west and south where the geothermal gradient is lower, it deepens and is found above the top of illite / smectite zone.

5.3 Epidote Zone

The line that marks the first continuous appearance of epidote is near 0 m a.s.l. to the north and east, in accordance with the hottest part of the field; it deepens towards the south and west (to -1000 / -1800 m s.n.m.) where the temperatures are lower.

5.4 Isotherms

The general trend of the 150°C isotherm is similar to that of the top of the illite / smectite zone, the silicified zone and the base of the caprock. To the north and east of the field it is found from 550 to 250 m a.s.l. and to the east from 200 / 0 m a.s.l. whereas to the west and south it is found in the range of -450 / -1000 m a.s.l. The trend of the 220°C isotherm correlates quite well with the presence of the illite zone where it is found at 150 to -100 m a.s.l. in the north and east (in agreement with the anomalous illite zone

in this part of the field). This isotherm deepens to -400 / -600 m a.s.l. towards the central part of the field and drops to -600 / -750 m a.s.l. to the west and south (figures 7 and 8).

6. CAP ROCK AND RESERVOIR TOP

The cap rock was interpreted from the clay type zonification (smectite zone and upper part of the illite / smectite zone), the base of the quartz / silica anomaly, the appearance of high temperature alteration minerals (epidote) and lost circulation zones found in the wells. The base of the cap rock marked with a dashed brown line in figures 5 and 6 is shallower and thinner in the areas closer to the volcano (north, northeast and east) and includes the Recent Products Unit, Pital Formation and part of the Liberia Formation and Bagaces Group. The base of the cap rock deepens to the south, southwest and west where the geothermal gradient is lower. The trend of the base of the cap rock is similar to the shape of the anomalous quartz zone and the top of the illite / smectite zone, indicating likewise the top of the geothermal reservoir.

7. DISCUSSION

Since 2011 the Las Pailas Geothermal Field has been supplying clean base-load power to the national grid in Costa Rica.

Due to the increasing electricity demand and the desire to increase the installed capacity of renewable energy resources, including geothermal energy, it is necessary to continue exploring and developing new geothermal prospects and this process must be based upon close and accurate analyses of the existing geoscientific data in order to take the right decisions and reduce the risk when searching to tap geothermal reservoirs.

Borehole geology is a fundamental discipline for identifying unit continuity, fault displacement, alteration mineralogy tendencies, clay zone distribution and isotherm contours in order to model the shape and location of the heat source, the extent of a geothermal reservoir and suggest the shape of the base of the cap rock.

To the west and south of the LPGF, boreholes have intersected dacitic lavas and ignimbrites of the Alcántaro Formation which is related to the Cañas Dulces Caldera border. On the other hand, to the north the Bagaces Group thins and to the east it thickens with distance from the caldera border.

Near the caldera border, where the Alcántaro Formation has been found, the high temperature alteration mineralogy deepens and the low temperature smectite clay zone thickens. Correspondingly, the base of the cap rock deepens towards the south and west.

The geoscientific variables studied in this report suggest that there is a promising geothermal resource to the east of Unit 1 at the LPGF.

8. CONCLUSIONS

The information presented suggests that the contacts between lithologic contacts will be shallower to the east, possibly due to proximity to the northeastern border of the Cañas Dulces Caldera.

The silicified zone (anomalous quartz zone), the first continuous appearance of epidote and the top of the illite / smectite zone coincide well with the 150°C isotherm, while the top of the illite zone corresponds to the 220°C isotherm. To the east these conditions are assumed to continue and possibly occur at shallower depths.

The tendency and distribution of the clay zones and the alteration mineralogy suggest that the base of the cap rock in the area being drilled for Unit 2 is near sea level (+/- 100 m).

The structural framework of the LPGF is characterized as having collapse caldera structures and fault systems oriented NW-SE, NE-SW, E-W and N-S. Some of these faults have been defined based on geologic and geophysical studies and corroborated by lost circulation zones in the deep wells. Similar characteristics have been observed by traversing faults NF3 in well PGP-64 and NF6 in well PGP-71. This suggests that the structural framework in Pailas 1 may extend toward the east where Unit 2 of the Las Pailas Geothermal Field is being developed.

To the north (production zone) the isotherms are more stable, homogeneous and the response of illite formation is shown by shallow high temperature zones which have been determined to have high gas content (PGP-19, PGP-20 and PGP-64) that are not considered to be part of the main geothermal reservoir and deep commercial production zones. To the south and west the deepening to the isotherms correlates well with the observed low-intermediate alteration mineralogy and the deepening of the illite / smectite zone.

Based on what has been observed in Pailas 1, the area to the north of Unit 2 Las Pailas Geothermal Field may have favorable characteristics for geothermal development. Well PGP-64 was the first directional well to be drilled to the south and was successful in finding a highly permeable zone possibly associated with fault NF 2b.

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