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## **STUDY OF CHACHIMBIRO AND CHACANA GEOTHERMAL PROJECTS, ECUADOR, AND VOLUMETRIC ASSESSMENT**

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### **ABSTRACT**

Chachimbiro and Chacana geothermal fields are located in the Andes ridge in the north of Ecuador. Previous prefeasibility studies of geology, geochemistry and geophysics were reviewed and the acquired information was used to generate different scenarios for volumetric assessment of the geothermal fields depending on the results from resistivity models and geothermometers.

Chachimbiro was treated as a high-temperature field in the volumetric assessment, supported by the presence of a high-temperature resistivity structure. Chacana was treated in a similar way, but as an intermediate- to low-temperature system. Using similar processes with different scenarios may help to advance them to the next stages of exploration. The true conditions of the fields must be discovered by drilling. With an exploratory drilling campaign, the estimation of the models would partly be fixed to more accurate parameters.

### **1. INTRODUCTION**

The main objectives of this study were to review available data from Chachimbiro and Chacana, geothermal fields in northern Ecuador, and using part of the information to make volumetric assessments. To reach these goals an overview was made of the geology, geochemistry and geophysics already published in the consultancy reports of prefeasibility studies in order to develop a conceptual model for the Chachimbiro and Chacana geothermal projects (SYR, 2012a; SYR, 2012b). Estimations of the potential and power capacities of the geothermal fields were deduced from volumetric assessments of both projects. Different scenarios were selected for the fields depending on the resistivity pattern and the temperatures deduced from geothermometers. Chachimbiro was treated as a high-temperature system; two areas in Chacana were treated in a similar way but as medium- to low-temperature systems, partly due to recent volcanism (in the 17<sup>th</sup> century). These are only examples, but further analysing of the data and using similar processes with different scenarios may be useful for comparison and for advancing to the next stages with respect to the exploration and development of the fields.

Additionally, it may be useful to compare some examples of volumetric assessment for Chachimbiro to an older model already done for that field (Torres and Urquizo, 2013). Extensive information was gained

in the review of previous work from the two geothermal fields. The results show different possibilities of the characteristic features of each geothermal field, suggesting the establishment of various modelling alternatives, including volumetric assessment based on their main parameters.

Ecuador is located in the northern part of South America, between  $01^{\circ}30'$  N and  $05^{\circ}00'$  S, and between  $75^{\circ}12'$  and  $81^{\circ}00'$  W (Figure 1). The surface area of Ecuador is 283,561 km<sup>2</sup>, and there are diversities in climate caused by the presence of the Andes ridge, the influence of the sea and jungles.

Ecuador is a country which, due to its geological and geographical conditions, has the capability to develop renewable energy, especially hydropower, from river flows. Geothermal energy is a very promising field for the national goals of changing the energy matrix through developing renewable energies. Currently, geothermal fields in Ecuador are being studied, which includes making conceptual models.

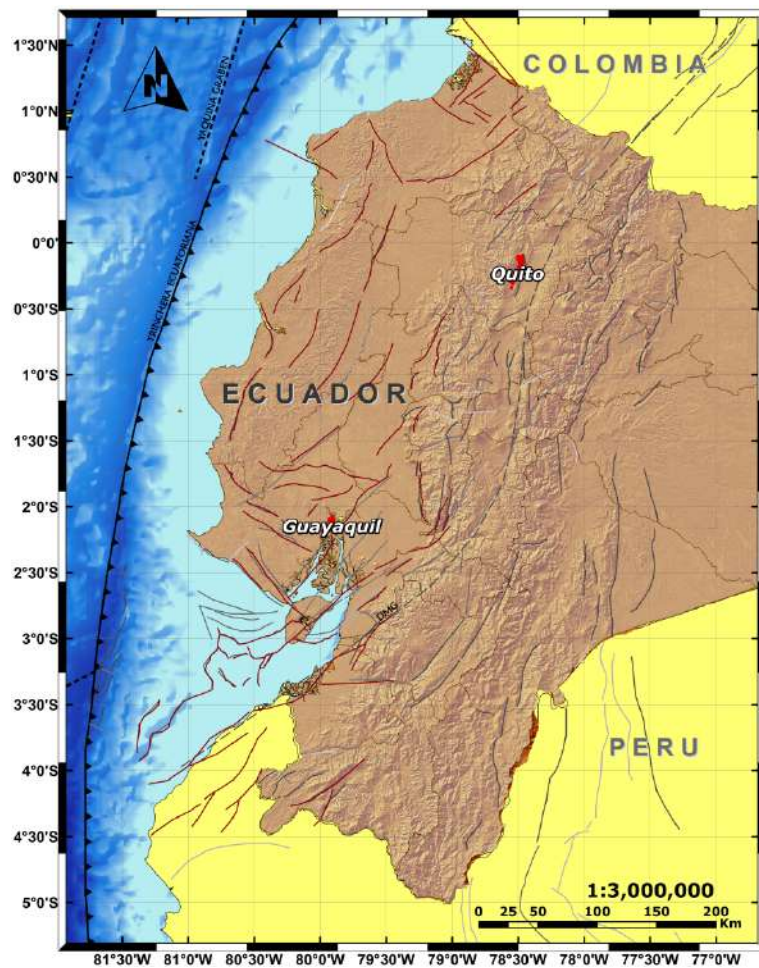


FIGURE 1: Geographical map of Ecuador, showing the capital city Quito, located in the Andes ridge

Chachimbiro geothermal field is located in the eastern part of the Andes occidental ridge, in the northern province of Imbabura (Figure 2), located 75 km north of Quito, the capital city. This complex is characterized by a set of mixed chloride-bicarbonate warm springs, with temperatures between 25 and 61°C, located up to 5.5 km apart from each other. In addition, this area of interest has cold gas manifestations with hydrothermal alteration in its higher topographical zones.

Chacana geothermal project is at the crest of Real Andes ridge, in the north-central mountainous region of Ecuador, located 40 km east of Quito (Figure 3). The topography of the area is rugged, and its elevation is between 3200 and 4600 m a.s.l. The isotopic composition of samples taken from the surface of warm springs shows that the water has a meteorological origin with a neutral alkaline-chloride chemistry, and temperatures between 58 and 72°C.

## 2. GEOLOGICAL SETTINGS OF THE GEOTHERMAL PROSPECTS

Chachimbiro and Chacana are parts of the Ecuadorian Quaternary volcanic arc, along with 60 volcanoes, formed by subduction of the Nazca Plate under the northern Andean block of the South American Plate.

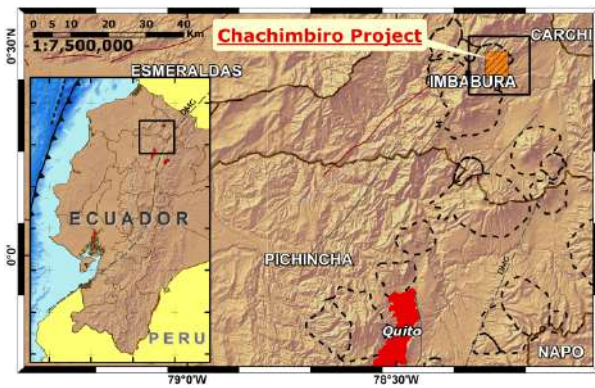


FIGURE 2: Chachimbiro geothermal project, located 75 km north of Quito

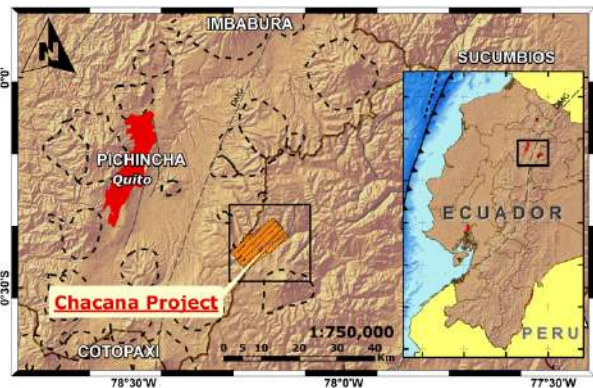


FIGURE 3: Chacana geothermal project is located 40 km east of Quito

The convergence between the Nazca and South American plates is estimated to be 60-80 mm/yr with the direction of convergence between N81°E and N120°E (SYR, 2012a; SYR, 2012b).

Several Quaternary volcanic centres occur near the Chachimbiro and Chacana projects, shown by black dashed lines in Figures 2 and 3.

## 2.1 Chachimbiro

### 2.1.1 Volcanic evolution of Chachimbiro

The Chachimbiro project area is located in the Chachimbiro volcanic complex (Figures 4 and 5), composed of andesitic lava flows and pyroclastic deposits associated with dacitic domes. The thickness of the Chachimbiro volcanic materials is approximately 1000 m (SYR, 2012a). The Chachimbiro volcanic complex was formed in three stages (Figure 4).

In the first stage an Andesitic stratovolcano was formed with big effusive flows of lava streaming radially from the eruptive centre. After the formation, the volcano suffered a collapse and generated a debris avalanche flowing towards the east. These events occurred in medium Pleistocene between 500,000 and 300,000 years ago. This stage is known as Chachimbiro 1.

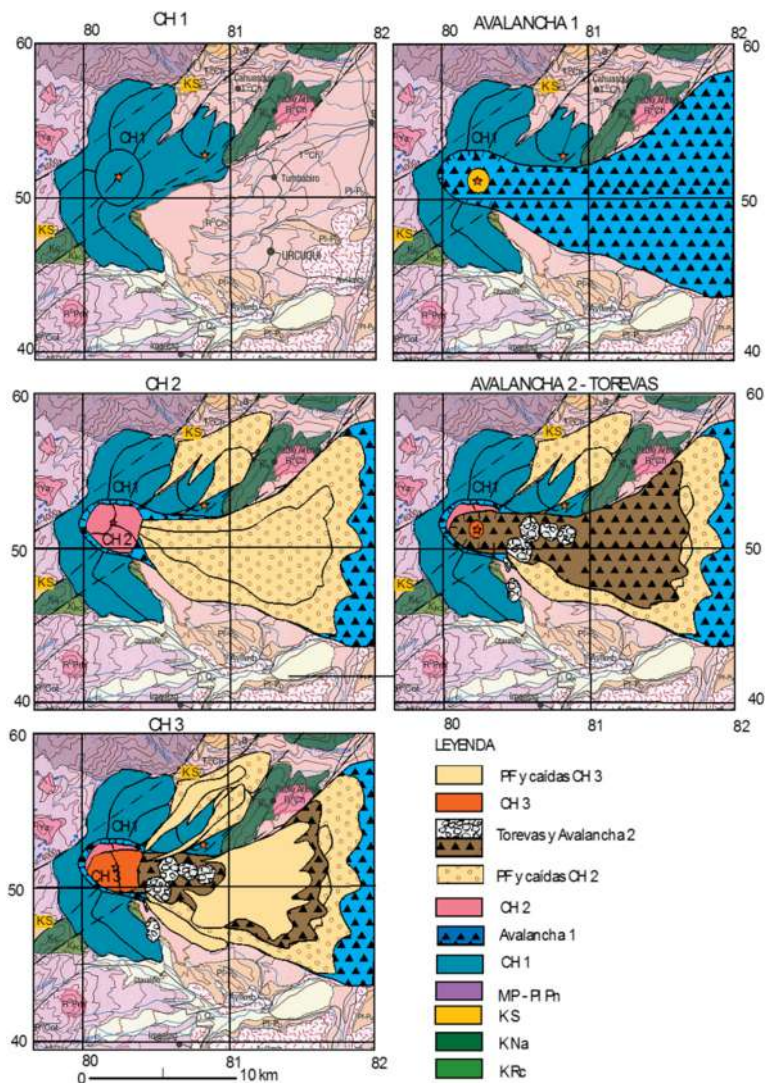


FIGURE 4: Evolution of Chachimbiro volcanic complex (Ruiz, 2011)

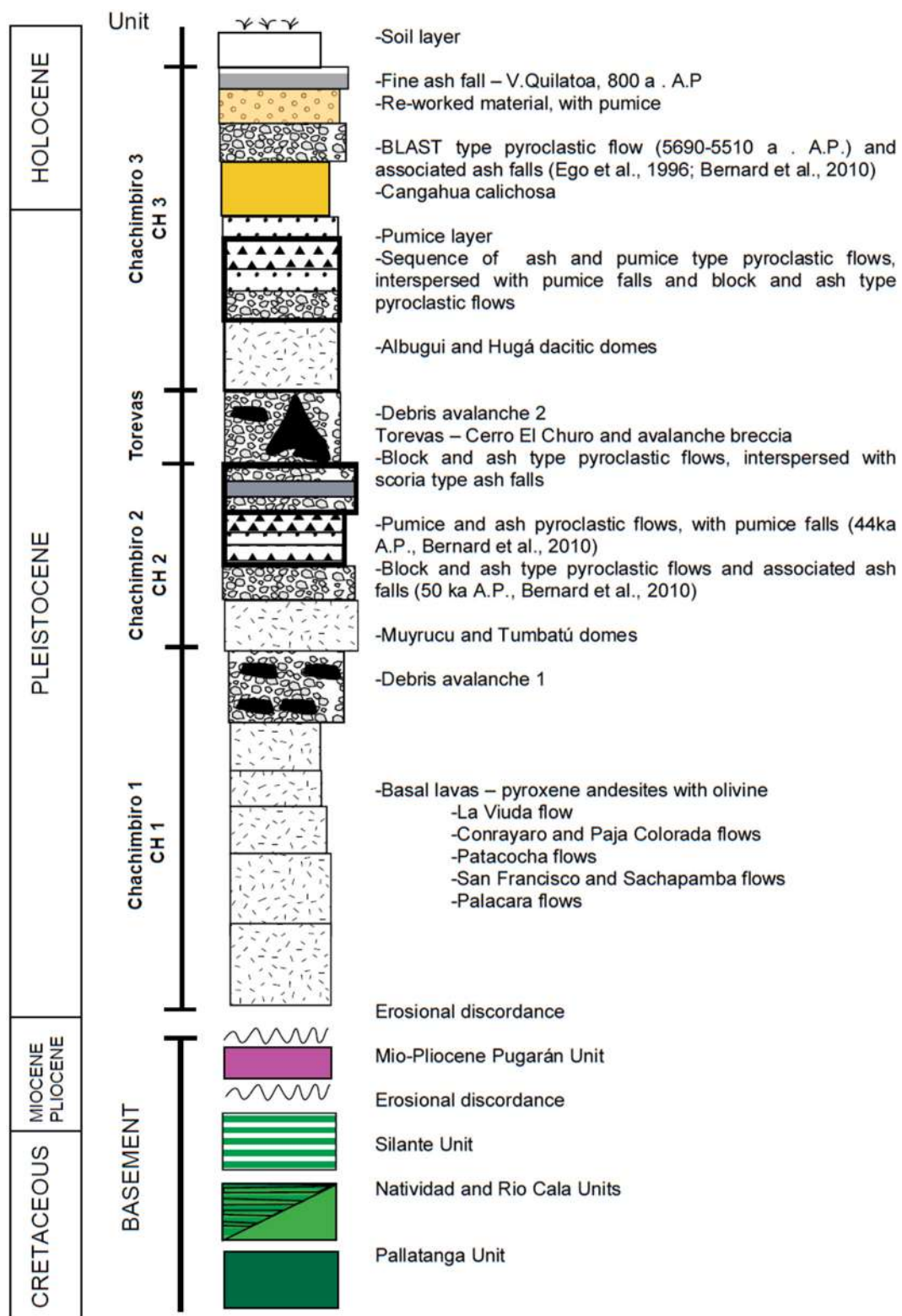


FIGURE 5: Lithological column of the volcanic and Cretaceous rocks at Chachimbiro (Ruiz, 2011)

In the second stage, andesitic and dacitic domes were formed by eruptions in the collapsed caldera. A second landslide occurred flowing to the east with an escarpment associated with the first collapse. Some of these domes were displaced from their original locations. This stage is called Chachimbiro 2 and the events occurred between 120,000 and 50,000 years ago.

In the last stage, new domes of dacitic-andesitic composition were formed extending into the Holocene, located at the same place as the second landslide. These events occurred 30,000 years ago, and are known as Chachimbiro 3. The stages of formation of the Chachimbiro caldera are shown in Figures 4 and 6 and the geological succession is shown in Figure 5.

**2.1.2 Stratigraphy associated with the Chachimbiro caldera**

The basement in the Chachimbiro caldera consists of Cretaceous rocks which piled up in the subduction zone, composed of five geological formations (Figure 5). The oldest geological formation in the basement is the Pallatanga unit which is formed by basaltic lavas and sediments associated with oceanic shelf basalts. The Río Cala unit consists mainly of massive lavas of basaltic-andesitic composition, and volcanic rocks with local sandstone lenses (SYR, 2012a). Above, the Natividad unit is a sedimentary sequence of turbiditic sandstones, mudstones, cherts, and interbedded lavas and tuffs that are basaltic to basaltic andesite in composition. The Natividad unit has a dominant Cretaceous lithology. The next geological formation is the Pilaton unit which is composed of sedimentary rocks with massive volcanic conglomerates, breccias, sandstones and cherts. Finally, the Silante unit consists of micro breccias and massive volcanic tuffs interbedded with layers of volcanic shale and sandstone. The Silante unit is of Upper Cretaceous age and depicts the continental volcanic products (Figure 5).

The tertiary volcanics in the Chachimbiro area are represented by the Pugaran volcanic unit of Upper Tertiary age, especially Miocene-Pliocene. This volcanic unit is composed of andesitic lava flows and hornblende dacite tuffs and breccias (SYR, 2012a).

In the study area, Quaternary volcanic products from other volcanic centres occur on the margins of the Chachimbiro complex. These include andesitic lava flows from the Cotacachi stratovolcano south of the map in Figure 6, and pyroclastic deposits associated with the Piribuela dacitic dome, also to the south.

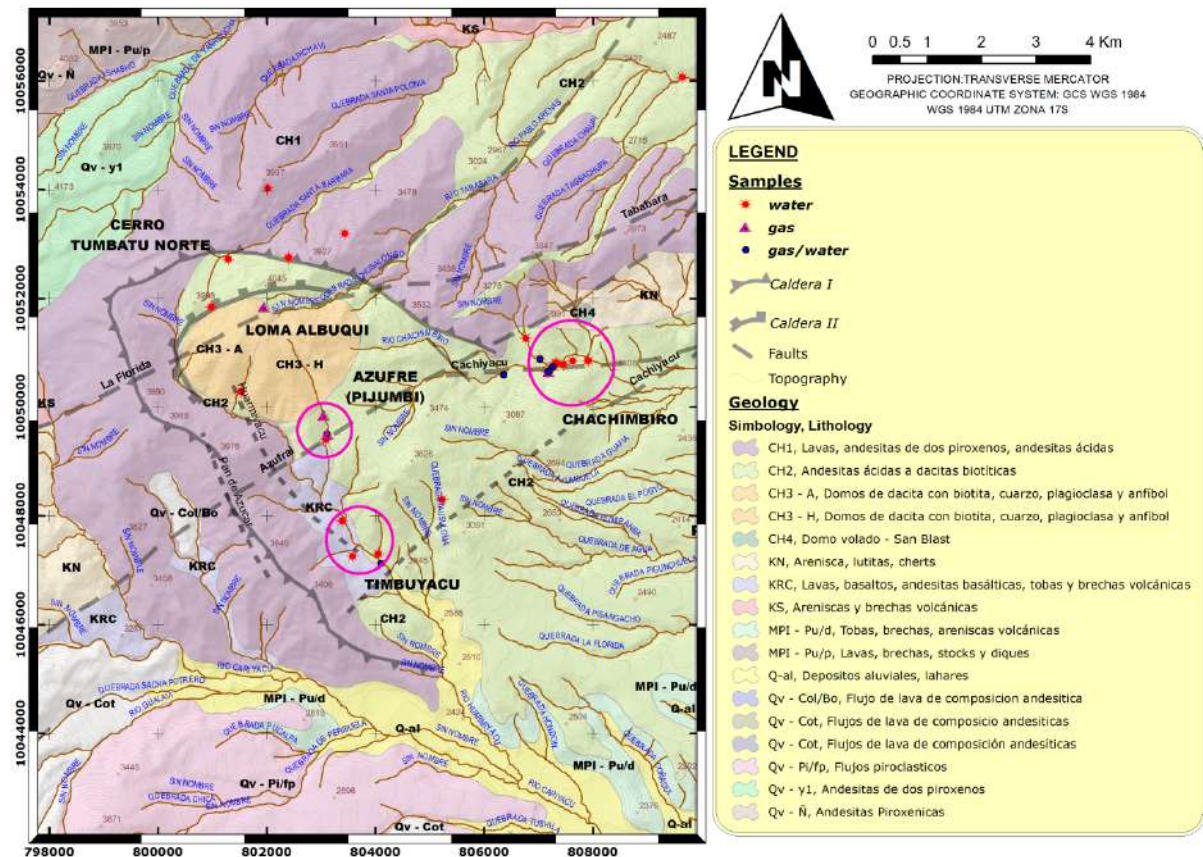


FIGURE 6: Chachimbiro geothermal project area: geological and structural map (modified from Torres and Urquiza, 2013)

Andesites and rhyodacites associated with the Yanaurco volcano overlap the Chachimbiro volcanic on the northwest slope (Figure 6). An unconformity is at the contact between the Cretaceous and overlying Tertiary and Quaternary volcanics (Figure 5). The thickness of the Chachimbiro volcanics varies, with a maximum of about 1000 m in the area of the Hugá dome, located in the centre of the caldera.

### 2.1.3 Structural geology

The fault system in the study area has played an important role in the origin of the caldera and the potential location and circulation of the geothermal fluids.

The NE-SW striking Florida fault system forms the contact between the Cretaceous Natividad and Silante units (Figure 6). This fault complex underlies the eruptive centres for the Huanguarillo volcano and the Hugá-Albuji domes, indicating that its deep fractures contribute to the rise of lavas from the Chachimbiro volcanic complex.

The Azufral fault system, in the central portion of the project area, also trends NE-SW (Figure 6), which indicates that it is a right lateral strike slip fault system (SYR, 2012a) which may represent the contact between the Natividad and Rio Cala formations. The Azufral fault system is marked by the occurrence of gas seeps and hydrothermal alteration, which could be evidence of the circulation of geothermal fluids.

### 2.1.4 Thermal manifestations

In the Chachimbiro geothermal project, four areas of thermal manifestation were studied. Two of them are warm springs called Chachimbiro and Timbuyacu, the others are gas manifestations in places called Pijumbí and Minas de Azufre (Figure 6).

The Timbuyacu field is located where the surrounding topography lies between 2750 and 2860 m a.s.l. The gas consists mostly of CO<sub>2</sub>, with low concentrations of H<sub>2</sub>S. The temperature of the water in the two hot spring areas is below 45°C. The Chachimbiro field is located where the surrounding topography lies between 2520 and 2620 m a.s.l. The water temperatures in the hot springs are up to 61°C. Pijumbí and Minas de Azufre gas manifestations are located in higher topographic places, along the Azufral fault in a northeasterly direction. The distance between the two places is approximately 2 km.

## 2.2 Chacana

### 2.2.1 Chacana volcanic caldera complex

Early studies of Hall and Mothes (1997) and Hall et al. (2000), showed that Chacana is a big caldera structure of rhyolitic composition with all its characteristic features, formed in large siliceous eruptions. The Chacana caldera complex is 40 km long in a N-S direction and 10-15 km long in an E-W direction. The diameter, including outer flanks, is approximately 50 km, making Chacana the largest caldera in the northern part of the Andes ridge. The evolution of the caldera dates back more than 2.5 My, according to its radiometric date (Hall et al., 2000).

The flanks of the Chacana caldera are composed of deposits of ignimbrites, ash flows, glassy lavas, breccias and tuffs (Figure 7). This volcanic succession is called “tablones”, and has a thickness of over 1200 m and an estimated volume of 670 km<sup>3</sup>, based on surface area and thickness.

The depression of the Chacana caldera was formed by subsidence and a collapse of the volcanic structure, due to emissions of large volumes of eruptive material and the eviction of magma from its magma chamber. The central depression is composed of pyroclastic material and younger lavas from Late Pleistocene. Subsequently, breccias and tuffs filled the depression.

Faults, dikes and breccias usually define the boundaries of calderas. In the Chacana caldera these boundaries do not have continuity due to regional tectonic faulting and deep erosion during the last glacial periods, especially in the central and eastern parts which are also affected by surface runoff. The western part of the Chacana caldera is well preserved.

### 2.2.2 Stratigraphy associated with the Chacana caldera

The basement of the caldera consists of metamorphic rocks from the Mesozoic era, defined as green pelitic schists, quartz-feldspar gneisses, and partly meta-granites. Above an unconformity, a sequence of lavas is deposited, breccias and tuffs of andesitic-basaltic composition approximately 200 m thick (Figure 8). This volcanic sequence is from late Miocene to Pliocene and is called the Pisayambo formation. Above, the geological formation Ninarumi was formed by lava flows and breccias of a sandy matrix with angular blocks of andesitic lava and lahar deposits. The estimated thickness is 200-260 m. None of these formations outcrop in the project area, but are seen at the surface to the southwest at the border of the caldera (SYR, 2012b).

Intrusions or dikes of fine-grained and andesitic-dacitic composition are associated with the collapse of the caldera through circumferential faulting (SYR, 2012b).

The intra-caldera fill in Figure 8 began with eruptive products during eruptions that filled the depression. These products are composed of fine- to medium-grained volcanic breccias and tuffs, as well as massive ignimbrites and lavas. The thickness is approximately 700 m. In addition, many volcanic centres of andesitic-rhyolitic composition inside the caldera erupted and were affected by propylitic alteration. This sequence of events is known as the Baños rhyolite series, and it is shown in Figure 8 as SRB (SYR, 2012b).

Black lava flows were deposited on top of the Baños rhyolite series, composed of lavas of Si-rich andesitic-dacitic composition, interbedded with layers of auto-breccias (SYR, 2012b). Its total thickness is between 200 and 400 m; this sequence is known as black dacitic and andesitic lavas (LDA in Figure 8).

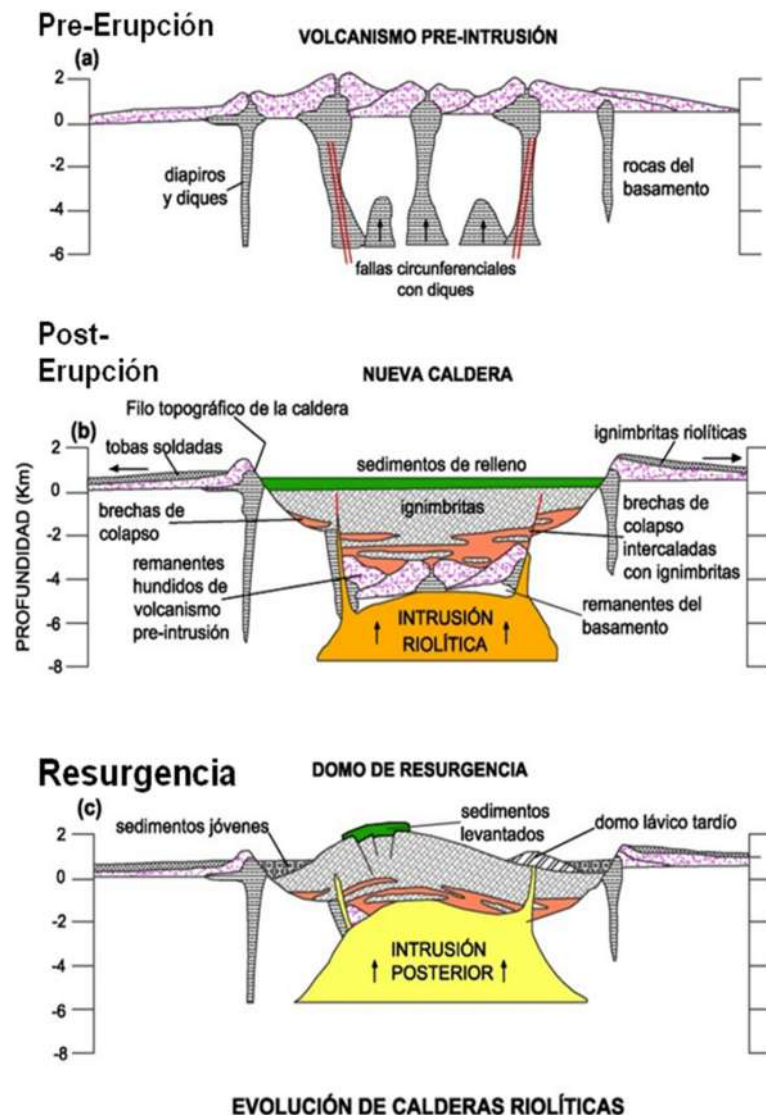


FIGURE 7: Evolution of the Chacana caldera complex (SYR, 2012b)

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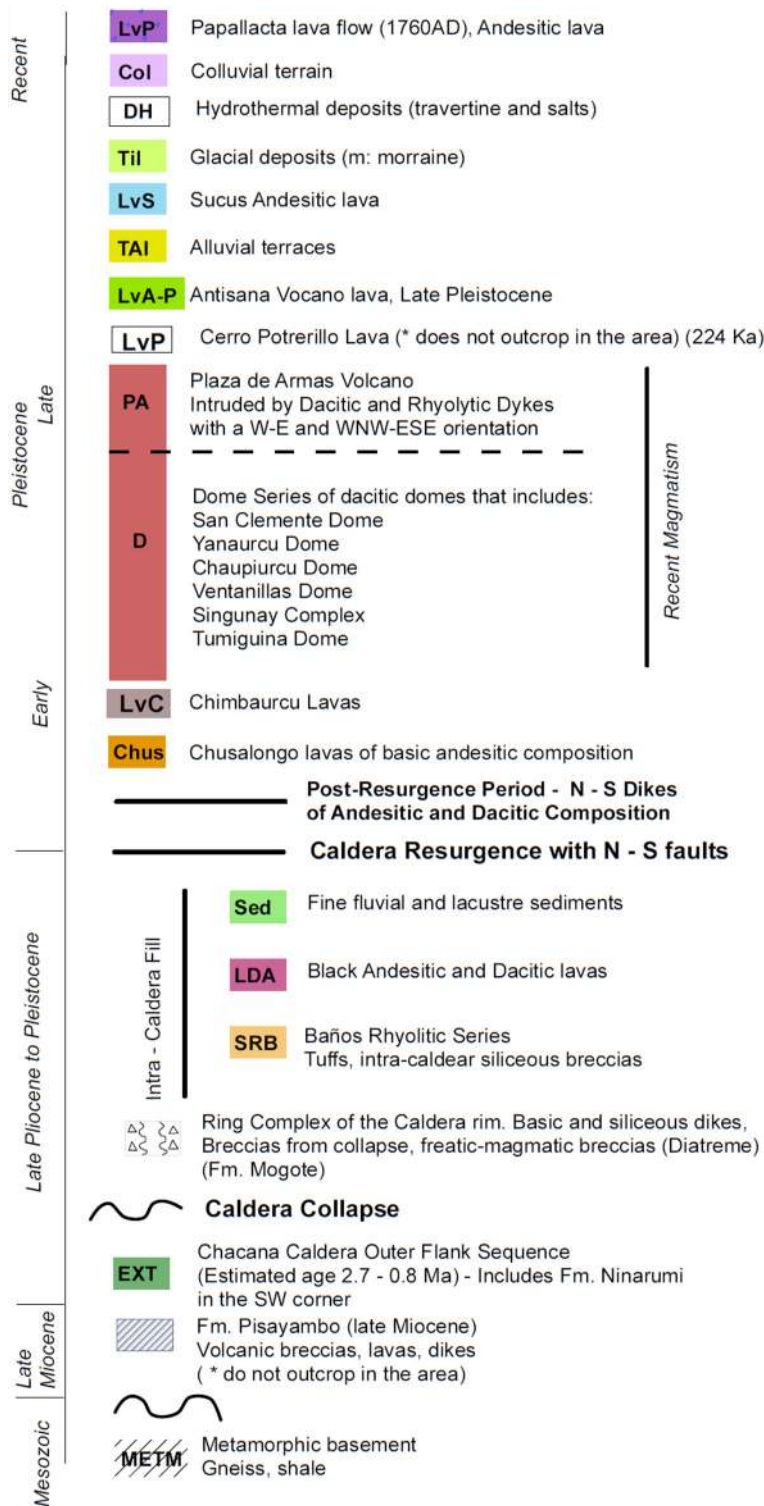


FIGURE 8: Lithological column associated with the Chacana caldera (SYR, 2012b)

The thick dashed yellow line corresponds to the western caldera rim, intersected by mapped faults. A fault in a NNE-SSW direction is at the contact between the metamorphic basement of Mesozoic age to the east and the Chacana caldera to the west, as shown with the thin dashed yellow line in Figure 9.

Finally, over the black lava flows, a sedimentary sequence composed of layers of sandstones, breccias, or cobbles was deposited. The bottom of this sedimentary sequence was formed by fine-grained sandstones of lacustrine origin and detrital micro-breccias. The thickness is approximately 150 m, seen at the centre of the caldera.

The resurgence stage of the Chacana caldera (Figure 7) occurred after deposition of LDA and during the sedimentary sequence, between 1.5-0.9 My, through Si-rich dikes, intrusions of dacitic composition in the axial zone of the caldera.

### 2.2.3 Structural geology

The main structural feature of the Chacana caldera is related to the resurgence stage. It has N-S direction and has been the main source of magma and eruptive activity during the late Pleistocene, and for the rhyolytic province of Ecuador, i.e. during the last 200,000 years, and especially during the last 50,000 years (Mothes and Hall, 2008). It is known as the Chacana rift and is located in the central axis of the caldera depression. Its youngest volcanic activity is expressed in lava flows that are believed to be about 31,000 years old.

In the project area and its surroundings, several regional faults of tectonic origin were mapped (Soulas et al., 1991; Yepes et al., 1990; Yepes and Ramón, 2000), as shown in Figure 9. Five of them are considered important for the past volcanism and important for the circulation of geothermal fluids due to their permeability (SYR, 2012b).



The Rio Blanco fault is shown as number 6 in Figure 9. It has a NE-SW direction and is more than 40 km long. Tumiguina fault is represented by number 2 in Figure 9 and this lineament has a NE-SW direction. Tambo fault runs in a NE-SW direction, parallel to the Tumiguina fault, and is associated with Jamanco, Cachiyacu and Papallacta geothermal springs in the Chacana field, represented by no. 3 in Figure 9. The Sucus fault has a NE-SW direction and can be identified as no. 4 in Figure 9. Towards the north in the caldera is the Ramos Sacha fault, in a NE-SW direction, shown as no. 5 in Figure 9; it intersects the Chacana rift. No. 1 in Figure 9 corresponds to the Rio Antisana fault with a NW-SE direction, i.e. almost perpendicular to most of the other faults, caused by displacement and faulting as a result of the NE-SW trending movements of Tumiguina, Sucus, and Ramos Sacha faults (SYR, 2012b).

Finally, red dots represent dacitic domes along the Chacana rift, and yellow stars represent the thermal manifestations at the surface (Figure 9).

#### 2.2.4 Thermal manifestations

Three main geothermal springs are known in the Chacana project area (Figure 10). The hottest spring (73°C) is near Jamanco (3450 m a.s.l.) and lies on a small E-W fault near its intersection with the Tambo fault. The second hottest spring (64°C) is at Cachiyacu (3880 m a.s.l.), located at the intersection of the Tambo and San Clemente faults. The third hottest spring (59°C) is at Termas (3300 m a.s.l.), a commercially developed recreational site, located near the intersection of the Tumiguina fault and the metamorphic basement boundary. The first and second springs lie near the intersection with the Chacana Rift (Figure 9).

### 3. GEOCHEMISTRY

#### 3.1 Chachimbiro – liquid and gas geothermometers

The Chachimbiro geothermal field is composed of a set of hot springs of chlorine-sodium and chlorine-bicarbonate waters, the temperature is around 61°C, and they are used as a tourist attraction with swimming pools. Timbuyacu field is located 5.5 km southwest of Chachimbiro, and has the same

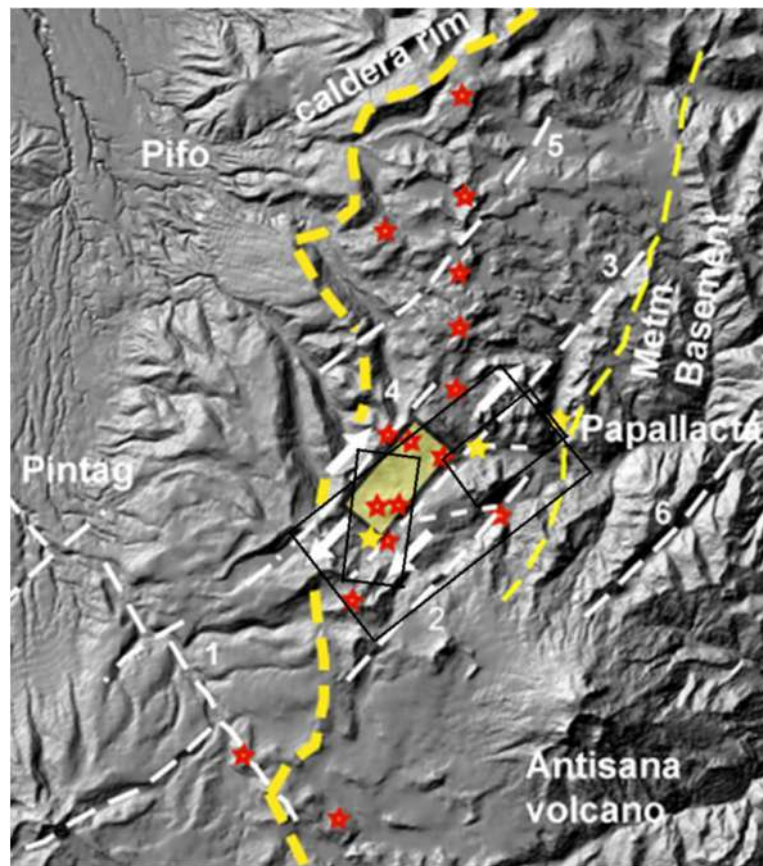


FIGURE 9: Chacana project: Diagram of the principal lineaments and faults in the project area: Symbols for faults and lineaments: 1= Rio Antisana; 2= Tumiguina; 3= Tambo; 4= Sucus; 5= Ramos Sacha; 6= Rio Blanco; thin dashed yellow line = border of caldera structure and metamorphic basement; red stars denote late Pleistocene volcanic centres of Chacana Rift; yellow stars = main hot springs (SYR, 2012b)

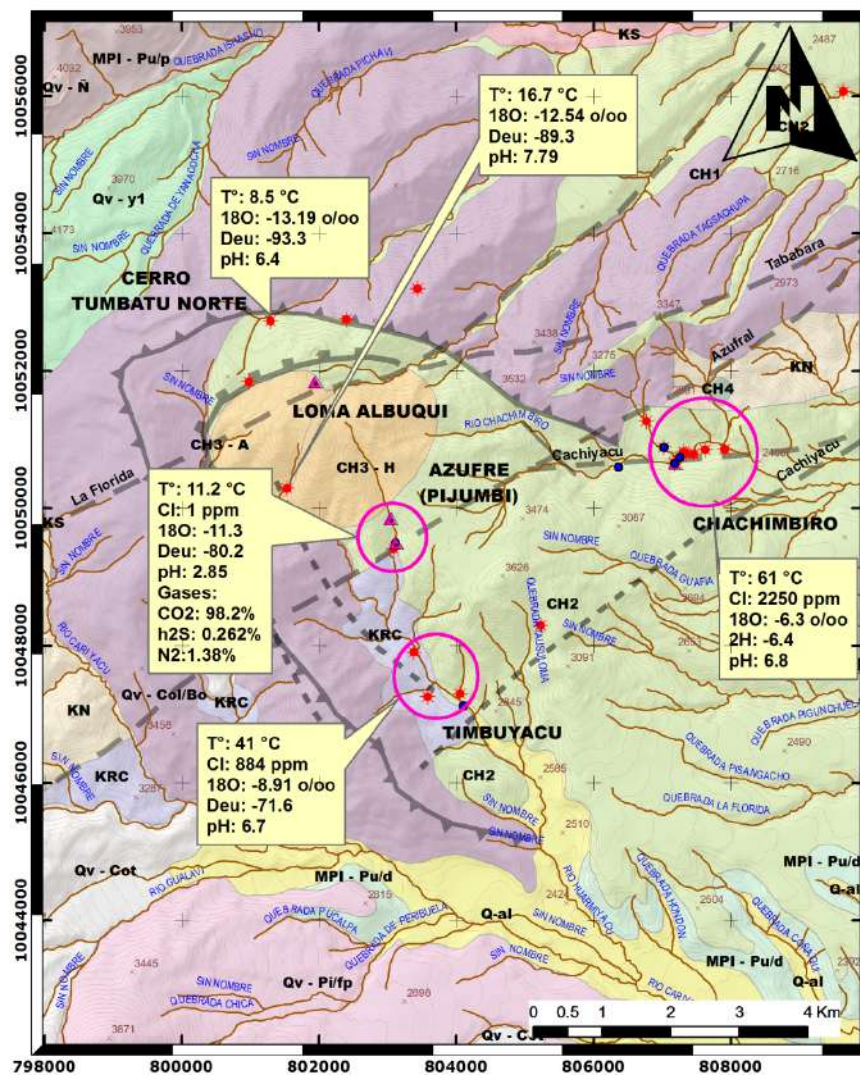


FIGURE 10: Geochemical map of Chachimbiro (modified from SYR, 2012a)

inferred by cation geothermometers and Giggenbach's geothermometers applied to samples of water which have characteristics of geothermal water with high concentrations of  $\text{HCO}_3$ . Also, the temperature of the reservoir was inferred by gas geothermometers. In addition, the recharge and recharge zone were defined. Finally, a geochemical conceptual model was developed (SYR, 2012a).

In the previous study (SYR, 2012a), the composition and chemical properties of samples from warm springs and gas manifestations did not conclude in a satisfactory geochemical model of Chachimbiro, after comparison with known results of other geothermal systems. With respect to thermal characteristics, the geochemistry of Chachimbiro suggests three scenarios of a hydrological model (Figure 11).

The first scenario suggests an intermediate-temperature geothermal system, characteristic of a magmatic-hydrothermal and alkaline-chloride reservoir, based on the chloride composition of warm springs, isotopic evidence of a magmatic source of water, carbon, sulphur and helium, and through geothermometers of  $\text{Na/K}$  and  $\text{CO/CO}_2\text{-CH}_4/\text{CO}_2$ , with temperatures at 225-235°C and 280-315°C for liquid and gas, respectively (Figure 12) (SYR, 2012a).

chemical properties as the Chachimbiro field. The temperature at Timbuyacu is approximately 41°C (Figure 10). Timbuyacu provides hot water for tourist sites. In addition, this area of interest has cold gas manifestations with hydrothermal alteration in its higher topographical zones, at over 3300 m a.s.l., at the surface of the Azufreal, Pijumbi and Minas de Azufre streams (Figure 10) (Torres and Urquizo, 2013).

From the chemical and isotopic analyses of the water samples, the origin of the water is defined as well as its interactions with rocks, and the fluid temperature (Figure 11). In this study, the water samples were classified through Giggenbach diagrams  $\text{Cl-SO}_4\text{-HCO}_3$  (Figure 12), the relationship between  $\delta\text{D}$  vs.  $\delta^{18}\text{O}$  (Figure 13), and by defining the origin of the waters. The temperature of a possible reservoir was

Samples from Chachimbiro and Timbuyacu have characteristics of geothermal water with high concentration of  $\text{HCO}_3$  (Figure 12) and, therefore, support the hypothesis of the first scenario. The samples from Azufre are composed of sulphides of volcanic origin. On the other hand, in the water classification in the Giggenbach diagram (Figure 12), the samples called Cerro Tumbatú, Azufre met, Timbuyacu met and Loma Albuji represent meteorological water (Torres and Urquizo, 2013).

From the percentage of Deuterium (D or  $^2\text{H}$ ) and  $^{18}\text{O}$  ( $\delta\text{D}$  vs  $\delta^{18}\text{O}$ , Oxygen-18) isotopic analyses, it was also possible to define the origin of the water samples (Figure 13). The water samples from Cerro Tumbatú, Azufre met and Azufre show a good alignment with the worldwide meteorological line (Torres and Urquizo, 2013).

The second scenario suggests that the geothermal fluids correspond to immature water, and the temperature is 110-125°C. This model suggests that the water is of deep metamorphic origin and could be warmed by igneous intrusions. This model is supported by decreasing temperatures in the streams located at higher elevations (Figure 10) (SYR, 2012a). The temperature range was obtained through K-Mg geothermometers and oxygen and sulphur isotopes.

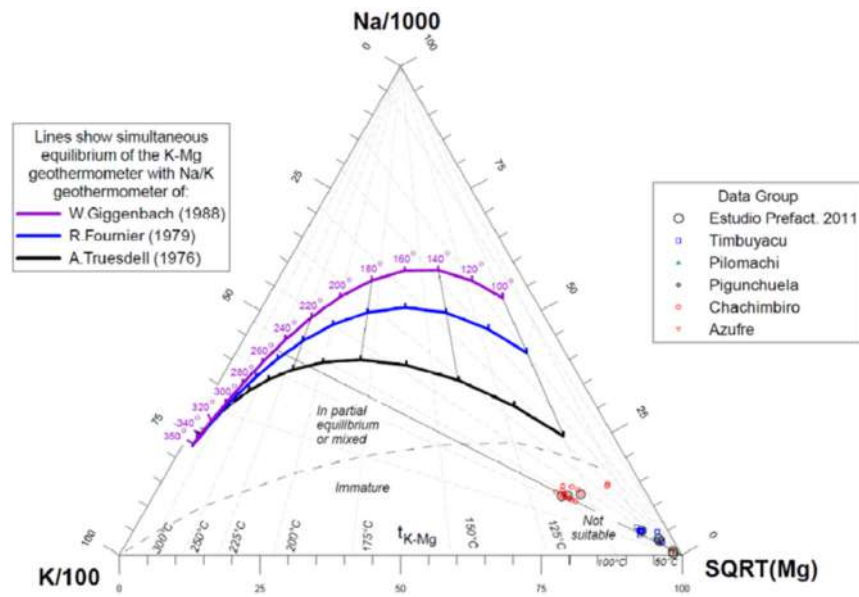


FIGURE 11: Ternary diagram showing relative concentrations of Na, K and  $\sqrt{\text{Mg}}$  in relation to three Na/K geothermometers and the K-Mg geothermometer; the Chachimbiro waters plot in the field of “immature” waters due to their relatively high Mg; the maximum K-Mg temperature is approximately 110°C; the Na/K ratios reach temperatures of 210-250°C, depending on the geothermometer equation used (GeothermEx, 2011)

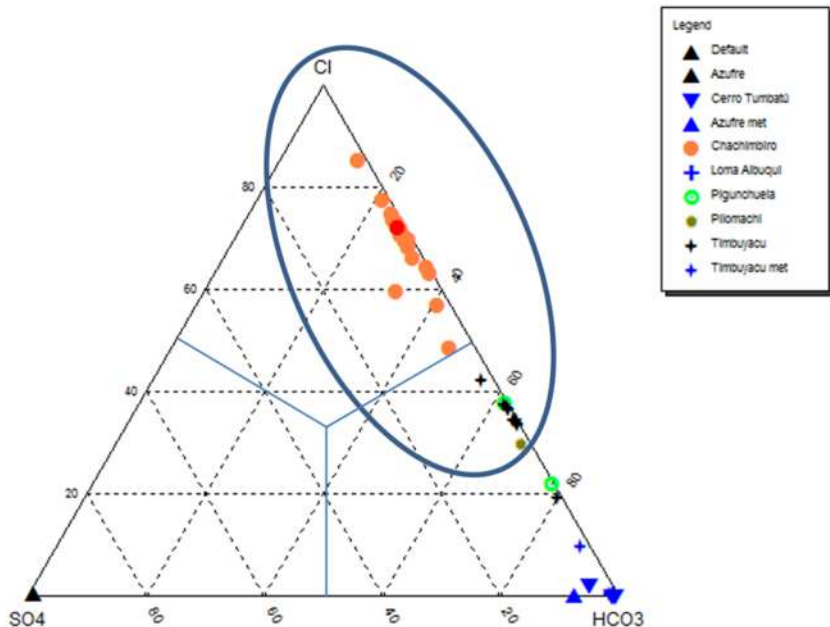


FIGURE 12: Giggenbach diagram  $\text{Cl-SO}_4\text{-HCO}_3$ ; the samples inside the oval represent the waters of the Chachimbiro project and have chemical properties of a geothermal reservoir (Torres and Urquizo, 2013)

The third scenario suggests a cooling geothermal system with temperatures between 110 and 125°C as in the second scenario, supported by the same reasons as for the second scenario (SYR, 2012a), i.e. that the water is of deep metamorphic origin and could be warmed by igneous intrusions, supported by decreasing temperatures in the streams located at higher elevations (Figure 10).

**3.2 Chacana – liquid, gas and mixed method geothermometers**

The Chacana caldera complex is characterized by young volcanism, as late as in the 17<sup>th</sup> century, which represents the heat source of this system. Inside the Chacana complex, water samples from the Cachiycu, Jamanco and Papallacta thermal springs were collected and analysed (SYR, 2012b). The focus is on the results from Cachiycu and Jamanco; Papallacta was not included.

These groups of thermal springs show a clear SW-NE alignment called the Tambo fault (Cachiycu-Jamanco-Papallacta), indicating the presence of lineament-controlled permeability (Figure 14) (SYR, 2012b).

The chemical composition of the water samples shows partial equilibrium with high concentrations of HCO<sub>3</sub>-CO<sub>2</sub>. To establish whether chemical equilibrium between water, gas and rocks has been reached, the saturation index (SI) was calculated for each sample. The equilibrium temperatures are shown in the SI vs. T diagram and are approximately 180 and 230°C for Jamanco and Cachiycu, respectively (Figures 15 and 16) (SYR, 2012b).

Quartz and Na/K geothermometers were utilized and mostly confirmed these deep temperatures. The quartz geothermometer gave temperatures of around 150°C for Jamanco and 170°C for Cachiycu. The Na/K geothermometer gave higher

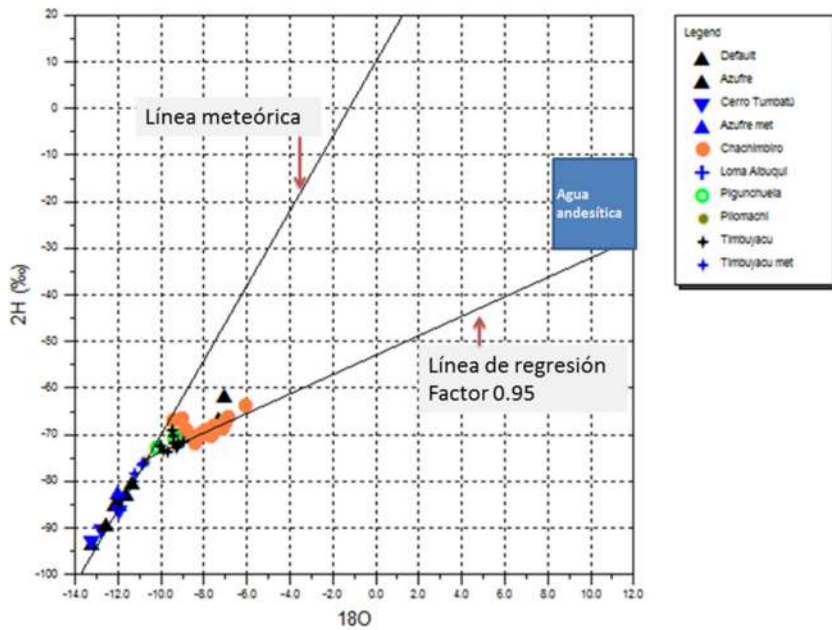


FIGURE 13: δD vs. δ<sup>18</sup>O isotopic analyses suggest meteorological origin of the water (Torres and Urquiza, 2013)

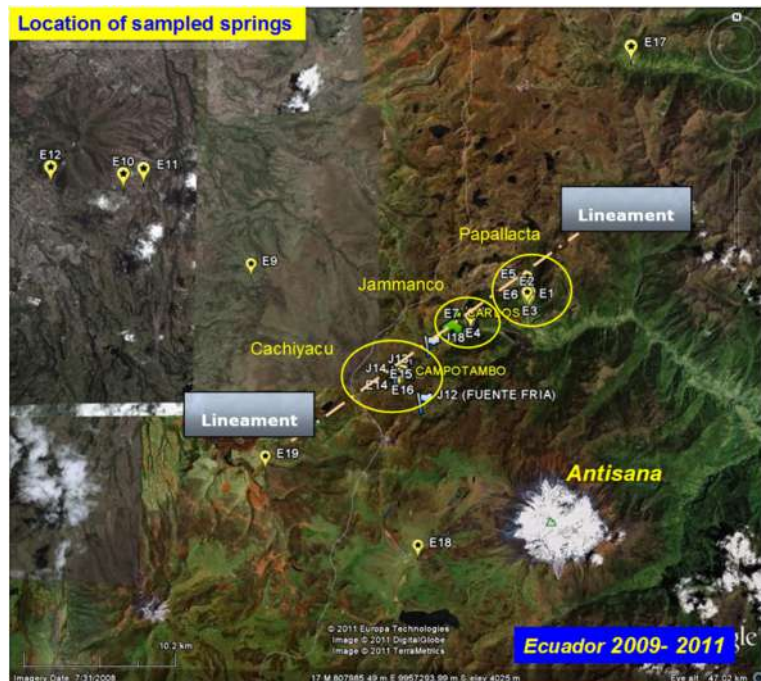


FIGURE 14: Location of the sampled thermal springs; the alignment of the Cachiycu, Jamanco and Papallacta hot springs has been highlighted, suggesting the presence of a high-permeability zone (or lineament) (SYR, 2012b)

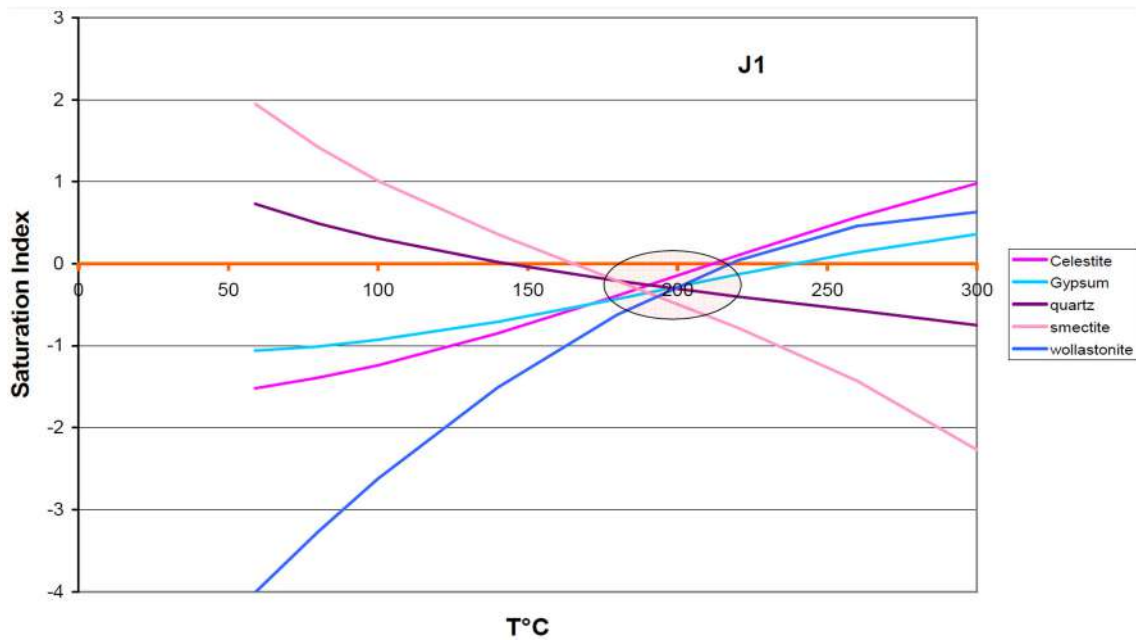


FIGURE 15: Temperature vs. Saturation Index for Jamanco hot spring J1 (SYR, 2012b)

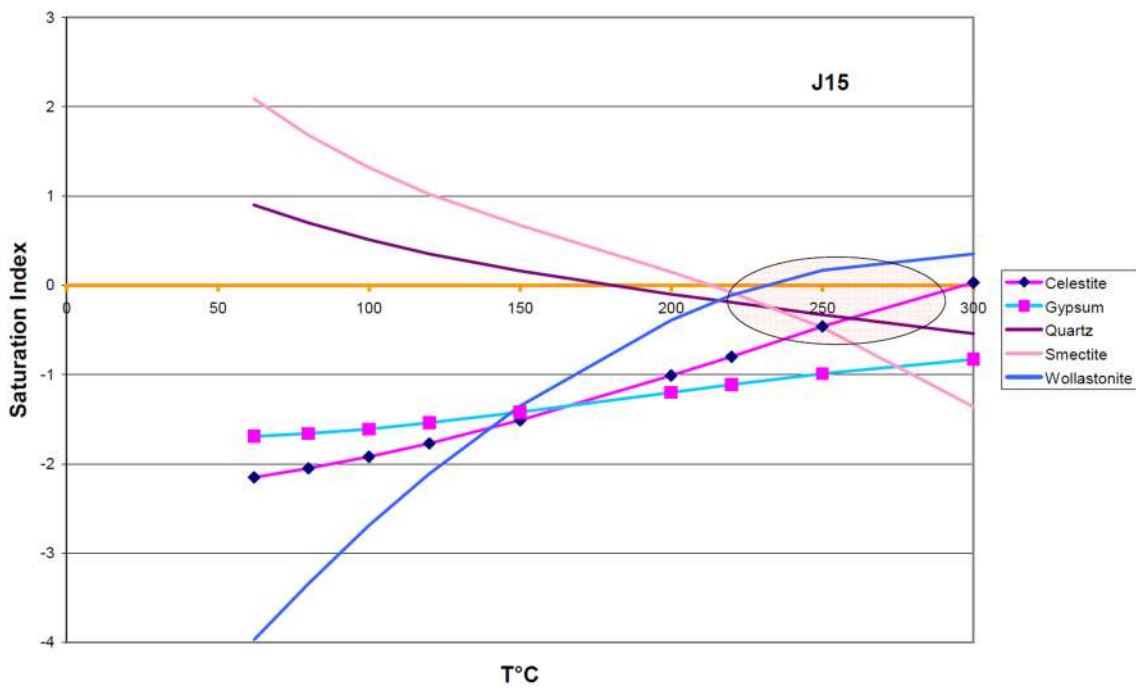


FIGURE 16: Temperature vs. Saturation Index for Cachiyacu hot spring J15 (SYR, 2012b)

temperatures, 180 and 230°C for Jamanco and Cachiyacu, respectively, confirming the estimation made based on the saturation index of minerals (SYR, 2012b).

Samples from Cachiyacu and Jamanco have high concentrations of helium due to bubbling gases with CO<sub>2</sub> content. The isotopic composition of helium, up to 7.6 R/Ra, shows clearly that the heat source is magmatic, and is rich in volatiles. Using gas geothermometers, the estimation of temperatures is approximately 240 and 360°C for Jamanco and Cachiyacu, respectively (SYR, 2012b).

Differences in the salinity from water samples from Cachiyacu and Jamanco confirm a mixing process and/or dilution process between deep saline fluids and shallow fluids of meteorological origin.

From the acquired data, three geochemical fluid models for the Chacana project were defined (SYR, 2012b):

- The first model suggests an intermediate-high-temperature source, 180 and 240°C for Jamanco and Cachiyacu, respectively, supported by the Na/K geothermometer and gas geothermometers.
- The second model suggests a temperature of approximately 130-150°C at Jamanco and 170-200°C at Cachiyacu, based on the quartz geothermometer, anhydrite saturation (at Jamanco) and mixed method geothermometry.
- The third model suggests a geothermal system with immature waters due to recent magmatic intrusions that did not reach water-reservoir rock chemical equilibrium. This is supported by high concentrations of magnesium and calcite.

Geothermal fluids of the Cachiyacu and Jamanco fields show similar chemical and isotopic compositions but have different water-rock interaction processes and mixing processes with shallow fluids, which is explained by the fact that there is not a uniform isotopic composition of deuterium, which would be evidence of one deep reservoir (SYR, 2012b).

#### 4. GEOPHYSICS

The geophysical methods applied for the exploration of Chachimbiro and Chacana projects are as follows: a resistivity survey including MT (magnetotellurics) and TEM (transient electromagnetics); magnetic survey; gravimetric survey and micro seismicity survey (SYR, 2012a and SYR, 2012b).

The parameters controlling the resistivity of rocks are: water content, the salinity of the fluid, temperature and the alteration of the rock. In geothermal research the resistivity methods are the main methods applied to determine the size of high-temperature geothermal reservoirs as the resistivity structure of a geothermal system reflects the geothermal alteration of the rocks. At temperatures of 150-230°C, smectite and zeolites are the dominant alteration minerals. Smectite is a layered clay silicate with high cation exchange capacity and, hence, has low resistivity. At temperatures exceeding 240°C, the smectite is transformed into chlorite, a more resistive mineral and, at temperatures exceeding 250°C, chlorite and epidote are the dominant minerals. The resistivity structure of a high-temperature system with reservoir temperature exceeding 250°C reflects the alteration of the system and is characterized by a low-resistivity cap underlain by a high-resistivity core. This characteristic reflects the temperature in the geothermal system, which caused alteration by the heating of the rocks and reflects the peak temperature experienced by the system, be it at present or in the past. Thus, resistivity measurements reveal the alteration but do not indicate whether cooling has occurred after the alteration was formed because the resistivity profile only captures the alteration in the formation, irrespective of any later cooling of the system. If the reservoir undergoes cooling, the resistivity will prevail and, in that case, the resistivity structure will not reflect the present temperature in the geothermal system (Arnason et al., 2000).

It is well known that geothermal fields, at least in volcanic environments, are commonly overlain by a caprock with low-resistivity smectite clay alteration. The permeability of the formation is significantly reduced by quite low smectite concentrations; in particular, secondary permeability is inhibited in smectite-bearing rocks even when they are fractured (Hickman and Davatzes, 2010; Lutz et al., 2010). Smectite-bearing rocks, therefore, act as a cap dividing the geothermal field hydrology into a shallower field's cooler meteoric zone and a deeper higher temperature zone. This deeper zone, or "geothermal reservoir", will be more resistive than the smectite cap as the temperature-dependent smectite is

converted to the more resistive chlorite and illite clays (Ussher et al., 2000; Flóvenz et al., 2005) which are altered at higher temperatures.

By the inversion of magnetotelluric (MT) data, the clay caprock can be defined; its extension and its shape as the high-resistivity core defines the reservoir. This method is used to determine the size of the reservoir. MT soundings may endure a static shift due to irregularities at the surface, as is often the case in high-temperature areas where low resistivity reaches the surface. Prior to the inversion, this shift in the soundings is corrected for by the use of TDEM soundings at the same location as the MT sounding.

A magnetic survey (Lopez, 2012a and b) was carried out inside the Chacana caldera to get information on hydrothermal alteration. A gravimetric survey (Lopez, 2012a and b) was also carried out to confirm the main faults and geological structures that dominate the flow of geothermal fluids. Finally, a microseismic survey (Ruiz, 2012a and b) was carried out to find the relationship of permeability with the main active faults.

In high-temperature geothermal systems, usually the caprock overlies the geothermal system and the base of the caprock may exhibit the temperature where smectite alters to more resistive minerals, around 230°C. By joint comparison of geology, geochemistry and other scientific information, the natural state of a geothermal reservoir and its flow pattern will be inferred (Cumming, 2009).

It is necessary to know whether the reservoir of a geothermal system is defined by a resistive anomaly of depth such as a dome, a positive gravimetric anomaly, or a negative magnetic anomaly (Torres and Urquizo, 2013).

With recent developments in MT inversion code and computer capacity, 3D MT inversion now generally has sufficient resolution to resolve most of the static shift related to topography and lateral resistivity variations, so TDEM serves mainly as a check on quality and data consistency (Cumming and Mackie, 2010). There is, however, a dispute on this and the 3D codes may or may not correct for static shift. Using TDEM at every MT station to correct for the static shift is, therefore, recommended for use (Árnason, personal information).

## **4.1 Chachimbiro**

Interpretation of MT, TDEM, gravimetric and magnetometric data was used to define the boundaries of the geothermal reservoir, to identify the possible production zone, geothermal aquifer and caprock (Torres and Urquizo, 2013).

### **4.1.1 MT/TDEM Survey**

MT soundings were made at 70 locations and a 3D resistivity model was generated by inversion of the MT data. A grid of 150 m × 150 m × 15-100 m for the final inversion model, including topographical information, (x, y and z, the depth) was used.

A TDEM survey was made at 36 stations to mitigate static shift of the MT stations as a static shift was observed in resistivity curves at high frequencies. The joint inversion of MT and TDEM data was used to find and correct for the static shift. After the corrections, the data was verified as being of good quality. Consequently, the data was processed and the results are shown in the cross-sections, whose locations are shown in Figure 17, while Figures 18 to 21 show the cross-sections.

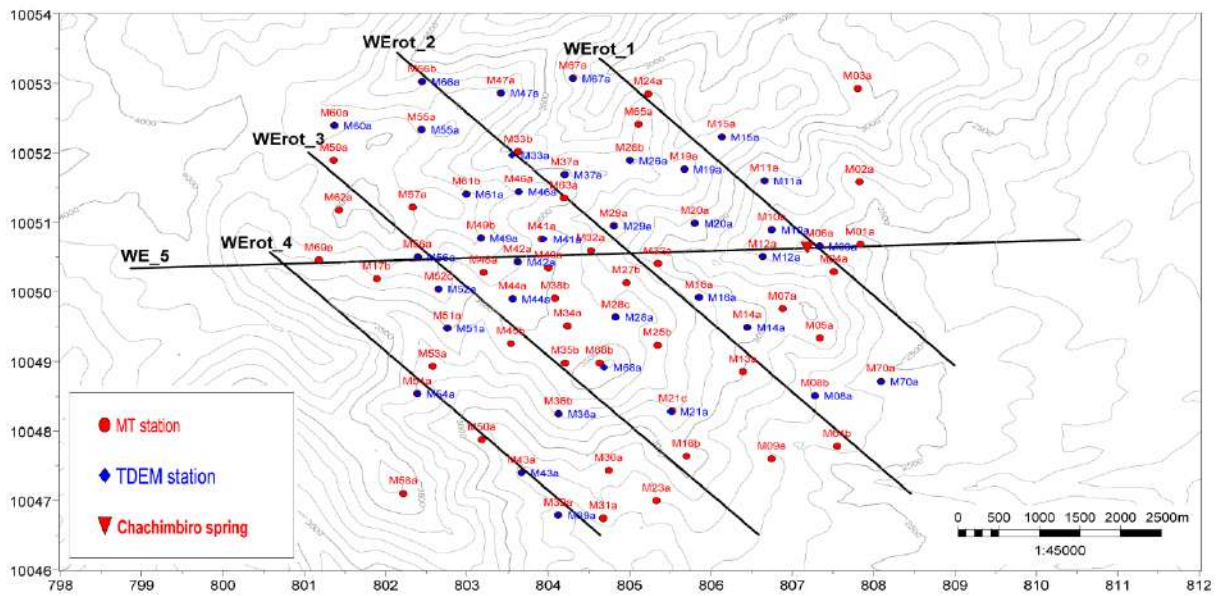


FIGURE 17: Chachimbiro project: Location of MT stations (red dots), and MT-TDEM stations (blue dots) (modified from WesternGeco, 2012)

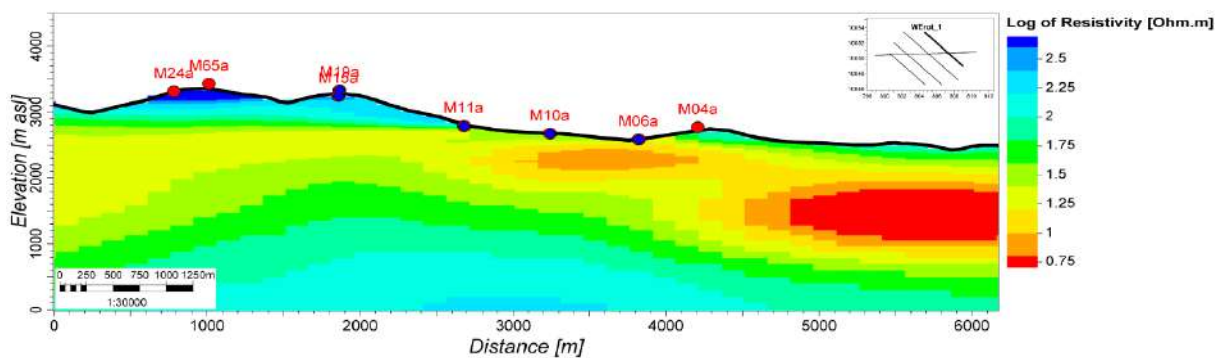


FIGURE 18: Chachimbiro, section WE\_rot1, NW-SE resistivity cross-section (modified from WesternGeco, 2012)

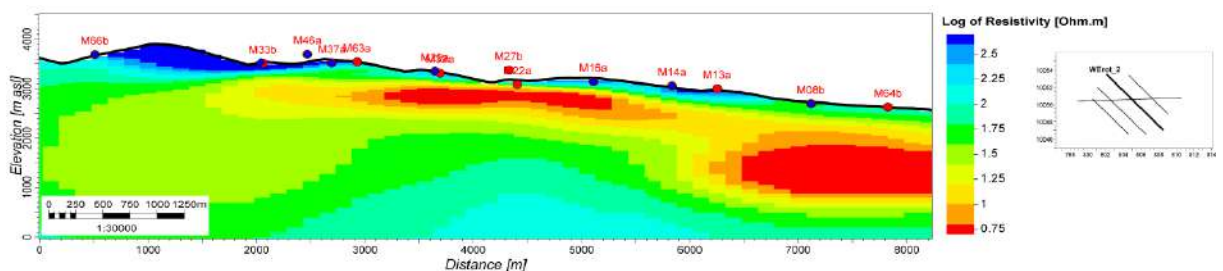


FIGURE 19: Chachimbiro, section WE\_rot2, NW-SE resistivity cross-section (modified from WesternGeco, 2012)

The results from the MT inversion displayed on the resistivity cross-sections show a characteristic high-temperature system with a low-resistivity cap underlain by a high-resistivity core. This is clearly seen in Figure 22 where the isotherms have been sketched based on the resistivity images and geochemical data, following the conceptual guidelines detailed by Cumming (2009) (SYR, 2012a).



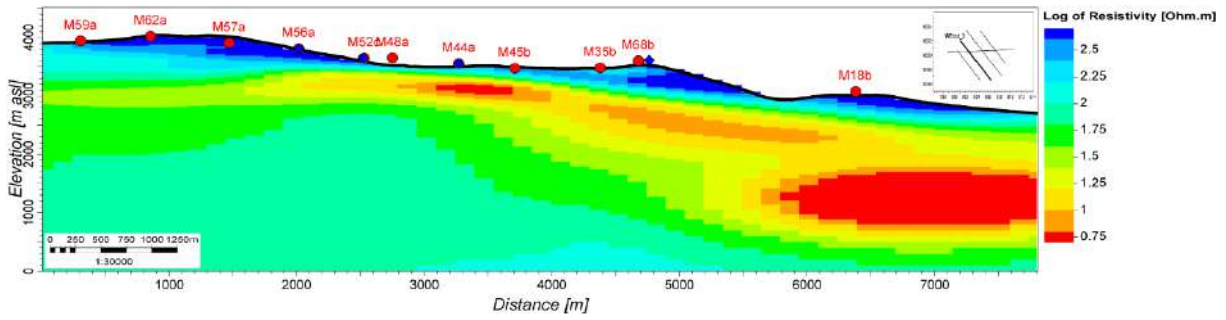


FIGURE 20: Chachimbiro, section WE\_rot3, NW-SE resistivity cross-section (modified from WesternGeco, 2012)

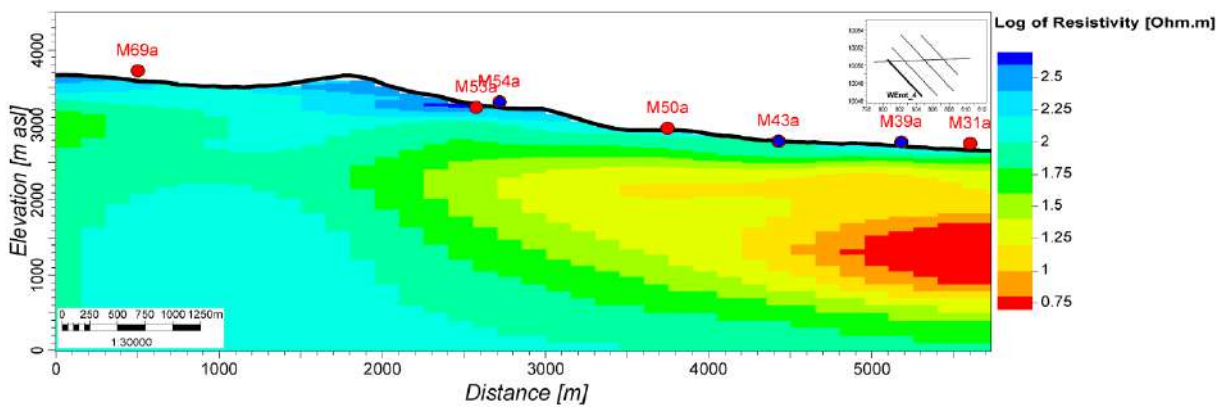


FIGURE 21: Chachimbiro, section WE\_rot4, NW-SE resistivity cross-section (modified from WesternGeco, 2012)

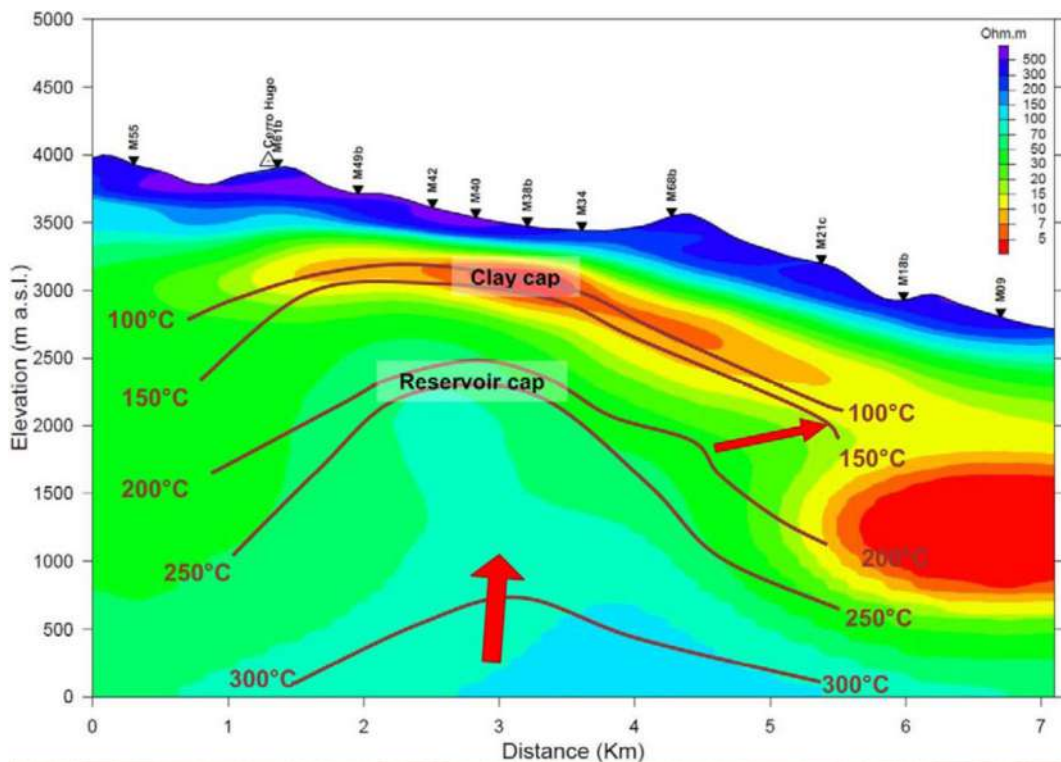


FIGURE 22: Section WE\_rot2Profile, NW-SE resistivity cross-section (WesternGeco, 2012)

### 4.1.2 Other geophysical methods

In Chachimbiro project area, a gravity survey was carried out, with 700 points with 500 m spacing in the project area and surroundings. Most points were taken in areas accessible by roads, but a few were measured in areas where accessibility was limited. The results show that Chachimbiro has a big contrast in density values between ash and tuff, with values of 1.2-2.2 g/cm<sup>3</sup>, and lava flows at the surface with values of 2.3-2.8 g/cm<sup>3</sup>. The tuff density values increase, on the other hand, as do lavas when the reservoir temperature is above 200°C (SYR, 2012a).

A magnetic survey was performed on 14 geo-referenced profiles in a NW-SE direction and 2-4 km in length. The main target of this study was to detect hydrothermal alteration associated with the destruction of magnetite by sulphate water commonly found at the surface in high-temperature geothermal fields. The results are generally consistent with the pattern of deeper alteration detected by the MT (SYR, 2012a).

In the Chachimbiro project area, a set of 6 seismic stations were installed to gather information and interpret the seismic behaviour of the field. During the seismic study, 862 seismic events were registered; 40 of them were located in the project area. These seismic events were below magnitude 3 on the Richter scale. In addition, most of the low-frequency events were detected around the seismic stations.

## 4.2 Chacana

### 4.2.1 MT survey

In the Chacana geothermal project, the geological settings of the area are complex, chaotic, and therefore probably have a corresponding complex resistivity structure. Inversion of MT data is commonly used to obtain resistivity values below 500 m of depth (SYR, 2012b). The MT soundings included 100 points on a regular grid at 1000 m spacing, covering the entire Chacana project area. In addition, 30 additional stations with 700 m spacing were added to the survey for most promising areas based on initial results (for location see Figure 23). According to acquisition and quality assurance, the

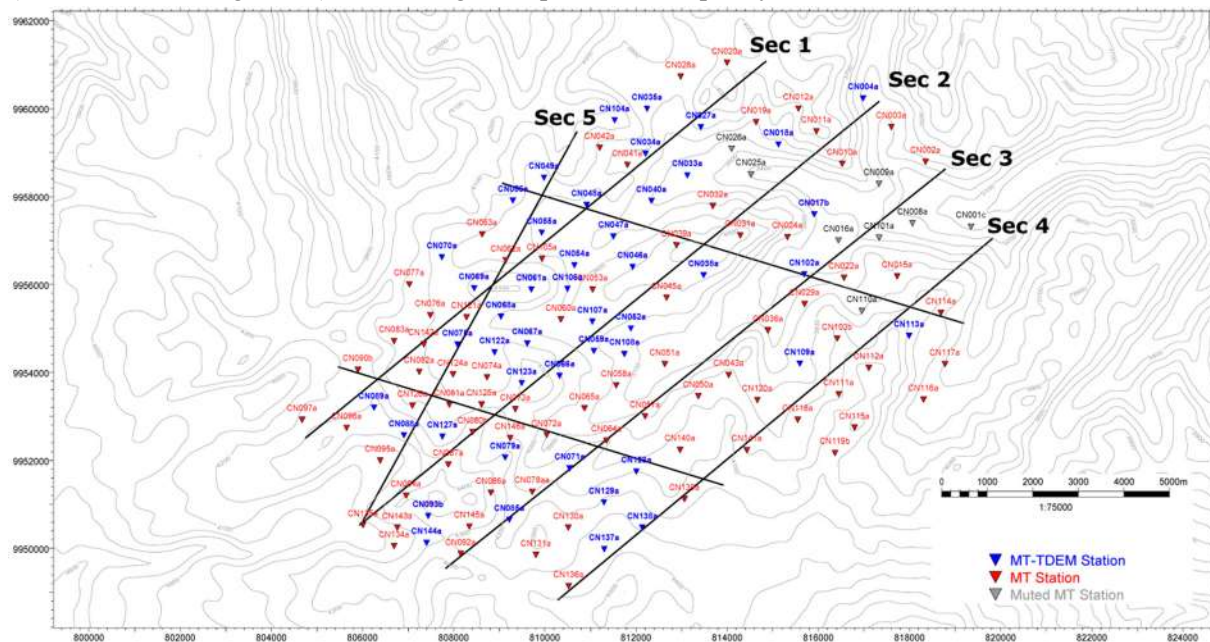


FIGURE 23: Chacana project, location of MT stations (red triangles) and MT-TDEM stations (blue triangles) (modified from WesternGeco, 2012)

signals close to 1 Hz define the base of the caprock. Also, the absence of noise sources for MT sites helps in obtaining good quality data. In addition, 50 TDEM soundings were carried out at MT sites that experienced the greatest static shift (Figure 23). Given the limited number of TDEM soundings, and their wide spacing, a map of the shallow resistivity structure is not considered meaningful.

The interpretation of the Chacana resistivity structure is based on the 3D resistivity inversion described by WesternGeco (2012) (SYR, 2012b). 1D inversion models were used to compare the 3D inversion performance, and were consequently corrected by TDEM soundings at 50 sites which showed static shift. The areas of interest are the low-resistivity anomalies. Conductive low resistivity anomalies were found in the Jamanco, Cachiyaçu, Chimbaurcu and Plaza de Armas locations (Figure 24).

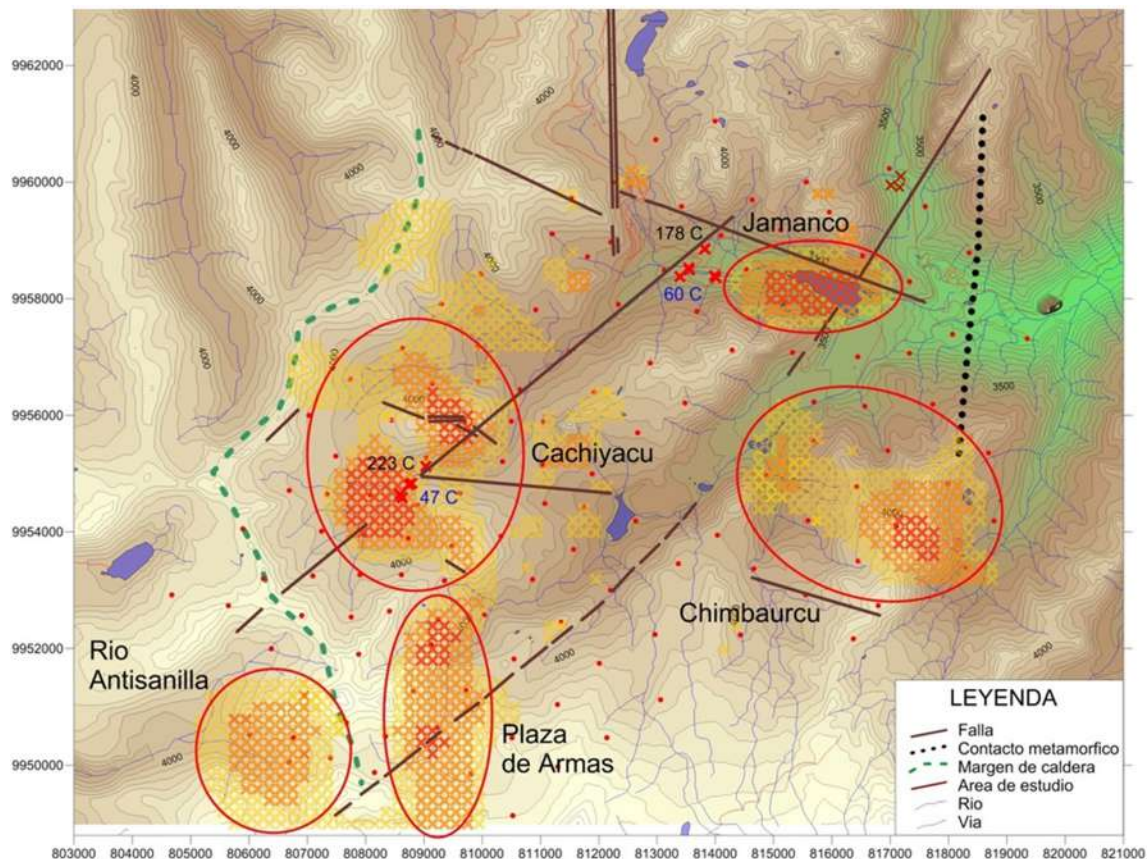


FIGURE 24: Low-resistivity anomalies in Chacana, also showing temperatures of hot springs with average temperature (blue nos.); and Na/K (Giggenbach, 1988) geothermometer temperatures (black nos.); high-resistivity areas are superimposed in red on topography (modified from SYR, 2012b)

After analysing the cross-sections in Figures 25-28, the results of the resistivity measurements can be summarized in the presence of three resistive layers. The first layer corresponds to resistivity values between 3 and 50 ohmm and can be associated with the caprock of the geothermal system. The second layer has resistivity values between 50 and 300 ohmm, and is believed to relate to geothermally altered rocks (high-resistivity core) with the possible existence of a geothermal reservoir. The last layer has resistivity values above 300 ohmm and could be related to the metamorphic basement according to the geological settings of the Chacana geothermal project.

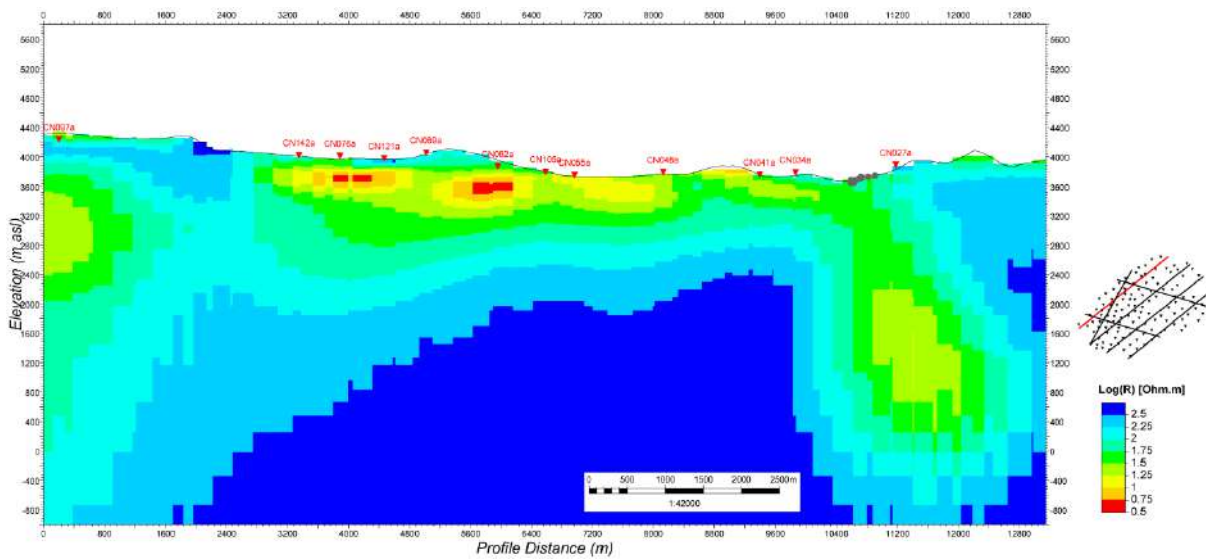


FIGURE 25: Chacana; Section 1, SW-NE resistivity cross-section with two conductive anomalies between 3.2 and 6.4 km, located in Cachiyacu zone (modified from WesternGeco, 2012)

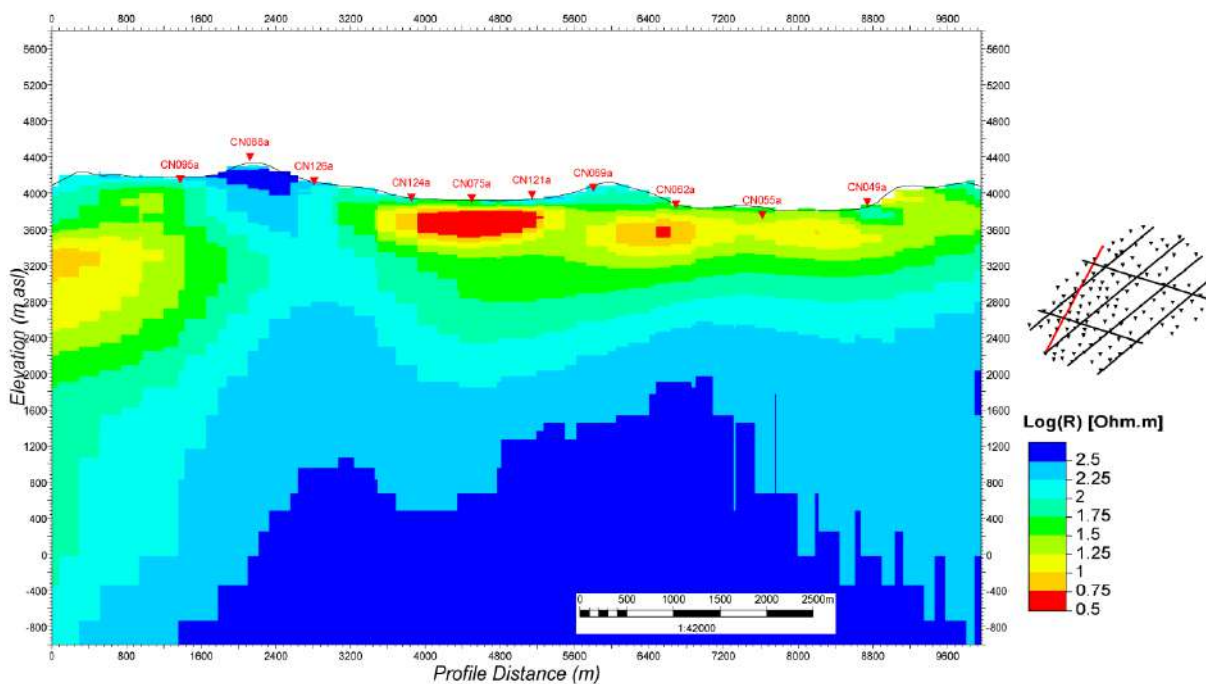


FIGURE 26: Chacana; Section 5 SW-NE cross-section with Cachiyacu conductive anomaly between 4 and 6 km (modified from WesternGeco, 2012)

Some of the low-resistivity anomalies coincide with geothermal manifestations on the surface in all sections, evidence of the ascent of geothermal fluids with its interaction with the rocks (clay alteration) through faults. The conductive anomaly in Section 2 (Figure 27) coincides with Jamanco hot spring. Another conductive anomaly can be seen in Figure 28, and its location coincides with the south of Plaza de Armas, where a convex structure like a dome of low resistivity appears. This anomaly is intersected by the main fault in a SW-NE direction that cuts the caldera rim.

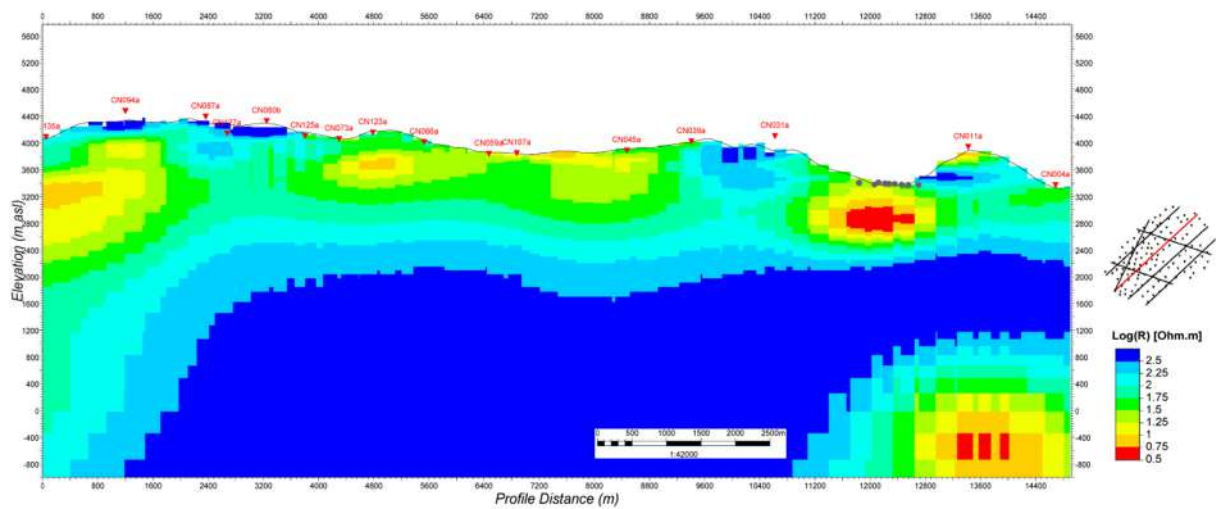


FIGURE 27: Chacana; Section 2 SW-NE cross-section with conductive anomaly in Jamanco zone at 12 km (modified from WesternGeco, 2012)

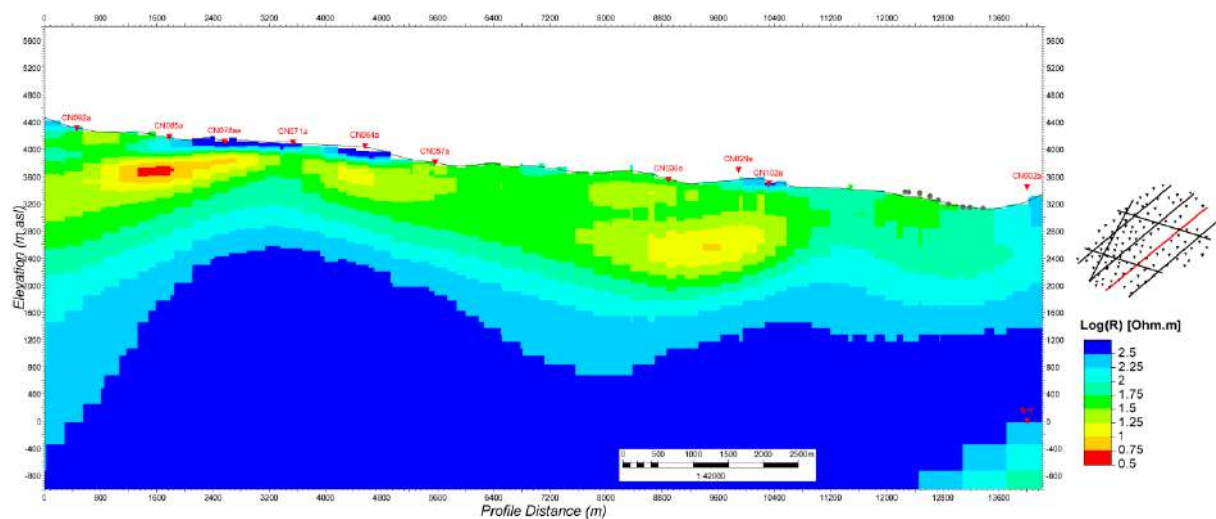


FIGURE 28: Chacana; Section 3 SW-NE cross-section showing a conductive anomaly between 1.5 and 3 km in Plaza de Armas zone (from WesternGeco, 2012)

As is shown in the cross-sections in Figures 27-30, the conductive anomalies present different shapes and a non-uniform pattern. Depending on the zone, the caprock will be absent. The thickness, depth and resistivity of the layer at the springs are encouraging and, if there is geothermal up-flow, it is likely to be at this location, probably associated with the fault system. At depths below 1000 m, the metamorphic basement may be delineated, with high-resistivity values to the east of the inferred contact and lower resistivity within the caldera to the east. Below 1000 m of depth, the resistivity values change from 30 to 50 ohmm. Such low contrast in resistivity values, suggests that the depth of the caldera floor in this region is between 1000 and 1500 m (SYR, 2012b). Low-resistivity values (< 50 ohmm) are found inside the caldera down to 750 m depth, and even further down 1500 m depth on the southeast border of the caldera. This may suggest alteration from a fossil geothermal system (SYR, 2012b).

To determine if the Chacana area is a high-temperature system cannot be inferred by the resistivity structure alone. The resistivity characteristic could be that of a high-temperature system, or the remnant of one. The low-resistivity cap is not continuous. However, the resistivity characteristic could be that of a high-temperature system that has, at some point, reached or exceeded temperatures of 250°C.

Geothermometers do not indicate such a high temperature at present, so we can assume that the geothermal system has cooled down but with the resistivity characteristic still prevailing.

If the temperature in the system has never exceeded 230°C the resistivity character could be interpreted in a different way. In that case, the low-resistivity anomaly would be indicative of a geothermal reservoir caused by the hot geothermal fluid in the rock matrix.

#### 4.2.2 Other geophysical methods

Other geophysical methods were applied in the Chacana project as explained at the beginning of this section, but that data is not necessary for the goals of this report. The main method used was MT measurements. Below, a brief description is though given of the rest of the geophysical methods which were used in the Chacana project (SYR, 2012b).

A gravity survey with a total of 700 gravity points was done in the Chacana field and north of it. The survey was focused on a finding of long scale structures as contrasts between ash and tuff formations. The density values of the ash and tuff formations would be between 1.8 and 2.2 g/cm<sup>3</sup>, and lava flows at the surface have a density value of between 2.3-2.8 g/cm<sup>3</sup>, as was described for Chachimbiro. When ash and tuff formations are heated to over 200°C, buried and located at the subsurface, their density values are closer to the lava flow density values. In these cases, it is preferable to make a more careful mapping of the surface geology. It is also necessary to consider the density values of the rocks in the Chacana area which has such a rugged and scarped topography. The gravity anomalies are related to topographic elevation, and by working with different density values, it was possible to define the boundaries and structures in the Chacana caldera. Inside the Chacana caldera, the density values are below and up to 2.0 g/cm<sup>3</sup>; these would include the anomalies close to Cachiyacu hot springs. This material corresponds to a tuff formation with sedimentary layers. In the southwest part of the caldera, filling material was identified.

A magnetic survey was also made, with the objective of detecting hydrothermal alteration associated with the destruction of magnetite by sulphate water commonly found in high-temperature geothermal fields. The magnetic field pattern shows a good correlation with the gravity survey results in the studies made by SYR (2012b), especially in the Cachiyacu area.

Finally, a total of 10 portable seismometers were located inside and outside the Chacana caldera. The epicentres of seismic events were correlated with the NE-SW direction of the faults through the Chacana caldera, and the NW-SE lineaments to the north and west of the caldera. Most of these seismic events are tectonic or volcano-tectonic, caused by fractures in the rocks. Long period events, associated with a flow of fluids, are located on the flanks of Antisana volcano; these suggest the existence of an active hydrothermal system.

As a result of this study, it could be assumed that the basement has active fractures associated with permeability, but this permeability would be limited in the absence of seismic events north of the caldera.

## 5. VOLUMETRIC ASSESSMENT

To calculate the potential or power capacity of a geothermal field, one of the methods most applied is the volumetric method. The volumetric method is considered one of the main static modelling methods, and is used in the first stage of development when the data is limited (Muffler and Cataldi, 1978). The volumetric method is often applied with the Monte Carlo method (Sarmiento and Steingrímsson, 2007). Due to non-uniform factors such as changes in permeability, and changes in recharge and transmissivity, the production capacities of reservoirs with the same heat content can be different. Furthermore, the dynamic response of a reservoir to production is also not considered in the volumetric method. However,

the volumetric method has a basis that allows for comparison between different geothermal systems (Axelsson et al., 2013).

The volumetric method is based on estimating the total thermal energy stored in a volume of rock. The fraction of the thermal energy recovered from this volume of rock compared to the total thermal energy is defined as the recovery factor and is difficult to estimate. The recovery factor depends on the nature of the system and, if reinjection is applied, the permeability, porosity, recharge etc. (Axelsson et al., 2013).

The new results presented in this study are volumetric assessments of Chachimbiro geothermal field, and Cachiycu and Jamanco areas from Chacana geothermal field. Due to a lack of boreholes and exploratory drillings, some values of the different parameters for volumetric assessment were assumed, making approximations and comparisons with other geothermal fields. The accuracy of this must be confirmed through drilling in the future.

Based on the resistivity studies, the Chachimbiro field is treated as a high-temperature field and the assessment assumes a flash power plant utilization when calculating the power production capacity. The Cachiycu and Jamanco areas are treated as low- or intermediate-temperature fields and the assessment assumes a binary power plant utilization when calculating the power production capacities of the areas. To determine if the Chacana area is a high-temperature system cannot be inferred by the resistivity structure alone. The resistivity characteristics could be that of a high-temperature system, but it may also show remnant alteration.

#### Surface area

The size of a geothermal resource defines the economic aspects for its exploration and development. If the geothermal resource is large, the economic profit can be expected to be large as well. The geoscientific data for the Chachimbiro project area is estimated between two geological structures, the Azufral fault in SE-NW direction and the border of the caldera. Inside this area, the Hugá dome is located as a possible boundary limiting the promising area; the Cachiycu fault intersects the Azufral fault. Then, with regard to the geological information, the boundaries of the possible reservoir are between two NE-SW trending faults, intersected by the borders of the caldera (Torres and Urquizo, 2013). Thus, according to the geology, the surface area for Chachimbiro is of the size 3-12 km<sup>2</sup> (Figure 29). According to the MT 3D model, the horizontal area that delineates the high-

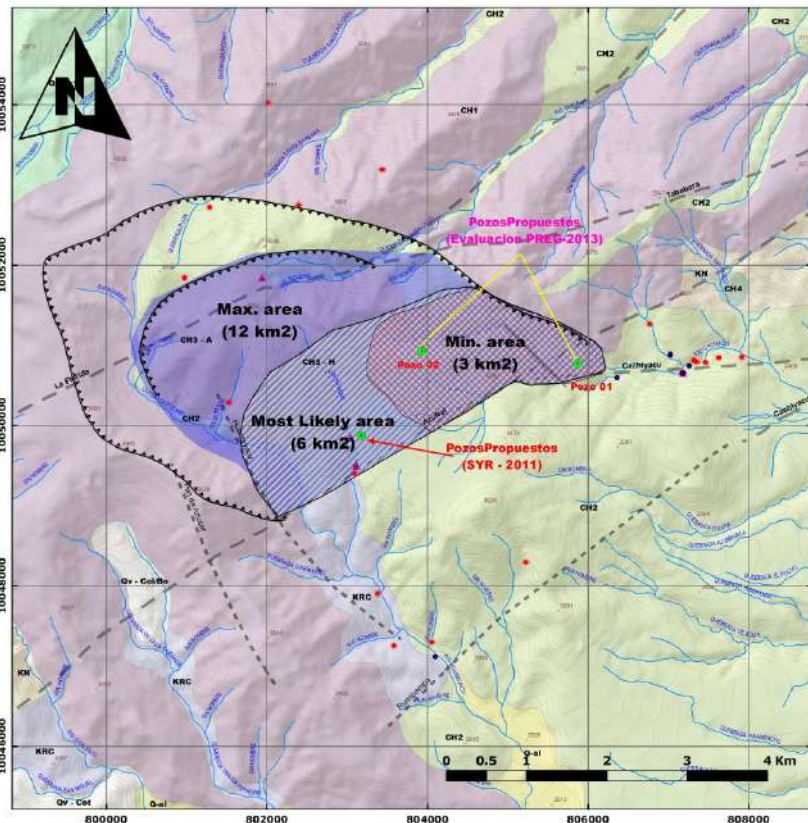


FIGURE 29: Map of the probable size of geothermal areas in Chachimbiro project (modified from Torres and Urquizo, 2013)

temperature system, i.e. the area delineated by contact between the low-resistivity cap and the high-resistivity core (250°C), is approximately 16 km<sup>2</sup>. The surface area for Chachimbiro used in the volumetric assessment is 3-12 km<sup>2</sup> and a most likely value of 6 km<sup>2</sup> is assumed (Table 1). In the calculations here we will use the cautious approach of 12 km<sup>2</sup> as the maximum.

For Chacana, the surface area of the reservoir is defined by a probabilistic assessment related to geological and geophysical information. Due to the considerable uncertainty associated with this, an appropriate range was defined according to the resource potential. It must be emphasized that the Chacana project has five areas of interest defined by resistive anomalies, but in two of them thermal manifestations are at the surface, i.e. Cachiyacu and Jamanco, and the analysis involved these two areas. Thus, the resulting resource areas for the alternative boundaries for Cachiyacu are between 0.56 and 5.5 km<sup>2</sup>, and most likely an area of 1.75 km<sup>2</sup> (Figure 30 and Table 2). For Jamanco the surface area is estimated between 0.25 and 1.72 km<sup>2</sup>, with a most likely area of 0.65 km<sup>2</sup> (Figure 30 and Table 3) (SYR 2012b). According to the MT results, the low-resistivity anomaly under Cachiyacu has a horizontal extension of 6 km<sup>2</sup>. The low resistivity anomaly under Jamanco has a corresponding size of 2 km<sup>2</sup>. This was found by comparing the resistivity cross-sections published here to resistivity maps in the report from SYR (2012b). Under Jamanco, a deep seated low-resistivity anomaly may be an indication of the heat source.

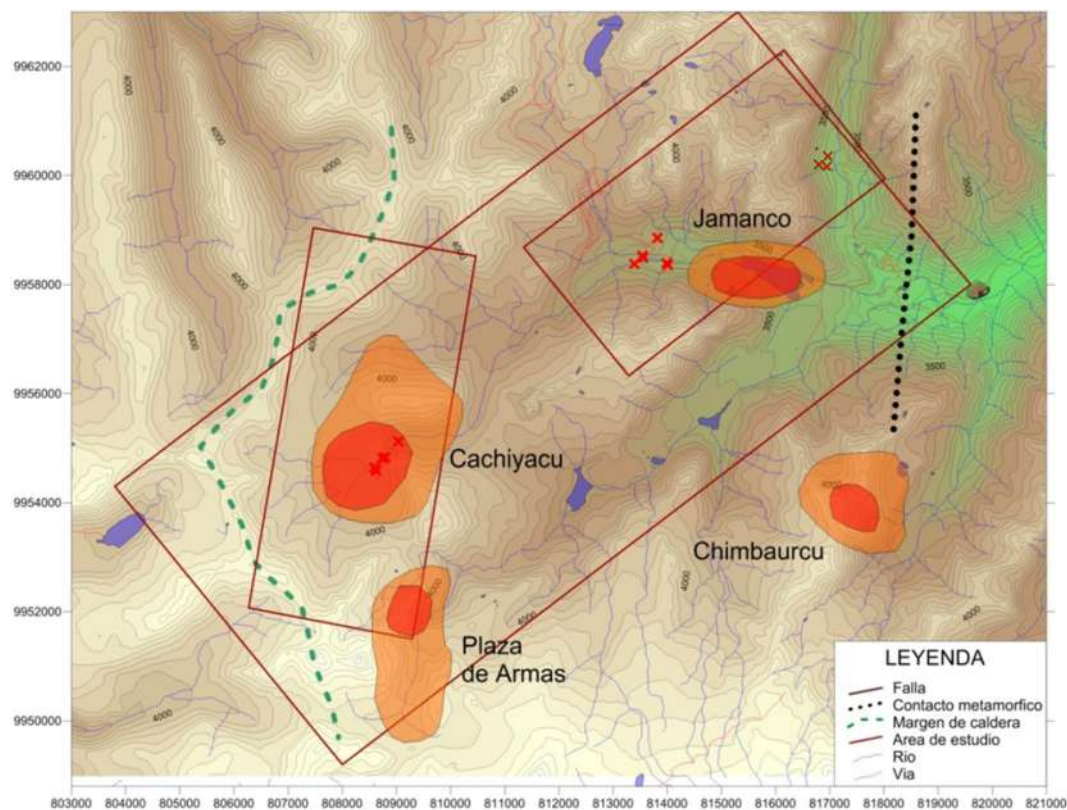


FIGURE 30: Map of resource boundaries for the Chacana project resistivity anomalies; boundaries are also shown for Plaza de Armas and Chimbaurcu anomalies (SYR, 2012b)

### Thickness

For Chachimbiro project area, the base of the reservoir is defined as between 2000 and 2100 m depth, and the top is approximately at 500 m depth, derived from the MT models. Therefore, the most likely value for the thickness is assumed as being 1500 m in the volumetric assessment. A minimum and a maximum values are set to 1000 and 2000 m, respectively, due to uncertainties of the depth of the reservoir. The reservoir depth cannot be derived directly from MT models in the case of high-temperature systems. For Chacana, the same thickness is used as in the Chachimbiro model with



Chacana considered to be a high-temperature system that is cooling down, i.e. 1500 m. On the other hand, if Chacana is considered to consist of separate low-temperature fields, the thickness of the reservoir would be the thickness of the low-resistivity anomaly at each area. For the two areas in question, Cachiyacu and Jamanco, the thickness would be the same, 500 m. Because of this uncertainty, the thickness in the volumetric assessment is assumed to be in the range of 500-1500 m with a most likely value of 1000 m.

#### *Rock density*

The reservoir rock for Chachimbiro project corresponds to andesitic composition rocks from the Natividad geological unit of Tertiary volcanism and, therefore, is assumed to have a rock density of  $2700 \text{ kg/m}^3$ , based on an average from comparison with similar geothermal fields.

In the Chacana project, the reservoir rock is composed of lavas and breccias interbedded by andesitic and basaltic compositions from the Pisayambo geological formation from Upper Miocene-Pliocene. The density of this kind of rock is assumed to be  $2700 \text{ kg/m}^3$ .

#### *Porosity*

The porosity is the ratio between the volume of the pores and the total volume of the rock matrix, including the pores. These rock properties change depending on the system. For the Chachimbiro project, the porosity is assumed to have an average value of 10%. For the Chacana project, the porosity is assumed to be in the range of 5-15%, given that the Chacana field is dominated by fractures and its volcanism is younger than in the Chachimbiro project.

#### *Rock specific heat*

The andesitic rocks in the Chachimbiro project have an average rock specific heat of  $990 \text{ J/kg}^\circ\text{C}$ . For the Chacana project, the possible value assumed is  $900 \text{ J/kg}^\circ\text{C}$ ; these will be confirmed or modified after drilling begins.

#### *Temperature*

The temperature of a reservoir can be estimated using isotopes and liquid and gas geothermometers. Geothermometers are based on temperature-dependent, water-rock reactions which control the chemical and isotopic composition of thermal water. These methods are applicable only to hot-water systems with the common chemical constituents of thermal water ( $\text{SiO}_2$ , Na, K, Ca, Mg, Cl,  $\text{HCO}_3$ , and  $\text{CO}_3$ ) (Brooke et al., 1978).

For the Chachimbiro project the maximum temperature selected is  $320^\circ\text{C}$ , based on the results from the geothermometers. Geophysics, through MT cross-sections, clearly shows the presence of a resistivity anomaly, like a dome, supporting the suggestion that a conductive core below the caprock is a reservoir with similar properties to other high-temperature geothermal systems. Therefore, the minimum and most likely temperatures selected are  $200$  and  $240^\circ\text{C}$ , respectively.

In the Chacana project, in addition to geothermometers, the mixed method was applied. Remember that the two areas of interest, Cachiyacu and Jamanco fields, have different temperature manifestations at the surface. Using geochemical information for each area, the maximum temperature for Jamanco is  $180^\circ\text{C}$ , and the minimum temperature ranges between  $140$  and  $170^\circ\text{C}$ . Finally, for the Cachiyacu area, the maximum temperature is approximately  $240^\circ\text{C}$ , and the minimum temperature ranges between  $170$  and  $180^\circ\text{C}$ . These ranges of values are supported by the MT cross-sections and suggest a cooling down geothermal system of intermediate-low temperature, where the resistivity anomalies would be considered as the reservoirs.

#### *Fluid density and specific heat*

The fluid density and specific heat were calculated from steam tables, based on temperature and considering a constant liquid pressure.

*Recovery factor*

To estimate the potential of a geothermal system involves defining a recovery factor that is a fraction of the heat content inside the reservoir which could be extracted to the surface (Brooke et al., 1978; Cumming, W., 2009). Due to the different behaviour of geothermal systems, usually this is estimated to be between 10% and 25%, according to studies presented by Brooke et al. (1978), and Sarmiento and Steingrímsson (2007). This range of values is assumed for Chachimbiro and Chacana projects in all the areas.

*Conversion efficiency and rejection temperature*

The heat of a reservoir cannot be transformed to electricity with 100% efficiency, because thermal energy needs to be converted into mechanical energy, and must use part of the generated work to generate electrical energy (Brooke et al., 1978). Old studies show that temperatures over 150-200°C have a conversion efficiency of 10-20% (Grant et al., 1982).

The conversion efficiency is dependent both on the reservoir and the rejection temperature. In the volumetric assessment, the Chachimbiro geothermal field is treated as a high-temperature field. Therefore, a flash power plant utilization scheme is considered with a final/rejection temperature of 40°C. The conversion efficiency was chosen in the range of 8-12% accordingly.

The Chacana geothermal field is treated as a low- or intermediate-temperature field. Therefore, a binary power plant utilization scheme is considered, with a final/rejection temperature of 80°C and the conversion efficiency is in the range of 13-16% and 10-14% for Cachiyacu and Jamanco areas, respectively. The conversion efficiency is lower for the case of Jamanco since the reservoir temperatures are assumed to be lower.

*Plant life*

The minimum lifetime estimated is 25 years, necessary to recover the investment, considering an internal rate of return (IRR). For Chachimbiro and Chacana project, 25 years are used.

The volumetric assessment was carried out using the Monte Carlo method. The input data for the calculations is presented in Tables 1-3 for the three cases: Chachimbiro geothermal field, and Cachiyacu and Jamanco areas from Chacana geothermal field. Results for the Chachimbiro geothermal field are presented as a discrete probability distribution in Figure 31, and as a cumulative probability distribution in Figure 32. The main results for all three cases are presented in Table 4 below.

TABLE 1: Input parameters for the volumetric estimate of Chachimbiro

<b>Input variables</b>	<b>Units</b>	<b>Minimum</b>	<b>Most likely</b>	<b>Maximum</b>	<b>Distribution</b>
Surface area	[km <sup>2</sup> ]	3	6	12	Triangle
Thickness	[m]	1000	1500	2000	Triangle
Rock density	[kg/m <sup>3</sup> ]		2700		Fixed
Porosity	[%]		10.0		Fixed
Rock specific heat	[J/kg°C]		990		Fixed
Temperature	[°C]	200	240	320	Triangle
Fluid density	[kg/m <sup>3</sup> ]	667	813	865	Triangle
Fluid specific heat	[J/kg°C]		4770		Fixed
Recovery factor	[%]	10.0	15.0	25.0	Triangle
Conversion efficiency	[%]	8.0	10.0	12.0	Triangle
Plant life	[years]		25		Fixed
Rejection temperature	[°C]		40		Fixed

According to the statistics of the probability distribution in Figure 31, it is seen that the volumetric model predicts with 90% confidence that the electrical power production capacity of the Chachimbiro field lies between 75–185 MWe for 25 years. From the statistics of the cumulative probability in Figure 32, it can be seen that the volumetric model predicts with 90% probability that at least 74 MWe can be produced from the field for the same production period.

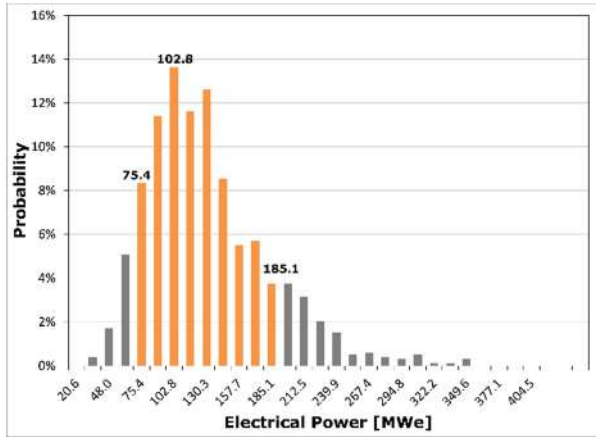


FIGURE 31: Monte Carlo volumetric discrete probability distribution for electrical power distribution in Chachimbiro

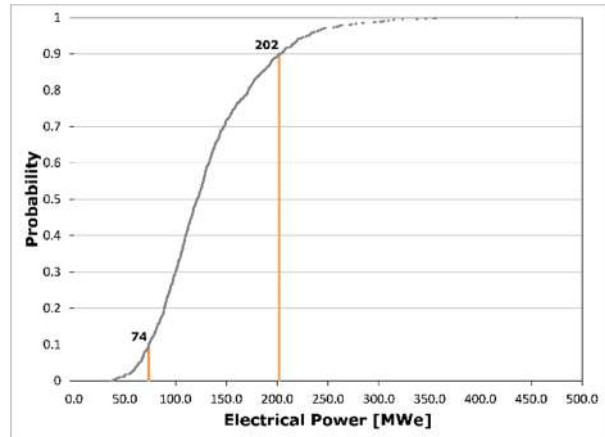


FIGURE 32: Monte Carlo volumetric cumulative probability distribution for electrical power production in Chachimbiro

TABLE 2: Input parameters for the volumetric estimate of Cachiyacu

Input variables	Units	Minimum	Most likely	Maximum	Distribution
Surface area	[km <sup>2</sup> ]	0.56	1.75	5.5	Triangle
Thickness	[m]	500	1000	1500	Triangle
Rock density	[kg/m <sup>3</sup> ]		2700		Fixed
Porosity	[%]	5.0	10.0	15.0	Fixed
Rock specific heat	[J/kg°C]		900		Fixed
Temperature	[°C]	170	190	240	Triangle
Fluid density	[kg/m <sup>3</sup> ]	813	876	898	Triangle
Fluid specific heat	[J/kg°C]		4450		Fixed
Recovery factor	[%]	10.0	15.0	25.0	Triangle
Conversion efficiency	[%]	13.0	15.0	16.0	Triangle
Plant life	[years]		25		Fixed
Rejection temperature	[°C]		80		Fixed

TABLE 3: Input parameters for the volumetric estimate of Jamanco

Input variables	Units	Minimum	Most likely	Maximum	Distribution
Surface area	[km <sup>2</sup> ]	0.25	0.65	1.72	Triangle
Thickness	[m]	500	1000	1500	Triangle
Rock density	[kg/m <sup>3</sup> ]		2700		Fixed
Porosity	[%]	5.0	15.0	15.0	Fixed
Rock specific heat	[J/kg°C]		900		Fixed
Temperature	[°C]	140	170	180	Triangle
Fluid density	[kg/m <sup>3</sup> ]	886	898	926	Triangle
Fluid specific heat	[J/kg°C]		4400		Fixed
Recovery factor	[%]	10.0	15.0	25.0	Triangle
Conversion efficiency	[%]	10.0	13.0	14.0	Triangle
Plant life	[years]		25		Fixed
Rejection Temperature	[°C]		80		Fixed

For the Cachiyacu and Jamanco areas from Chacana geothermal field, the results of the volumetric model are presented in Table 4. The model predicts with 90% confidence that the electrical power production capacity of the two areas lies between 10-40 MWe and 1-5 MWe for 25 years, respectively. The model predicts with 90% probability that at least 11 MWe can be produced from the Cachiyacu field and at least 1 MWe can be produced from the Jamanco area for 25 years. This is shown in Figures 33 to 36.

TABLE 4: Monte Carlo volumetric generation capacity estimates for Chachimbiro geothermal field, and Cachiyacu and Jamanco areas from Chacana geothermal field

Statistical sizes	Power [MWe] Chachimbiro	Power [MWe] Cachiyacu	Power [MWe] Jamanco
Most probable value	103	18	2
90% confidence interval	75 - 185	10 - 40	1 - 5
90% limit	74	11	1

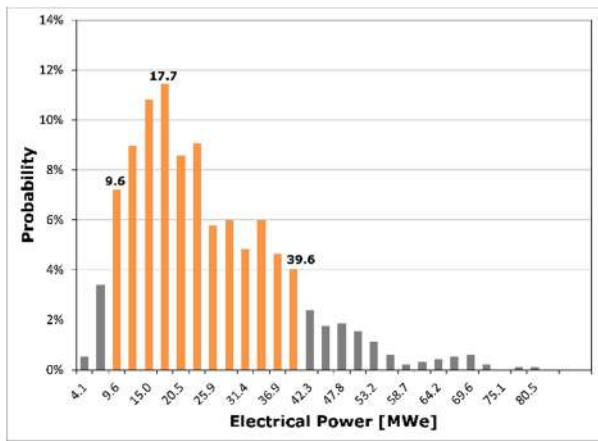


FIGURE 33: Monte Carlo volumetric discrete probability distribution for electrical power distribution in Cachiyacu

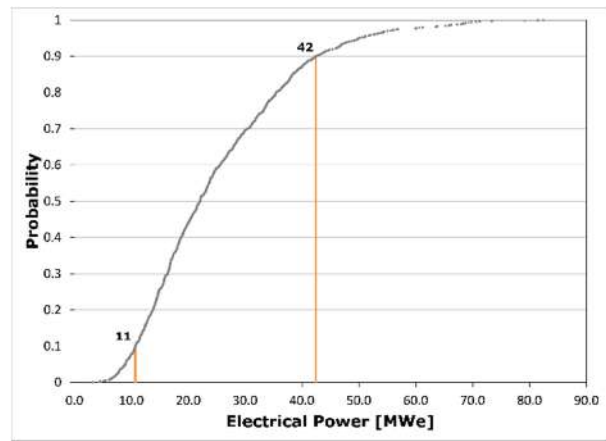


FIGURE 34: Monte Carlo volumetric cumulative probability distribution for electrical power production in Cachiyacu

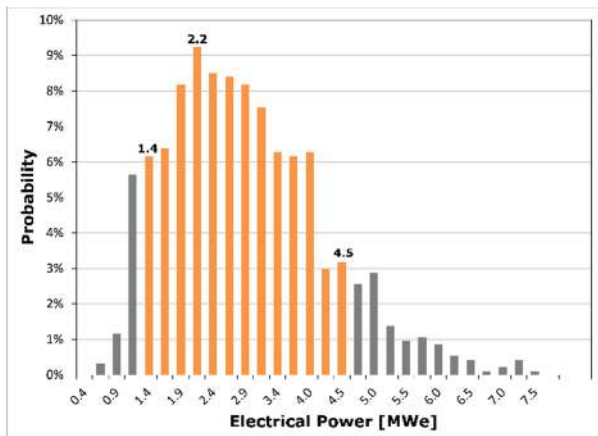


FIGURE 35: Monte Carlo volumetric discrete probability distribution for electrical power distribution in Jamanco

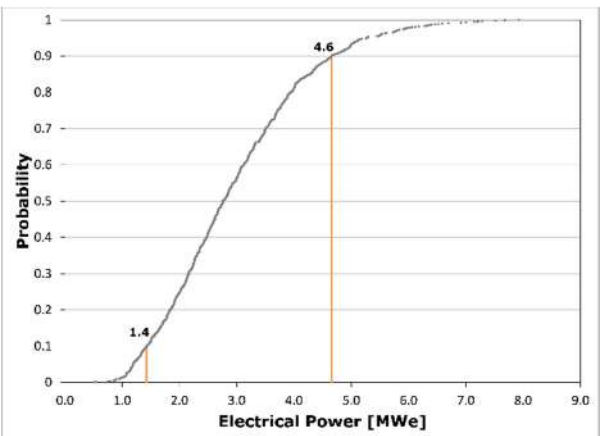


FIGURE 36: Monte Carlo volumetric cumulative probability distribution for electrical power production in Jamanco

## 6. CONCLUSION AND RECOMMENDATIONS

A review of prefeasibility studies (SYR, 2012a; SYR, 2012b) of two geothermal fields in Ecuador was shown to be a good preparation for selecting the most important information to use in a volumetric assessment of the geothermal systems. The main outputs from this study can be presented as follows:

- Volumetric assessments of the Chachimbiro and Chacana geothermal fields are presented in this study. Due to a lack of boreholes and exploratory drillings, some values of different parameters for the volumetric assessment were assumed through approximations and comparisons with other geothermal fields. The accuracy must be confirmed by the drilling campaign in the future.
- **Chachimbiro** geothermal field was treated as a high-temperature field in the volumetric assessments. This was based on the resistivity structure and confirmed by the geothermometers that indicated a reservoir temperature range of 200-320°C. The minimum size of the geothermal area was assumed from surface manifestations as 3 km<sup>2</sup> and the maximum size derived from the resistivity model was assumed to be 16 km<sup>2</sup>. The thickness of the reservoir was defined as 1500 m. The assessment assumed a flash power plant utilization when calculating the electrical power production capacity.
- **Chacana** geothermal field was treated as a low- or intermediate-temperature field based on the geothermometers. The resistivity character could be that of a high-temperature system, or a remnant of one. Determining if the Chacana field is a high-temperature system could not be derived from the resistivity structure alone. The Chacana field was divided into two sub-areas, Cachiyacu and Jamanco areas, based on surface geology, geochemistry and the results of the MT resistivity model. The temperature range indicated by geothermometers was 170-240°C for Cachiyacu, and 140-180°C for Jamanco. The minimum size of the Cachiyacu, derived from the surface manifestations, was assumed to be 0.56 km<sup>2</sup> and the maximum size derived from the resistivity model was assumed to be 6 km<sup>2</sup>. The minimum size for Jamanco was 0.25 km<sup>2</sup> and the maximum size 2 km<sup>2</sup>. In the case of a high-temperature system that has cooled down, the thickness was defined as 1500 m whereas for the case of a low-temperature reservoir, the thickness was defined as that of the low-resistivity anomaly, i.e. 500 m. These values were used as maximum and minimum thicknesses in the volumetric calculations. The assessment assumed a binary power plant utilization when calculating the electrical power production capacities.
- The volumetric model predicted with 90% confidence that the electrical power production capacity of the Chachimbiro field lies between 75–185 MWe for a production period of 25 years. For Chacana geothermal field, the volumetric model predicted with 90% confidence that the electrical power production capacity lies between 10-40 MWe and 1-5 MWe for 25 years for Cachiyacu and Jamanco areas, respectively.
- The next stage in the development of these geothermal projects should be the drilling of exploration wells. Chachimbiro and Chacana projects could have many scenarios leading to different estimations of the potential capacity generation of the fields.
- The true conditions of the fields must be discovered through drilling. Through drilling of exploration wells, the estimation of models could partly be fixed with more accurate parameters. That would help to make better decisions regarding the development of the geothermal fields.

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