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Las Pailas geothermal field - Central America case study: Deciphering a volcanic geothermal play type through the combination of optimized geophysical exploration methods and classic geological conceptual models of volcano-tectonic systems

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Abstract. Sustainable exploitation strategies of high-enthalpy geothermal reservoirs in a volcanic geothermal play type require an accurate understanding of key geological structures such as faults, cap rock and caldera boundaries. Of same importance is the recognition of possible magmatic body intrusions and their morphology, whether they are tabular like dikes, layered like sills or domes. The relative value of those magmatic bodies, their age, shape and location rely on the role they play as possible local heat sources, hydraulic barriers between reservoir compartments, and their far-reaching effect on the geochemistry and dynamics of fluids. Obtaining detailed knowledge and a more complete understanding at the early stages of exploration through integrated geological, geophysical and geochemical methods is essential to determine promising geothermal drilling targets for optimized production/re-injection schemes and for the development of adequate exploitation programs. Valuable, extensive geophysical data gathered at Las Pailas high-enthalpy geothermal field at northwestern Costa Rica combined with detailed understanding of the geological structures in the underground may represent a sound basis for an in-depth geoscientific discussion on this topic. Currently, the German cooperation for the identification of geothermal resources in Central America, implemented by the Federal Institute for Geosciences and Natural Resources (BGR), supports an international and interdisciplinary effort, driven by the Instituto Costarricense de Electricidad (ICE) with different international and national research institutions, including the Leibniz Institute for Applied Geophysics (LIAG). The discussions and joint studies refer to the optimized utilization of geophysical and geological methods for geothermal exploration in the Central American region, using the example of Las Pailas Geothermal Field. The results should contribute to a better understanding of the most appropriate geothermal exploration concepts for complex volcanic field settings in Central America.

1. Introduction

In the 1970´s the United Nations Organization selected Costa Rica as one of the Central American countries to receive a scientific delegation to search and develop renewable resources for electric energy production. Mostly related to the 1973 world oil crisis and based on Costa Rican geothermal resources as one of those potential renewable energy resources, this was an attempt to overcome the high fuel prices, which affected the energy market in the country. At that time, the Guanacaste Province in the North of Costa Rica was chosen as a priority area for geothermal exploration, development and research. From three prospects, the Miravalles geothermal field was designated for development as the most promising site. As a result, the first geothermal power plant of Costa Rica started operation in 1994, known as the Dr. Alfredo Mainieri Protti Power Plant and now, 25 years later, it is still producing. Only in 2011 Las Pailas I was inaugurated as a 42 MW binary power plant. Most recently, in July 2019 a third 55 MW geothermal power plant (Pailas II) started operation and the planning for further geothermal power plants is defined until 2065, with the approved development of the Borinquen Geothermal Field until 2026. These recent efforts intend to increase geothermal production up to 315 MW with clean and stable energy to the country. The efforts of ICE supported by the German Cooperation expect to enhance the quality of exploration results, improve the characterization of the high-enthalpy geothermal reservoirs and hence reduce exploration risks. Geothermal development areas in volcanic play types in Costa Rica can be seen in Figure 1.

Properly characterizing the geologic controls on geothermal systems requires the integration of multiple geophysical, geological and geochemical analyses at different scales [8]. In particular, the geologic controls on the permeability structure and fluid and heat transport in such a volcanic play type are discussed in the present work. Regional plate tectonic as well as local volcano-tectonic considerations and related structural geology are taken into account to constraint combined geophysical interpretation and geochemical analyses. The specific properties, structure and behavior of individual geothermal systems strongly depend on site-specific elements and conditions such as origin, depth and distribution of the heat source, porosity and permeability structure of the reservoir (reservoir volume and compartmentalization), fluid and heat transport mechanisms and fluid/rock interaction and chemistry [13 and references therein].

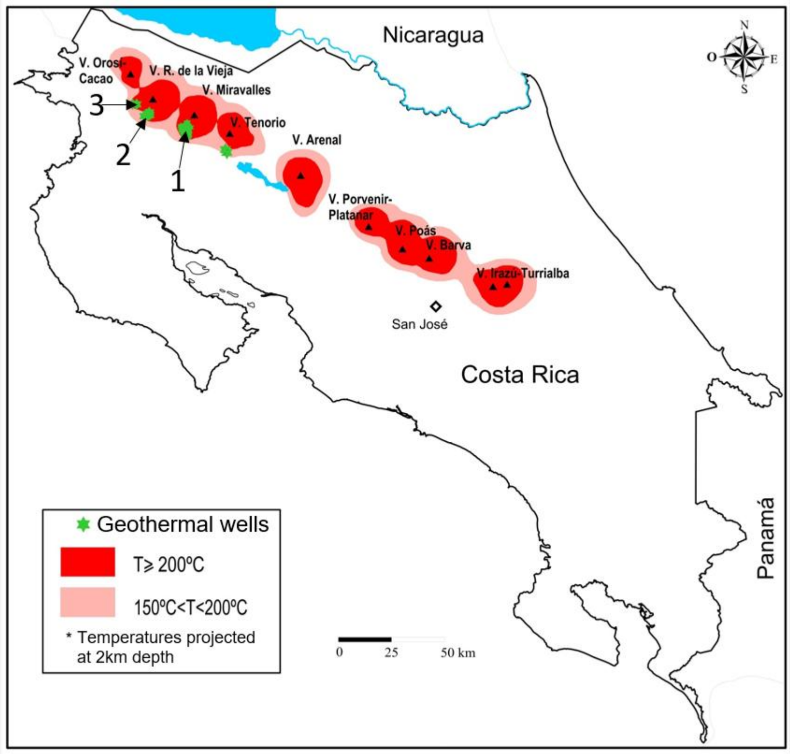

Figure 1. Location of existing developed geothermal areas in Costa Rica with deep wells (1500-2300 m). 1 - Dr. Alfredo Mainieri Protti Geothermal Field (formerly known as Miravalles), 2 - Las Pailas Geothermal Field (Production Units I and II), and 3 - Borinquen Geothermal project. Based on the 200°C and 150°C isotherms distribution projection at 2 km depth according to geothermal well data. Modified from CSRG-ICE (2014).

Most intensively in recent years, geophysical data from Las Pailas high-enthalpy geothermal field has been reanalyzed according to the development and drilling of this geothermal field. Therefore, it is an optimal entry point for the discussion of the application of a volcano-tectonic-based approach for the Area of Interest (AOI) proposed by the present study based on: (I) the analysis and integration of geophysical data (e.g. obtained from magnetotelluric, gravity and magnetometry surveys), (II) the interpretation using different theoretical approaches for volcano-tectonic structures and models for a volcanic play type, (III) worldwide prominent examples reported in several international geoscientific articles, and (IV) the support of new geoscientific evidences from recently drilled wells and clay geothermometers analysis. Based on the knowledge and experiences gained in this work we aim at contributing to the long-standing discussion about which are the most appropriate and cost-effective geophysical techniques in any exploration program related to a volcanic geothermal play type [8 and references therein]. Essentially, this work does not address the different aspects of geophysical exploration methods for the assessment of geothermal resources such as (I) quality and suitability of the equipment, (II) appropriate survey parameters, (III) proper operation of the equipment in the field and (IV) understanding noise sources, even though these challenges are well known aspects in the region. Through the reevaluation of available data, this work focusses on the amount of geological information that can be extracted from the integration of several geophysical data through quality control (QC) of collected data and appropriate data processing and interpretation.

2. Las Pailas Geothermal Field case

Las Pailas Geothermal Field is located at the southern flank of the Rincón de la Vieja Volcano. This geothermal field encompasses a high-enthalpy liquid-dominated reservoir characterized by sodium-chloride fluids with a maximum measured temperature of 268°C at -900 m.a.s.l (1.686 m.b.g.l.) in the PGP-73 well (S Castro, personal communication, July 05, 2019). Las Pailas geothermal field has 41 deep wells, 20 well connected to the Unit 1 and 21 to the Unit 2 power plants.

3. Geological setting

The local geological history of Las Pailas geothermal field is related to the evolution of the Cañas Dulces and Guachipelín calderas and more recently with the activity of the Rincón de la Vieja volcanic complex. According to Tassi et al [22], the Rincón de la Vieja complex, a composite andesitic stratovolcano located in NW Costa Rica near the border with Nicaragua, shows a wide range of hydrothermal fluid-related surface manifestations (a hyper-acidic crater lake, boiling – and mud-pools, thermal springs and associated gas discharges).

A lithostratigraphic column has been interpreted from deep wells that include six separate volcanostratigraphic units. These six units can be correlated to regional formations dating from the Miocene to the Holocene: (1) Aguacate Group, (2) Bagaces Group, (3) Liberia Formation, (4) Domes Unit (5) Pital Formation, and (6) Recent Products Unit. Of these formations, the only unit not represented in an area outcrop is the Aguacate Group. Based on deep well geological data, the geothermal reservoir is restricted to the basal section of the Bagaces Group and the Aguacate Group [3]. This can be seen in Figure 2.

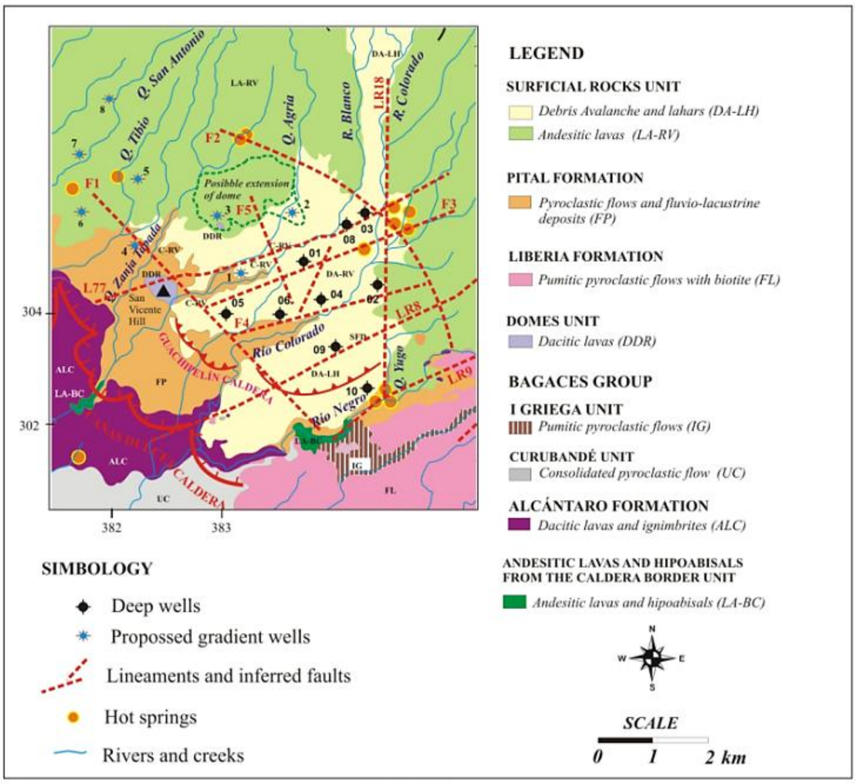

Figure 2. Geologic map of the Las Pailas Geothermal Field after Chavarría et al [3]. Coordinates are in Lambert north. Major lineaments and inferred faults may represent hydraulic barriers or conduits according to their orientation with respect to the present-day stress field. A detailed hydrotectonic analysis of this volcanic system can contribute to a better understanding of the permeability structure of the reservoir and hence to the understanding of the reservoir compartmentalization.

4. Magnetotelluric data analysis

Since the 1990s several magnetotelluric (MT+AMT) campaigns have been carried out by the ICE in Las Pailas Geothermal Field. In 2013 an extensive TDEM survey was conducted since the 1D modelled cap rock according to Herrera (personal communication, 2013) might show inaccuracy due to static shift phenomena. After the campaign and partly as a result of an analysis described by Herrera [21] it became clear that just 21 of the 126 soundings were reliable without the correction (see Figure 3). This is attributed to the fact that most of the MT soundings presented distortion and thus affecting the cap rock model as can be observed in Figure 4. and compared to Figure 5.

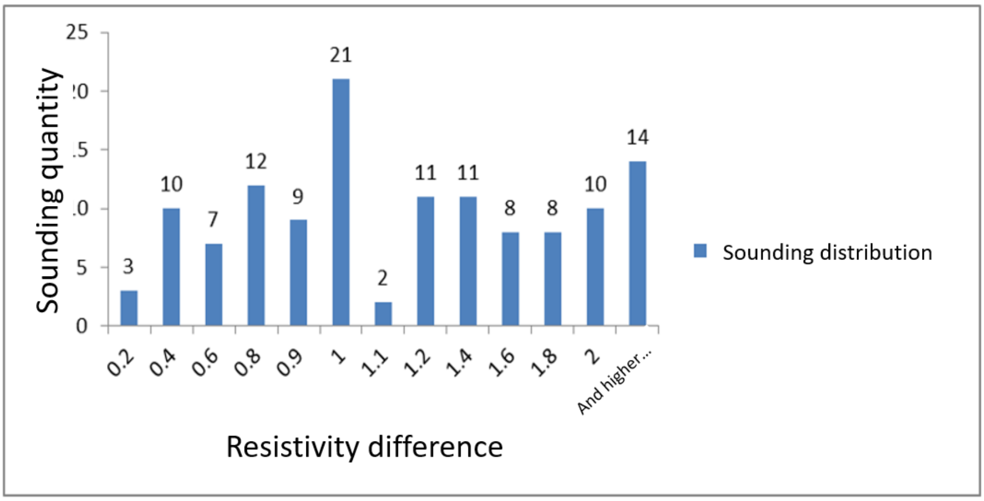

Figure 3. Histogram showing the sounding populations and its respective error previous to the static shift correction through TDEM soundings after Herrera [9]. Only 21 from 126 MT soundings have a resistivity difference (deviation) of less than 10% with respect to the expected resistivity and are in line with the alteration mineralogy findings.

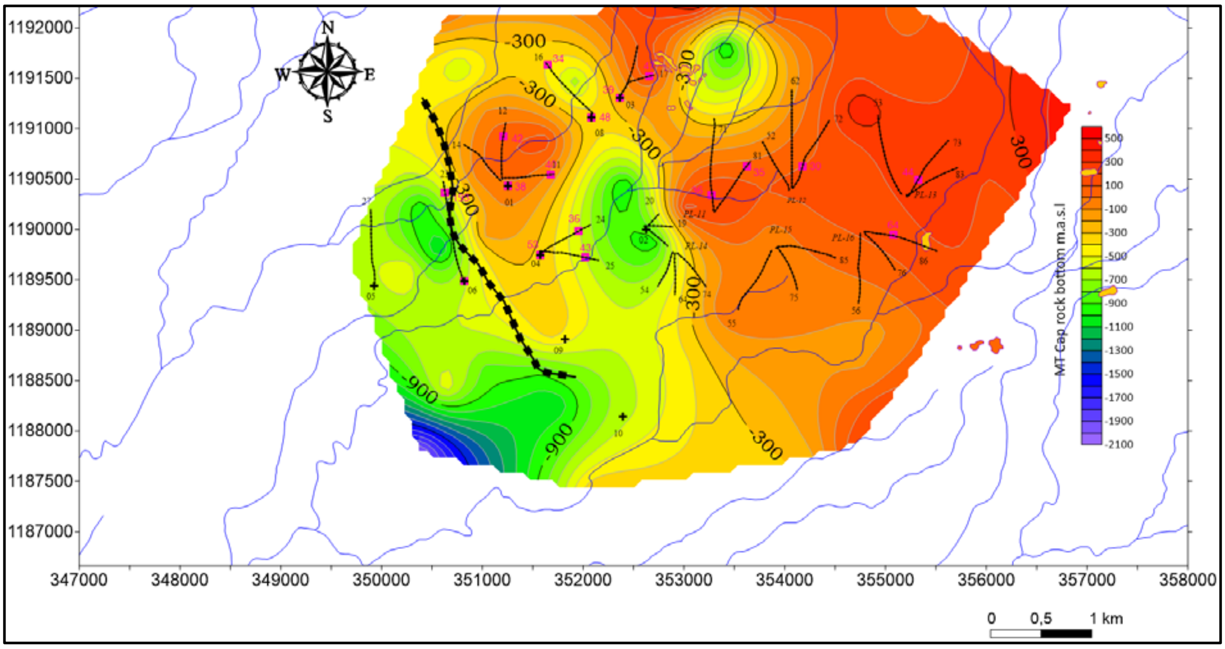

Figure 4. MT bottom of the cap rock contour (MT BOC, resistivity lower contour from the 1-10 ohm-m layer, obtained from 1D inversion) in m.a.s.l without TDEM correction. Pronounced black line with boxes shows the known W and SW boundaries of the geothermal reservoir after Solís & Herrera [21]. Thinner dashed lines represent production/reinjection geothermal wells.

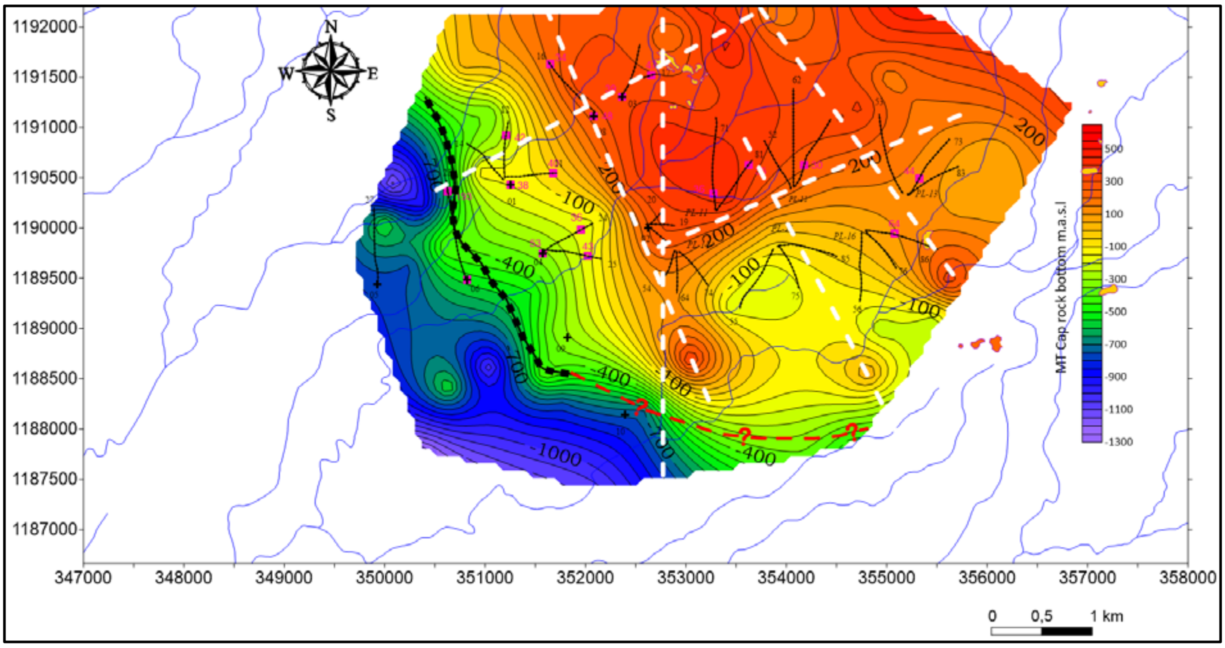

Figure 5. MT BOC (see also Figure 4) in m.a.s.l corrected with TDEM. Pronounced black line with boxes shows the known W and SW boundaries of the geothermal reservoir. Reddish dashed line with question marks depicts the inferred boundary according to the MT BOC tendency. Interpreted prominent structures (faults) are displayed with white dashed lines. Modified from Solís & Herrera [21].

Previous to the analysis of the geophysical data from Las Pailas Geothermal Field, a qualitative morphotectonic drainage pattern analysis had been performed. As Mumipour et al [15] state “drainage networks are usually influenced by the type, orientation and recent activity of regional and local faults and folds in tectonically active regions”. This reasoning was used to establish a possible reference between clear lineaments at surface and any possible anomaly detected through different geophysical methods.

After the MT data was corrected using TDEM soundings, several alignments shown in Figure 5 were determined (using the previous morphotectonic lineaments) as important tectonic structures playing different hydraulic roles from high permeable paths for fluid migration, to boundaries between what is considered to be compartments of the reservoir. The known boundary shown in the previous corrected image has a remarkably good correlation with the permeability, temperature, and mineralogical distribution observed from deep wells in Las Pailas Geothermal Field.

Figure 6 shows the correlation between the corrected MT bottom of the cap rock and the alteration clay minerals distribution. As can be seen, the MT BOC location depth matches mainly between the smectite and illite/smectite transition zone (measured temperatures between 160 and 180°C). At the SE and E area (Las Pailas II Unit) the correlation tends to be less significant mainly at the Pl-13 and Pl-15 well platforms. In the same sense, the analysis of the MT soundings shows some isolated narrow vertical high resistivity bodies (higher than 400 ohm-m) specifically located beneath the MT bottom of the cap rock as revealed in Figure 7. That signal persists throughout two or more profiles (see Figure 8), indicating possible linear bodies (e.g. dikes) located in both well platforms (Pl-13 and Pl-15).

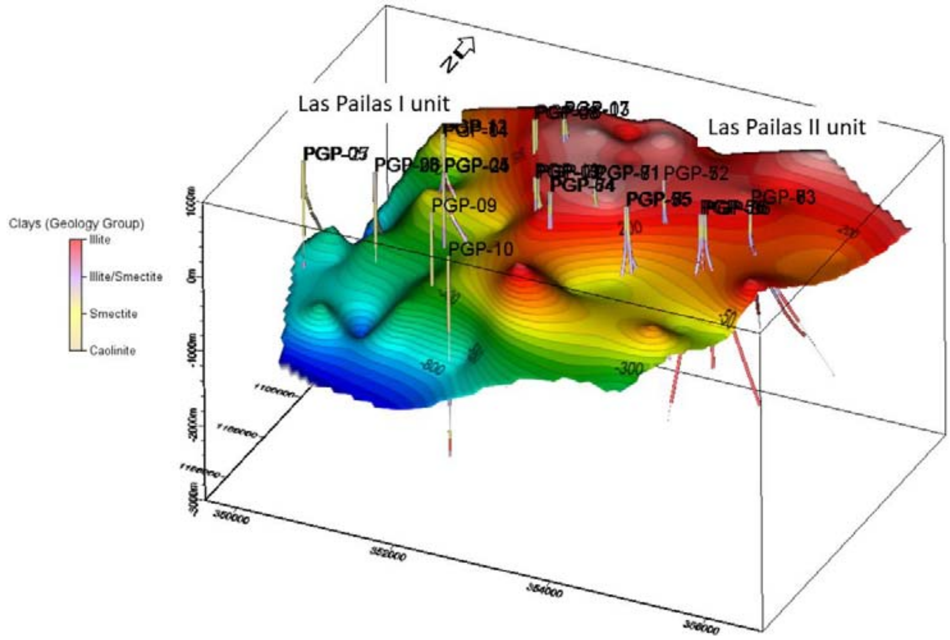

Figure 6. 3D model showing Las Pailas Geothermal Field with geothermal production/injection wells. MT BOC in m.a.s.l shows good agreement with the lower temperature alteration mineralogy (<180°C) represented by the smectite (light yellow) to higher temperatures shown by the appearance of the illite/smectite transition zone (light purple) determined by the ICE Geology group (Costa Rica). Beneath the MT BOC the presence of the high-temperature and -permeability illite (pink) related to highly productive zones can be seen.

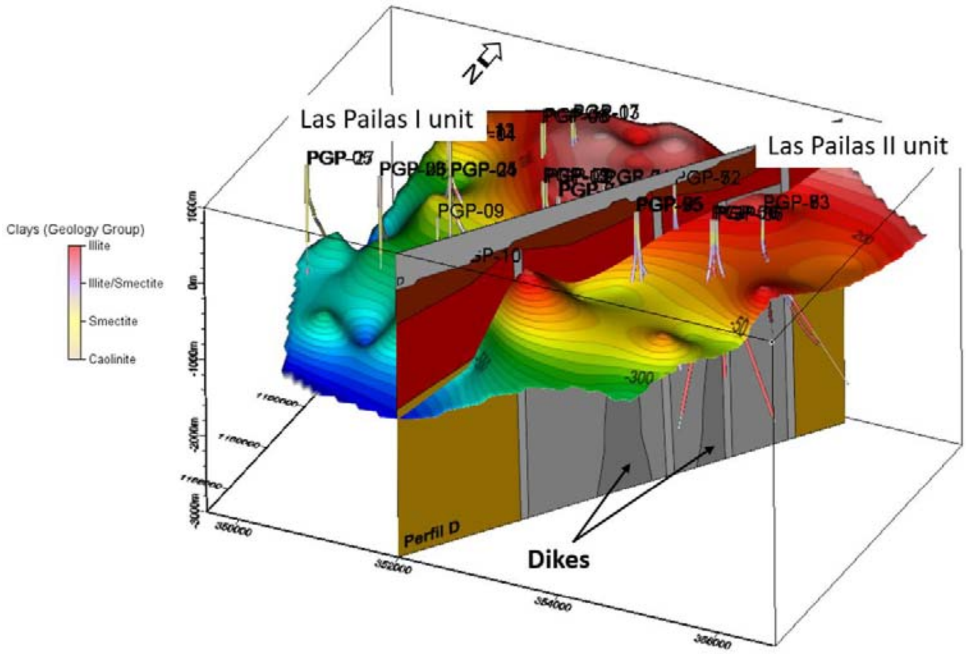

Figure 7. In this image the MT section profile D (Perfil D), derived from the interpolation of several 1D inversion sounding data, shows a different reservoir context according to resistivity interpretation as explained: Dark brown color represents materials above the cap rock (tuff, lahars, lavas, etc., with resistivities above 10 ohm-m); red color depicts cap rock (mainly smectite through illite/smectite transition layer, with resistivities between 1-10 ohm-m); grey color shows reservoir (mostly composed of sequences of tuff and lavas between 20-120 ohm-m); greenish brown color displays lateral areas outside the reservoir where the cap rock suddenly falls; light grey vertical stripes show possible tectonic structures(faults); while narrow dark grey vertical bodies beneath the MT bottom of the cap rock are interpreted as shallow intrusions such as dikes (above 400 ohm-m).

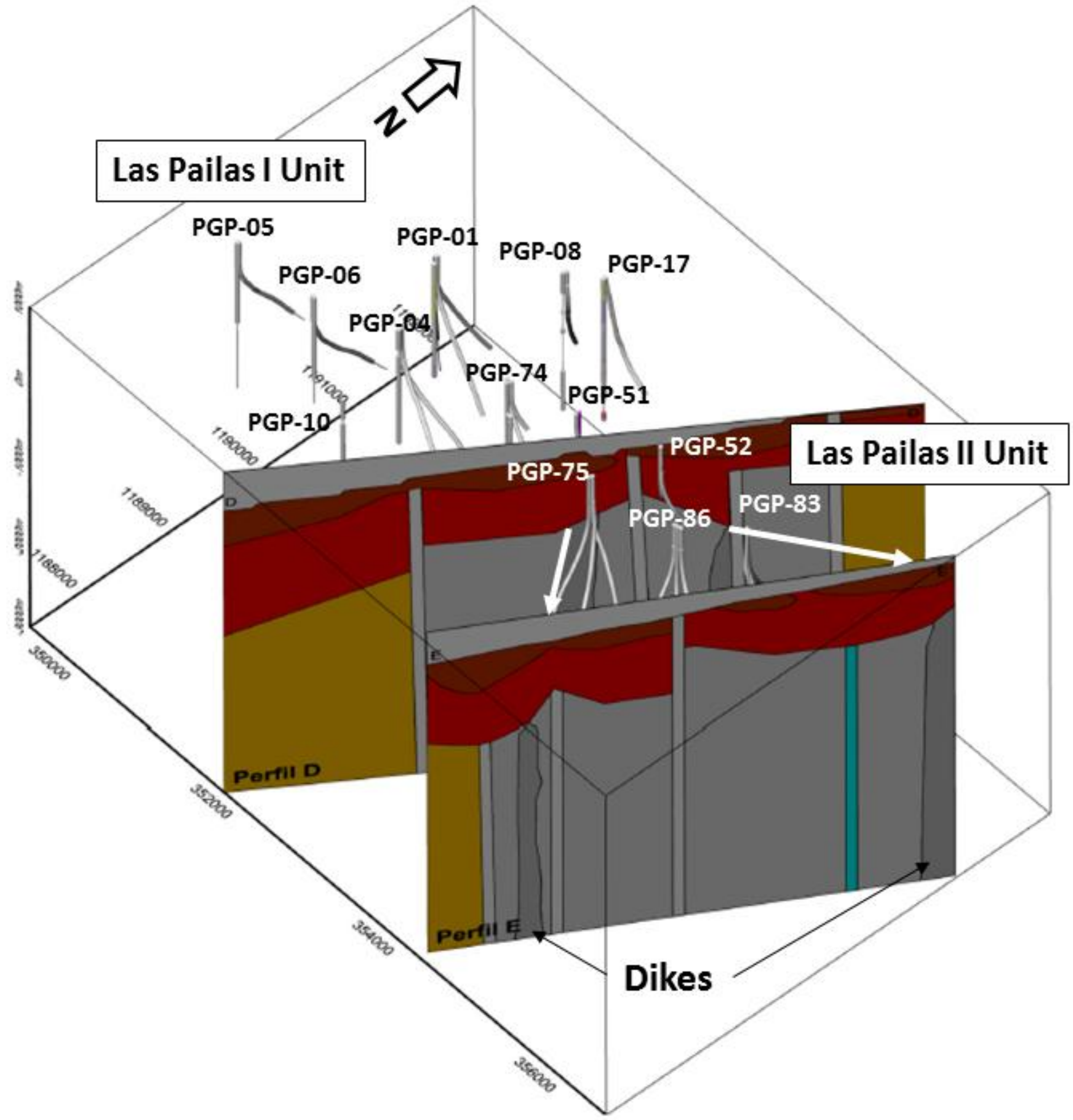

Figure 8. MT section profiles D and E (Perfil D and E). Dark grey narrow vertical bodies resembling "fingers" located inside the reservoir zone (light grey) seem to be laterally continuous and aligned as indicated with the white arrows. Light grey and cyan vertical stripes represent possible structures (faults).

Where narrow vertical high-resistivity bodies appear, as shown in the previous images, the location of the MT BOC at depth and the relation with location of the geothermometer clays observed in the wells tend to show an unusual vertical displacement. The MT BOC appears deeper, nearby the illite zone, rather than the usual and shallower location close to the smectite contact. This anomalous behavior is interpreted as a possible disturbance caused by the presence of deeper highly conductive minerals (possible sulphides and other minerals) reported in alteration aureoles related to the edges of sills. In the case of Las Pailas Geothermal Field, these sills morphologically expressed at the MT BOC as a saucer shape, roughly located at the center of the round pattern, which can be seen in Figure 9. These observations have been well described for an andesitic sill intrusion by Spacapan et al [19].

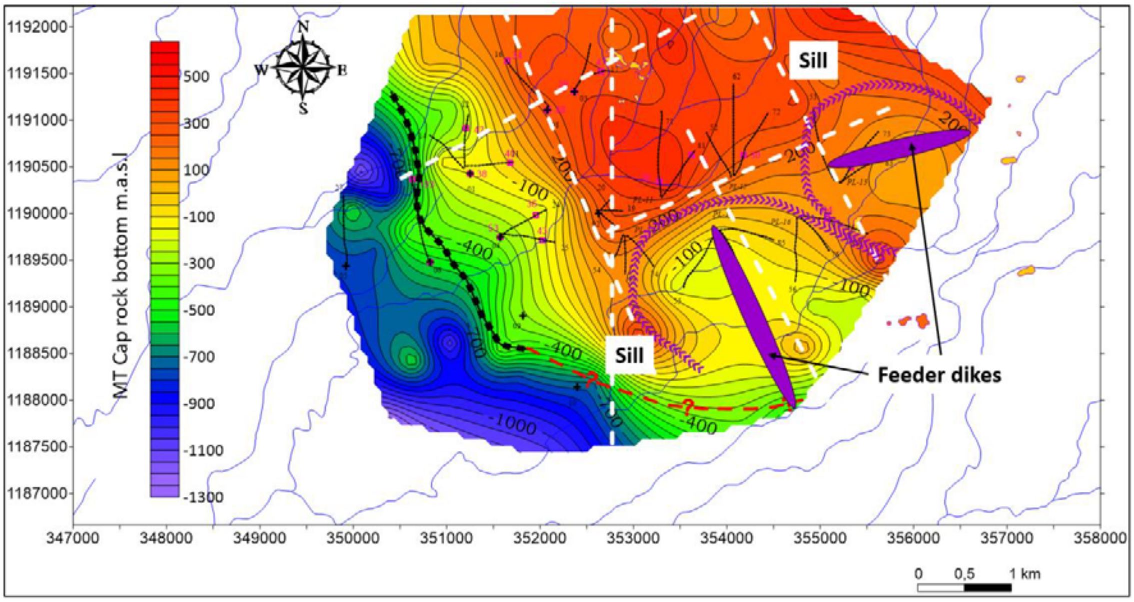

Figure 9. The image shows the contour of the MT BOC in m.a.s.l with two some round morphologies, indicated with the round-shaped chevron purple patterns. As interpreted through MT inversion, this pattern seems to be related to possible sills, which are roughly limited by peripheral faults (dashed white lines). These bodies seem to be directly connected to probable feeder dikes denoted by solid purple oval-shaped features.

5. Gravity and magnetic analysis

In 2013 six gravity and magnetometry profiles were conducted in Las Pailas Geothermal Field with stations deployed every 100 m. Interesting results arose from the analysis of the data gathered in these geophysical campaigns. According to Figure 10, gravity data shows a marked contrast between Las Pailas I Unit and the Pailas II Unit, exhibiting relatively denser values at Las Pailas II Unit and correlating well with the possible magmatic intrusions detected by the MT in those areas. According to these observations, the reservoir does not seem to be delimited by a low central gravity anomaly, but it is rather compartmentalized. In the case of Las Pailas II Unit, this could be hypothesized as the dooming area of the reservoir. Another interesting feature is that these presumably magmatic bodies are also relatively aligned to gravity anomalies - the same value is kept throughout their entire length. The latter shows a pattern of comparatively narrow structures well in accordance with many of the projected structures found in the MT analyses.

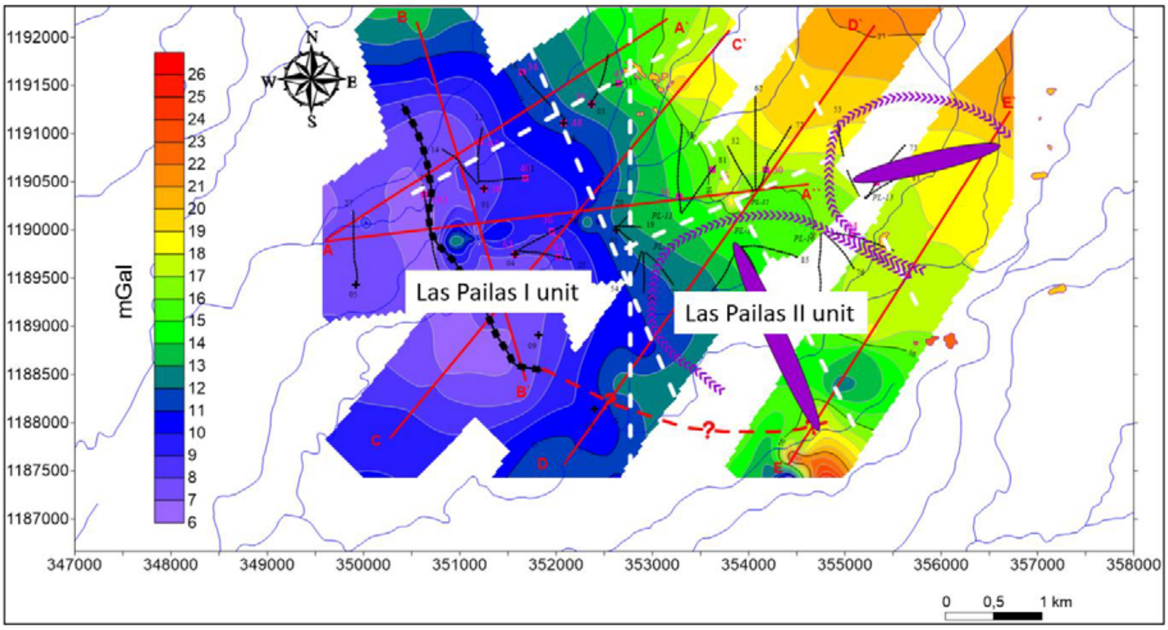

Figure 10. Complete Bouguer anomaly map of Las Pailas Geothermal Field. The map shows the six profiles (gravity and magnetometry from the survey conducted in 2013), which can be observed in red lines listed from A to E. A NNW-SSE oriented separation in the displayed gravity pattern is observed between the areas of Las Pailas I Unit and Las Pailas II Unit. Relatively denser materials seem to prevail in Las Pailas II Unit area. The location of the saucer shape anomalies of the MT BOC can be seen in a round-shaped chevron purple pattern and the suggested feeder dikes in solid purple oval-shaped features. Modified from Solís & Herrera [21].

Further important geophysical data has been obtained from magnetic survey data processing, using pole reduction and removal of the regional trend. The results showed that projected faults are essentially orientated with NNW-SSE and N-S strikes and are mostly linked to negative to low magnetic signals.

Tontini et al [23] explained the location of low-magnetization regions along the caldera walls at Palinuro by ring faults providing preferred pathways for the upflow of hydrothermal fluids. Using the same approach, negative to low magnetic signal with round-shaped patterns suggest major permeable structures such as ring faults in the study area.

Thus, low to negative magnetic values seem to be related to important hydraulic paths, whereas regions exhibiting high values of magnetic susceptibility reveal dike-shaped structures, most probably acting as hydraulic barriers (see Figure 11).

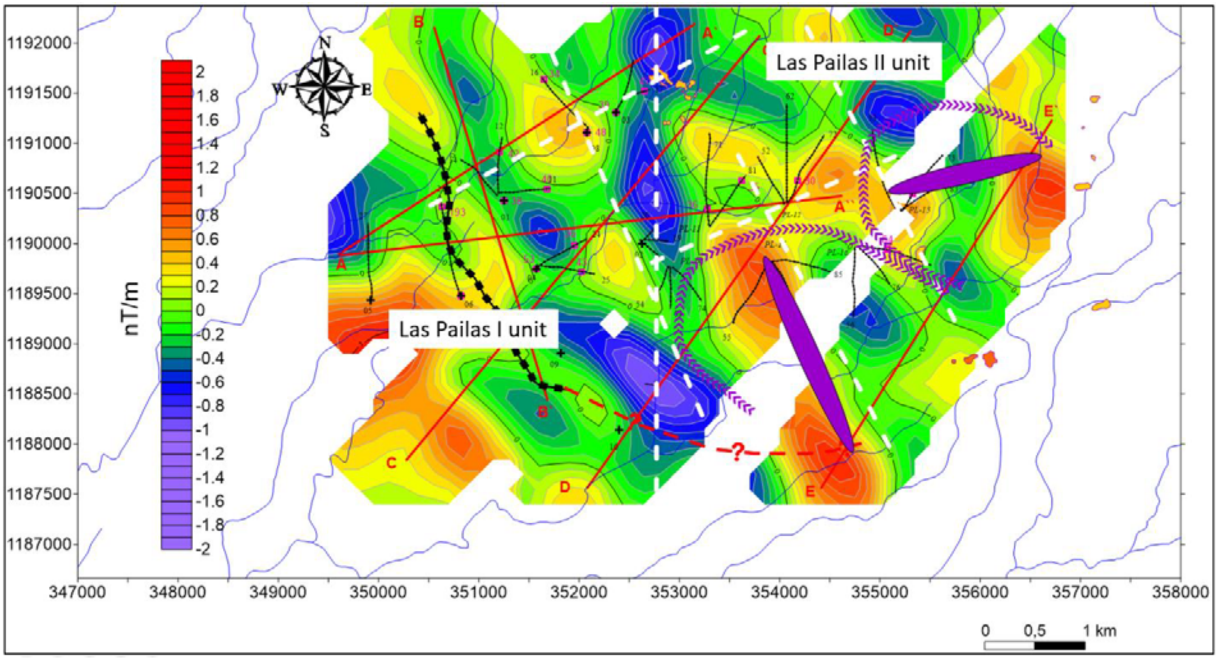

Figure 11. Reduce to pole (RTP) and directional trend removal magnetic anomaly map of Las Pailas Geothermal Field. Main tectonic and volcano-tectonic features and elements interpreted with the help of this method match remarkably well with the majority of the projected faults and the presence of ring faults with minimum magnetic values and the notorious presence of linear high magnetic values in the areas of the feeder dikes. Modified after Solís & Herrera [21].

6. Geochemical data analysis

According to Malimo [11], the soil-gas method used to infer the nature of subsurface geology/geochemistry is based on the concept that gases, which are released from active geothermal systems can freely rise through the overlying cover to be detected in the shallow subsurface. Volcanoes release gases not only from the central crater and through openings such as fumaroles, but also on their flanks by diffuse degassing of gaseous species such as carbon dioxide (CO2), helium (He) and radon (Rn). Whereas the high-temperature gases in craters tend to be highly acidic and reactive (e.g. SO2, HCl), some species like CO2 and Rn do not react with country rocks. The distributions, thermodynamic properties and quantities of these gases provide information on the overall permeability structure of a volcanic edifice, the potential for lateral degassing from areas other than the active crater and the ability of a volcano to diffusively release large quantities of CO2 and other gases. An estimation of radon in the soil-gas has been suggested as a tool for many investigations such as exploration of uranium, earthquake prediction, groundwater transport and assessment of geothermal resources [11].

Rodríguez et al [18] conducted a soil-radon gas campaign at Las Pailas Geothermal Field. The tendencies of the NNW-SSE and N-S projected faults through the integration of different geophysical methods presented in this work agree remarkably well with the ones proposed by those authors (Figure 12). These mentioned fault strikes are also confirmed by a reservoir tracer test performed by the Geochemistry group of the ICE in Costa Rica [20] and later by Torres and Fajardo (2013) (see Figure 13). NNW-SSE, N-S and

NE-SW strikes of interpreted faults are also highly supported by a recent geoscientific conceptual modelling analysis conducted by Chavarría et al [4].

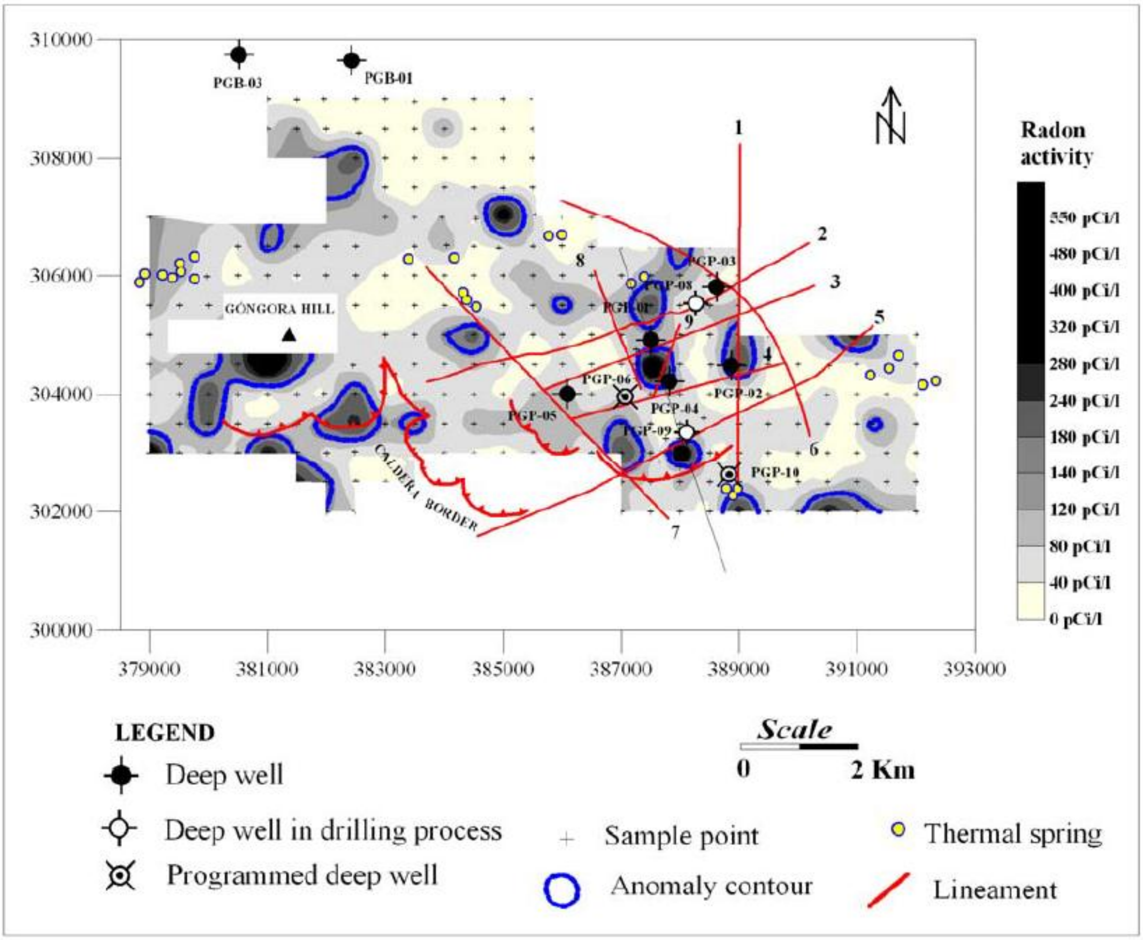

Figure 12. 222 Rn activities and main structural features after Rodríguez et al [18]. The image shows the ground radon gas levels measured in a regular grid and later interpolated at the area of Las Pailas Geothermal Field (West from Las Pailas I unit and part of Las Pailas II unit) and several structures such as faults in red lines and the border of the caldera in red line with triangles. Authors describe lineaments from the found concentrations in N-S trend near the PGP-02 that extents to the PGP-10 (e.g. lineament 1) and a group of anomalies aligned in a NNW-SSE trend, which are notoriously coincident with the ones proposed using the geophysical methods integrated in this work.

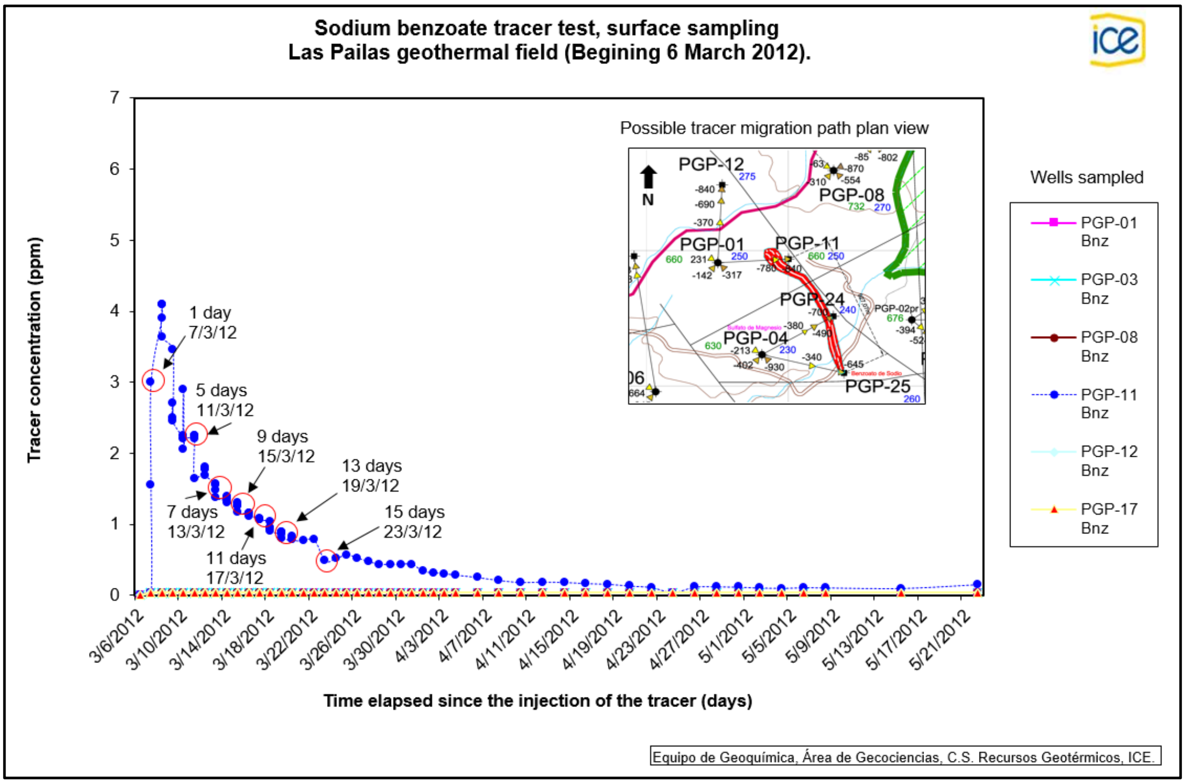

Figure 13. Chemical reservoir tracer test of Sodium Benzoate dilution conducted on Las Pailas Geothermal Field showing the relation between tracer concentration vs time in days. The thick red NNW-SSE line observed in the plane view image shows the migration path of the tracer injected in the PGP-25 hot reinjection well and sampled in the PGP-24 and PGP-11 wells in days. Picture stems from Solís [20]. The graphic of the concentration of tracer sampled in the wells with the typical delayed and abrupt tracer arrival suggests an early thermal breakthrough between the PGP-25 (reinjection well) and the PGP-11 (production well), and hence suggests a short circuit (early thermal breakthrough) in this NNW-SSE direction.

7. Wellbore static hydraulic data analysis – Reservoir compartmentalization

Complementing the previous analyses, an isobar map elaborated by the Reservoir Engineering Group of the ICE (Costa Rica) from pressures measured in the wells show a decrease in pressure from the East to the West, suggesting an apparent compartmentalization of the reservoir separated by NNW-SSE faults as proposed. This can be seen in Figure 14 and Figure 15.

This observation is supported by different international studies. Elfina [5] claimed for the Patuha Geothermal Field in Indonesia the control of the reservoir permeability by some faults, particularly the Cibuni, Putih, and Ciwidey Crater faults. Faults at the edge of the reservoir behave there as tight boundaries. Faults also appear to compartmentalize the main reservoir and explain the sizeable lateral pressure gradients from west to east of the study area. In the same sense, Quinoa et al [17] stated for the Rotokawa Geothermal Field in New Zealand a semi-permeable compartment behavior reflected by the difference in pressure drawdown between groups of wells.

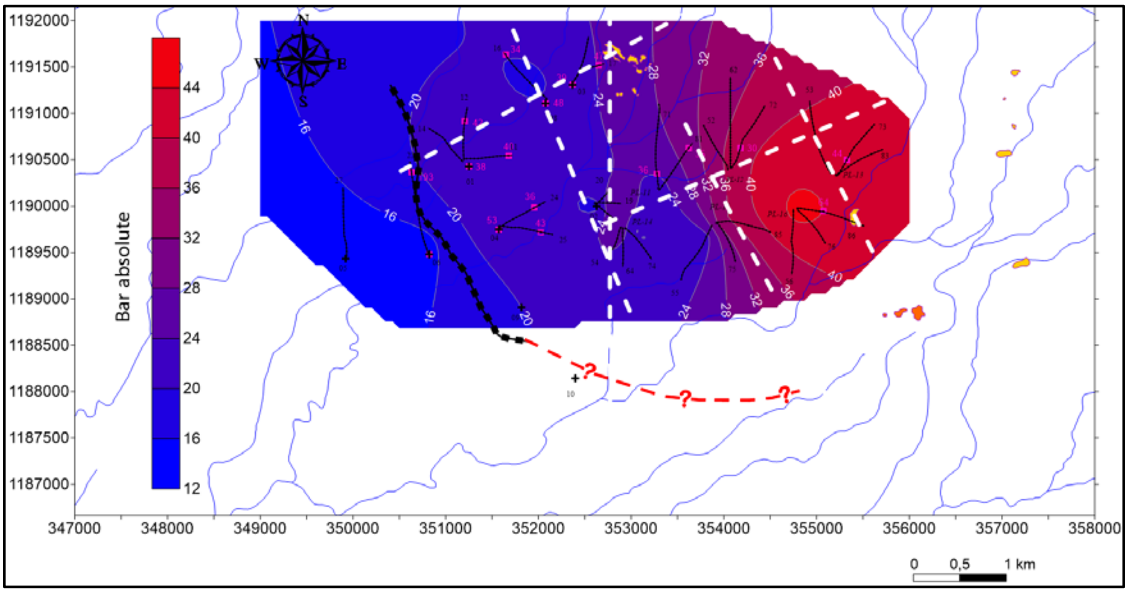

Figure 14. Wellbore static pressure measured in bar absolute at 0 m.a.s.l in Las Pailas Geothermal Field (after ICE Reservoir Engineering group, Costa Rica). Modified from Chavarría et al [4]. Image shows the higher pressure at Las Pailas II Unit area while the pressure tends to decrease towards Las Pailas I Unit. This suggests reservoir compartmentalization separated by structures with NNW-SSE strike, some other minor structures show a NE-SW trend.

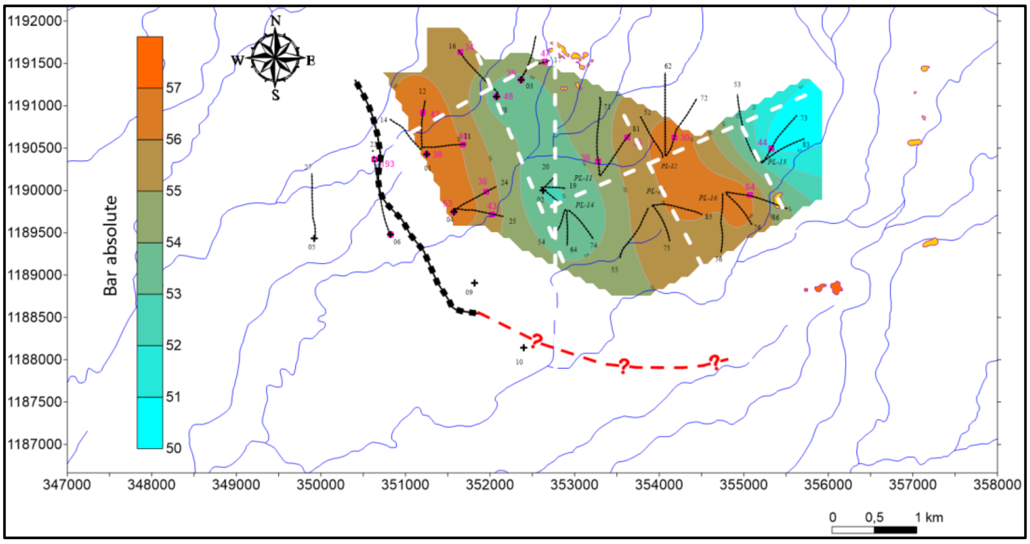

Figure 15. Wellbore static pressure measured in bar absolute at -400 m.a.s.l in Las Pailas Geothermal Field (after ICE Reservoir Engineering group, Costa Rica). Modified from Chavarría et al [4]. Similar to

the previous picture, pressure tendencies persist from one depth to the other suggesting major structural controls and possible reservoir compartments.

Figure 16 displays a 3D model showing the relation between the MT bottom of the cap rock (BOC) and the geothermometer clays found in the wells in Las Pailas geothermal field. The MT BOC contour layer can be observed in the illite/smectite transition zone near the bottom of the smectite layer. Figure 16 also contains a MT resistivity section cutting transversally the MT BOC contour layer, showing a brown layer from top to bottom. The latter represents the surface materials with diverse resistivities (most of the values above 10 Ωm). The subsequent underlying red layer shows the cap rock layer (1-10 Ωm); the probable borders of the reservoir are represented in greenish brown; the reservoir (40 Ωm average resistivity for Las Pailas I Unit and 100 Ωm for Las Pailas II Unit) is shown in light grey color. Besides, vertical narrow highly resistive bodies (feeder dikes) appear in dark grey, and possible faults in the vertical direction in light grey stripes. The model has the magnetic map reduced to pole with filtering of the horizontal trend at the bottom.

Notably, the MT BOC shows two well pronounced round-shaped patterns, which also coincide with high resistivity vertical bodies and the high magnetic anomalies. These observations have been interpreted as sills and their corresponding feeder dikes.

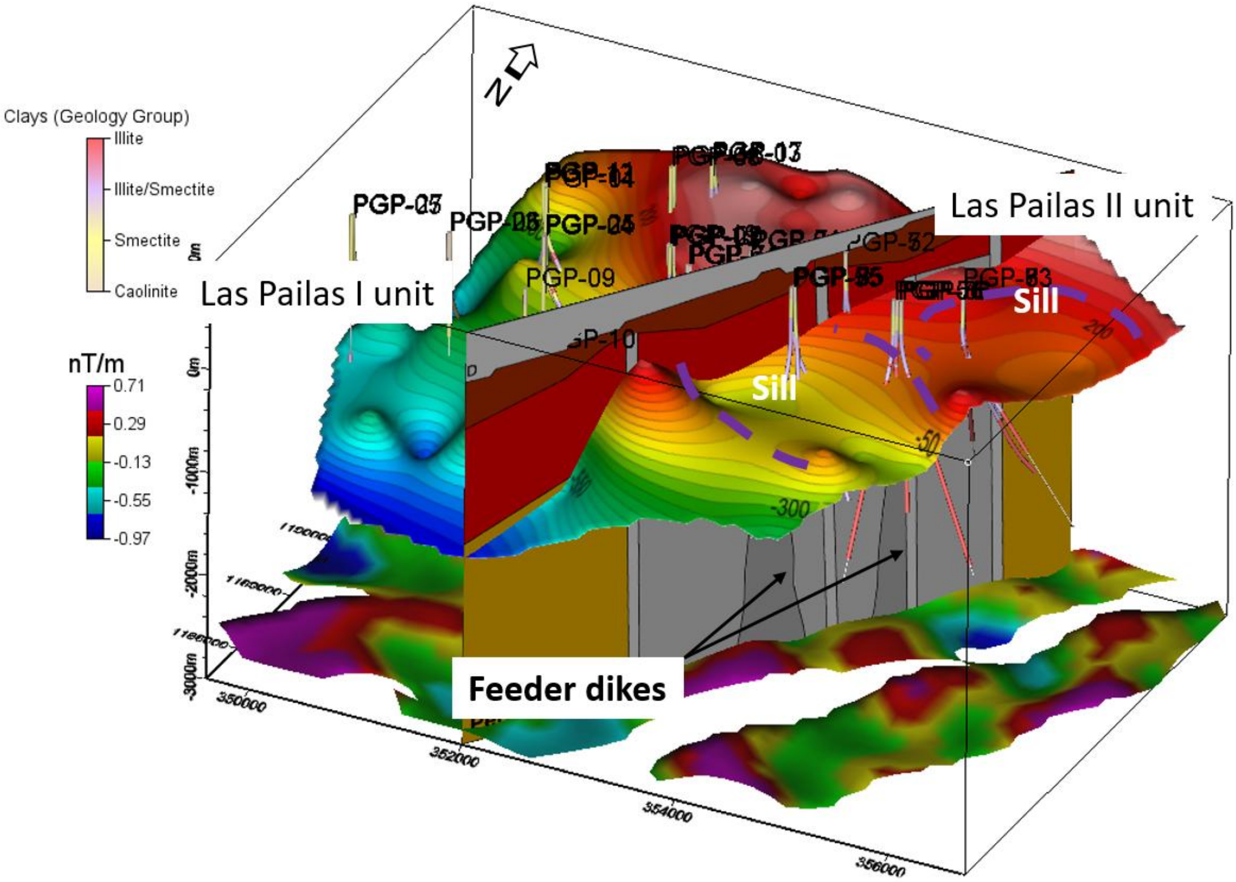

Figure 16. The image shows the geothermometer clays determined by the ICE Geological group (Costa Rica) based on well logs. The MT BOC contour layer of Las Pailas Geothermal Field shows two saucer shaped sills projection in purple dashed lines with their respective feeder dikes shown in the MT resistivity section. The resistivity section also shows the probable borders of the reservoir (greenish brown), the reservoir (grey) and some faults (in light grey vertical stripes). At the bottom of the 3D model the magnetic anomaly map with reduced to pole (RTP) and horizontal gradient filter can be observed.

8. Evidence from plumbing systems of classic volcanic edifices to support the hypotheses

The formation of shallow-level intrusions implies a previous transport of magma from deeper sources that are located either in the mantle or in the middle or deep crust [24]. When magma solidifies in such a tabular pathway a dyke forms. In vertical dykes, magma flow is commonly assumed as vertical, from the deep magma source towards the emplacement level. However, within such pathways, magma can flow in either vertical, oblique or horizontal directions (e.g. Marsh (2010)).

As a consequence of the mechanical interplay between growing sills and the doming of the overburden at shallow depths, saucer shapes are the result of growing sills. This specific saucer-shaped sill, as seen in Figure 17, fits the observed shape of the MT bottom of the cap rock contour.

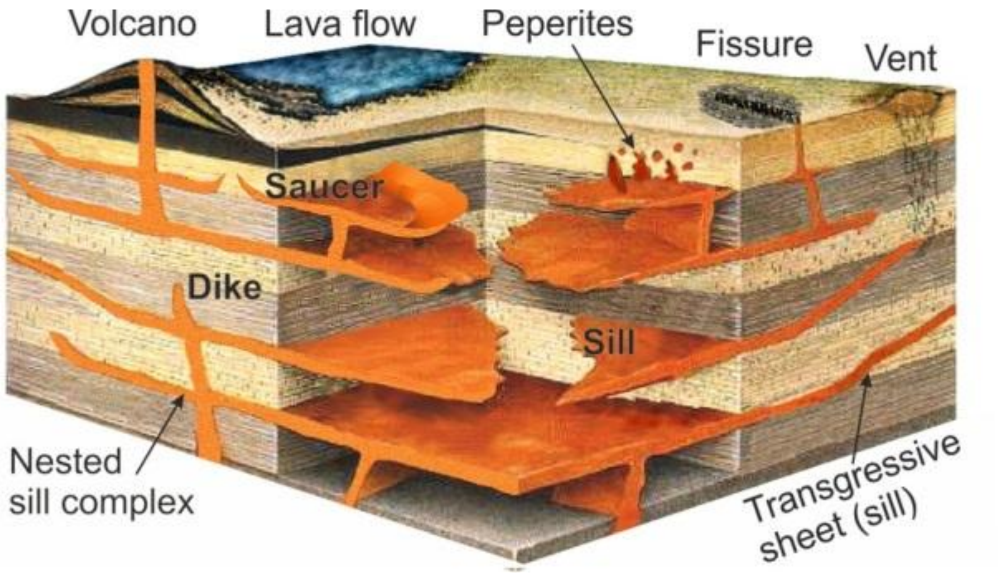

Figure 17. Cartoon showing the main igneous elements in a volcanic basin [16].

According to the model proposed by Carey [1] and shown in Figure 18, since the saucer-shaped structures found in Las Pailas sills have a central high resistivity vertical anomaly and also a high magnetic response, they could be expected to be symmetric with respect to the feeder dikes. Following the principle conceptual model developed by Iyer et al [10], an alteration aureole is formed in the surroundings of a sill intrusion as shown in Figure 19. This alteration aureole generates deposits in the surroundings of the sill showing low resistivity, as is the case of pyrite as indicated by Spacapan et al [19].

In this case it is inferred that the sill modifies the signal of the cap rock in the illite/smectite transition zone, deepening closer to the illite zone rather than the usual close vicinity to the smectite zone.

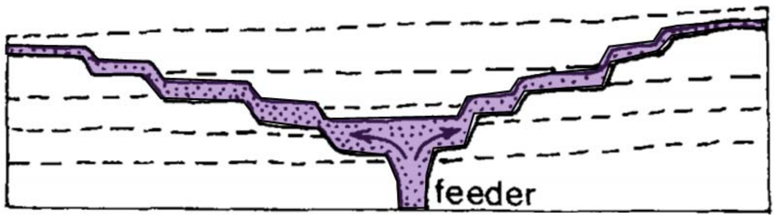

Figure 18. Symmetric sill emplacement by a central feeder dike. Picture stems from Carey [1].

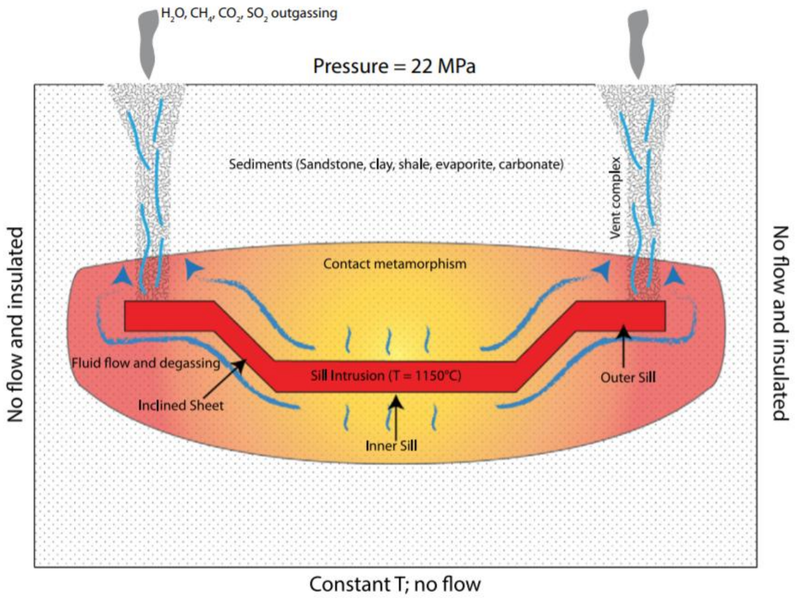

Figure 19. Conceptual sketch of a model domain with boundary conditions. The sketch shows a sill intrusion emplaced instantaneously within a sedimentary basin. Heating of surrounding sediments results in contact metamorphism. Dehydration reaction and organic cracking within the contact aureole releases water and methane which may ultimately reach to the surface through hydrothermal vents. The picture stems from Iyer et al [10].

In accordance with the hypothesis of an intrusion, after several wells were drilled in the southern part of Las Pailas II, Gálvez & Ramírez [6] described for instance in the PGP-85 well final report a chlorite-smectite zone with a very similar pattern to the one revealed by the MT BOC (Figure 20). This suggests possible contact metamorphism evidence. In the same year, Mora & Acuña [14] described in the PGP-56 final report the occurrence of sills and dykes intrusions for the same areas and at the same elevations as interpreted in the MT bottom of the cap rock (Figure 21).

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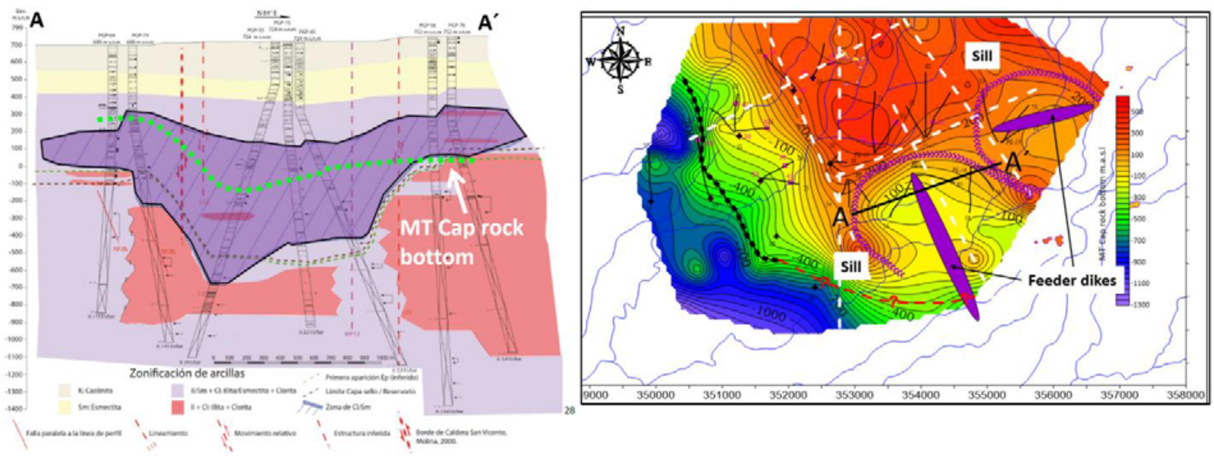

Figure 20. Left picture: Clay zones correlation profile and permeable zones in profile A-A'. A clear chlorite-smectite zone depicted in purple is visible in the profile. The green dot line reveals the contact of the MT BOC according to the section. Right picture: Location of the profile can be seen in the right image. Modified after Gálvez & Ramírez [6].

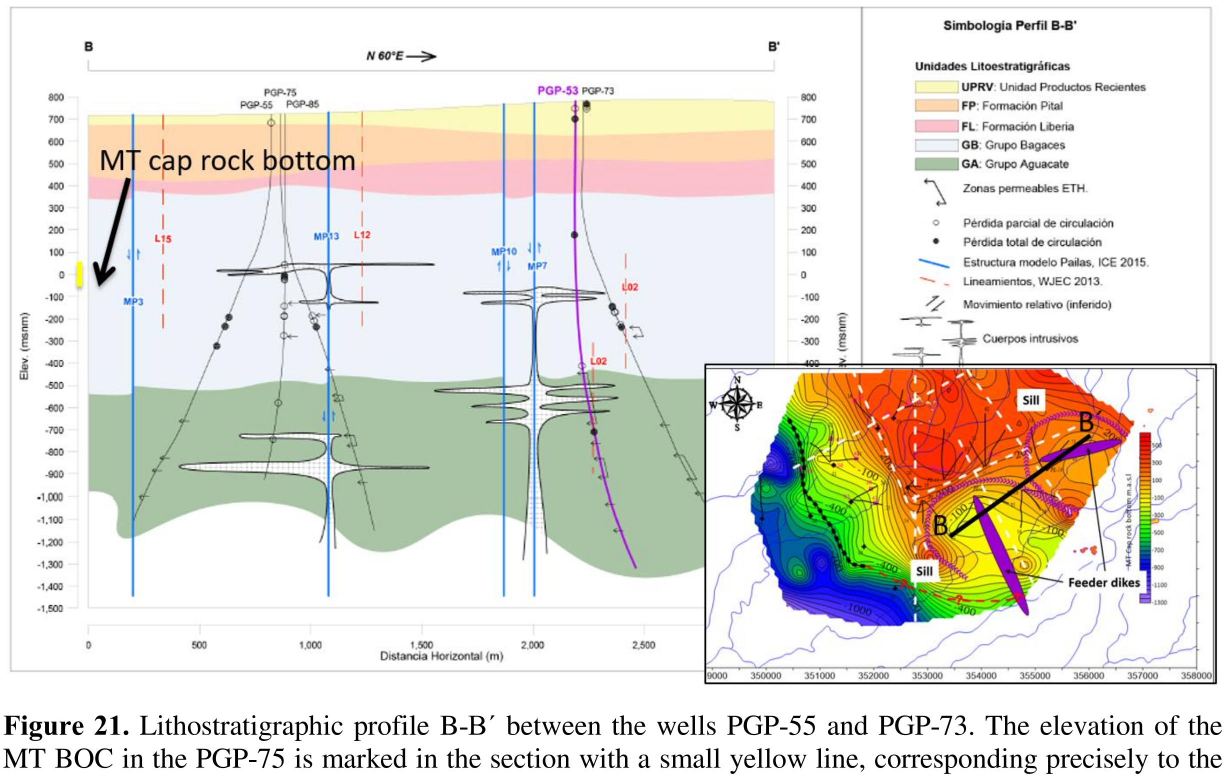

Figure 21. Lithostratigraphic profile B-B′ between the wells PGP-55 and PGP-73. The elevation of the MT BOC in the PGP-75 is marked in the section with a small yellow line, corresponding precisely to the

described sill by the ICE Geology Group (Costa Rica). For the description of the right lower picture see Figure 9. Modified after Mora & Acuña [14].

The ICE Geochemical Group [4] describes the presence of a light acidic aquifer in the wells PGP-83 and PGP-86, southeast of Las Pailas Geothermal Field at the PL-13 and PL-16 well platforms respectively where the feeder dikes appear, and both sills share boundaries. This leads to the assumption of a possibly intruded domain. González et al [7] also indicate for the same PL-13 and PL-15 well platforms that they tend to show low permeability but exhibit high temperatures (with a maximum measured temperature of 266 °C) mainly at the PL-13, where the second and shallower saucer shape is located.

9. Final remarks

Geophysical, geological and geochemical data gathered during Las Pailas Geothermal Field development in Costa Rica shows that the main challenge of geothermal exploration at the different stages of a geothermal project constitutes the identification of locations where geothermal resources can be put into sustainable production at reduced cost and risk. Geothermal exploration is based in turn on the derivation and a profound understanding of the geological controls on subsurface heat accumulation and transport. Developing a suitable and efficient exploration program for the site-specific volcanic geothermal play type in Central America involves the reduction of uncertainties in the location, volume, compartmentalization, fluid chemistry and dynamics as well as productivity characteristics of the geothermal reservoir. Optimized geothermal exploration programs for Central America should include the inference of the site-specific geological factors that control enthalpy, transmissivity and rock-fluid interaction and distribution in the reservoir by the integration of play type specific geophysical and geochemical methods.

In particular, sustainable exploitation strategies of high-enthalpy geothermal reservoirs in a volcanic geothermal play type require an accurate understanding of the key geological structures present such as faults, cap rock and caldera boundaries. As demonstrated for the example of Las Pailas high-enthalpy geothermal field in Costa Rica, this can only be achieved by a concerted and sustained effort of integrating all geoscientific working groups and investigation results. During the entire development of Las Pailas Geothermal Field, as new geoscientific data has become available, the reservoir architecture and thermodynamic conditions have been better understood along the exploration. Knowledge gained through the combination of static and dynamic data (e.g. production data) has been crucially important for the drilling phases of new wells throughout the whole life cycle of the geothermal field. In any case, for the detailed characterization of the inner structure of the reservoir, exchange on multiple investigation levels is essential and needs to be enforced to optimize the approaches on processing and interpretation.

Especially concerning geophysical soundings, ICE was able to develop geothermal exploration programs using a cost-effective and adequate suit of tools. Aiming to the mitigation of uncertainties and risks, diverse geophysical campaigns in Las Pailas Geothermal Field were conducted throughout the last decades, which made the identification of presumable magmatic body intrusions and their morphology possible by the integration of important geoscientific information. In particular, the successful application of a number of most appropriate geological, geophysical and geochemical techniques led to the assessment of temperature, depth, shape, geochemistry, productivity and sustainability of the geothermal reservoir. Possible local volcano-tectonic structures such as ring faults, radial faults as well as regional tectonic faults could be inferred by the combination of valuable geophysical data. The integration of hydrotectonic concepts as an important geothermal exploration method has been recognized by the authors of the present work to advance the knowledge and understanding of the reservoir compartmentalization and fluid dynamics. Fault network and orientation with respect to the present-day stress field may contribute to the identification of important hydraulic barriers or conduits in the reservoir. This, in turn, is critically important for the development of optimized and sustainable reservoir exploitation strategies.

In addition, the combination of experienced geological interpretation, volcano-tectonic concepts as well as magnetotelluric, gravity and magnetic analyses resulted in the inference of sills linked to central feeder dikes at Las Pailas Geothermal Field. This is critically important since the identification of the sills distribution, shape and depth in reservoir provides insightful information on the role they play as possible local heat sources and hydraulic barriers between reservoir compartments. Moreover, the dike-fluid interaction shows far-reaching effects on the geochemical composition distribution of fluids in the reservoir, exhibiting more acidic fluids in certain domains of the reservoir and more neutral fluids elsewhere in the reservoir. The relevance of the proper identification of dikes and sills in Las Pailas Geothermal Field is additionally strengthened by the effect of dikes and sills on the local thermodynamics of fluids in the reservoir. Measurements carried out at different wells reveal extremely high temperature but low permeability. Another striking feature of intrusion bodies relates to their age. They might also work as local heat sources and can be hydraulically stimulated for production/reinjection purposes.

Hence, obtaining detailed knowledge and a more complete understanding of the geothermal system at the early stages of exploration through integrated geoscientific exploration methods and in conjunction with other geoscientific analysis is essential to develop reliable conceptual models. Furthermore, this latter aspect is crucial at the different stages of reservoir development for the reduction of sustainability risks, for the selection of promising geothermal drilling targets, for optimized production/re-injection schemes and for the development of adequate and sustainable exploitation programs (reservoir management). However, although the geological interpretation of integrated geophysical data is a strong tool for the reduction of different risks, geophysical data remains the subject of interpretation (soft data). Hard data acquired by test drilling phases should calibrate and validate previously gained conceptual models and improve knowledge on the overall structure of the reservoir. Additional geophysical and geological borehole methods have to be integrated at Las Pailas Geothermal Field to substantiate the conceptual model, optimize reservoir exploitation strategies and minimize risks.

Profound and detailed analysis through the integration of 2D and 3D geophysical data as well as additional borehole data are planned for a more complete geothermal reservoir characterization. For these and other optimization works, an international and interdisciplinary cooperation is essential. Currently, the Instituto Costarricense de Electricidad (ICE), the Leibniz Institute for Applied Geophysics (LIAG) and others, supported by the Federal Institute for Geosciences and Natural Resources (BGR) in the framework of the German Cooperation, focus on the integrated application of geoscientific methods for enhanced geothermal exploration. The results of these efforts should provide insightful information related to the transferability of the site-specific most appropriate integrated exploration strategies to other similar volcanic geothermal play types in Central America.

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