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Identification of Magmatic Intrusions Through Integrated Geophysical Methods. A Contribution for a Sustainable Geothermal Energy Development: Borinquen Geothermal Project - Central America Case Study

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ABSTRACT

This work focuses on the most appropriate geothermal exploration and development strategies of the Borinquen Geothermal Project in Costa Rica. High-enthalpy geothermal reservoirs in a volcanic geothermal play type require an accurate comprehension of the key site-specific geological structures such as faults related to volcano-tectonic activity, cap rock and caldera boundaries, to develop accurate and sustainable exploitation strategies. The identification of possible magmatic body intrusions and their two-dimensional or three-dimensional morphology is equally important. The relative importance of those magmatic bodies relates to their age, shape and location within the geothermal system. Particularly, their considerable relevance relies 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 (fluid-rock interaction). Obtaining comprehensive knowledge and a more complete understanding at the initial stages of geothermal exploration through integrated geophysical and geological methods is crucial to determine promising geothermal drilling targets, construct sustainable production/re-injection schemes and for the development of adequate exploitation programs. Reliable, extensive geophysical data collected at the Borinquen high-enthalpy geothermal project at northwestern Costa Rica together with an adequate knowledge of the geological structures in the underground may represent a sound basis for an in-depth geoscientific discussion on this topic. Current international and interdisciplinary joint efforts taken by the Instituto Costarricense de Electricidad (ICE) in Costa Rica, the Leibniz Institute for Applied Geophysics (LIAG) and the Federal Institute for Geosciences and Natural Resources (BGR) in Germany focus on the application of joint geophysical and geological methods to assess the most appropriate geothermal exploration concepts for this complex volcanic field setting. This team-based and joint endeavor is made within the framework of the German Cooperation Program for enhanced geothermal exploration in Central America.

1. INTRODUCTION

It has long been known that countries situated in the Pacific Ring of Fire host vast high-enthalpy geothermal resources. Apart from several exceptions located close to or in the middle of the interior of tectonic plates (hotspots), major high-enthalpy geothermal systems are found along or near plate boundaries, where geologic unrest prevails (Wohletz & Heiken, 1992). In the 1970´s Costa Rica was one of the Central American countries selected by the United Nations Organization to send a scientific delegation in order 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 being one of those clean, renewable and high-quality baseload energy resources, this was an attempt to tackle the high prices of fuels which critically influenced the energy production. At that time the northern part of Costa Rica, the Guanacaste province, was chosen as the principal area for geothermal exploration, research and development. Three prospects were analyzed, and the Miravalles geothermal field classified as the most promising to develop. Extensive geological, geophysical and geochemical exploration surveys were carried out over decades in the Guanacaste province. Geological and hydrogeological studies combined with geophysical and geochemical interpretation greatly contributed to the identification of the location and extension of the geothermal resources in the area under investigation. As a result of this remarkable endeavor, in 1994 the first geothermal field started production in Costa Rica known as the Dr. Alfredo Mainieri Protti (formerly Miravalles) and 25 years later it is still producing 164 MW. Later, in 2011, the second geothermal field known as Las Pailas geothermal field started production with a 42 MW binary power plant. Likewise, in July 2019, the second production unit went into operation with 55 MW in the latter geothermal field. Currently, joint efforts are focused on optimized geological, geophysical and geochemical exploration methods within the framework of the Borinquen geothermal project so that in 2026 Borinquen will become the third geothermal field with a 55 MW flash type plant. These recent efforts are intended to increase geothermal production up to 315 MW with clean and stable energy for the country. Geothermally developed areas in volcanic play types in Costa Rica can be seen in Figure 1. Understanding and properly characterizing the geologic controls on geothermal systems requires the integration of multiple geophysical, geological and geochemical analyses at different scales (Harvey et al., 2016). In particular, the geologic controls on the permeability structure as well as fluid and heat transport in such a volcanic play type are discussed in this work. Regional plate tectonic as well as local volcano-tectonic considerations and related structural geology are taken into account to constrain combined geophysical interpretation and geochemical analyses. Particularly, the inference and characterization of key geological elements of igneous plumbing systems such as sills and dikes are focused on in this work through integrated geophysical analysis. Moreover, caldera-related volcano-tectonic features such as ring and radial faults is especially looked at in the study. The specific properties, structure and behavior of individual geothermal systems strongly depend on site-specific geologic elements and conditions such as origin, depth and distribution of the heat source, porosity and permeability structure of the reservoir (reservoir volume and compartmentalization). In addition, fluid and heat transport mechanisms as well as fluid-rock interaction and resulting geochemistry of fluids are in turn controlled by geological factors and reigning thermodynamic conditions (Moeck, 2014).

Therefore, the present work concentrates on high-enthalpy reservoir characterization in the Borinquen geothermal project, which is currently being explored in the Guanacaste province, Costa Rica.

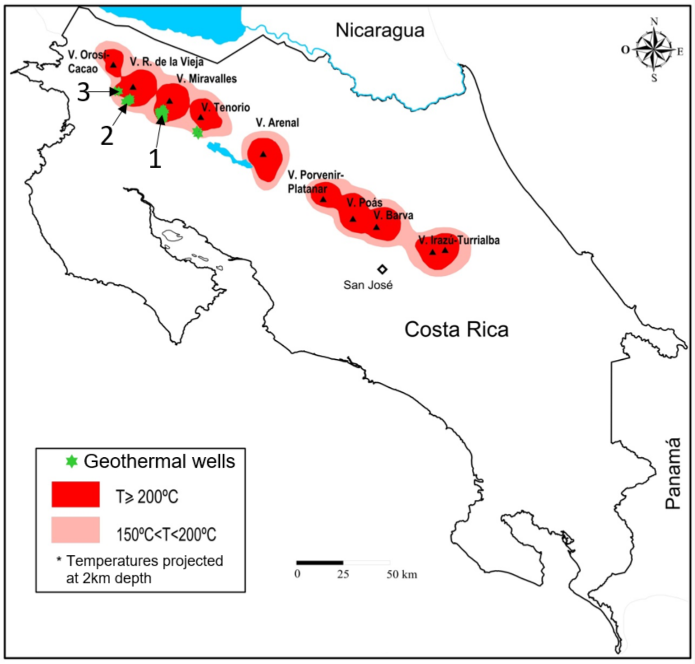

Figure 1: Location of developed geothermal areas in Costa Rica with deep wells (1500-2300 m). 1- Dr. Alfredo Mainieri Protti Geothermal Field (formerly known as Miravalles), 2- Las Pailas Geothermal Field (Production Units I and II), and 3- Borinquen Geothermal Project. Marked areas of anomalously high temperatures are 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).

2. BORINQUEN GEOTHERMAL PROJECT CASE

The Borinquen Geothermal Project has been developed since 2004 at the western flank of the Rincón de la Vieja Volcano in northern Costa Rica (see Figure 2). In order to successfully drill deep wells, several geoscientific campaigns had been conducted previously in the area. From 1999 to 2019 at least 97 magnetotelluric surveys with TDEM soundings for static correction were carried out. In addition, at least 450 gravity and magnetic stations were deployed along 9 profiles by the Costa Rican Institute of Electricity (ICE) geophysical staff in the area under investigation. Although comprehensive geoscientific data has been collected, the Borinquen Geothermal Project can still be considered to be in early stages of development.

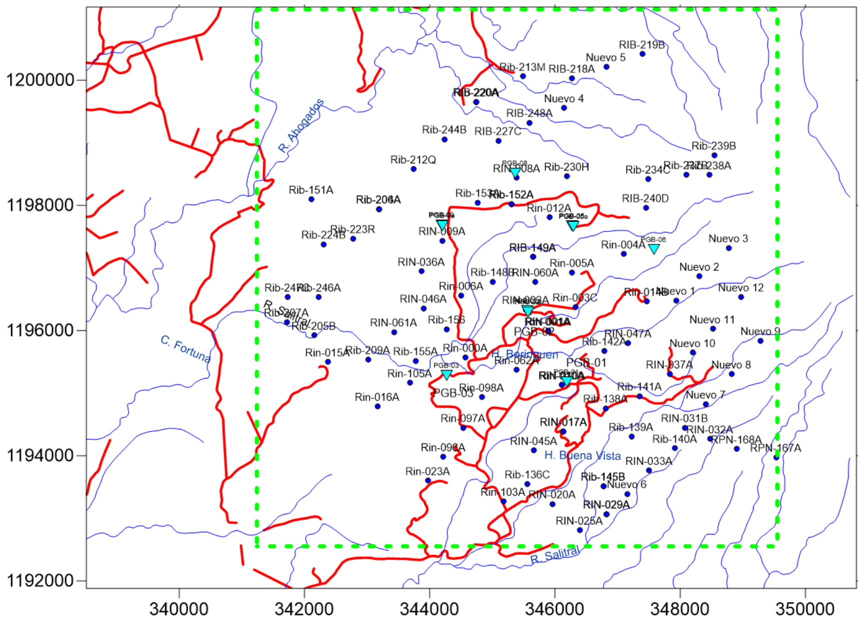

Figure 2: Location map of the Borinquen Geothermal Field and distribution of the MT+TDEM stations (blue dots). Cyan triangles display already drilled deep geothermal wells, and roads are depicted in red lines. Coordinates are in CRTM05.

Based on Moeck (2014) geothermal resources classification, key geological factors that led to the accumulation of geothermal resources in this geothermal field are associated to a volcanic play type. The geothermal system comprises a convective, high-enthalpy, liquid-dominated reservoir, mainly characterized by sodium-chloride fluids with a maximum measured temperature of 273°C at a depth of 2000 m. This geothermal project is still in progress but accounts already for 7 deep drilled wells, 5 designated to the production unit 1, as mentioned before. By the year 2026, it is expected that the Borinquen Geothermal Project will be fully developed and delivering another 55 MW of clean energy to the country.

2.1 Geological setting

According to Kempter (1997), the Cañas Dulces caldera is located in the foothills of the Rincón de la Vieja stratovolcano, with an assigned diameter of at least 8 km and a border running around the Cañas Dulces domes. The Guachipelín caldera was assumed to be the result of the Liberia ignimbrite eruption and to have erased much of the Cañas Dulces caldera, generating in that process a new caldera ~20 km wide in diameter. Finally, the Guayabo caldera is located ~20 km southeast of the Rincón de la Vieja stratovolcano (Molina et al., 2014). A geologic map of the area can be seen in Figure 3.

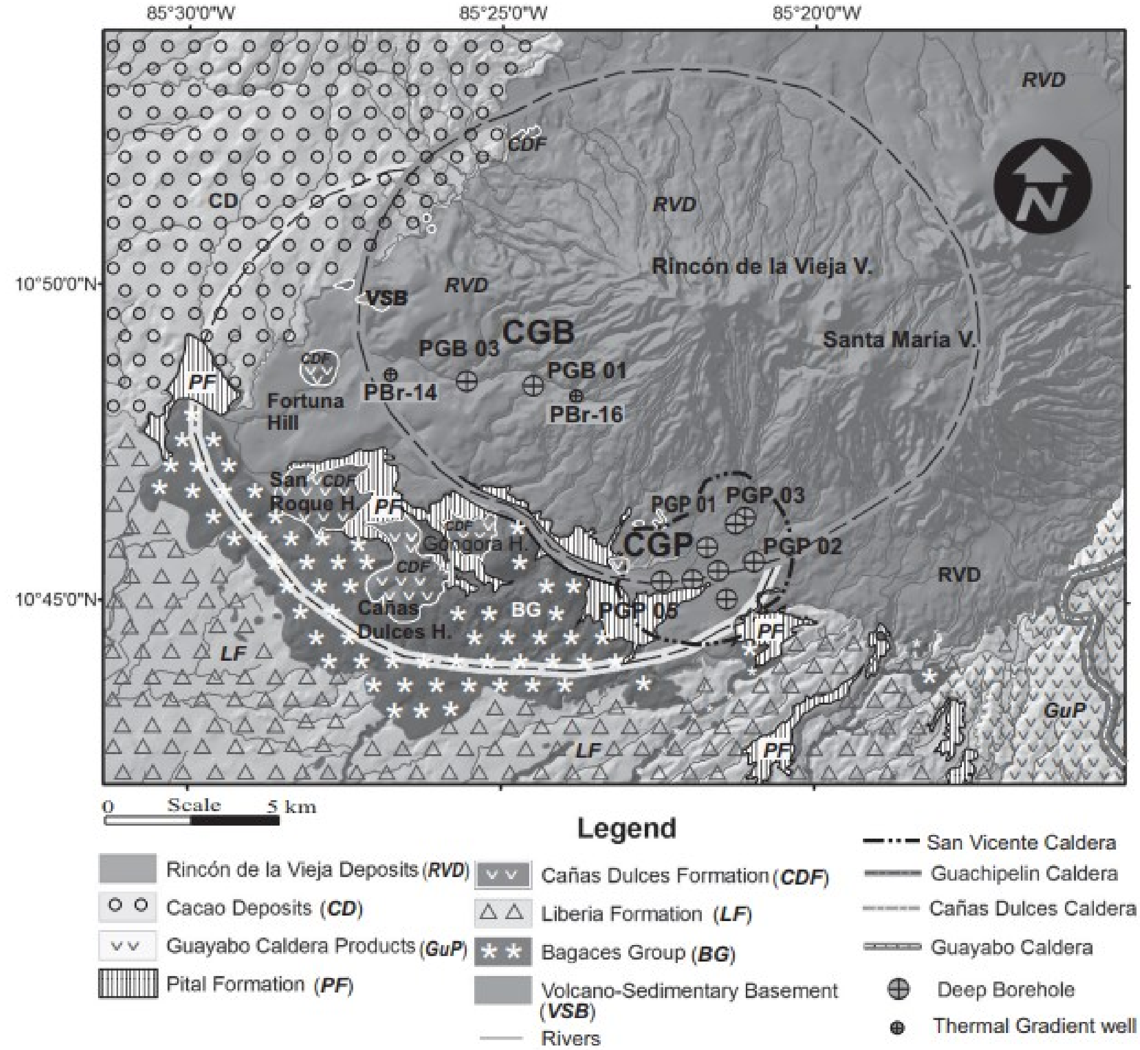

Figure 3: Geologic map of the Borinquen geothermal field after Molina et al. (2014). Drilled geothermal wells in the Borinquen geothermal field can be identified in the picture as PGB. Coordinates are in WGS84.

The Borinquen geothermal field is primarily a byproduct of the formation of the collapse caldera of Cañas Dulces, a volcanic depression formed 1.43 Ma ago with an estimated volume of 183 km^3. Molina et al. (2014) associated this collapse to a massive eruption favored and controlled by the presence of pre-existing faults. The collapse of the caldera, situated in the northwestern part of the internal magmatic arc of Costa Rica, led to a release of rhyolitic-dacitic materials, which partially covered the volcanic topographic depression. This major volcano-tectonic episode and subsequent processes triggered the emplacement of new magmatic systems, propelling the growth of the Rincón de la Vieja-Santa María volcanoes. The latter, in conjunction with the structural settings, created particularly suitable conditions for a high productive geothermal system within the limits of the caldera system.

2.2 Magnetotelluric data analysis

As mentioned previously, ample MT soundings were carried out in Borinquen, Costa Rica between 1999 and 2014 with a total of 97 surveys. In the year 2014, a TDEM campaign was conducted to correct the static shift effect. In this geothermal project, the top as well as the bottom of the cap rock (BOC) were analyzed based on MT data, obtaining interesting results that can be primarily linked to volcano-tectonic structures. These results are strikingly consistent with the findings reported by Troll et al. (2002) in relation to the Tejeda caldera at the Gran Canary Island (Canary Islands). Author's analogue models are intended to reproduce a sequence of events between chamber inflation and deflation and their surface morphological expressions through the formation of ring and radial faults. In the geological interpretation of the Borinquen geophysical data, some assumed prominent volcano-tectonic structures were identified. Previously, some of the structures were derived using a drainage pattern qualitative analysis. An inferred boundary of the reservoir is identified according to a circular deformation of the cap rock since the cap rock is developed following the distribution of the main heat storage in the reservoir. This can be seen in Figure 4 and Figure 5.

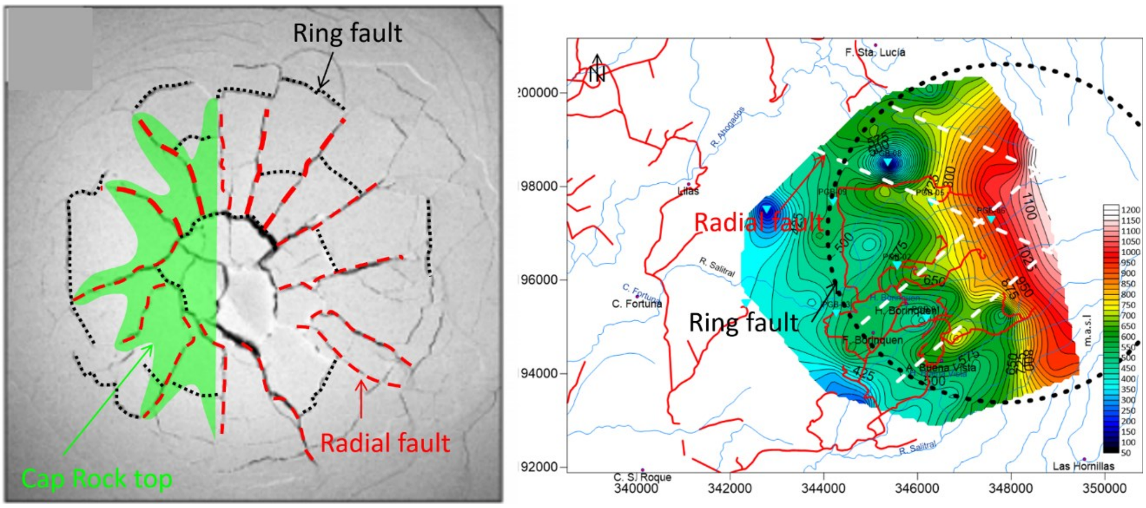

Figure 4: Left: Laboratory analogue simulation of a caldera collapse and its surface morphology at an inflation stage. Red dashed lines show radial fractures and black dashed lines represent ring faults. The analogue model includes the presumable morphology of the MT top of the cap rock (depicted in green). Modified from Troll et al. (2002) - without scale. Right: The Top of the cap rock (in m.a.s.l) shows similarities to volcano-tectonic structures of the analogue simulation at inflation stage. Radial fractures are marked with white dashed lines and ring faults are depicted with a black dashed line, local roads in red line, and already drilled wells are represented as cyan triangles. Modified from Solís et al. (2015).

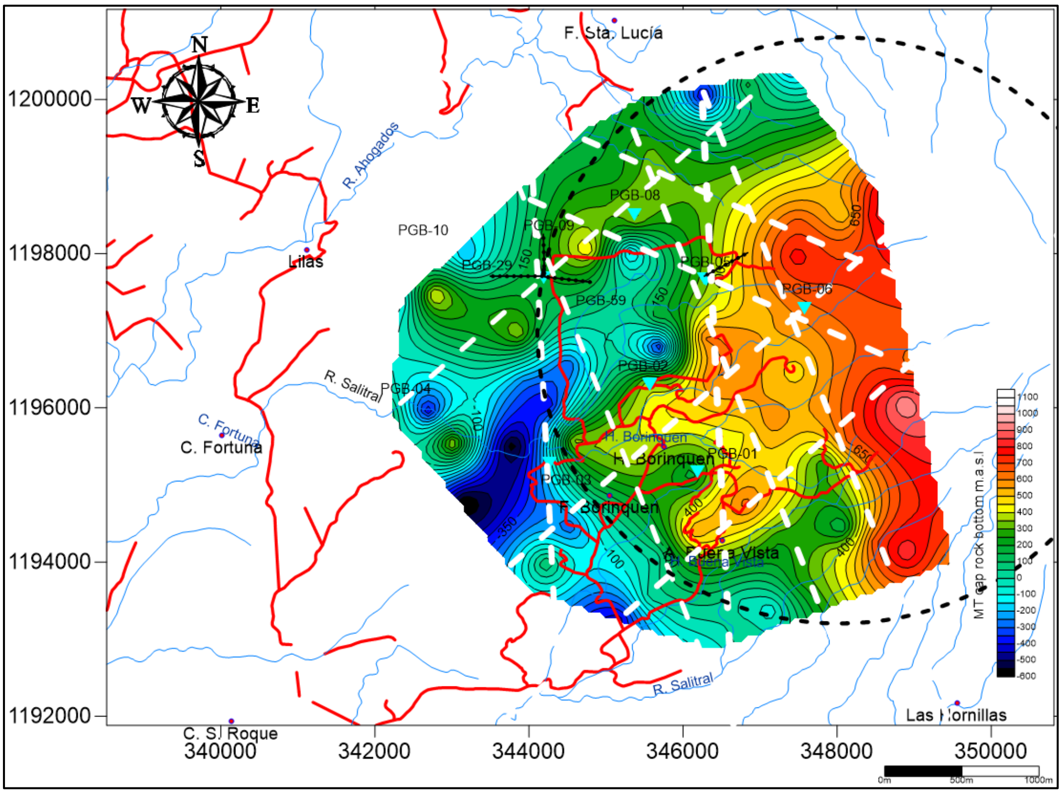

Figure 5: MT BOC contour map in m.a.s.l, corrected with TDEM. Black dashed circular line shows the possible boundary of the reservoir. Some presumably volcano-tectonic structures (faults) are depicted with white dashed lines. Cyan triangles represent geothermal wells (PGB). The picture has been modified from Solís et al. (2015).

Boundaries of the Borinquen geothermal system are still being refined with more precision as new data and information acquired in new geothermal wells become available, but they agree reasonably well with low permeability zones registered in some peripheral wells already drilled. Both MT top and bottom of the cap rock (BOC) show several alignments that correlate remarkably well with important volcano-tectonic structures that might act as high permeable paths for fluid migration. Especially where regional tectonic faults intersect local volcano-tectonic faults, high permeability structures are expected. NNW-SSE strikes are considered possible boundaries between what is considered as compartments of the reservoir. Figure 6 shows the correlation between the corrected MT bottom of the cap rock (BOC) and the alteration clay minerals. Analysis of the MT data corrected with additional TDEM soundings revealed some individual, narrow, vertical, high-resistivity bodies (≥180 ohm-m), located beneath the MT bottom of the cap rock (BOC) and emplaced between a lower resistivity surrounding context, as displayed in Figure 7 and Figure 8: Left: Magnetotelluric W-E (profile A-B) profile between PLB-09 and PLB-05 pads, showing the different resistivity contexts associated with the geothermal reservoir. Note the narrow vertical resistive body identified near the PGB-05 well (eastern part of the Borinquen geothermal field, MT stations are displayed in blue triangles). Right: same profile illustrating alteration clays developed by the ICE Geology group. Modified from Hackanson et al. (2019). MT BOC map shows the position of the profile in the geothermal field (top picture)..

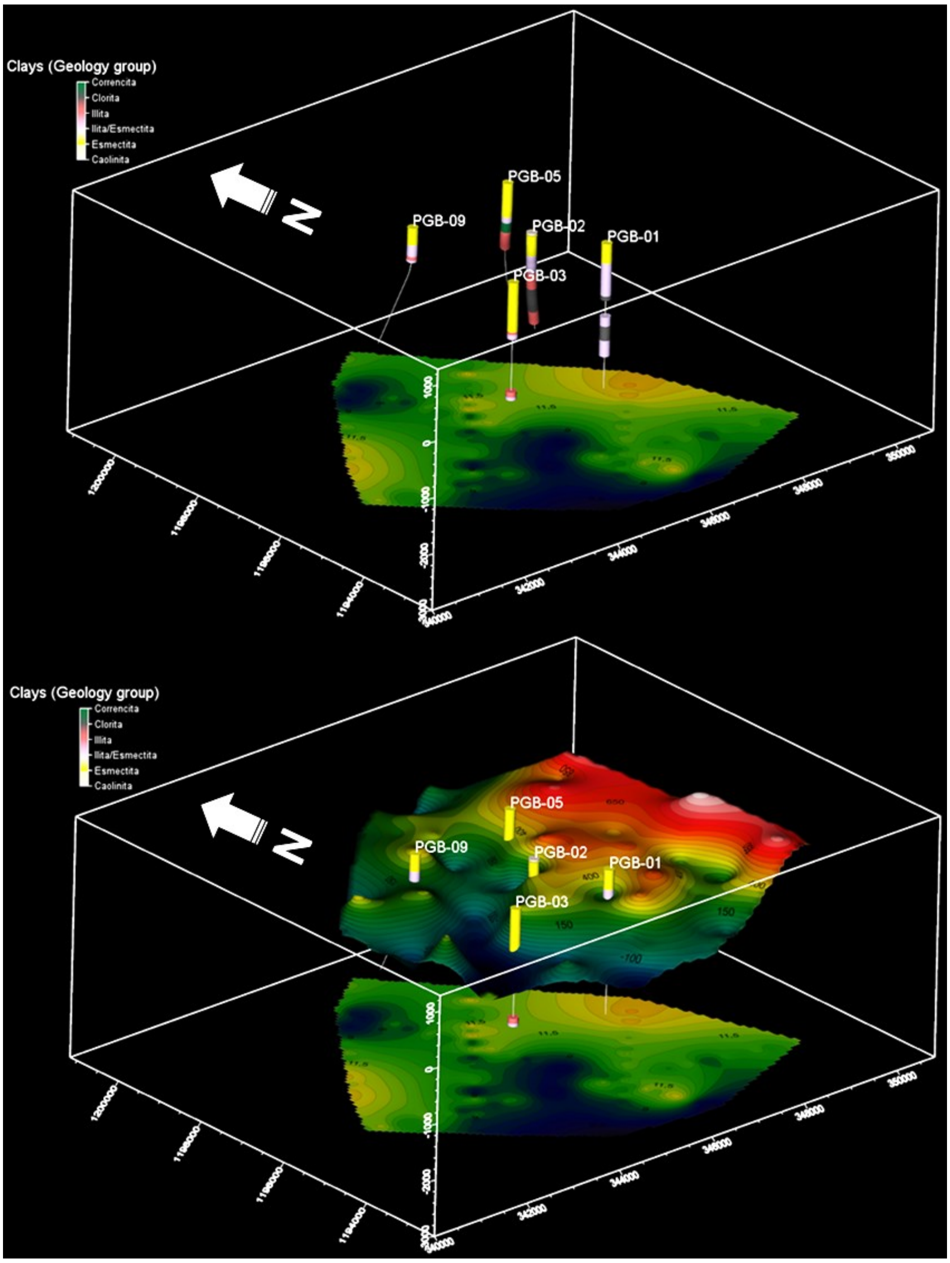

Figure 6: Upper image: The picture depicts the alteration clay sequence defined for the drilled wells by the ICE Geology group (white: caolinite, yellow: smectite, light purple: illite/smectite, pink: illite, gray: chlorite and green: correncite). Lower image: MT BOC contour map shows good agreement with the smectite (yellow) to smectite/illite transition zone (light purple), determined by the ICE Geology group, Costa Rica. On the bottom of both images, the Complete Boguer map is allocated for the sake of better contextual visualization (denser materials are displayed in light yellow colors and lower density materials are depicted in dark blue colors). Reference coordinates are in CRTM05 and m.a.s.l.

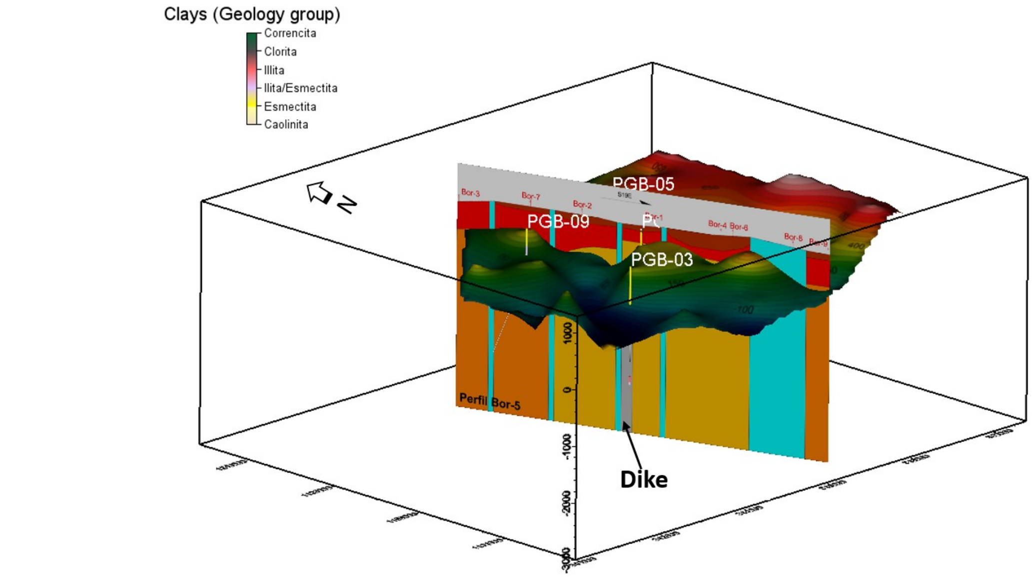

Figure 7: MT section profile Bor-5 (Perfil Bor (Borinquen)-5) shows narrow high-resistivity (above 180 ohm-m) vertical body located beneath the BOC near the PGB-5 well. The latter corresponds to the gray vertical band indicated as dike. The MT BOC, where the dike reaches the cap rock, tends to be abruptly displaced deeper according to possible highly conductive minerals in the surrounding of the inferred intrusion. The interpretation is based on 1D MT data inversion analysis.

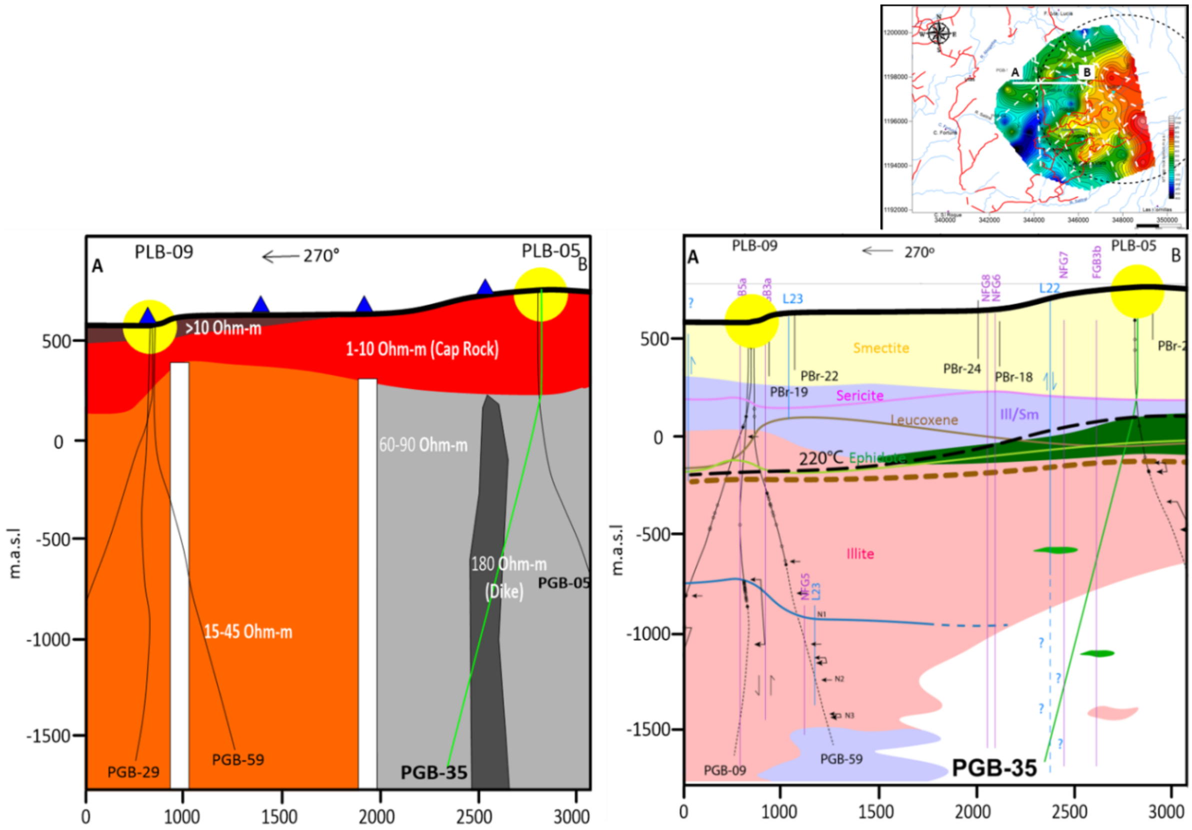

Figure 8: Left: Magnetotelluric W-E (profile A-B) profile between PLB-09 and PLB-05 pads, showing the different resistivity contexts associated with the geothermal reservoir. Note the narrow vertical resistive body identified near the PGB-05 well (eastern part of the Borinquen geothermal field, MT stations are displayed in blue triangles). Right: same profile illustrating alteration clays developed by the ICE Geology group. Modified from Hackanson et al. (2019). MT BOC map shows the position of the profile in the geothermal field (top picture).

The displacement of the MT bottom of the cap rock (BOC) with respect to the clay minerals distribution is interpreted as being linked to the emplacement of sills (saucer-shaped) and presumable feeder dikes in the respective areas. In this case, the feeder dikes seem to be located laterally with respect to the interpreted sills, intruded through radial fractures as illustrated in Figure 9.

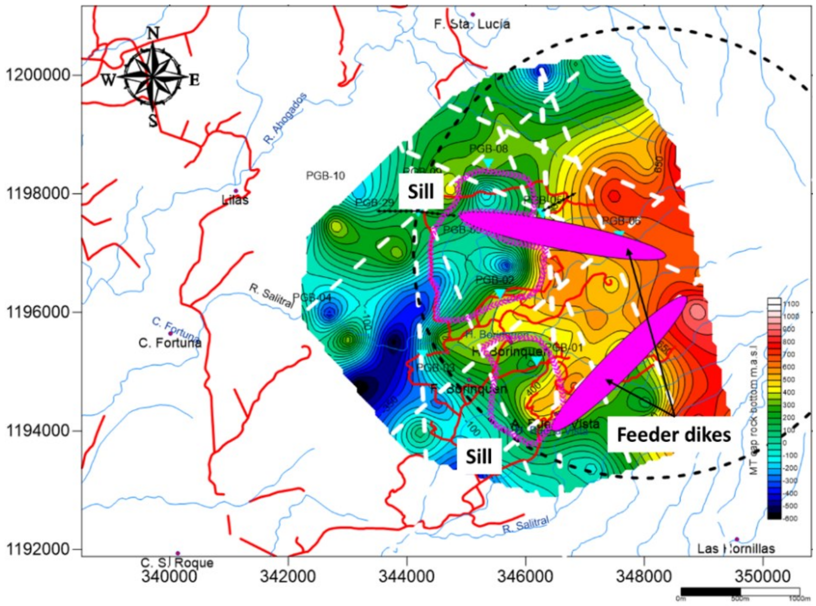

Figure 9: MT BOC contour map in m.a.s.l. The denoted morphology in purple chevron pattern line in the MT BOC is attributed to possible sills arrested by faults. The latter are shown in the image by means of white dashed lines. Those bodies, directly connected to presumable lateral feeder dikes, are depicted with the help of solid purple ovals, intruded through radial fractures. The inferred limit of the reservoir is represented with a black dashed circular line. The picture is modified after Solís et al. (2015).

2.3 Gravity and magnetic analyses

In 2014, besides the TDEM campaign for static shift correction of the BMT soundings and in order to improve the drilling target strategy required for the drilling phase, 9 gravity and magnetometry profiles were conducted in the Borinquen geothermal field with stations placed every 100 m for both techniques (see Figure 10).

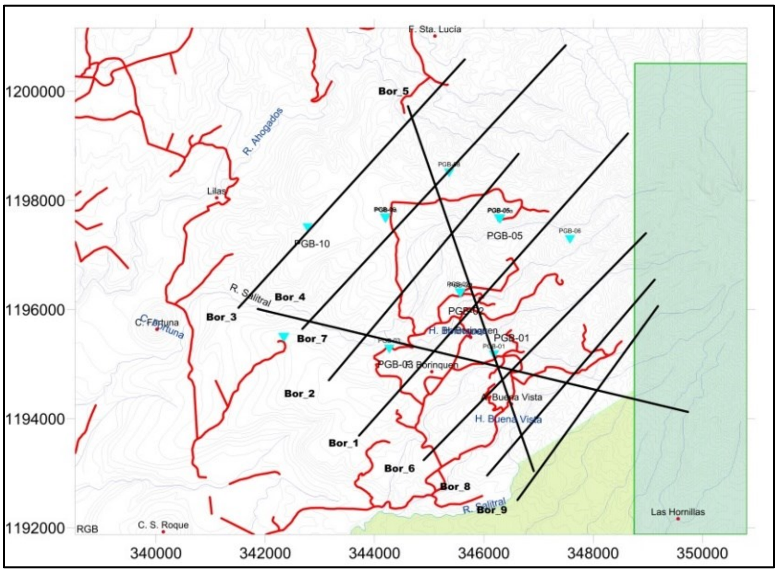

Figure 10: Location map of the Borinquen geothermal field and the position of the 9 gravity and magnetic profiles displayed with black solid lines. Cyan triangles indicate the location of the existing and projected wells. Existing wells: PGB-01, PGB-02, PGB-03, PGB-05 and PGB-09 and projected wells: PGB-06, PGB-07 and PGB-10.

In Figure 11, the complete Bouguer anomaly map is displayed. Gravity modelling results show that higher gravity values are detected in the eastern part of the area under investigation. Interestingly, this coincides with the active Rincón de la Vieja volcano and this, in turn, correlates well with the MT bottom of the cap rock (BOC) tendency to be shallower in that area. Two major radial gravity alignments are inferred to be possible dike intrusions (radial dikes). Similar to the case of Las Pailas geothermal field, the reservoir is not delimited by a low central gravity anomaly but rather has presumable compartments separated by NNW-SSE orientated faults. Plutonic and caldera-related structures interpreted in the MT analysis and a qualitative drainage pattern analysis are well in accordance with alignments observed in the complete Bouguer anomaly map.

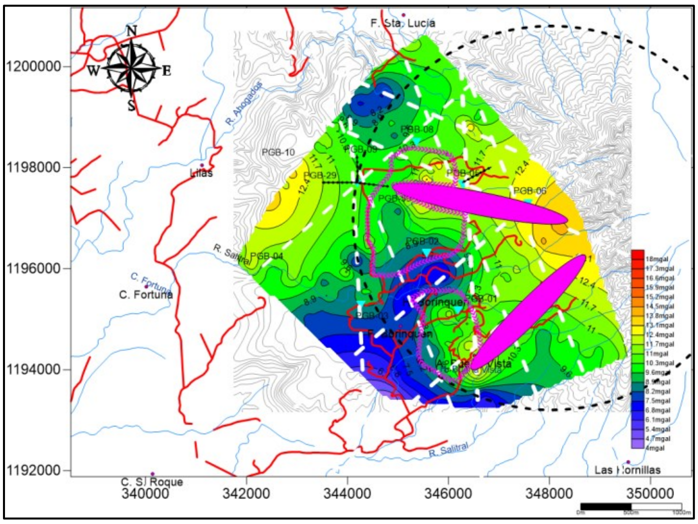

Figure 11: Map illustrates the complete Bouguer anomaly in the Borinquen geothermal field. The picture shows the striking agreement of the saucer-shaped anomalies (depicted in purple chevron pattern) with the presumable feeder dikes (shown in solid purple ovals) locations, delimited by the MT BOC, and its correspondence with the complete Bouger map. The map also displays local tectonic structures (faults, represented with white dashed lines) and the interpreted border of the reservoir (specified with a black dashed circular line). The picture is modified after Solís et al. (2015).

Filtering of the magnetic data, gathered in the surveys conducted in the Borinquen geothermal field, included pole reduction. Once processed, the data showed clearly that the projected faults with NNW-SSE and N-S strikes are mostly linked to the alignments on the magnetic map (see Figure 12). Dikes are interpreted as zones that display high magnetic values, whereas middle to low magnetic values at the end of the dikes are thought to be associated to possible sill saucer expressions.

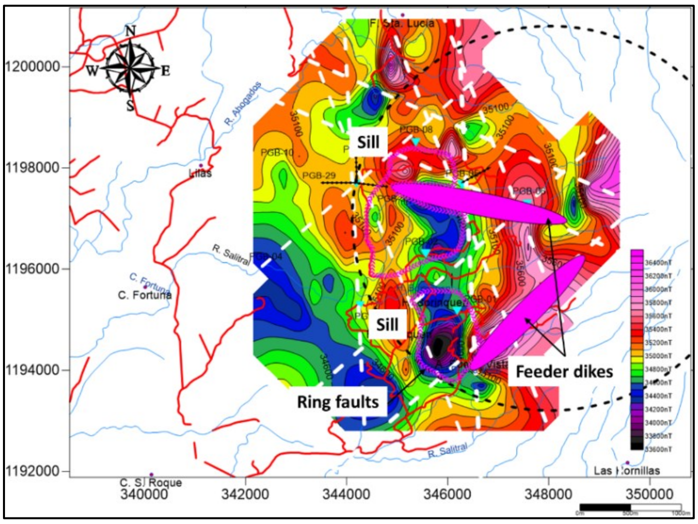

Figure 12: Reduced to pole (RTP) map of the Borinquen geothermal field. The map illustrates that the inferred faults (in white dashed lines) are consistent with alignment arrays in the magnetic values. Feeder dikes (specified in solid purple ovals) are considered to be expressed by higher magnetic values, whereas the inferred areas for the sills (shown in purple chevron pattern lines) exhibit relatively low magnetic values. The border of the reservoir is indicated with a black dashed circular line. The picture is modified after Solís et al. (2015).

Figure 13 compiles a 3D view from the NW sector of the Borinquen geothermal field. The MT bottom of the cap (BOC) rock tends to be shallower and higher in elevation towards the Eastern sector of the area, revealing the impact of the proximity to the Rincón de la Vieja active volcano which is considered as a secondary heat source of the system. Mineral data gathered from the already drilled wells exhibits a good correlation between the depth of the MT BOC and the illite/smectite transition zone near the smectite layer. On one hand, abrupt deepening of the cap rock in conjunction with the lowest magnetic values seem to be linked with the emplacement of sill bodies. On the other hand, the resistivity section shows high-resistivity (around 180 ohm-m) narrow vertical bodies, which correlates well with relative high magnetic values and denser materials according to the gravity analysis; thus being interpreted as the feeder dikes that enabled the emplacement of the sills.

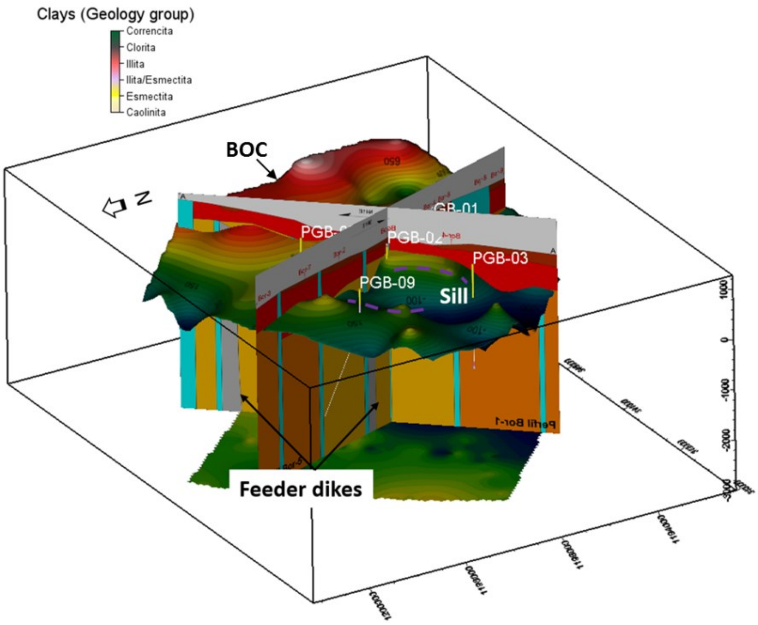

Figure 13: The image shows the shallower section of the clay alteration minerals determined by the ICE Geological group, Costa Rica in the respective drilled wells. The geothermal wells are named as PGB, which stands for Borinquen Geothermal Well in Spanish. A good correlation between the location of the mineral transition zone, characterized by the smectite-illite zone (light purple) near the smectite (yellow) layer contact, and the position of the MT BOC at depth can be clearly seen. Areas, where the MT BOC contour show an abrupt deepening, are attributed to the presence of saucer-shaped sills (denoted in purple dashed lines). As displayed in the MT resistivity cross sections (Bor-1 and Bor-5), where the sills can be recognized, it is inferred that the latter are linked to feeder dikes with high resistivities (around 180 ohm-m), shown as narrow vertical bodies (gray bands), and relative denser materials. Other features seen in the image are derived faults (cyan). At the bottom of the 3D model, the complete Bouguer anomaly map can be observed. Higher densities are depicted in light green and lower densities are shown in dark blue.

2.4 Additional data and principle conceptual models of igneous plumbing systems to support the hypotheses

A principle conceptual model for sill emplacement, developed by Carey (1958), can be seen in Figure 14. This classical conceptual model is used for the hypothesis formulated for the presumable sills interpreted in the Borinquen geothermal field. Fundamentally, lateral dikes are expected to feed the sills. Iyer et al. (2013) indicated that in the surroundings of a sill intrusion an alteration aureole is formed as shown in Figure 15. Such deposits in the surroundings of the sill show low resistivity such as for the case of smectite-chlorite (corrensite) and pyrite, as indicated by Spacapan et al. (2019). Consequently, the response of the cap rock could be expected deeper than the signal generated by the normal transition of smectite to illite/smectite.

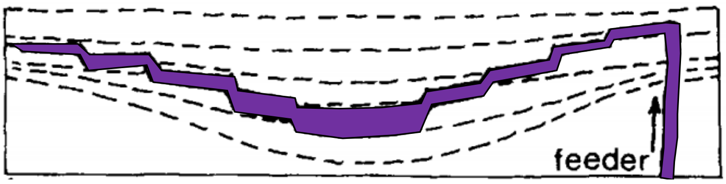

Figure 14: Sill emplacement through a lateral feeder dike. The picture originates from Carey (1958). Consistent with the hypothesis of an intrusion, the ICE Geology group in Costa Rica modelled in Hackanson et al. (2019) for the PGP-35 well projection a correncite mineral pattern contour similar to the one suggested by Iyer et al. (2013). This hints at a possible contact metamorphism evidence, such as the one presumed to be attributed to the presence of a sill intrusion.

Further data is being compiled as new geothermal wells are being drilled and new geological, geophysical and geochemical surveys are being conducted in the Borinquen geothermal field. During the entire life cycle of geothermal field development, as new static and dynamic data is being gathered, the reservoir architecture is updated and there is a better understanding of the permeability structure, thermodynamics, fluid and heat transport mechanisms as well as rock-fluid interaction in the reservoir. However, the integration of site-specific optimized geothermal exploration methods at this early stage of exploration and development of the Borinquen geothermal field substantially contributes to the reduction of costs and risks. We consider hydro-tectonics as key to geothermal exploration. Combining the orientation of faults with respect to the present-day stress field may significantly contribute to the identification of drilling targets and the understanding of reservoir compartmentalization also in a volcanic play type (e.g., Moeck 2005).

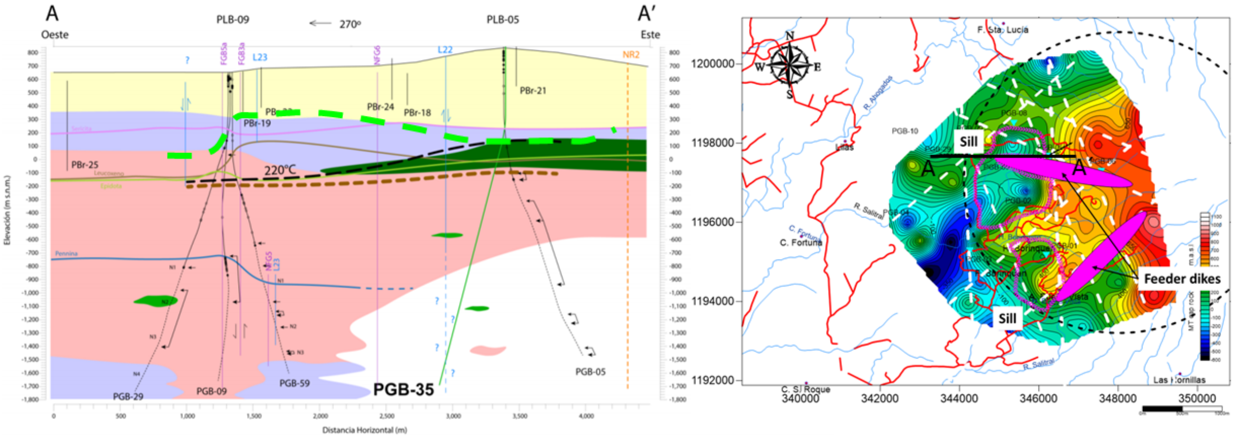

Figure 15: Left: Vertical profile A-A´ shows clay alteration zones correlation and permeable zones (ICE Geology group, Costa Rica). A clear correncite (chlorite-smectite) zone, shown in dark green, is visible in the profile. The green dashed line reveals the contact of the MT BOC according to the cross section. The picture was modified after Hackanson et al. (2019). Right: Map displays the MT BOC contour in m.a.s.l. and the location of the profile. The sills locations are denoted in purple chevron pattern, while the positions of the possible feeder dikes are exhibited in solid purple ovals.

3. CONCLUSIONS

Developing geothermal exploration and exploitation strategies for high-enthalpy geothermal reservoirs in a volcanic play type requires an accurate understanding of the key geological structures present such as faults, cap rock and caldera boundaries. As shown for the Borinquen geothermal field, this can only be accomplished by interdisciplinary efforts from the entire geoscientific group in charge of developing this geothermal project. The integration of magnetotelluric, gravity and magnetic data interpretation has been conducted in this work for the Borinquen geothermal field in Costa Rica. In addition, geochemical studies and borehole geological data have contributed to the inference of geological structures. Regional geology and volcano-tectonic elements were considered for the interpretation of geophysical data. In particular, the identification and characterization of key geologic elements of igneous plumbing systems and caldera-related structures have been focused on in this work. It has been recognized in this work that the identification and characterization of sills and dikes as wells as radial and ring faults are key to geothermal exploration in a volcanic play type. Besides, hydro-tectonic analyses that take into account faults orientation with respect to the present-day stress field to gain a better insight on the permeability structure of the geothermal reservoir may be key to geothermal exploration. Ring faults represent structural elements oriented in all directions, and as a result, those favorably orientated with respect to the present-day stress field may constitute promising drilling targets. Especially the intersection of regional major faults with local volcano-tectonic faults such as radial faults may constitute zones of high permeability.

Based on the integrated analysis of magnetotelluric, gravity and magnetic data, clay mineral alteration studies and temperature measurements in a few wells, we could identify relevant structural and morphological elements of igneous plumbing systems. From our analyses and methodologies, we conclude that a profound understanding of caldera architecture and evolution may be critical for geothermal exploration in volcanic play types in Central America. As exemplified for the Borinquen geothermal field in Costa Rica, the combination of analogue simulation results of caldera-related deformation processes and fundamental conceptual models of igneous plumbing systems may critically contribute to a more reliable interpretation of geophysical data. Since a large number of volcanic settings in other countries in Central America display similar structural patterns, the methodologies and approaches used in this work may be applied to other high-enthalpy geothermal fields in Central America.

The Geophysical team, as part of the broader Geoscience group of the Costa Rican Institute of Electricity (ICE), has been able to preliminarily derive possible magmatic body intrusions and their morphology through the comparison with other useful geoscientific information available. As mentioned earlier, possible structures such as ring faults, radial faults and regional faults could be inferred by the integration of comprehensive and reliable geophysical data.

Another important finding in this work relates to sills and their feeding mechanisms. Sills linked to lateral feeder dikes could be inferred for this geothermal area based on magnetotelluric, gravity and magnetic analyses, and utilizing volcano-tectonic concepts as well as key geologic elements of igneous plumbing systems. The critical importance in identifying and characterizing size, shape and location of these geologic features relies on the role they play as possible local heat sources, hydraulic barriers between reservoir compartments and their far-reaching effect on the geochemistry and fluid dynamics. Another important fact associated with relatively young intrusion bodies is that if they are fully understood in the absence of high permeable structures, they can be hydraulically stimulated for production/reinjection purposes, since they constitute geologic elements of anomalously high temperature.

To sum everything up, obtaining detailed knowledge of the key geologic controls on fluid and heat transport in the reservoir at the early stages of geothermal exploration through integrated geological, geophysical and geochemical methods in conjunction with other geoscientific analyses is decisive to reduce costs and risks. The latter goes hand in hand with (I) the identification of promising geothermal drilling targets for optimized and sustainable production/re-injection schemes, (II) the development of efficient and most suited exploitation programs that take into account a sustainable reservoir management and (III) the minimization of risks related to negative interference between neighboring wells, earlier than predicted pressure and temperature decline, premature thermal breakthrough and geochemical problems associated with scaling and corrosion. Despite valuable geological, geophysical, geochemical and borehole data from a few drilled wells being gathered, the Borinquen geothermal field must be considered as being in an early stage of exploration and development. Further and more detailed geoscientific analyses is needed for the next steps of development in this geothermal project through 2D and 3D geophysical surveys and the subsequent two- and three-dimensional data processing and interpretation. In addition, geological and geophysical borehole data is crucially important to better calibrate and constrain previous geophysical data. Geothermal exploration using airborne gravity and magnetic data is planned for the study region to complement surface geophysical exploration in areas with difficult access. In this matter, current international and interdisciplinary joint efforts are being taken by the Instituto Costarricense de Electricidad (ICE), the Leibniz Institute for Applied Geophysics (LIAG) and the Federal Institute for Geosciences and Natural Resources (BGR) in Germany along with other Central American counterparts to address these challenging tasks. This multidisciplinary joint endeavor focuses on the application of joint geophysical, geochemical and other geoscientific methods for a better understanding of the most appropriate geothermal exploration concepts for this complex volcanic field setting. The findings of this international geoscientific collaboration should result in the development of most suitable site-specific geothermal exploration methods for volcanic play types in Central America as well as high-enthalpy reservoir characterization, modelling and simulation. This team effort is made within the framework of the German Cooperation Program for enhanced geothermal exploration in Central America.

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