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A 3D Model of the Chachimbiro Geothermal System in Ecuador

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ABSTRACT

The Chachimbiro Geothermal System is the most important Geothermal Prospect in Ecuador. Various geothermal models have been presented based upon geological, geochemical and geophysical data collected at different epochs. Currently, Chachimbiro Prospect is ready to enter the exploration-drilling phase. This is why it is important to identify the best drilling targets. Petrel allows the combination of all surface exploration data in order to identify different geothermal anomalies and create a 3D model to visualize all features of the system. This model uses lineaments as boundaries of the system based on structural mapping and locations of earthquake epicentres. The heat source is related to magma chambers that feed the main emission centre but is also controlled by faults that influence possible up-flow. This up-flow is located beneath a cap rock (0-10 Ωm) related to a high resistivity core which shows a concave shape (30-70 Ωm).

The Na/K geothermometers show temperatures around 240°C; however, the water in Chachimbiro has poor equilibrium with the rock. The resistivity analysis shows possible temperatures from 200 to 250°C, but this range of temperature does not represent the current temperature of the system. The origin of the fluids in Chachimbiro is meteoric based upon isotopic analysis. The interaction between fluids with the up-flow into the sub-surface forms the possible reservoir. Hot springs and gas manifestations (CO_2-H_2S) are outflows of the system that also indicate volcanic activity in the system and expressions of the reservoir on the surface. The intersection between Chachimbiro and Azufral faults and the Chachimbiro Fault has been identified as well targets in the system, which could be reached by directional drilling from three different locations. These locations have been chosen by combining the structural features, the resistivity anomalies, possible outflow and up-flow zones, the hydrothermal areas and temperature anomalies which were modelled and analysed in Petrel..

1. INTRODUCTION

Conceptual models are based on geological interpretation, results of geophysical survey, information on chemical and isotopic content of fluid at surface manifestations and reservoir fluid samples collected from wells, information on temperature and pressure conditions based on analysis of available well logging data as well as other reservoir engineering information. A comprehensive conceptual model provides an estimated size of the reservoir, the heat source, recharge zone locations, general flow patterns within the reservoir as well as its temperature and pressure conditions. Nevertheless, not all geothermal conceptual models incorporate the whole information at the same time, in fact only a few do so. In the early stages, knowledge is limited and only surface information will be available. (Axelsson, 2013). Three-dimensional modelling software are great tools in order to visualize and merge various types of data in a conceptual geothermal model. Petrel E&P is a software which platform provides a full range of tools to solve the most complex challenges from regional exploration to reservoir development. Petrel allows the integration of structural geology, lithology, geochemical and geophysical data obtained in the early stages of the geothermal system development (Schlumberger, 2016). Using this software, it was developed the first 3D model of Chachimbiro Geothermal System in Ecuador described in this paper. This model can be modified during the time and opens the initiative to replicate this process at different similar projects in Ecuador.

Chachimbiro is a geothermal prospect currently at the pre-feasibility stage. The area is located on the eastern slopes of the Western Cordillera, at about 70 km North of Quito, which is Ecuador's capital and 18 km West of Ibarra which is the nearest major load centre. The area straddles the Cotacachi – Cayapas Ecological Reserve, and it bounds to the North by Chota Basin, on the East by Interandean Valley on the South and West by Cotocachi and Yanahurcu de Piñan Volcanoes, respectively (Figure 1).

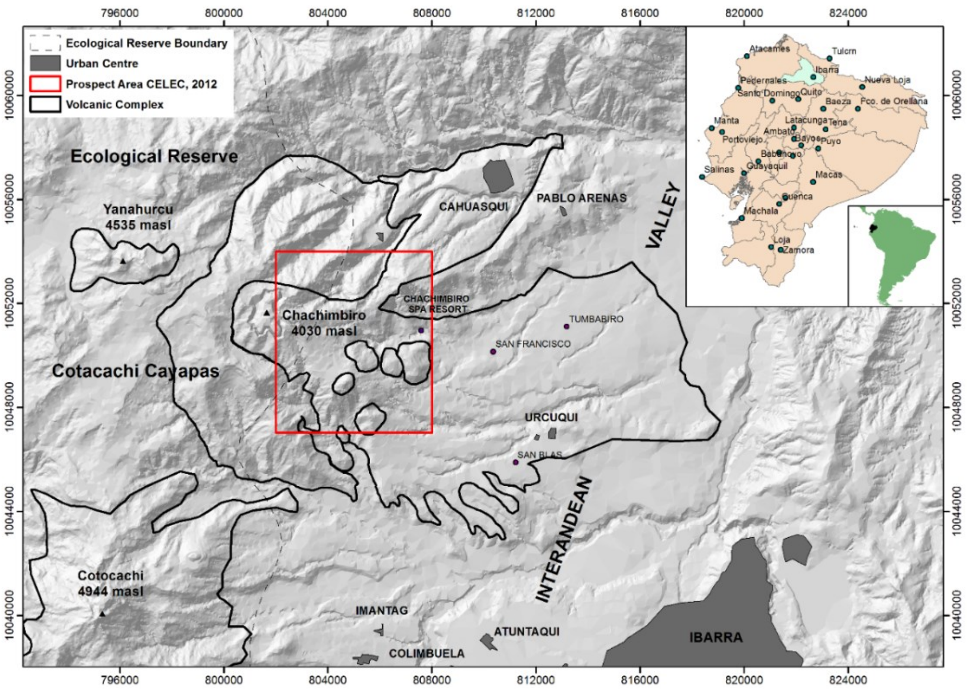

Figure 1: Location of the Chachimbiro Volcanic Complex.

This paper summarizes the geothermal model of the Chachimbiro Geothermal System in the Petrel E&P software platform integrating the results of geological, geochemical and geophysical investigations obtained by CELEC EP / SYR in 2012 and partial results by CELEC EP / MMC in 2016. The objectives are to visualize the features of the conceptual models, to propose news investigation areas, and to propose locations and well targets.

2. GEOLOGICAL AND GEODYNAMIC SETTING

Regional evidence has shown fragmentation of Farallón Plate, forming the Cocos and Nazca Plate during the early Miocene (Lonsdale, 2005). The interaction among South American, Cocos and Nazca plates control the cortical deformation, the high seismicity and the volcanism in the North-Andean Block (Figure 2). The convergence between the Nazca and South American plates is estimated to be 7.0 cm/year (Schellart et al., 2007). The tectonic state of stress is homogenous in the South of 5°N latitude; this state produces an East-West-oriented compression, which is responsible for the crustal deformation. (Ego et al., 1996).

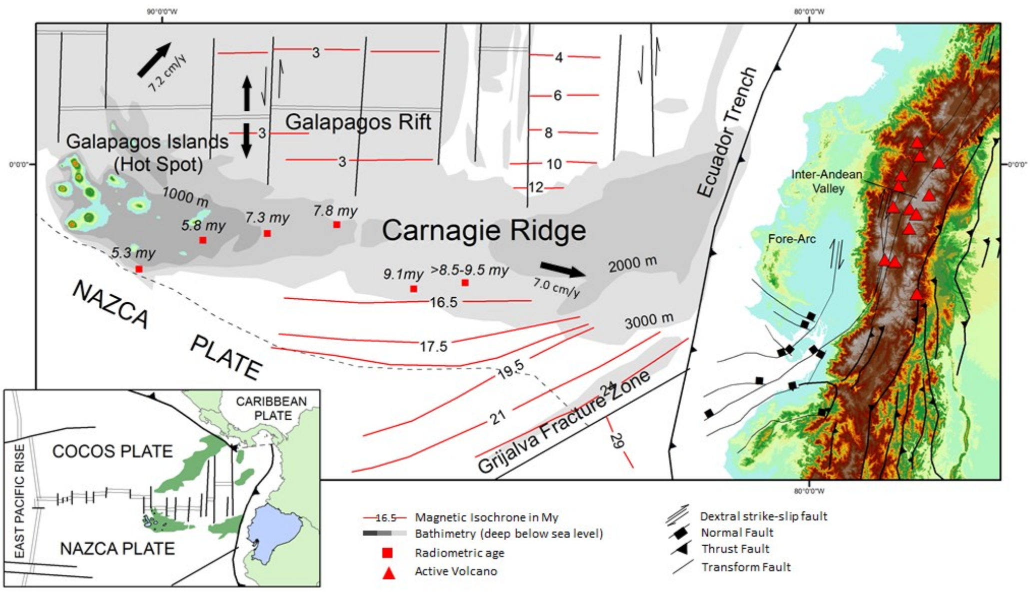

Figure 2: Geodynamical Setting Geodynamic Setting of Ecuador, showing mainland Ecuador on the South American plate and the Galapagos Islands on Nazca plate. (Redrawn after the Plate Tectonic Map of the Circum-Pacific Region (1981) and modified from Spikings et al., 2001).

3. METHODOLOGY AND DATA BASE

3.1 Geology data

Ruiz G. (2011) and Granda (2011) mapped the geology of the Chachimbiro prospect in detail. They reviewed previous reports and interpreted aerial photographs and other remote sensing images. Plenty of samples were collected for petrography, chemical analysis and dating. In addition, the lithology information showed by Vallejo (2007) and Bernard et al, (2010) was base data in order to show the Evolution of Chachimbiro Volcanic Complex. This evolution model is in a technical report by SYR in 2012 with a geological map in the scale 1:25000 as a result of the fieldwork.

Wrightson (2011) made the structural analysis in the volcanic complex. The data set includes orientations of fault segments and fractures in the Cretaceous basement rocks for the SYR, 2012 report. In the same context, Ponce (2011) described hydrothermal alteration observed in the rocks.

MMC-MMTEC and CELEC EP carried out geological fieldwork during April to July in 2016 in order to improve the geological model. Several new rock samples were collected. Thermoluminescence method was used to characterize the heat source, new hydrothermal alteration zones were stated and new geological lineaments were founded.

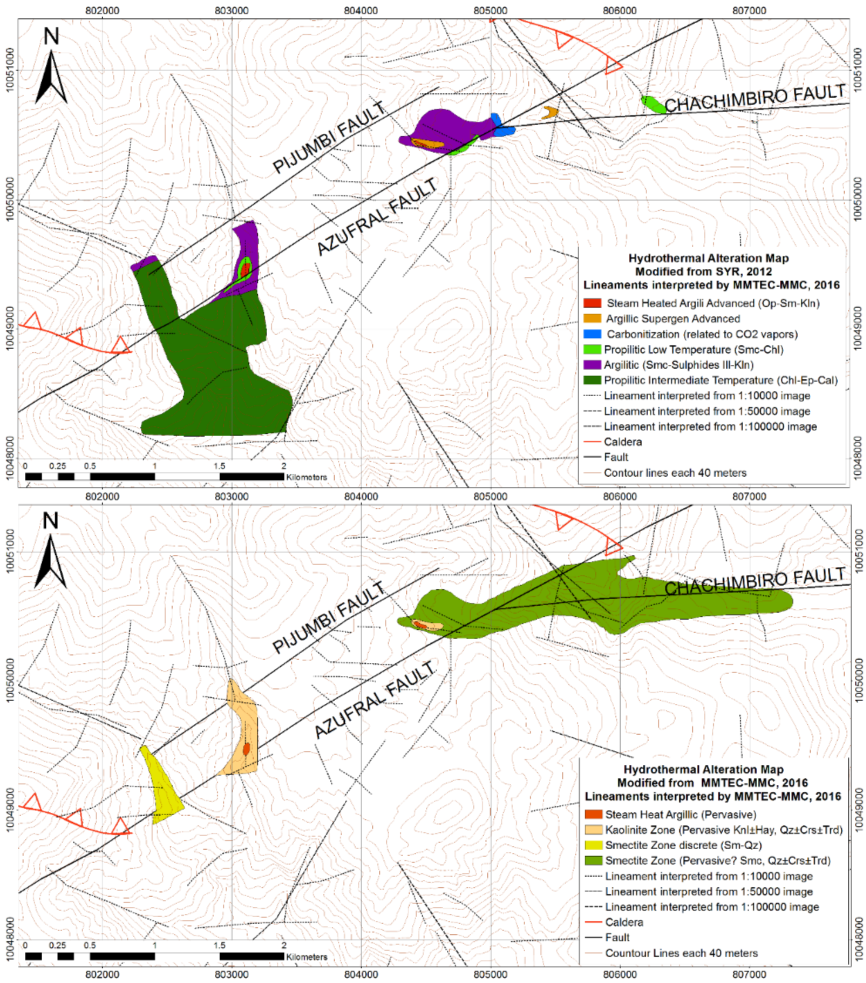

Figure 3: Hydrothermal alteration maps (modified from SYR, 2012 and MMTEC-MMC, 2016) which show the different zoning of the hydrothermal alteration areas, except for Steam Heat Argillic Zone.

3.2 Geophysical data

Western Geco Integrated EM CoE collected the Magneto Telluric data in 2011. In total 70 MT stations were installed and distributed as an irregular grid with a 0.35 km as a minimum spacing between stations. These data were processed at 1D and 3D inversions (SYR, 2012). The data were acquired by five component stand-alone remote reference MT stations with a nominal bandwidth from 0.001 to 10000 Hz. However, there are serious gaps in the survey because suitable sites were hard to find in the rugged terrain. Those areas are northwest of Minas de Azufre, north of Timbuyacu hot spring, south of Quebrada Azufral, near MT station M33, north of Santa Susana hot spring, and several gaps of less conceptual interest (Figure 4).

CELEC EP acquired MT/TDEM equipment set which composed of six Electromagnetic Geophysical Data Acquisition System in order to obtain a new data in the area where a low resistivity anomaly was found. These new data were collected from May to August of 2016.

This study takes eleven resistivity cross-sections made by Manabu Sugioka specialist of JICA-CELEC, who was supporting the geophysical exploration in Chachimbiro Prospect. The cross section shown below have been selected specifically for this study (Figure 4)

The MT data were processed using ASC-II files (Petrel format) for each cross section. These show the resistivity values as attributes with depth. In order to visualize the data in 3D, two main task were made: a) to define a grid in X, Y, Z directions and b) to populate the grid with data.

The grid was defined as a data cube, which covers all cross sections from the surface (Top Limit) to -4000 meters below sea level (Base Limit). The grid increment was defined at 50x50 m. in the X, Y and Z directions. Petrel allows the use of several interpolation methods for computing values in cells where there is no measured data. In this study, these methods were tested on the main input data. The Gaussian Methods show distortion in the results and do not allow to define clearly the resistivity anomalies. The Closest Method shows the interpolation in data blocks and distortion in the boundaries of the resistivity layers. The Functional Methods shows resistivity layers with soft boundaries; nevertheless, in areas with low resistivity, it shows distortion and unusual forms. The User Define Algorithm and Moving Average Methods show intercut cross sections and do not define resistivity layers.

The Kriging methods produce similar results to the methods mentioned above. The Kriging theory refers to smoothing and exact interpolation at the same time. In addition, the kriging method is a very flexible gridding method (Yang et al., 2004). In this study the Kriging Interpolation Method defined low and high resistivity layers with a minimum distortion compared to the results of other methods, allowing us to visualize the best manner results.

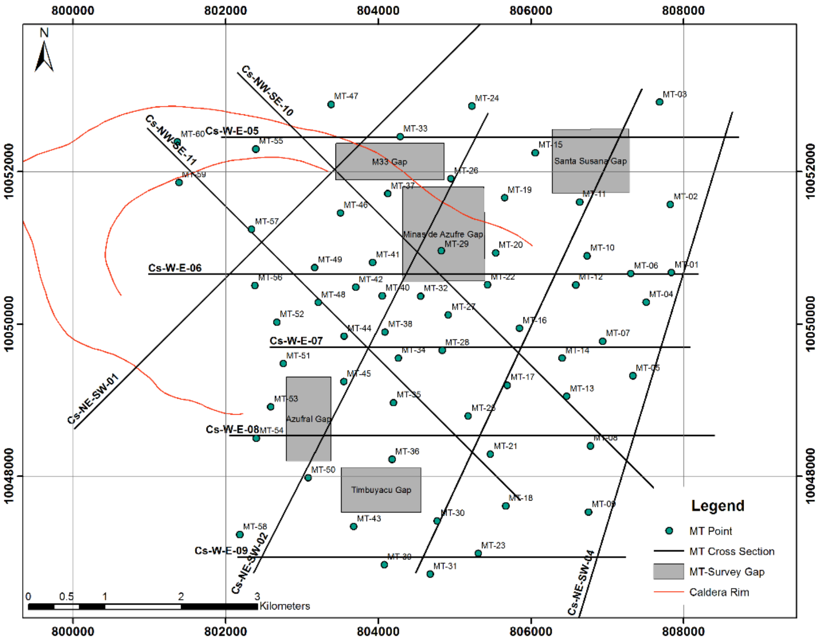

Figure 4: Magneto Telluric data points and cross sections used in order to create a data grid in Petrel Software.

3.3 Geochemical data

The Chachimbiro Geothermal Prospect is based upon a set of mixed chloride-bicarbonate hot springs (temperature up to 61°C) located along Quebrada Chachimbiro in the northeastern part of the prospect area. Currently, tThese springs are utilized as thermal spas. There is also a small set of hot springs at Timbuyacu (temperature up to 41°C) on the southeastern edge of the prospect area. Sulphur gas come up along the stream wall in local fractures, but this gas has been sampled with air contamination.

GeothermEx, Inc designed the sampling and analysis schedule, sampled the fluids (water and gas), reviewed the lab operation and results, and compiled, integrated and interpreted the geochemistry data (SYR, 2012). The areas sampled were the Chachimbiro, Timbuyacu, Pinguchela, Pilomanchi (hot springs) and Quebrada Azufral (gas and cold fluids, Figures 5A, 5B and 5C).

During the field campaigns, data were collected regarding physical and chemical parameters (T°, pH, Eh, Ec, flow estimation). The lab results show concentrations of major elements, minor elements and isotopes from in hot and groundwater, and also gas dry analyses. These chemistry data have been used to calculate liquid and gas geothermometers.

GeothermEx (2011) also took into account geochemistry data published by Aguilera et al. in 2005. These data have been reviewed by SYR in order to create a complete database.

MMC-MMTEC and CELEC EP worked together and completed a field surveys from April to June 2016. The main objective was to sample gas and water fluids at the same locations as GeothermEx (2011) and sample new hot spring locations (included Minas de Azufre gas manifestation, Figure 5D). This study used the ArcGIS 10.3 software in order to create shapefiles containing the element concentration as attributes. Petrel allow to import shape files as points on topography and create surfaces that show concentration of chemical elements or temperature anomalies (Figures 21, 22, 25 and 26).

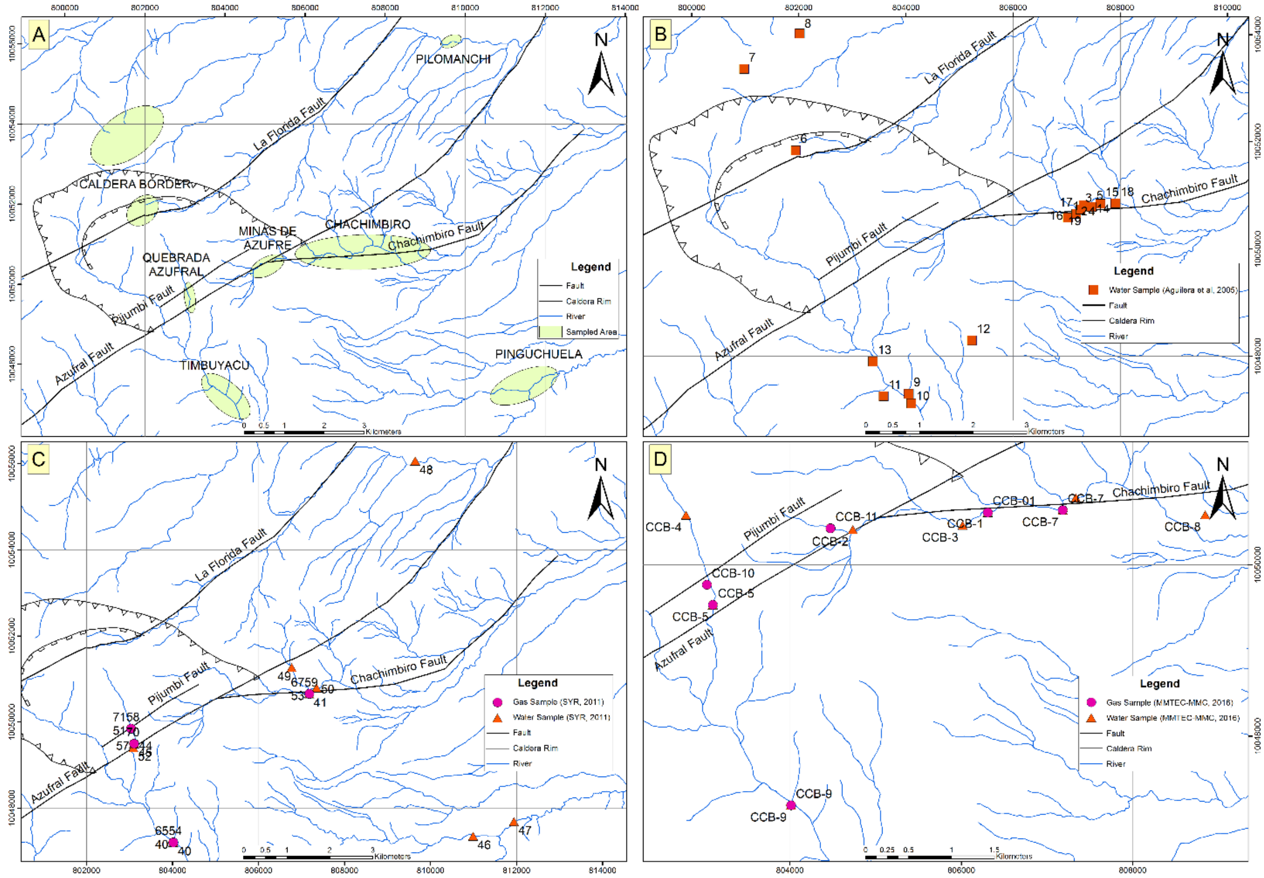

Figure 5: Geothermal manifestation Areas and area sampled (Gas, hot springs and fresh water) during field campaigns in 2005, 2011 and 2016.

4. INTERPRETATION USING THE PETREL SOFTWARE

4.1 Structural Analysis

Hydrothermal alteration is controlled by the Azufral and Chachimbiro Fault systems and NW-SE lineaments. Low emission of CO_2 and H_2S has been found in Pijumbi and Azufral Faults next to the hydrothermal alteration. The gas flow and alteration disappear in Northwest direction from this point. There are no springs or gas founded further than Pijumbi Fault and Azufral stream intersection. This would suggest the Pijumbi Fault is a boundary of the geothermal system. Hot Springs are located along the Chachimbiro Fault and the intersection with the Azufral Fault. This indicates that those faults control the upward movement of fluids and that the faults are permeable (Figure 5).

The quantity of lineaments increases next to the intersection between both faults and alteration zones, suggesting a fracture system associated with the main structures. MMTC-MMC (2016) point out a set of W-E lineaments caused by shearing activity of the Azufral Fault at Minas de Azufre area. This also indicates permeability in the system controlled by the Azufral Fault (Figure 6). There are parallel alignments of earthquakes to the Azufral and Chachimbiro faults in NE-SW and E-W directions respectively, and these lineaments coincide with lineaments interpreted by MMTEC-MMC (Figures 6).

It is important to note that the current regional structural system has main stress in E-W direction. This creates a subparallel fault system in NE-SW direction as Azufral and La Florida Fault trend, and creates the Chachimbiro Fault System at the same time. These fault systems allow permeability and upward movement of fluids in the system and create structural barriers.

4.2 Magneto-telluric data analysis

Geothermal systems show electrical resistivity anomalies related to clay minerals, and one of the most common is smectites. The formation of clay minerals in geothermal systems depends on the temperature and chemical conditions of the fluids that flow through rocks. Low resistivity (high conductivity) anomalies are observed on the outer and upper margins of the reservoir. It means that the low resistivity represents a seal (Cap Rock) which underlay a resistivity core (Sakindi, 2015).

Low resistivity (lower than 5 Ωm) has been connected to the smectite - zeoliote alteration zone in geothermal systems. The resistivity increases with depth until the chlorite and epidote zones is reached, which usually forms a resistivity core. As mentioned above, these mineral zones depend on temperature conditions. The smectite-zeolite zone forms at temperatures between 50-100°C and chlorite-epidote zone chlorite-epidote forms at temperatures exceeding 250°C (Árnason et al., 2000).

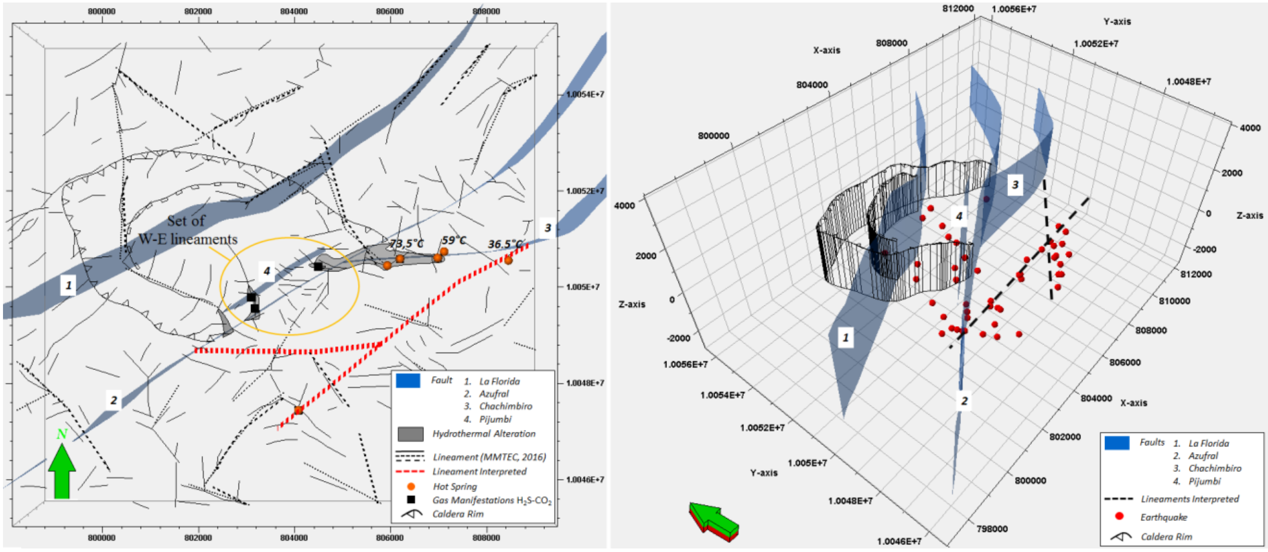

Figure 6: (Left) Map of lineaments interpreted that show increase of lineaments at Azufral and Chachimbiro faults and staggering lineaments in W-E direction at Minas de Azufre area. (Right) Alignments of earthquakes subparallel to Chachimbiro (4) and Azufral (3) faults.

A 3D grid was built to visualize the resistivity layers in Petrel. Then, iso-values of resistivity were generated filtering out areas of specific resistivity. As a result, a 3D shape of low resistivity emerges that shows the distribution of the anomalies. This allows the user to decide the direction of cross-sections. Once these have been determined, the cross-sections were completed with data already uploaded in the cube grid (Figure 7).

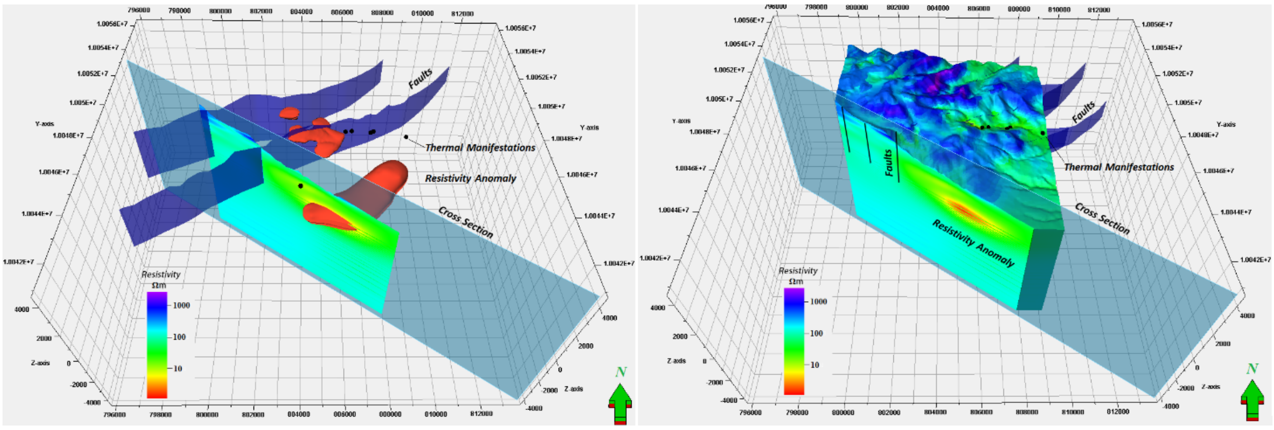

Figure 7: (Left) Determination process to define a cross section in Petrel software. (Right) Resistivity cross section through the cube grid populated with resistivity data.

Petrel allows creating cross sections at different directions. The distribution of the resistivity in Chachimbiro shows different layers. The shallow part with high resistivity (>160 Ωm) corresponds to both Quaternary volcanic rocks and tills. The low resistivity zone (<10 Ωm) would be related to the cap rock, which probably is composed by smectite. Below the cap rock, the resistivity increases gradually from 10 to 160 Ωm and includes a high resistivity core from 60 to 160 Ωm (Figures 8).

Lineaments interpreted are shown in the cross section associated with subsurface earthquakes (Figure 8). The projections from the surface to the subsurface of Pijumbi, La Florida and Azufral faults are aligned with earthquakes concentration and reach the high resistivity core. This interaction creates hot springs and gas emissions at the surface. It means that fluids in the core are connected to the surface through the Pijumbi, Azufral and Chachimbiro Faults.

4.3 Geochemical analysis

For the purpose of this report, the geochemistry data analyse will be focus on: 1) geographical distribution of the geothermal manifestation, 2) origin of the geothermal fluids, 3) temperature of the reservoir and 4) the permeability zone.

Isotope analysis is an indispensable tool to understand a flow pattern in geothermal systems. They are sensitive to changes in temperature, water-rock interaction, and other physicochemical process such as mixing and steam separation, and they are suitable as tracers for the origin water and regional flow direction.

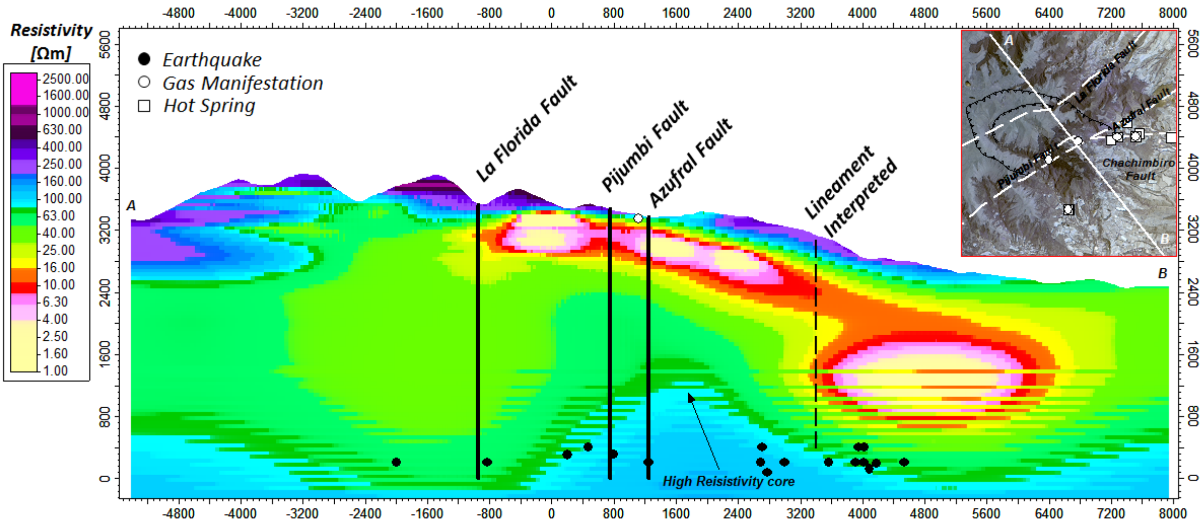

Figure 8: Resistivity cross section A-B that shows the high resistivity core and the relation among the lineament interpreted, earthquakes, fault, gas manifestations and resistivity anomalies.

The δ18O values of geothermal waters are most often higher (less negative) than those of local meteoric waters. The oxygen isotope shift has been termed in the diagram δ18O-δ2H. This is interpreted as an isotopic exchange between water and rock at high temperature (Abaya et al, 2000).

The Azufral water samples (CCB4 and CCB-5) are on the local meteoric trend line (Figure 9). These samples are cold groundwater without rock interaction at subsurface. The hot spring samples (CCB-1, CCB-2, CCB3- CCB-6, CCB-7, CCB-8, CCB-9) in Chachimbiro and Timbuyacu areas show an oxygen isotope shift, and these samples have similar values of δ2H isotope. It means that these hot springs have a meteoric origin with subsurface rock interaction (Abaya et al, 2000).

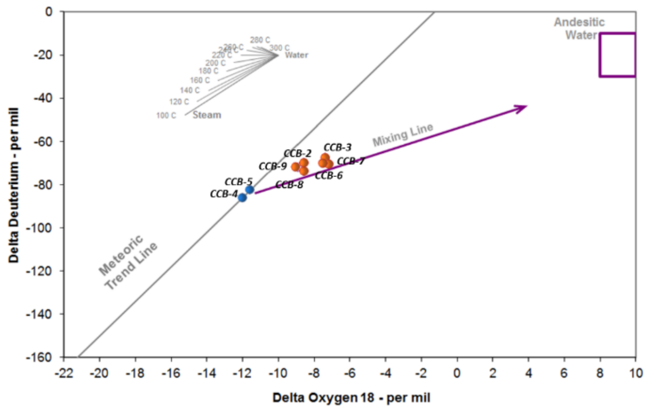

Figure 9: Diagram δ18O - δ2H, applied on the Chachimbiro water samples.

Figure 20 also shows a mixing line trend to the andesitic water. It means that there is an input of andesitic water to the geothermal system from significant depths, which is mixed with geothermal fluids.

Geothermometers and isotope analyses probably constitute the most important geochemical tool for the exploration phase. During the ascent of geothermal waters from a deep reservoir to the surface, they may suffer heat loss due to contact with colder rocks or boiling process. When geothermometers are applied, basic assumptions are always stated like the partial equilibrium between secundary mineral and solution, the fluids are not affected by mixing with colder solutions, and changes in the composition of steam and liquid due to boiling are taken into account. (D'Amore and Arnórsson, 2000).

This paper shows the temperature estimations based on liquid geothermometers using the chemical data collected by MMTEC-MMC (2016). The analysis of the results is in Appendixes 5 and 6. The chemical data were processed with Plotting Spreadsheet developed by Powell and Cumming in 2010. Only four samples have been taken to account to use geothermometers due to ionic balance analysis between anions and cations.

The Na and K cations usually are in high concentration at deep areas in the reservoir, and they show low concentration in meteoric water. Thus the Na/K ratio does not change even there is a mixing process between hot water and cold water. The geothermometers that use Na and K cations are the best for fluids derived from a thermal environment > 180°C (Yock, 2009). The highest temperature based upon Na/K geothermometers is around 285 °C (Tonini, 1980), but the average value is 240 °C. These values are close to the temperature values reported by SYR (2012) in their first model (260°C), which is related to a neutral chloride reservoir.

The temperature-estimated were used to create temperature iso-lines at different times in Petrel Software (Figures 10) based upon geochemistry data collected in 2011 and 2016. Figure 21 shows core temperature areas over 300 °C. This anomaly covers Minas de Azufre, Quebrada Azufral and partially the intersection between Chachimbiro and Azufral faults. The figure shows also an area with Na/K temperature less than 200°C that overlaps the hydrothermal zone.

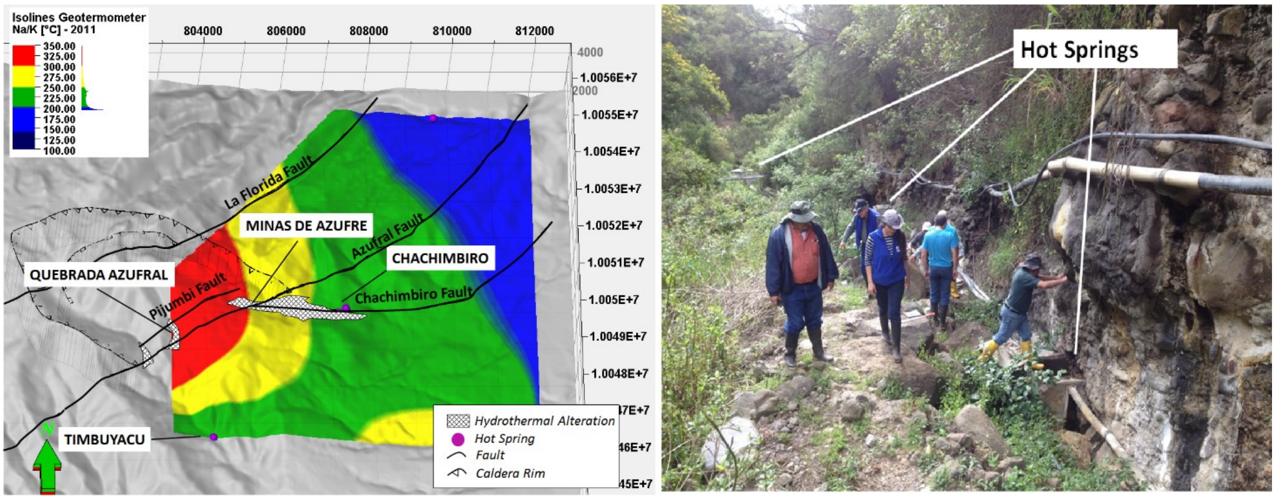

Figure 10: (Right) Hot Springs entrapped in cement box at Chachimbiro Area. (Left) Isolines based upon temperature obtained with K/Na Geothermometer, using ion concentration from hot spring samples collected by GeothermEx in 2011.

The hottest springs are located a long of the Chachimbiro Fault at Chachimbiro area. These hot springs precipitated CaCO3, and there is no emission of H2S in the area. Most of the hot springs are entrapped in cement box, which are used for the Chachimbiro Spa (Figure 10). It shows that the most permeable area is related to the Chachimbiro fault where the hot springs surge. The high temperature trends from Chachimbiro to the North, to the Southeast and to the Southwest. However, the iso-lines do not represent temperature gradient; the rock is not an isotropic environment, and the iso-lines have been interpolated based upon hot spring temperatures.

5. INTERPRETATION USING THE PETREL SOFTWARE

In this chapter, a conceptual model is shown as a result of the observations and assumptions above explained. This is an early model, so it is simple and based on analogies with geothermal fields better understood. Axelsson (2013) mentions the main components of geothermal systems. This study uses those guidelines and takes into account that not all geothermal conceptual models incorporate all the components.

5.1 Estimate of the system size

The sizes of geothermal systems worldwide tend to follow a size distribution in accordance with geological boundaries. In Chachimbiro there is considerable uncertainty concerning boundaries, temperatures and thickness of the system. This study defines the boundaries using the dimensions of the low resistivity anomaly as the areal extent. This could be interpreted as the largest possible area of a resource. Currently, the areal extent of the system is believed to be 11.06 km^2, which is the low resistivity anomaly between 0-10 Ωm and the thickness is about 3400 meters from the surface to the possible up-flow (resistivity anomaly 90 Ωm).

5.2 Nature of the heat source(s)

SYR (2012) suggests that the heat source is located near the Huga Dome due to its emplacement age (occurred 30.000 years ago) and composition (rhyodacite). These domes have been interpreted as magmatic intrusions controlled by La Florida Fault (Figure 11). On the other hand, Bernard et al. (2014) documented volcanic activity between 3640 and 3510 years BC that extruded a ~650-m-wide and ~225-m-high rhyodacite dome. This vent was located 6.3 km east and related to magma chambers emplaced at two different depths (~14.4 and 8.0 km). The deep reservoir at ~940 °C fed the central vent, while the shallow reservoir (~860 °C) had an independent evolution controlled by regional faults. It means a partial migration of the heat source to the East located below of Chachimbiro Dome (CH4) at shallower depths.

5.3 Location and strength of the hot up-flow/recharge zones, and origin of the fluid

The δ18O and δ2H isotopes show a clear meteoric origin of the hot spring in Chachimbiro (Figure 9). The geological structures allow the infiltration of the rain-ground water into the subsurface where it is heated up by convection, and then rise to the surface as hot springs.

The low resistivity layer partitions the geothermal hydrology field into a shallow-cold meteoric zone and a high-deep temperature zone. The low resistivity (lower than 5Ωm) is associated with a cap rock composed of clay with low permeability (Árnason, 2000). This cap rock is over the geothermal reservoir and accumulates heat by trapping the buoyant thermal up-flow. The up-flow zone is the reservoir zone in which flow is predominantly vertical and the temperature generally increases with depth (Cumming, 2009). It means that the up-flow in Chachimbiro is located where the resistivity core show up (beneath the caprock) and apparently controlled by Azufral Fault (Figure 11).

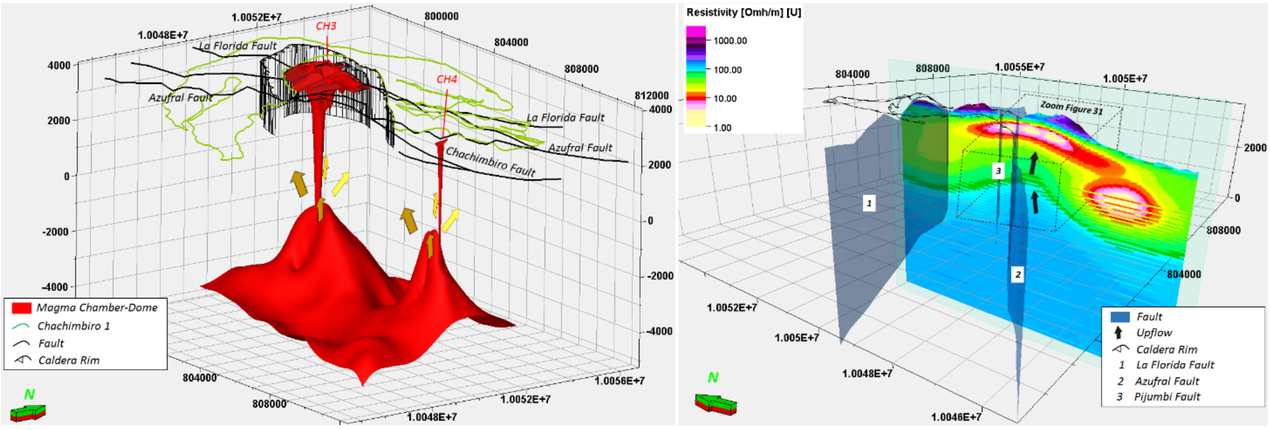

Figure 11: (Left) Magma intrusions that function as geothermal system heat source and fed the emission centre in Chachimbiro volcanic complex. (Right) Up-flow controlled by Azufral Fault.

5.4 Location and strength of colder recharge zones

Marginal recharge represents the influx of colder marginal meteoric waters into the geothermal reservoir. Cold water can flow into geothermal up-flow zone through permeable channels from the borders of the system, and may enter from overlying aquifers at higher elevations (Cumming, 2009).

The Chachimbiro volcanic complex is covered by Páramo (Andean ecosystem) which absorbs and percolates 600-1000 mm/year of rainwater at more than 3000 masl to the subsurface (Hofstede et al., 2014). The river system shows several hydrography sub-basin outlined by geologic structures that border and occur inside the volcanic complex. SYR (2012) point out fracture zones like border Caldera-1, lava flow fractures and contact zones, flow foliation in the dacite domes, contact zones between individual domes, and vertical fractures bordering the dome feeder dykes that helps the permeability of the system. These structures and lineaments will allow the groundwater to enter to the up-flow zone and host the geothermal resource.

5.5 General flow pattern in the system, both in the natural state and changes in the pattern induced by production.

As mentioned above, the low resistivity anomaly often is correlated with more intense alteration overlying up-flows. Water dominated reservoirs usually have outflow zones where buoyantly hot water flows up through tabular aquifer under the smectite cap rock. The outflow is predominantly horizontal, and the temperature declines with depth below the main outflow zone (Cumming, 2009).

Steam-dominant systems are usually sealed by a smectite layer and associated with fumaroles, no sinter and ± mud pots. On the other hand, liquid-dominant systems have discharge zones (out-flow) where the hot water reaches the tabular aquafers above of the caprock and show sinter, fumaroles and ± mud pots. Chachimbiro apparently is a liquid-dominant due to the chemistry of the hot springs in its natural state.

In the reservoir and core resistivity, the fluids are in convection due to the interaction between hot/basal recharge from a magmatic chamber and fluid meteoric water that percolates through the open structures. The geothermal fluids are accumulated beneath the cap rock. There is no chemical evidence for magmatic fluid input.

The outflow is established through the system faults. This is evidenced by several hot springs and gas manifestation located on faults that bound the low resistivity anomaly. It means that there is a subsurface connection among the up-flow zone with Chachimbiro (hottest spring), Azufral and Pijumbi Fault (gas manifestations). The Timbuyacu springs do not have a structural connection with the up-flow zone (outermost zone). It may be explained as a lateral discharge of the system through a hidden structure. The Pilomanchi and Pinguchuela hot springs show lateral discharge that has been mixed with groundwater as indicated by their low temperature (24.8 and 30°C, respectively) and high concentration of magnesium with regard to Chachimbiro hot-springs (Figure 12).

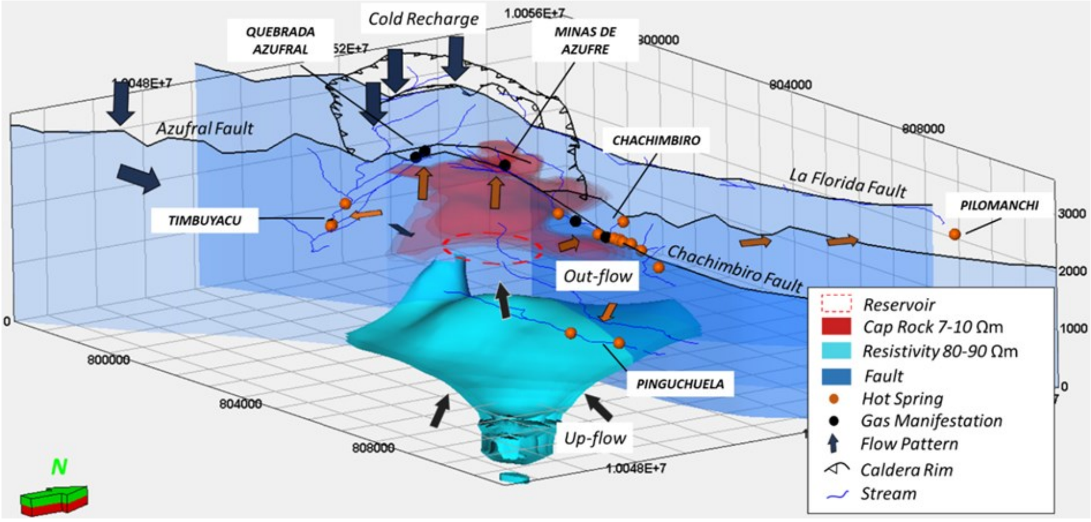

Figure 12: Flow Pattern Fluids (perpendicular view to the main faults) that shows the cold recharge areas at Chachimbiro highlands (Caldera Rims and Domes and the up-flow zones beneath of cap rock (high resistivity).

5.6 Temperature in the system.

For the purpose of this study, the temperature was estimated by two methods. The first method involves Na/K geothermometer used in the samples collected in 2016. This shows temperatures from 240°C. to 260°C. The second method uses the resistivity. It shows an increase in resistivity beneath the low resistivity layer. However, the resistivity method indicates the temperature reached at one stage of the system in a period of time. Thus, it does not indicate the current temperature of the system.

In many high-temperature geothermal systems, the transition from low to high resistivity anomalies corresponds to the mixed clay/chlorite zone. Below these zones, the resistivity increases considerably due to the chlorite-epidote zones formation. It indicates temperatures above 250°C (Arnason, 2000).

Figure 13 has been sketched following the conceptual guidelines detailed in Arnason (2000) and Cumming (2009), and based on the Chachimbiro resistivity survey and geochemical data. This shows a caprock defined by the <10 Ωm anomaly, which is compound by hydrothermal smectite. Below this anomaly, a neutral geothermal reservoir at >240°C is located, and an intermediate aquifer flows and carries the hot water to the permeable Chachimbiro fault where the hot springs rise to the surface.

5.7 Locations of main permeable flow structures.

The permeable structures in the Chachimbiro area are located where the hot water rises to the surface. The Chachimbiro fault controls the ascent of the water in the area. This has E-W trend limited by Azufral Fault and cut the cap rock. Thus, it indicates that the Chachimbiro fault controls the fluid flow from the reservoir to the surface. The Minas de Azufre and Quebrada Azufral areas show hydrothermal alteration (smectite) in outcrops related to the cap rock registered in the magneto-telluric model. These areas only show CO_2 and H_2S emissions at low pressure. It means that these areas have low permeability compared to Chachimbiro Area. It is important to point out that the H_2S and CO_2 emissions indicate volcanic activity in the subsurface, but no necessarily an active geothermal system. The main signal of the geothermal system in Chachimbiro is the presence of hot springs (Figure 13).

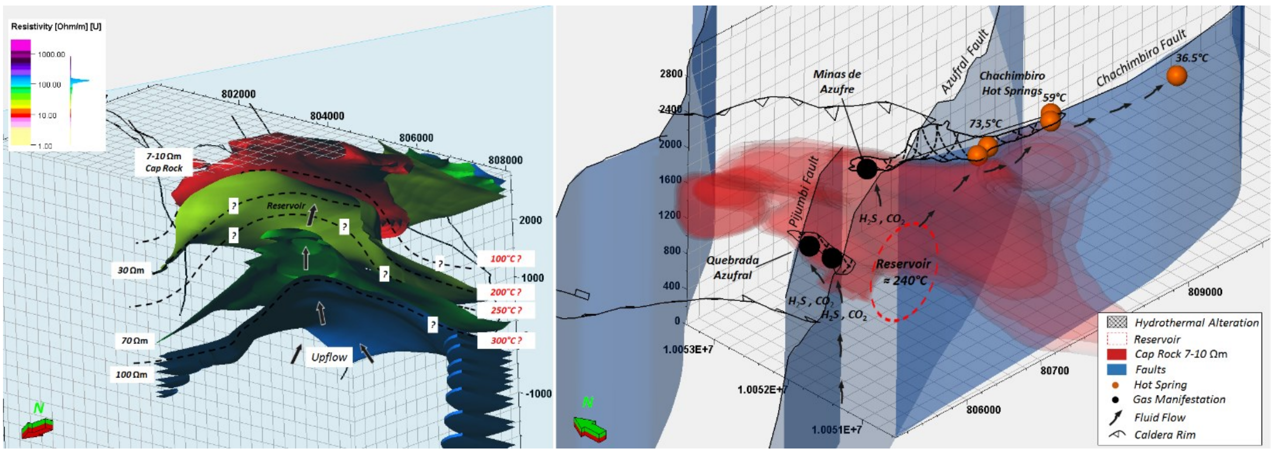

Figure 13: (Right) The isotherms in Chachimbiro Geothermal System sketched based upon guidelines detailed in Arnason (2008) and Cumming (2009). (Left) High Permeability at Chachimbiro hot Springs controlled by Chachimbiro Fault and Low Permeability at Azufral Quebrada and Minas de Azufre controlled by Azufral and Pijumbi Faults.

5.8 Delineate of cap-rock in the system (horizontal and vertical boundaries)

The Chachimbiro System has a caprock as horizontal boundary defined by interpolation of magnetotelluric data in Petrel software and forms an irregular shape that covers 11 km2 with a thickness of~340 metres. Possibly, the low resistivity cap rock corresponds to temperatures in the range from 50 to 100°C. The transition from the low resistivity cap to the resistive core corresponds to a temperature range from 230 to 250°C, where the reservoir would be emplaced. The horizontal natural boundaries are the Chachimbiro, Pijumbi and Azufral faults. These control the hydrothermal alteration and geothermal fluids in the past and present time. These structures partially enclose the cap rock in the north (Chachimbiro Fault) and crosscut the middle of the cap rock (Pijumbi and Chachimbiro). However, geological structures have not been recognised in the south and east to enclose the system.

Axelsson (2013) mentions other components in the Geothermal Systems such as pressure in the system, locations of phase zones, as well as steam-dominated zones and division of systems into subsystems. The Chachimbiro Project is in Prefasiability phase, which means there were no boreholes in the area during this study. The first borehole was run at the end of 2017. Thus, there was not enough available data to describe all the outlined components of the model.

6. DISCUSSION AND PROPOSAL WELL

The Geothermal models of Chachimbiro have been presented by Aguilera (2005) and SYR (2012) using surface database concluding that Chachimbiro has a small-moderate resource with high temperature. New geochemistry data collected by MMTEC-MMC (2016) have been analysed in this report, and the results are not different from SYR's (2012) (reservoir temperature ~240°C). This report models the resistivity data collected by SYR (2012) with Petrel and shows an areal extent between 11 km2 - 12 km2 similar than reported by SYR in 2012. Chachimbiro prospect will enter to full exploratory drilling phase. Before the first drilling well at Chachimbiro in 2017. The question was: Where should the first well target be located? Geothermal Systems have been developed where there are three common parameters: temperature, permeability and fluid concentration. These parameters are in continuous discussion in Chachimbiro even after the first drilling.

SYR (2012) proposed a vertical well (slim hole) at the coordinate 803500E/10049900N WGS 84-17S. This assumes that the Azufral fault has a slight dip and controls the permeability in the system. This point is located between both the Azufral and Pijumbi faults that control the permeability into the system. However, this point is on the limit of the anomaly. The recent drilling well was located at this coordinates but targeted to the centre of the system.

This report aimed to point out additional well-targets related to the permeability given by faults interaction and their relation with hot springs, gas manifestations, hydrothermal areas, temperatures, the cap rock, and the up-flow zone. The first target is the intersection point between Chachimbiro and Azufral Faults under the cap rock. The second target is the Chachimbiro fault, which is apparently the most permeable area and controls the up-flow of the hottest water to the surface. Three different locations are proposed to access these targets.

The second point proposed location is at the northern border (804970E /10050950N in WGS 84-17S). The permeability is controlled by Azufral and Chachimbiro faults interaction in this area. The drilling-well would reach the 30 Ωm resistivity anomaly (possibly 200°C) at ~1100 m depth and the 70 Ωm resistivity anomaly (possibly >250°C) at 1940 m depth.

The third point is located on the opposite side of the drill point proposed by SYR (805600E/10050200N in WGS 84-17S), but closer to the resistivity anomaly centre. The permeability in the sector would be controlled by Azufral and Pijumbi faults, and the well would reach the 30 Ωm resistivity anomaly (possibly 200°C) at 950m depth, and the 70 Ωm the resistivity anomaly (possibly >250°C) at 1750 m depth.

The first two options are directional wells to cross the fault intersection, and the third is a directional well that should cross the Chachimbiro fault. These wells should reach down around 2000 m deep, where the plausible reservoir is located (Figure 14). These drill sites have been selected without consideration of road access, protected areas, or settlements.

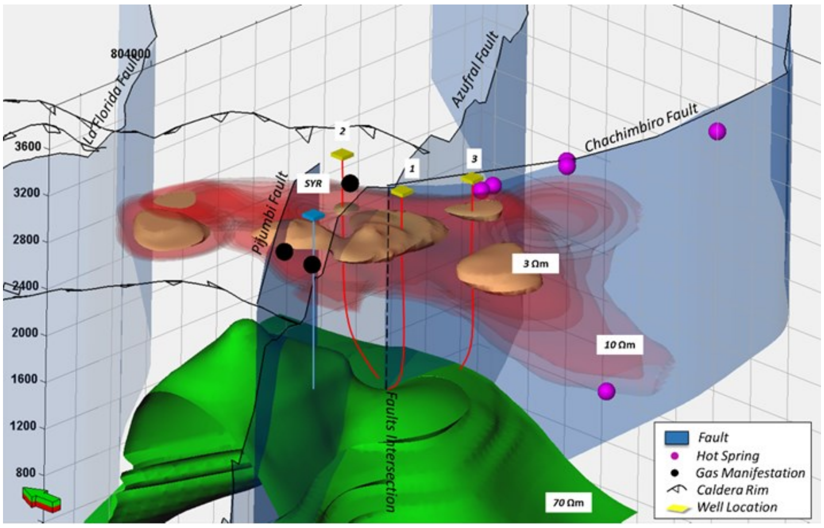

Figure 14: Proposal locations to drill the first geothermal well in Chachimbiro Prospect using Petrel.

7. CONCLUSIONS AND RECOMMENDATIONS

Petrel is a convenient tool to model Geothermal Systems. This allows the visualization in 3D using all surface data collected so far and allows new data to be included as it is obtained.

Lineaments interpreted and faults are lateral boundaries in the system and through which the natural discharge is emplaced. However, it is necessary to correlate these interpretations with gravimetric data. A magma chamber feeds the main and lateral emission volcanic centres in Chachimbiro that also is the heat source of the system. Nevertheless, the location of this magma chamber has to be confirmed with gravimetric and new passive seismicity data.

The low resistivity data from 0 to 10 Ωm is interpreted as a cap rock above the reservoir. The resistivity model at different ranges of resistivity forms a concave shape where the up-flow could be emplaced. The Na/K liquid geothermometers are the most applicable in Chachimbiro, and these show temperature around 240°C in the reservoir. This is consistent with the resistivity layers from 30 to 70 Ωm (possible 200°C to 250°C). However, the Chachimbiro hot springs show poor equilibrium with the rock and the resistivity anomalies could not represent the current temperature in the system.

The flow pattern consists of cold recharges in the Chachimbiro highlands. This cold recharge is meteoric water (isotopic evidence) that interacts with the up-flow under the cap rock and forms a possible liquid-dominant reservoir. The expressions of this reservoir are the gas manifestation in the Quebrada Azufral and Minas de Azufre areas (low permeability) and the hottest springs in Chachimbiro Area (high permeability). Lateral flow discharges are located in Timbuyacu, Pinguchuela and Pilomanchi areas.

Two drilling targets are proposed in this study. The first is the intersection between Chachimbiro and Azufral Fault, and the second is Chachimbiro fault, which is apparently the most permeable area in the system.

It proposes two different sites to reach the intersection faults, and one site to cross the Chachimbiro fault. From these locations, directional wells should be drilled and reach around 2000 m in depth where the possible reservoir is located.

The current geothermal model gives a 3D visualization using Petrel, and it allows incorporating and improving this model with newly available data.

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