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Verification of applied geophysical procedures to standardize protocols for geothermal exploration in Central America

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Abstract. Although a large amount of geothermal exploration data exists in Central America since the 1960s, it has not yet lead to an even development of capacities in the region. Exploration methods and applied interpretations techniques did not evolve in many cases, due to a lack of knowledge exchange on a geoscientific level. To improve this situation, a verification of applied geophysical procedures will be developed by the Instituto Costarricense de Electricidad (ICE, Costa Rica). Current international standards and updated approaches, including environmental aspects, will be taken into consideration to create guidelines on the application of geophysical methods for geothermal exploration in Central America. This is an important step to equalize the capacities of regional governmental institutions in the field of geothermal exploration and to enhance the comparability of geophysical exploration results in the region. The project is supported by the Federal Institute for Geosciences and Natural Resources (BGR, Germany) in the framework of the German Cooperation with the Sistema de Integración Centroamericano (SICA) for the Identification of Geothermal Resources in Central America. The activities are in the conceptualization phase and a field campaign in the AOI Las Pailas II Geothermal Project is planned for the third quarter of 2018.

1. Introduction

Many countries in geothermal development in Central America face the same problem of insufficient data availability. Data exists in good quantities but is unstructured and often not digitized as it was acquired in the 80s or prior to that. Exploration methods and interpretations used in Central America did not evolve, as the exchange of knowledge is not very strongly implemented in the geoscientific field. Even some of the experienced scientists and practitioners in the field of geothermal exploration of the region often work in fields outside their original profession after having solely received an introductory course on Geothermal Exploration.

Different exploration methods and also newer interpretation and modelling techniques might help the region to develop better conceptual models, which could lower the risk during the development phase and gain the trust of investors and decision makers.

At the same time, Central America offers an interesting opportunity to international geoscientists for the testing of new exploration techniques as well as the comparison to established ones. Especially Costa Rica offers geothermal areas with existing power plants, extensive networks of boreholes and lots of existing data.



The creation of an international working group is one strategy to comply with the need of the region to evolve on international standards for geophysical exploration. The tasks of the working group should be to design a project for the verification of the applied methods, the exchange of experiences during field surveys between different geoscientific schools and to compare the approaches of data modelling and interpretation for geothermal exploration. As a final output, a guideline for the application of geophysical methods for geothermal exploration in the region would help to enhance the quality of the exploration of geothermal resources in Central America.

Costa Rica is an important SICA member country regarding ongoing exploration, development and monitoring activities for geothermal expansion in the respective country. In Pailas II a database with data from various investigations and from 40 boreholes is available and a detailed conceptual model based on data from the 1980s as well as on more recent data with good quality. Therefore, this location is suitable as the Area of Interest (AOI) for the activities of the working group. A specific circumstance make it even more suitable, as it is part the Rincón de la Vieja National Park in Costa Rica and the applied methods therefore have to consider extreme environmental requirements for protected areas.

The Area of Interest

Costa Rica is an important SICA member country regarding ongoing exploration and monitoring activities for geothermal development in the respective country. The area of interest (AOI), which has been selected according to the project goals, is located in the UNESCO Human Heritage Conservation Area “Parque Nacional Rincón de la Vieja” in Guanacaste (Liberia). It is situated in the South of the Rincón de la Vieja Volcano and is adjacent to the Las Pailas I and II geothermal power plants. Plenty of data from various geoscientific investigations and from 40 boreholes is available for this area as well as a detailed conceptual model of good quality based on data from the 1980ies as well as on more recent data. Therefore, this location is suitable as the Area of Interest (AOI) for the activities of the working group. Since the AOI is part of the Rincón de la Vieja National Park in Costa Rica the applied methods also have to consider the environmental requirements of protected areas.

This area offers data from 40 geothermal deep wells which vary between 850m and 2300m depth. 21 directional wells correspond to the new development at Pailas II.

The available geological data sources for this area are:

- geological surface information,
- data from geothermal gradient wells,
- petrographic macro and micro analysis of rock cuttings and core samples from deep wells, including thin section, bulk analysis and diffractometry.

Available geochemical data includes:

- water analysis of rivers and springs, downhole sampling,
- chemical production monitoring,
- tracer tests.
- liquid isotopes

And available geophysical datasets are:

- Magnetotellurics (AMT+MT) using TDEM data for static shift correction,
- Gravimetry and Magnetics (6 profiles with approximately 6km length each and station spacing of about 100m. 1D modelling has been carried out on the data).

Furthermore, thermohydraulic well logs with a characterization of injectability are available for this area. The first conceptual models for Pailas II have been created by Geothermex (USA) and West Jec (Japan). These models were then subsequently updated by ICE in 2015 and the later in 2017 as shown in Figure 1.

The available evidence indicates that the heat source of the geothermal systems at Pailas I (U1CGP) and Pailas II (U2CGP) is related to the Rincón de la Vieja-Santa María volcanic complex. It might consist of one or several magmatic chambers at shallow depth from which intrusions might be derived in the cooling process.

2. Geoscientific available data

Based on this vast amount of available data, the area appears to be suitable as a “laboratory” for the application of different geophysical methodologies in order to gain information on the volcanic geothermal systems of Central America and the adequate application of new and combined methods, analysis and modelling techniques.

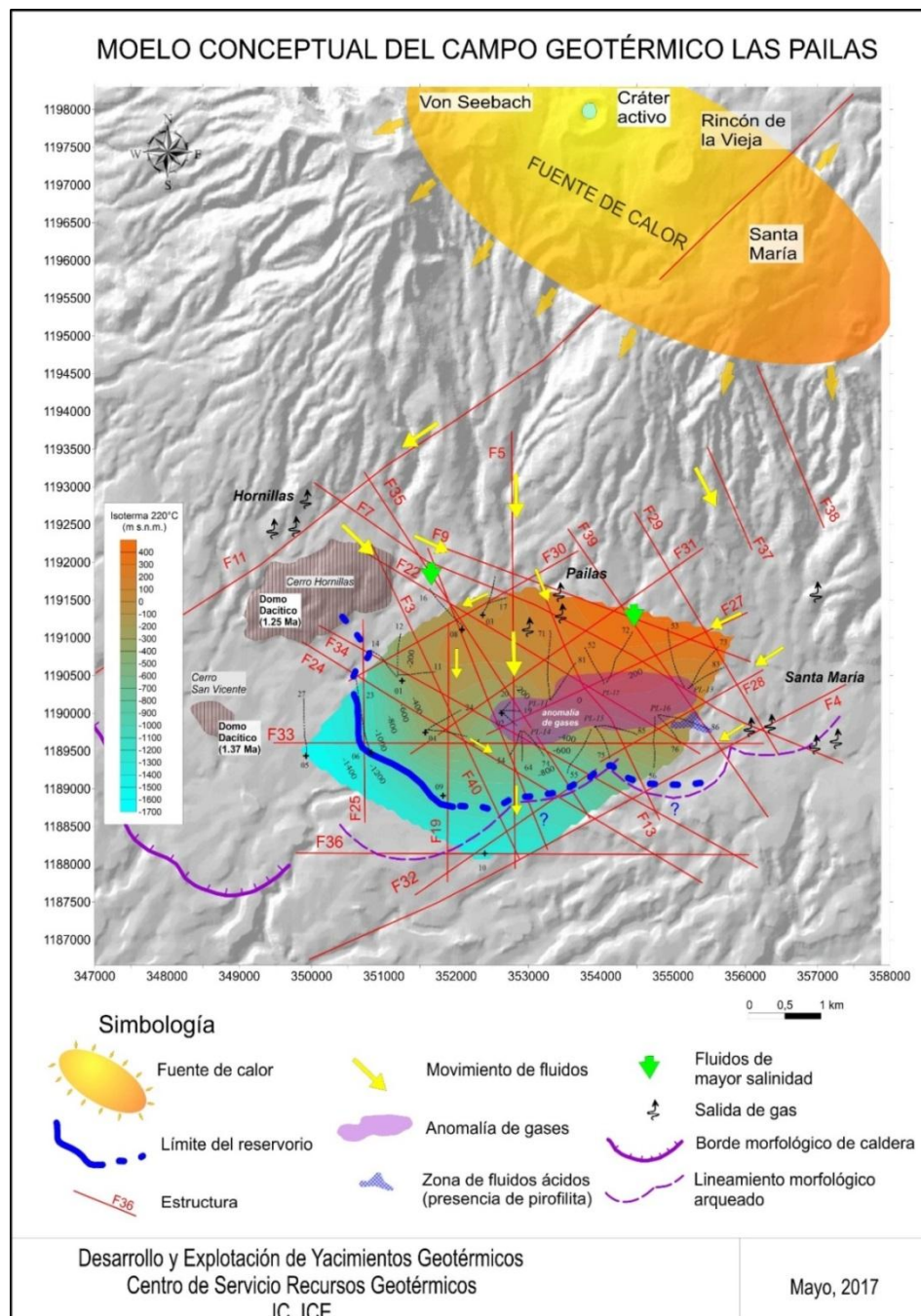


Figure 1. Geoscientific conceptual model of Las Pailas geothermal system [2]

2.1 Geology

The geologic history of the region is associated with the evolution of the calderas Cañas Dulces y San Vicente [1] and the more recent activity of the volcanic complex Rincón de la Vieja. The morphologic limits of the Caldera Cañas Dulces are explicitly evident in the West of the geothermal field Las Pailas (Campo Geotérmico Las Pailas, CGP). Here, domes of dacitic to rhyolitic-dacitic composition are present that exploited the fractures associated with the curved boundaries of the structure during extrusion. Because the Eastern and Northern area is covered by younger lithological units of the present volcanic edifice of the Rincón de la Vieja, evidence of the caldera at the surface is absent in

this zone. The Caldera San Vicente, the presence of which is supported by a geophysical anomaly, has a smaller diameter, and its surface expression is less than in the case of the Caldera Cañas Dulces. This Caldera encloses the sector with the majority of the deep wells of unit I of the CGP. The wells of the U2CGP (Las Pailas II geothermal project) are located in the East, possibly outside of the caldera [2].

According to Ramírez et al [2], based on geological surface and well data, the lithostratigraphic sequence was defined. Six volcano- stratigraphic units that can be seen in **Figure 2** were determined, which can be correlated with Miocene to Holocene regional formations, namely:

- Grupo Aguacate (GA): At a regional scale this sequence includes a lava sequence intercalated with pyroclastics, epiclastics, lacustrine sediments and some andesitic dykes of small thickness. These rocks do not outcrop in the area of the CGP.
- Grupo Bagaces (GB): At a regional scale this sequence includes ignimbrites, rich in scoria of dacitic composition, silicic ignimbrites and lava flow deposits that outcrop extensively in the ignimbritic plateau of Santa Rosa.
- Formación Liberia (FL): The Formación Liberia, which occurs in all boreholes of the CGP, consists of pyroclastic flows of white and rose hues. The composition is rhyolitic with crystals of plagioclase, corroded quartz, biotite and intermittently occurring hornblende as distinctive components.
- Unidad de Domos Dacíticos (UDD): This unit comprises dacitic-rhyolitic domes and lava sheets that outcrop south of the boundaries of the caldera Cañas Dulces and at the western and northwestern boundaries of the caldera San Vicente.
- Formación Pital (FP): This formation is present in all boreholes and was correlated with outcrops in the East and South of the CGP. It consists mainly of deposits of dacitic to rhyolitic pyroclastic flows, lithic tuffs and crystal- lithic tuffs, primarily pumice, and less frequently lacustrine and epiclastic sediment deposits.
- Unidad de Productos Recientes del volcán Rincón de la Vieja (UPRV): This unit of recent products of the volcano Rincón de la Vieja is composed of five types of deposits: lahar deposits, avalanches of detritus, conglomerates, undifferentiated pyroclastic products and lava sheets (andesitic and andesitic-basaltic). The latter are restricted to the northern part of the field.

A representative stratigraphic profile can be seen in **Figure 3**.

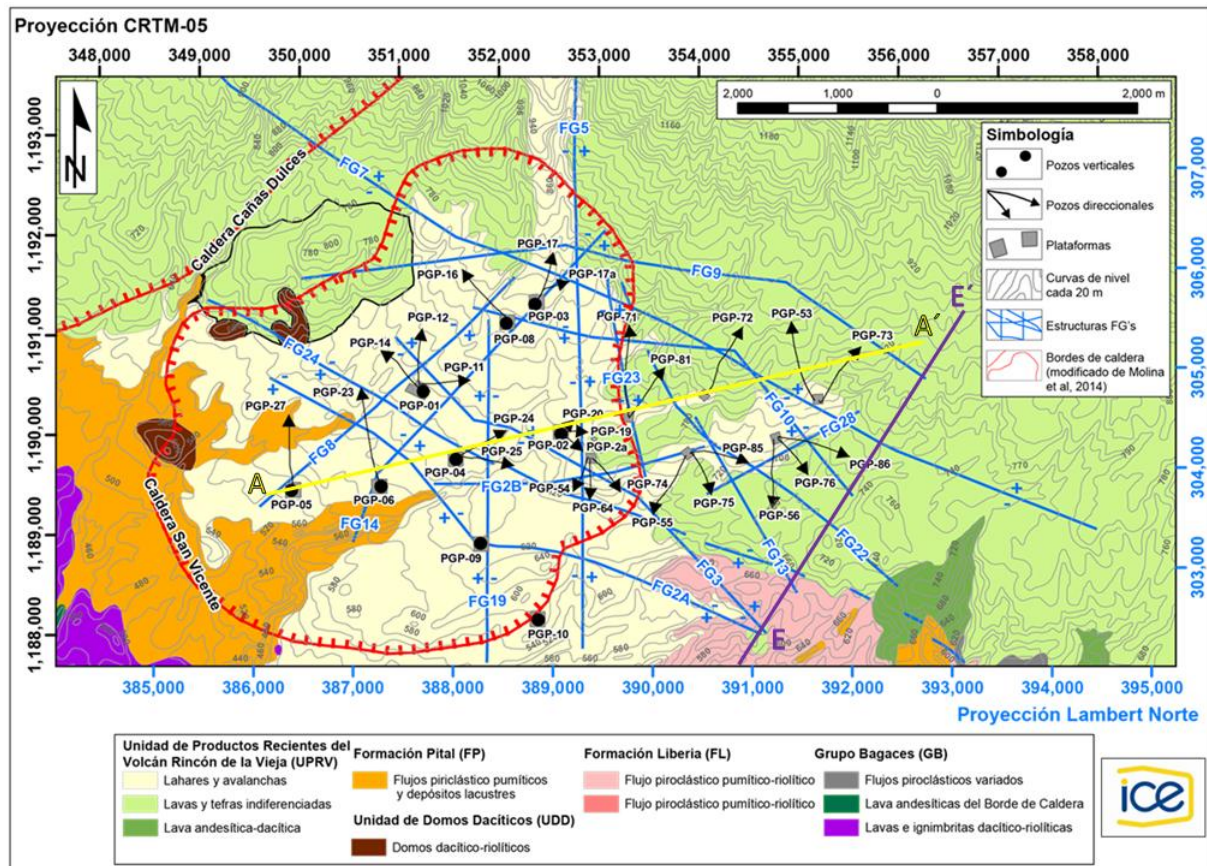


Figure 2. Geological Map and the geological formations present in Las Pailas. A-A' geological section in yellow line [3]

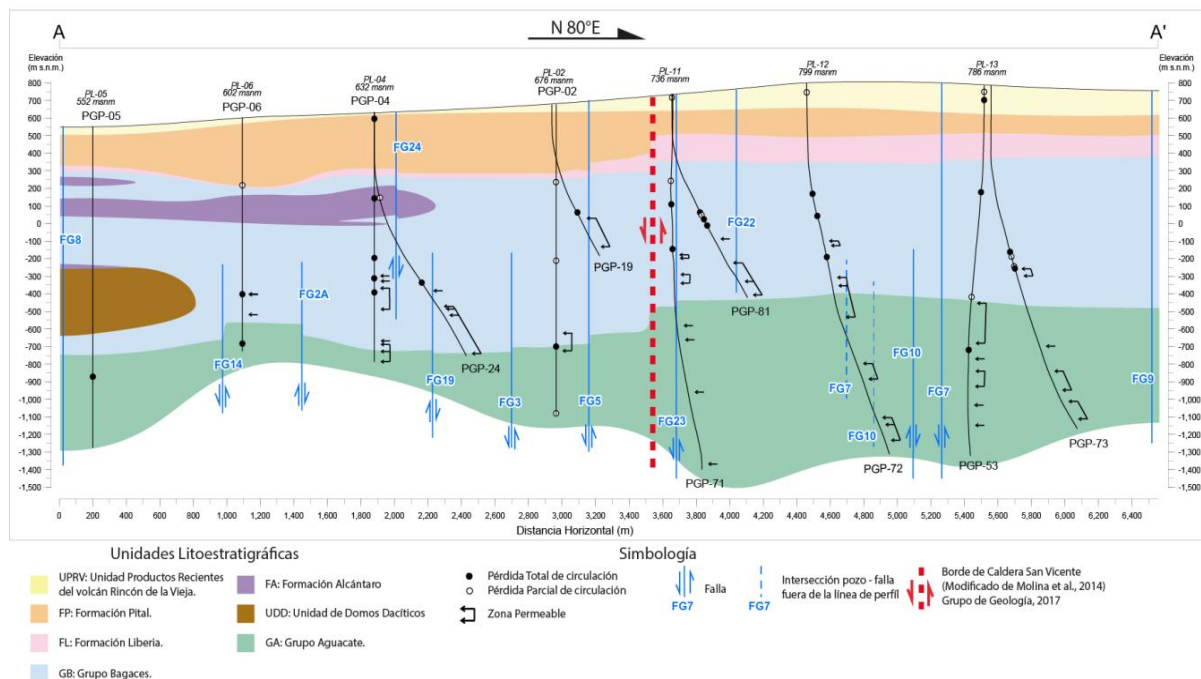


Figure 3. Geological Section N80°E [3]

2.2. Geochemistry

Torres & Fajardo [5] determined that the reservoir of Las Pailas is a water-dominated system. The wells of Pailas I and II produce fluids from aquifers of different chemical compositions and temperatures. Nevertheless, the main aquifer is sodium chloride dominated, pH neutral, highly saline and with a low content of gases with temperatures ranging between 240 ° C and 255 ° C. However, geochemical variations have been determined in the fluids of both sectors (Pailas I and II) as seen in **Figure 4**.

The results obtained from the different evaluations of the deep wells of Pailas I and Pailas II show that the fluids of Las Pailas have electrical conductivities between 18000 and 21600 $\mu\text{S} / \text{cm}$ and a chloride content between 6205 and 7631 ppm. The zones of higher salinities vary depending on production conditions, thus, some wells show mixing of different zones, while in other wells only one of them is present [5].

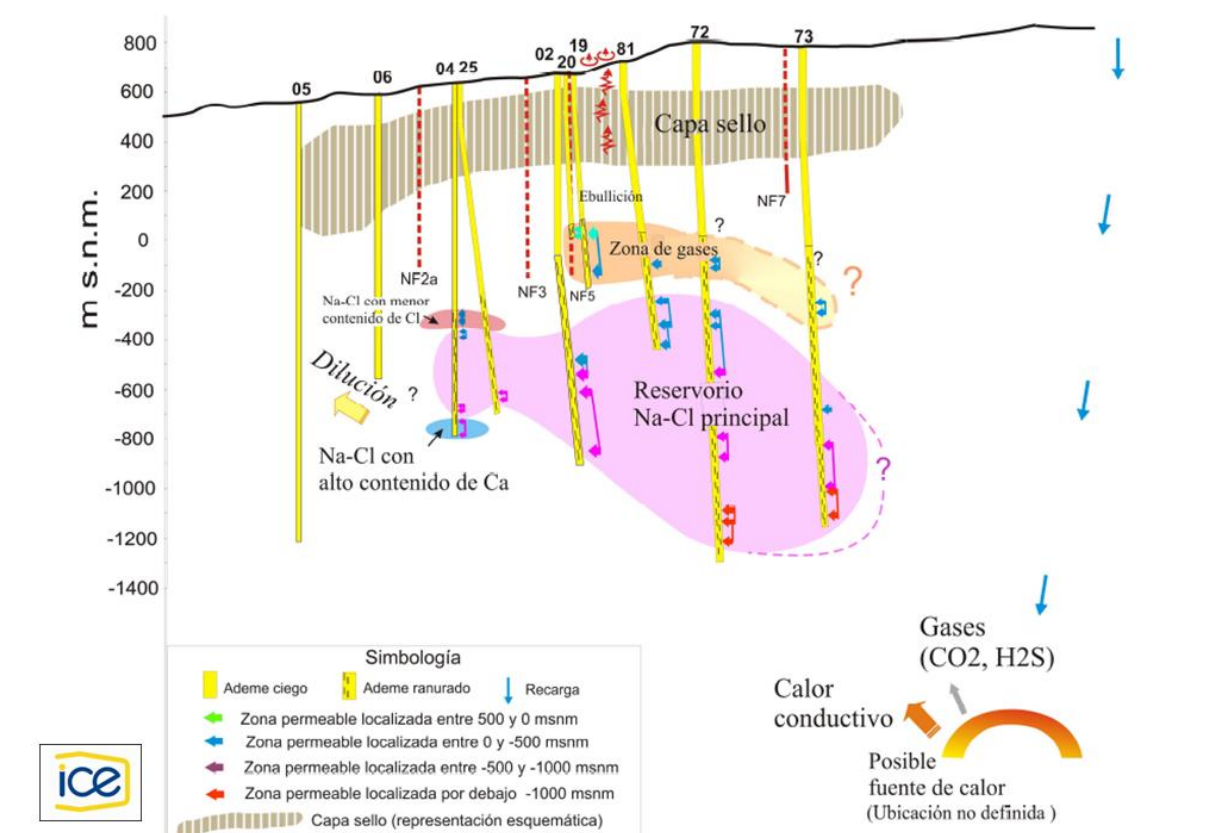


Figure 4. Geochemical Model of Las Pailas Geothermal System [5]

2.3. Geophysics

According to the exploration, the areas with the current production zones of the CG Las Pailas reservoir and Unit 2 CG Las Pailas, correspond to materials with resistivities between 30 and 250 ohm-m. A relative increase in resistivity can be seen to the east (sector of Unit 2 CG Las Pailas). The upper limit of the reservoir was determined as materials associated with the cap layer, with resistivities between 1 and 10 ohm-m. **Figure 5** shows the cap rock thickening towards the west and south of the analysed area. This is probably associated with the location of the possible heat source which is anticipated towards the northeast sector of the CG Las Pailas [4].

In 2016, a magnetic survey of the 6 profiles (A-A', A-A'', B-B', C-C', D-D' and E-E') was carried out. The information obtained was processed using the software Oasis Montaj 9.0.2 of Geosoft. From the

processing and analysis of the data (after being reduced to the pole and using filters to increase the signal) a pattern of aligned anomalies is observed, with alternating maximums and minimums. This pattern was analysed by considering the direction of the dipoles, and from this analysis, at least 5 tendencies or preferential directions were obtained. These trends served as the basis to determine possible systems of volcano-tectonic origin and correlate it between other methods also as seen in **Figure 5**.

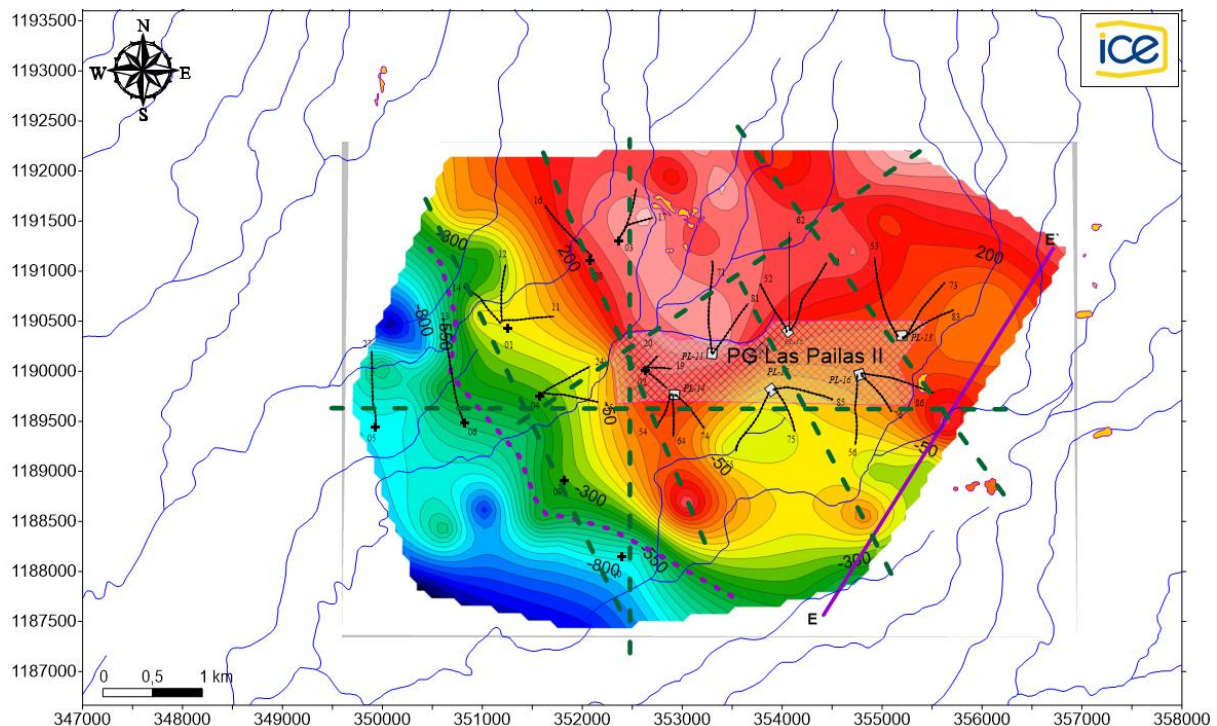


Figure 5. Elevation of the cap rock in m.a.s.l, and possible volcano-structural tendencies in green dot lines [4]

3. Research Question

As mentioned above, there are currently three areas of geothermal development in Costa Rica, Dr. Alfredo Mainieri Protti (formerly Miravalles), Las Pailas and Borinquen. In these geothermal areas various geophysical exploration techniques have been utilized, namely Magnetotelluric, Gravimetry, Magnetism and passive seismics.

The variety and amount of available data reflect that ICE has a lot of experience in the application of geophysical methods. However, as part of part of the continuous improvement related to best practices, ICE wants to update the institutional knowledge to the current international standard for the analysis, modelling and interpretation of the geophysical data. An update and exchange of knowledge can help to close the gap of capacities of national entities involved in geothermal exploration in Central America.

The following topics need to be addressed:

1. Standardization of procedures for the data collection, processing and modelling of data.
2. Standardization of procedures for quality control of the acquired data.

3. Verification of the compatibility between traditional investigation methods used in high enthalpy exploration and other methods and analysis techniques not yet used in the region.
4. Economics of data acquisition.
5. Exchange of experiences on an international and interdisciplinary level.

As a final result, the comparison of approaches and the outcomes of the working group activities will be published and resumed in a regional guide for the application of exploration methods for the region.

The guide will enable other regional actors to repeat the procedures and apply best practices, including environmental considerations for protected areas which will lead to a better comparability of exploration results on regional level and the harmonization of capacities of the various entities of geothermal exploration in the region and will stimulate the quality of geophysical exploration for geothermal development in Central America.

4. Methodology

- **The work is meant to take place in three phases:**
- **A phase for data revision, method comparison and interpretation, including a field campaign.**
- **A phase of replication and verification of the findings.**
- **A phase of knowledge transfer and standardization.**

Phase I, which focusses on the comparison of applied methods with new methods and different techniques of analysis and interpretation, is tackling the main problem of geothermal investigation in Central America. Namely, the actualization to new procedures and methods and the comparison and combination of methods.

After the establishment of the working group, a phase of individual data revision and recommendations will be the initial task of the working group. In a meeting prior to the field campaign, recommendations will be discussed and question will be clarified among the group.

The field campaign itself is meant to have a duration of 2 – 3 weeks. For the measurements the members can use existing instruments of ICE or can bring in own equipment. Formal procedures will be supported by ICE.

The different methods will be applied all in one field campaign in order to directly exchange and discuss among the multidisciplinary group. A strong viewpoint will be the combination of MT/TEM and seismic methodologies.

After the field campaign the group will meet to discuss the first results and methods of analysis/modelling, which will be done individually by each member, using the individual technique. In a finalizing meeting the results will be compared and discussed and a final recommendation for the application and combination of methods will be created. As a final product a publication at the GEOLAC 2019 or another international conference would be an optional output from the working group at this stage.

The studies will mainly focus on data and methodology gaps in the so far applied geophysical investigations currently applied by ICE. A working group, lead by ICE will be formed with members from different disciplines, which will carry outfield works and compare modelling and

interpretation techniques for the data. A baseline of needs for comparison is given by the actual methodologies used in Pailas I and II:

Magnetotellurics

The first MT studies used by ICE in Pailas were done with low frequency coils whose data were corrected using vertical electrical measurements. Subsequently, these measurements were complemented by high frequency data. All of the data was then interpreted by one-dimensional analysis only. In later stages, the static shift of the MT data was corrected using TDEM measurements instead. Currently, broadband coils are used in the MT surveys and TDEM is still used to correct the MT data.

The usual methodology for MT surveys is to carry out measurements at approximate every 300-500m from each other in more or less regular meshing or profiles. However, there is no standardized procedure to date for this survey.

Also, independently of the survey grid, only 1-dimensional analysis and modelling is carried out. A higher dimensional analysis and modelling are still lacking. During the work, this will have a major focus for enhancement of procedures.

Gravimetry

Many gravity measurements have been made in the 80s. The data was acquired along existing roads and accesses. The measurements were carried out on irregular meshes with stations separated no less than 500 m from each other. More recently in 2015 profiles with stations every 100 m have been carried out in Las Pailas and Borinquen geothermal areas.

Magnetics

Measurements have been carried out every 500m in the all geothermal fields, while for the geothermal fields Las Pailas and Borinquen new profiles with stations spacing of 100m were collected in 2015.

- Seimics

Passive Seismic analysis had been taken out as part of the constant monitoring. Active seismic hasn't been apply yet.

The second phase (Phase II) is aiming to replicate and verify the results of Phase I. In order to develop regional guidelines, the successful methods used in the AOI need to be successfully replicated in another area. The MEM Nicaragua is interested to provide with the Monte Galán Geothermal Complex an area for this task. They are hoping to support the standardization of geothermal exploration procedures for all SICA member countries.

In Phase III represents the standardization and knowledge transfer. As the previous phases tackle the problem of uncertainties in the application of methods and subjectivity of interpretations and weighing of results for decision making, this phase is aiming to use these results to create and promote the application of standards and SOPs. This includes the development of a guideline for the application of geophysical exploration procedures for the identification of geothermal resources in Central America.

The use of standards and standard procedures will raise transparency and comparability of data, which plays an important role in the communication of geothermal exploration results.

5. Expected Results

ICE plans to publish a **Regional Best Practice Guide for Geophysical Exploration**, which will be based on the findings of the working group, supported by the Technical Cooperation Module “Identification of Geothermal Energy Resources in Central America”, implemented by the Federal Institute for Geosciences and Natural Resources BGR.

The guideline will give appropriate direction to the basic steps of exploration. It will standardize procedures on international level for the identification of potential geothermal resources for decision making. The central objective is to maintain, reactivate and initiate activities focused to the exploration and development of geothermal resources in Central America.

The Following issues are anticipated to be addressed:

Advantages and disadvantages of exploration methods

Prerequisites for geophysical field campaigns at different stages of the geothermal exploration

Selection and sequence of applied methods for geothermal resource exploration

Design of geophysical field campaigns

Procedure for data analysis and modelling

Weaknesses and strengths of different modelling techniques

Integrated models

The challenge of data communication for decision making

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