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Geological Structure Identification from Gravity Data in Baños de Cuenca Geothermal Prospect, Ecuador.

Danilo ASIMBAYA, Matilde URQUIZO, Manabu SUGIOKA, Jun NISHIJIMA, Danilo IBARRA

Instituto de Investigación Geológico y Energético (IIGE), Av. de la República E7-263 y Diego de Almagro - Edificio Sky

Corporación Eléctrica del Ecuador (CELEC EP) – Dirección de Planificación de la Expansión, Av. 6 de Diciembre N26-235 y Orellana, Quito/Ecuador

Japan International Cooperation Agency (JICA), Infrastructure Management Department, 5-25 Niban-cho, Chiyoda-ku, Tokyo 102 8012, Japan

Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, 744 Motooka Nishi-ku, Fukuoka 819-0395, Japan

danilo.asimbaya@geoenergia.gob.ec, matiled.urquizo@celec.gob.ec, sugioka.manabu@jica.go.jp, nishijima@mine.kyushu-u.ac.jp, danilo.ibarra@geoenergia.gob.ec

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ABSTRACT

Located south of Ecuador, Baños de Cuenca, is a geothermal prospect which lies out of the northern active volcanic zone of the Andes, however with several hot springs with temperatures up to 75°C. Geothermal manifestations are developed over Oligocene volcanic deposits, Miocene sedimentary rocks from the Cuenca basin and Mio-Pliocene volcanic tephra from the extinct Quimsacocha volcanic center. Previous geological and geochemical studies categorized it as a low to medium enthalpy prospect. Nonetheless the heat source and the direction of geothermal fluids to flow up at Baños de Cuenca town are still in discussion. In order to define geological structures, 220 gravity stations were deployed on approximately 150 km^2. The analysis of Bouguer anomaly without topographic distortion and inversion of gravity data allowed finding out information related to possible geothermal system with negative flower termination, as well as several geological structures which segment the western part of Cuenca basin. These faults would be the pathways of geothermal fluids and Baños de Cuenca town the outflow of the system. The structural setting could improve the permeability of the area; consequently the geothermal potential could probably be higher than expected. In order to constrict the interest area, 42 MT stations are suggested to deploy in Baños de Cuenca geothermal prospect.

1. INTRODUCTION

Ecuador is located in the northwestern part of South America; the capital city is Quito and since 2008 with the approval of the new constitution, the government focused its effort to change the energy matrix, promoting the electricity generation from renewable energies, especially hydro, but also including geothermal, wind, solar and biomass. Their responsible, sustainable and environmentally friendly exploitation are contemplated in the Ecuadorian constitution and national development plans. Nowadays, the Public Corporation for Electricity (CELEC EP) and the Public Institute for Geological and Energy research (IIGE) are the governmental entities responsible for promoting geothermal use in Ecuador. They have built a laboratory for geological and geochemical analysis, acquired geophysical equipment for geothermal exploration and thermal response test for shallow geothermal applications; which altogether has allowed a significant advance of geothermal research in the last 10 years.

Baños de Cuenca prospect is located in the southern part of Andean region in Ecuador at about 490 km southward from Quito and 8 km westward of its main city, Cuenca. Baños de Cuenca is an urbanized area and the main villages related with this prospect are Minas, Yanasacha, Narancay, Soldados and Tarqui. It is implanted in the western cordillera of Andes mountain chain with elevations between 2700 masl and 3800 masl, Figure 1. The temperature and precipitation in average is 14°C and 800 mm per year, respectively; the vegetation is shrubby, common of Ecuadorian Andean highlands, and they are developed in a heterogeneous topography. Paved roads connect with the lower altitude villages and unpaved roads allow to access at higher altitude villages.

The geothermal prospect lies out of quaternary north active volcanic zone, in the southern Andes highlands geothermal play of Ecuador; where the conduction is the dominant mechanism for heat transfer (Beate, Urquizo, & Lloret, 2020), Figure 1A. It is bordered by two main regional faults, Gañarín and Girón fault systems, which extend in N-S to NE-SW direction, and control several plutons which were emplaced from Eocene to Miocene and mineralized some areas in the southern Cuenca (P. Dunkley & Gaibor, 1997; Hungerbühler et al., 2002; Pratt, Figueroa, & Flores, 1997; Steinmann, 1997), Figure 1B. The volcanic activity was represented by the Mio-Pliocene Quimsacocha volcanic center; a mainly andesitic to rhyolitic effusive volcano whose last activity was the emplacement of felsic domes 3.6 Ma ago (Beate et al., 2001).

Geothermal manifestations in Baños de Cuenca prospect are developed over Oligocene ignimbritic volcanic deposits (Saraguro group), Miocene sedimentary rocks from Cuenca basin (Turi Fm.) and Mio-Pliocene volcanic tephra (Tarqui Fm.) from the Quimsacocha volcanic center (Quimsacocha Fm.) (Beate & Salgado, 2005). It is composed by several hot springs (up to 75°C), hydrothermal deposits and hydrothermal alteration in the surrounding areas of Baños de Cuenca and Soldados villages. The presence of the hot springs is known even since pre-Columbian period (more than 500 years ago), and the continues activity have deposited a wide travertine hills which they were exploited for construction and ornamental purposes in Baños de Cuenca (Wolf, 1879). Nowadays, the geothermal energy use is restricted for direct uses in bathing resorts and swimming pools and 1.3 MWt capacity was estimated (Beate et al., 2020).

Previous geological and geochemical studies estimated temperatures between 100°C and 140°C in the reservoir, and clay deposits (kaolin) in the surrounding areas of Baños de Cuenca (Almeida, Sandoval, Panichi, Noto, & Bellucci, 1992; INER/SYR, 2014). Due to the presence of travertine deposits within the major Girón fault system and other deep geological structures (Marocco, Lavenu, & Baudino, 1995; Pratt et al., 1997) some interpretations show to geothermal gradient as a heat source for hot springs in Baños de Cuenca; however, isotopic information from Inguaggiato et al., (2010); revealed a magmatic signature (INER/SYR, 2014). Therefore, several geothermal models have been suggested for this geothermal prospect with different heat sources (e.g. INE, 1988; INER/SYR, 2014).

Structural setting, therefore permeability, is a key factor regardless with magmatic or amagmatic source in geothermal systems (J. Faulds et al., 2011; Hinz et al., 2016); for this reason, in the following sections we present the results of a gravity survey with the main purpose to understand the structural control in Baños de Cuenca geothermal prospect and to restrict the most likely geothermal model.

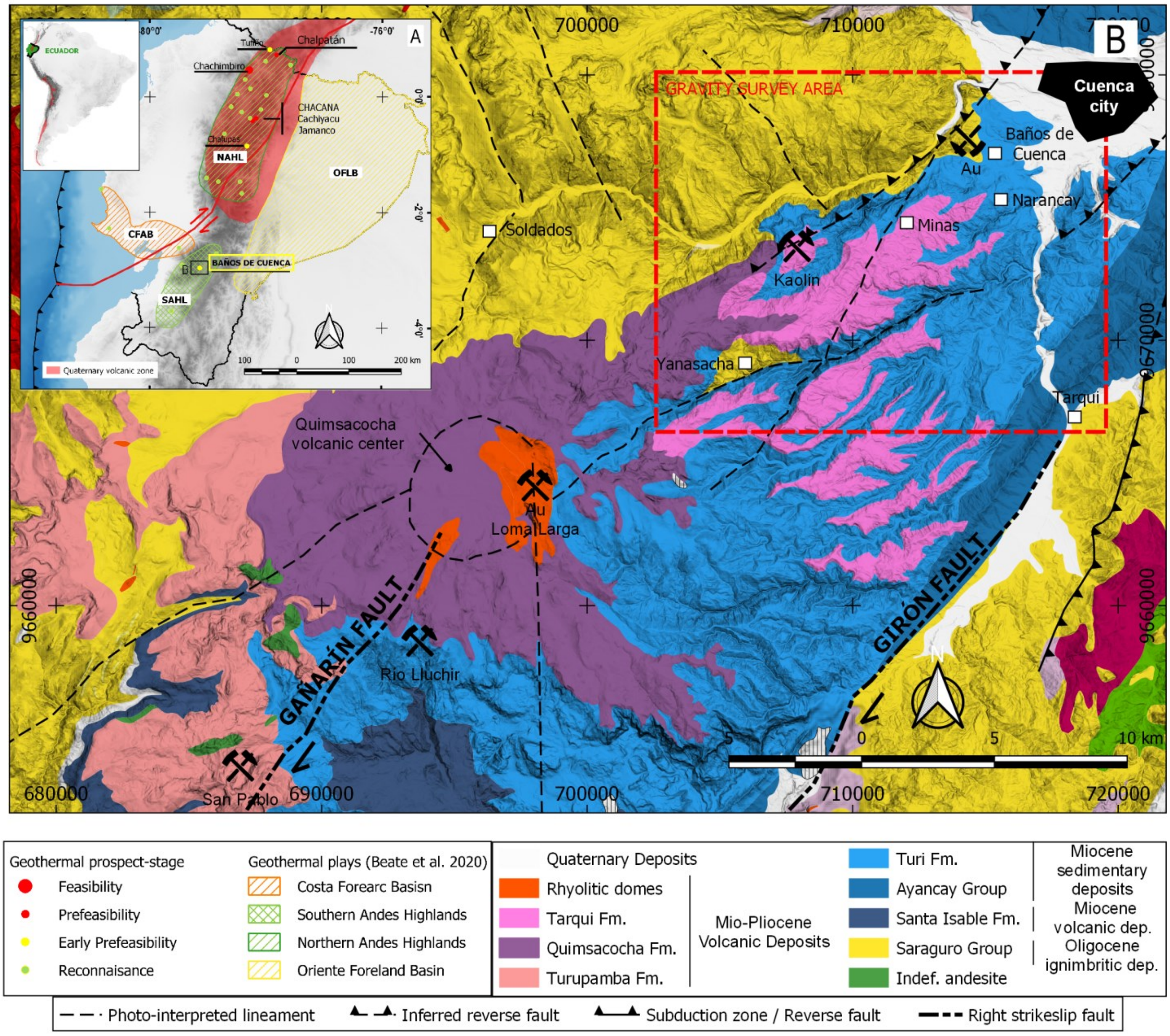

Figure 1: A. Location of Baños de Cuenca geothermal prospect. B. Simplified geological map with location of gravity survey area. Note the location of mining areas along Gañarín fault.

2. METHODOLOGY

The gravity survey was conducted in 2016 and 2017 by CELEC EP, under the technical assistance from JICA. CG5-Autograv gravity meter and two differential GPS (base and mobile), property of CELEC EP, were used for field work. The gravity measurements were distributed on approximately 150 km^2 with spacing between 1500 m and 150 m in areas of interest, Figure 2. Geothermal manifestations, geology, inferred geological structures, orography, accessibility and vegetation, were taken into account for location. In order to integrate the gravity data, punctual stations from 2016 were measured.

In order to get the Complete Bouguer Anomaly, latitude (Moritz, 1980), atmospheric (Featherstone & Dentith, 1997), free-air (Featherstone, 1995; Featherstone & Dentith, 1997), terrain (Cogbill, 1990; Davis, Kass, & Li, 2010; Zahorec, Marušiak, Mikuška, Pašteka, & Papčo, 2017) and Bouguer corrections (Hagiwara, 1975; LaFehr, 1991) were applied to measured gravity data. For terrain correction, SRTM 1 arc-second was gotten from USGS webpage. The density value was estimated according F-H method (Parasnis, 1951) and CVUR method (Komazawa, 1995); and a 2.3 g/cm^3 density was established. Finally the topographic distortion on Bouguer anomaly was corrected according Xia & Sprowl, (1991).

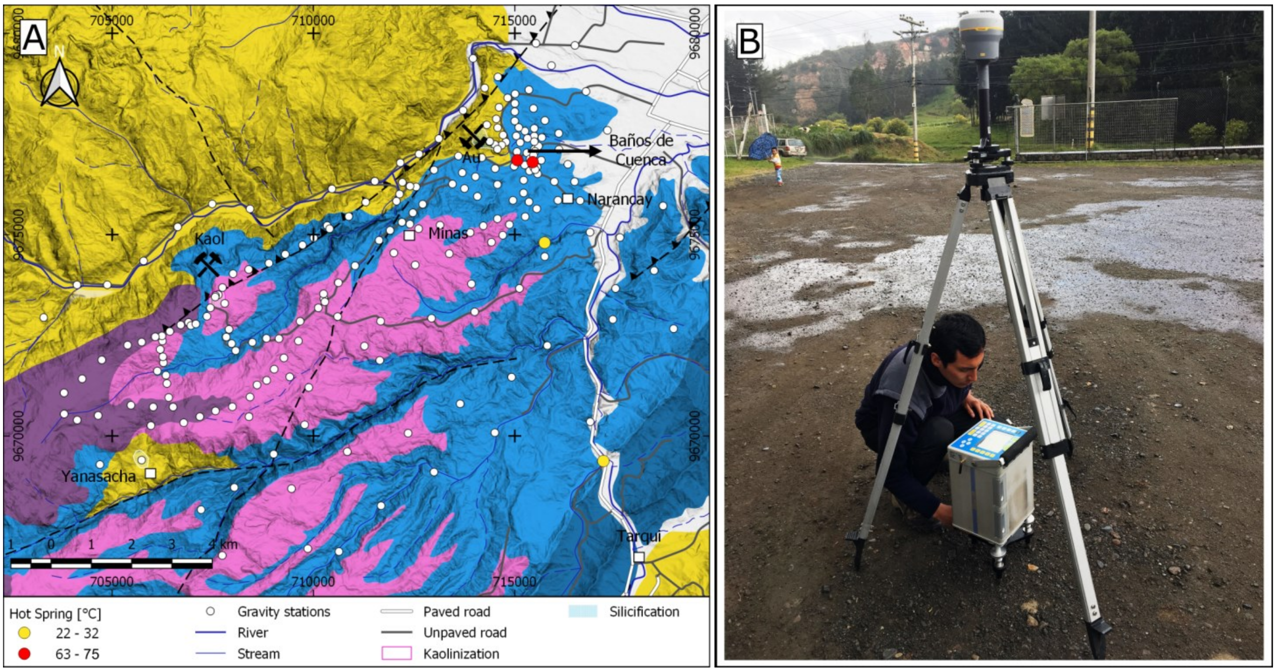

Figure 2: A. Simplified geological map of gravity survey area with the location of gravity stations. Additional symbols please refer to Figure 1. B. Instrumentation for the field survey.

The fault detection was carried out relating Bouguer Anomaly versus its terrain component. This relation allowed knowing the behavior of gravity data in contrast with density, as following:

$$\delta g_B = g_{obs} - g_{nrm} + Atm + FrA - \rho\{Bg - TC\}$$
$$\delta g_B = \delta FA - \rho\delta_{TC} \qquad (1)$$

where g_{obs} is the observed gravity, g_{nrm}, *Atm, FrA, Bg, TC* are the latitude (normal gravity), atmospheric, free-air, Bouguer and terrain corrections, respectively; δg_B is the Bouguer Anomaly; δFA is the free-air anomaly, δ_{TC} is the terrain component of Bouguer Anomaly; and ρ is density.

From (1) is possible to interpret a higher density than calculated show a positive trend (a in Figure 3), lower density than calculated show a negative trend (b in Figure 3) and same density as calculated show a flat behavior of gravity data (c in Figure 3).

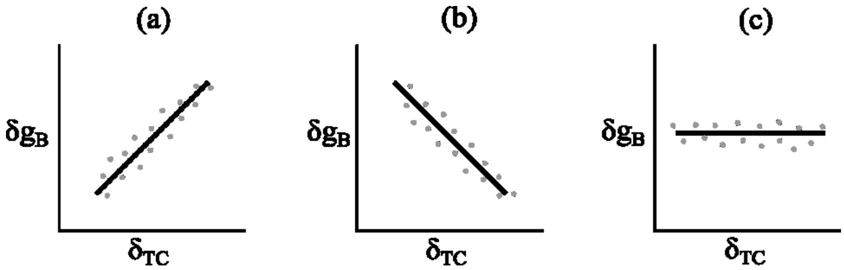

Figure 3: Illustrations of Bouguer Anomaly versus terrain component.

In addition, inversion of gravity data was conducted according Okabe, (1979). The processing with Kyushu University assistance allowed us to delineate the volcanic basement and its relation with the geological structures. Taking the geological features into account a density contrast equal to 0.5 g/cm^3 was fixed for inversion in 20 iterations, and in order to get an acceptable model, the gravity measurements were rotate 30°, and finally the external points were excluded.

3. RESULTS

The Bouguer Anomaly was made from 218 gravity stations. The Figure 4A, shows the Complete Bouguer Anomaly with gravity value ranging from -47.3 mGal to 0.0 mGal. A noticeable NE-SW boundary shows the contrast between the high anomaly at western part, and low anomaly at eastern part of study area. This boundary traverses the area in the main direction of structural control in Ecuador and is coincident with a photo-interpreted lineament in previous works (P. N. Dunkley & Gaibor, 1998). This structure (here called as Baños fault), could be represent one of some segments of southwestern structural boundary of Cuenca basin, when compressional regimen started and the intermontane stage was established with volcanic products as main source for post-late Miocene sediments (George, 2019, impress; Hungerbühler et al., 2002; Steinmann, 1997).

This characteristic is clearly showed in the Figure 4B where the Complete Bouguer Anomaly without the topographic distortion, shows gravity values ranging from -9.4 mGal to 22.0 mGal and a low anomaly restricted by higher anomalies, in the eastern and western part. The results are coherent with the geological settings of Cuenca basin: a Neogene sedimentary basin which extends in a NE-SW direction, affected by synsedimentary structures in the same direction and bordered by Oligocene ignimbritic rocks, where the western and eastern cordilleras coexist (Hungerbühler et al., 2002; Lavenu, Noblet, & Winter, 1995; Steinmann, Hungerbühler, Seward, & Winkler, 1999).

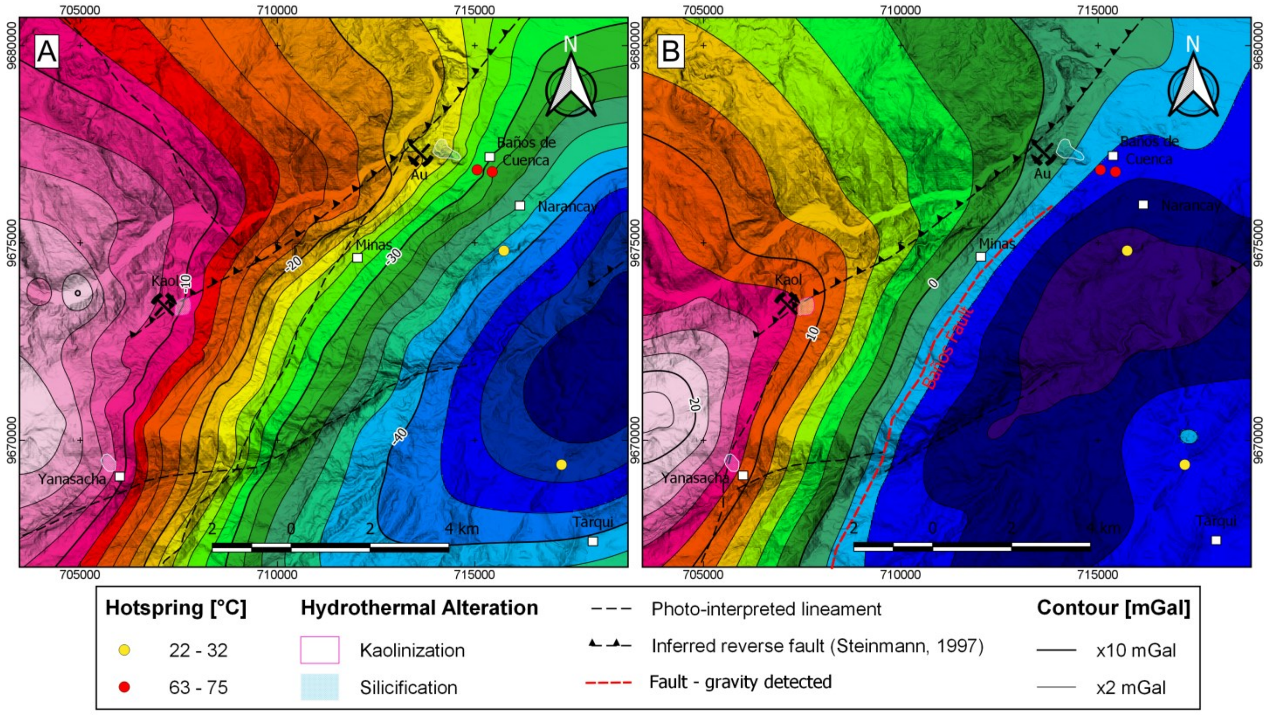

Figure 4: A. Complete Bouguer Anomaly. B. Complete Bouguer Anomaly without topographic distortion. Note the detected Baños fault.

Analysis of the Bouguer Anomaly without the topographic distortion shows the behavior of gravity data in function of calculated density (2.3 g/cm^3), Figure 5. Six groups were identified according to characteristics discussed in Figure 3, the group 1 (G1) is located around the Baños de Cuenca town and showed a heterogeneous distribution, related with complex structure beneath surface. Groups 2 and 5 (G2, G5) showed a flat behavior and homogenous distribution in areas with density equal to calculated. Group 3 (G3) showed a negative and positive trends in areas with lower and greater density than calculated, respectively. Group 6 (G6) showed a positive trend in the gravity data with density greater than calculated. Group number 4 (G4) showed a positive trend however with steeper slope than G3 and G6, showing areas with much higher density than calculated. Taking the geological units into account, G2 and G5 would be related with sedimentary rocks from Cuenca basin; G3 and G6 with ignimbritic rocks from the Oligocene Saraguro group and G4 could be related with an intrusion located in the surrounding areas to kaolinization and silicification alteration, 10 km southwestern of Baños de Cuenca town.

In addition, Figure 5B showed gaps among gravity data (G2, G3), even in the same area; this pattern shows the action of geological faults as a result of underground displacements. In this way, 1 gap is showed in G3, G6 and 2 gaps are showed in G2; therefore, 2 geological faults would be interpreted in G2, at least 1 fault in the surrounding groups G3, G6; complex structural control in G1; low density rocks related with kaolinization areas in G3 and an intrusion with gravity analysis in G4, were found out in the survey area, even only from gravity data without any geological information. Geological faults detected here, belong to segments from R. Minas and Baños fault, Figure 5. In a regional point of view, Cuenca area was controlled by major strike-slip movement (Hungerbühler et al., 2002; Marocco et al., 1995; Nobletl & Lavenu, 1988) and generated NE trending faults, most of them were not reactivated in the quaternary (Alvarado et al., 2016), in addition, the last tectonic setting developed mainly strike-slip faults with reverse component in the same trending (Costa et al., 2020; Eguez, Alvarado, Yepes, Machette, & Dart, 2003); thus, altogether, the geological faults detected here (R. Minas and Baños fault) could be strike-slip with reverse component and mainly are blind covered by volcanic tephra from Tarqui formation.

On the other hand, a minimum 0.50 mGal - 0.27 mGal, root mean square (RMS) for the 3D gravity inversion (two layer modeling), was calculated. The results were coherent with the geological map, where the ignimbritic rocks outcrop (northwestern part), Figure 6. The model showed at least 2000 m thickness for the Saraguro group and 1700 m as a maximum thickness for sedimentary rocks from Cuenca basin. These results are in agreement with Pratt et al., (1997); who established a variable thickness which amount to 3000 m for Saraguro Group, and more than 1600 m thickness for Cuenca basin, has been reported (e.g. George, 2019, impress; Hungerbühler et al., 2002; Marocco et al., 1995). The southeastern part of survey area, showed an almost flat subsurface with 1500 m depth in average and decreases to eastern part.

The model showed up to 900 m of unevenness in the volcanic rocks (Saraguro group), below Baños de Cuenca town, and a particular circular shape, Figure 6A. Probably, the interaction of Baños and R. Minas faults in the vicinity of Baños de Cuenca, generated accommodation structures, Figure 6B; thus, greater permeability in the rocks from Turi and Tarqui formation. Geomorphological features and variable strike in the layers from Turi formation (INER/SYR, 2014) support this statement; as well as, the fact that prior to the urbanization, several cracks and innumerable areas where the hot springs flowed out, have been reported (Wolf, 1879).

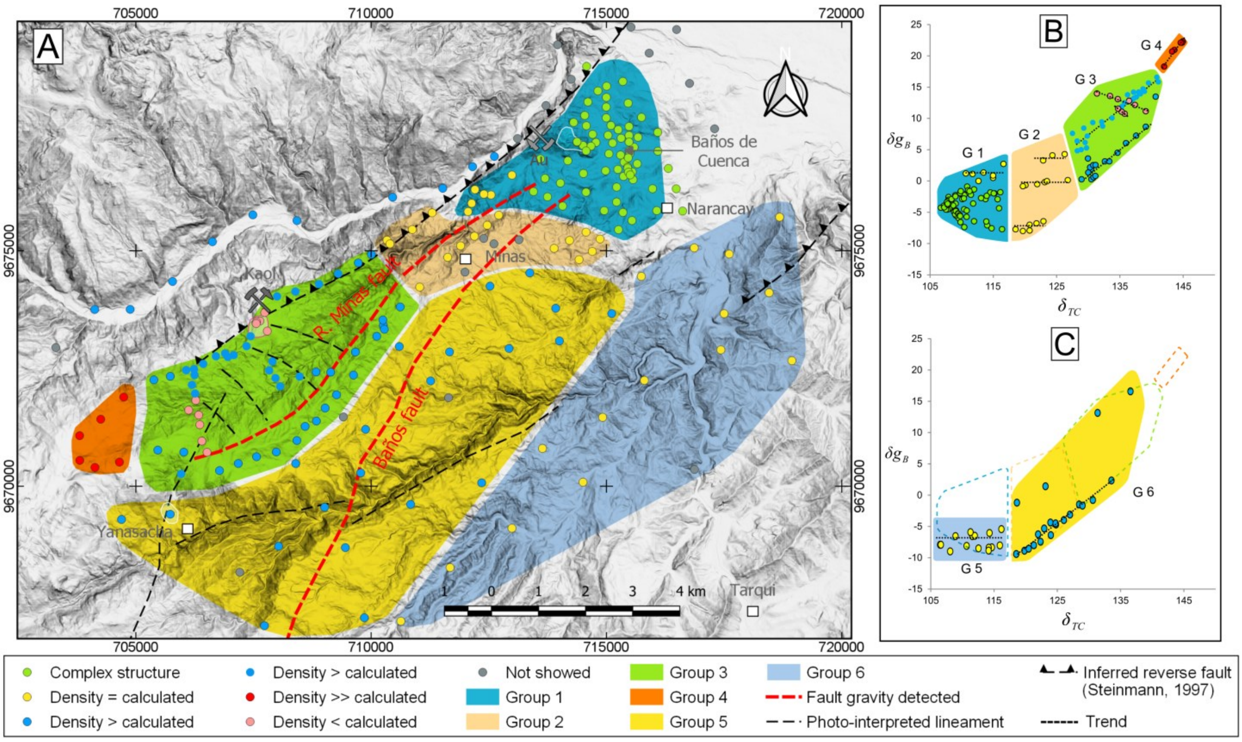

Figure 5: A. Location of groups according the relation δg_B vs δ_{TC}: (B) groups 1, 2, 3, 4; and (C) groups 5 and 6.

This characteristic is also notable in the vicinity of kaolinization zone, where the R. Minas fault and other antithetic structures, show more than 9 km^2 of geomorphological depression at its southeastern part, Figure 5A. Therefore, and taking the neotectonic setting into account, a duplex structure could be developed as a displacement transfer zone along R. Minas fault which allowed the rise up of geothermal fluids and consequently the alteration of surrounding rocks, Figure 6C. This structural setting has been seen in other areas which host geothermal systems (J. E. Faulds & Hinz, 2015), and in the Loma Larga mining zone for emplacement of mineralized bodies (Morán, 2017).

In summary, the gravity data analysis allowed us to found out a probable heat source related with an intrusive body, in the Baños de Cuenca highlands, besides areas with good permeability for geothermal feeding zones.

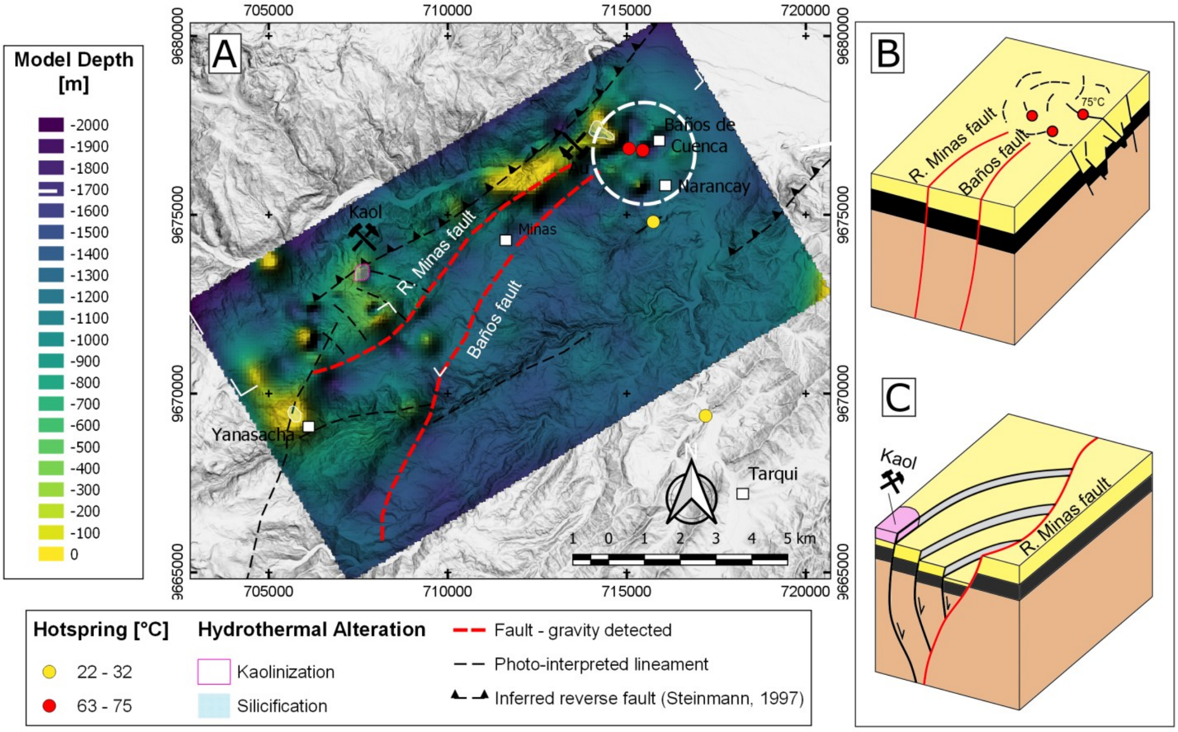

Figure 6: A. Depth of gravity basement (in meters) with density contrast of 0.5 g/cm^3. White lines show the direction of section in Figure 7. B. Accommodation structure model for Baños de Cuenca town. C. Extensional duplex structure model-negative flower termination, for southeastern part of R. Minas fault (Modified from Woodcock & Fischer, 1986).

4. DISCUSSION

Through gravity analysis and previous works, we propose the most likely preliminary geothermal model for Baños de Cuenca (Figure 7), which must be tested with further studies:

The recharge of the system consists of meteoric water, which would be located over 3000 masl (INER/SYR, 2014); where the precipitation is common. Subsequently, the infiltration and heating are the predominant phenomena. A heat source (remnant), probably Pliocene, heats the meteoric water and, through the geological faults, allowed the emplacement of intrusive bodies in the survey area. In this way, the likely location of the up-flow could be close to this intrusion where the geothermal fluid gets the isotopic signature of $\delta^{13}C$ reported by Inguaggiato et al., 2010.

Reservoir rock is assumed to the Oligocene ignimbritic deposits of the Saraguro group, below the kaolinization area (cap rock of the system), where extensional duplex structures along R. Minas fault take place. According INER/SYR, (2014); the most reliable temperature of the deep fluids in the reservoir seems to be between 100 °C to 140 °C, although cation geothermometers display temperatures up to 200°C. Moreover, the deposits of the Turi and Tarqui formation work as impermeable layers, which do not allow the geothermal fluids rising up. We propose that the R. Minas fault would be the main eastern boundary of the geothermal system, and Baños fault could be a secondary boundary which work as a pathway to transport the remaining geothermal fluids, and for this reason the hot springs, Narancay and Tarqui, are at lower temperatures, to the eastern part of this fault.

Outflow of the geothermal system would be located in the Baños de Cuenca town, where a secondary reservoir was created due to structural accommodation. In addition, the Baños and R. Minas faults, as well as the contact between the volcanic and sedimentary deposits would work as the main pathways. Throughout this circulation process, from southeastern to northeastern part, the geothermal fluids get the sodium-bicarbonate with significant chloride which characterized them (INER/SYR, 2014).

Therefore, we propose a hydrothermal geothermal system for Baños de Cuenca prospect, which despite containing low temperatures its complex structural system increases permeability and higher enthalpy can be expected; as has been seen in other geothermal systems at these temperatures, which produce up to 13 MWe (e.g. Karkey Umurlu, Turkey); as well as there are geothermal plants in regions with compression and transpression tectonic setting which produce electricity (e.g. Honshu, Japan).

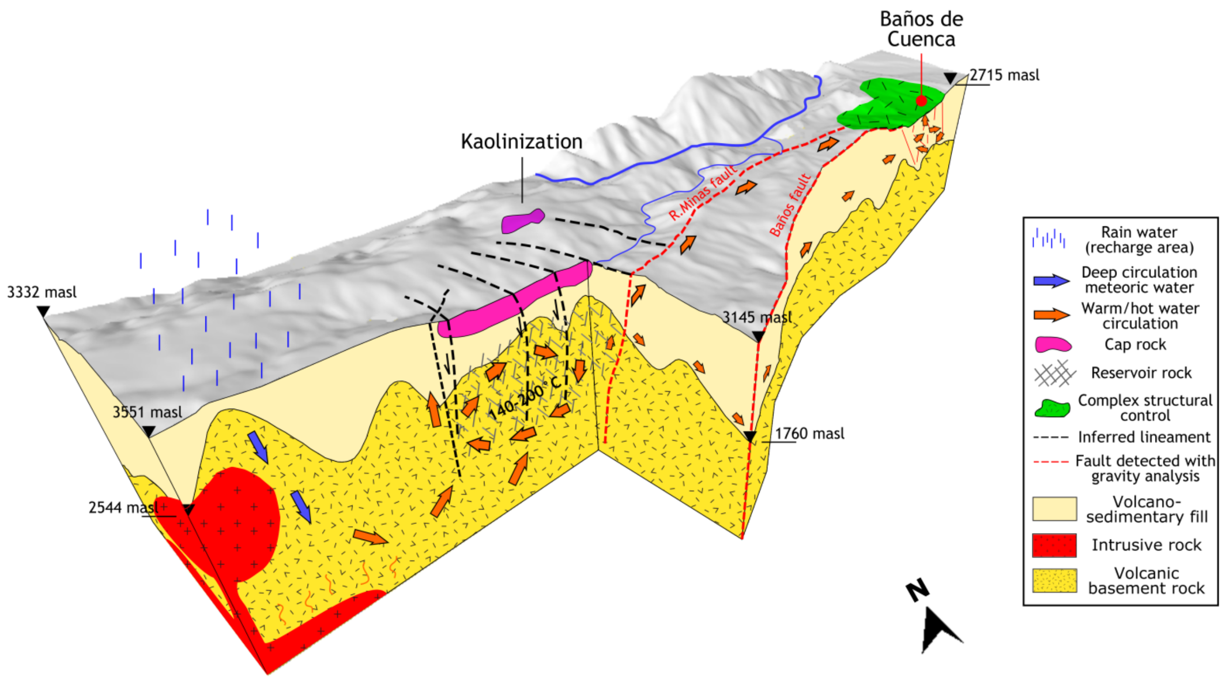

Figure 7: Preliminary model for Baños de Cuenca Geothermal prospect. Depth of volcanic basement (Saraguro group) was extracted from 3D gravity inversion.

5. CONCLUSIONS AND RECOMMENDATIONS

Baños de Cuenca geothermal prospect is a promising area located in the south of continental Ecuador, away from the northern active quaternary volcanic arc and outside of protected areas. It is implanted on Miocene sedimentary rocks from Cuenca basin, and Oligocene ignimbritic rocks from Saraguro group in a transpressive tectonic setting. Geothermal manifestations show a persistent activity with multiple hot springs, travertine and hydrothermal alteration deposits.

Through the gravity and inversion processing, one intrusive body, a complex structural setting and two main faults (Baños and Río Minas), were found out in Baños de Cuenca geothermal prospect. Taking geological and geochemical studies into account, a liquid-dominant hydrothermal geothermal system is proposed with good permeability and temperatures between 100 °C to 200°C, most likely 140°C (INER/SYR, 2014). The complex structural control could improve the enthalpy and to be considered for electricity production as similar geothermal plants with low deep temperatures and similar tectonic setting as has been seen in Turkey and Japan, respectively.

Therefore, considering that the Loma Larga mining project estimates 8.9 MW of electrical energy absorbed for the process plant and 3.3 MW for the filling plant (DRA Americas Inc., 2020); a geothermal power plant at Baños de Cuenca prospect could be a reasonable option to provide electricity to mining operations. In any case, multiple uses can be given to Baños de Cuenca area if the geothermal resource is used.

Follow-up studies at Baños de Cuenca geothermal prospect should take into account detail geological and geochemical exploration focused along R. Minas fault, as well as Helium and Sulfur isotopic analysis in order to reveal the heat source, must be carried out on hot springs. This work has enabled to continue this project to the next stage; and in order to constrict the interest area 42 magneto-telluric stations have been suggested, Figure 8.

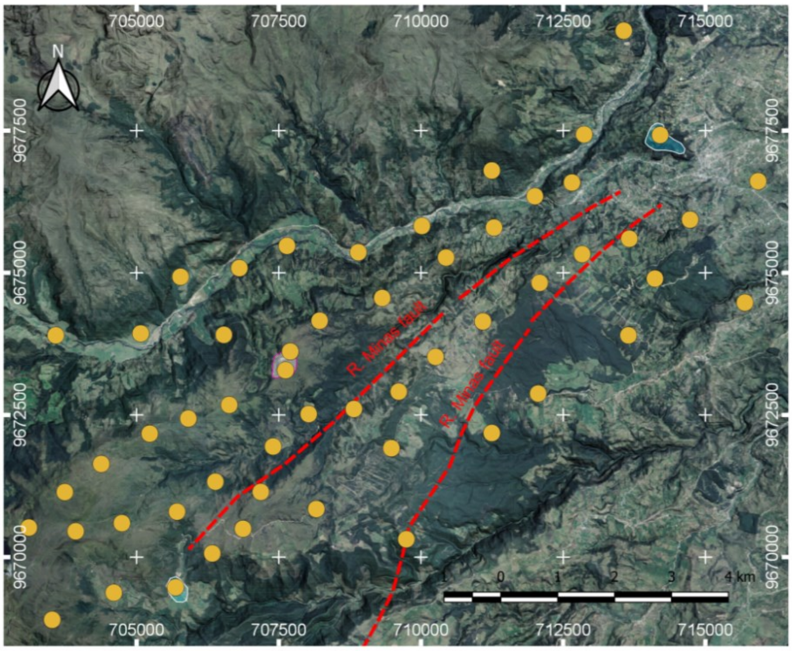

Figure 8: Location of suggested MT stations.

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