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The Abaya Geothermal Project, SNNPR, Ethiopia

Chelsea Cervantes[1], Hjalmar Eysteinsson[1], Yafet Gebrewold[2], Dario Ingi Di Rienzo[3], Snorri Guðbrandsson[1]

[1]Reykjavík Geothermal, Katrínartún 2, Höfðatorg, 105 Reykjavík, Iceland; [2]Addis Ababa University, Addis Ababa, Ethiopia; [3]University of Iceland, Reykjavik, Iceland

chelsea@rg.is

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ABSTRACT

Reykjavík Geothermal is an Icelandic geothermal development company that has been actively developing high-potential geothermal prospects worldwide for the past decade. Developing geothermal resources in Ethiopia has been an area of focus with three different geothermal projects underway: Corbetti, Tulu Moye, and Abaya. These projects are all located within the Main Ethiopian Rift, a prominent continental rifting zone part of the Great East African Rift System. The Abaya geothermal project is located on the western flank of the Southern Main Ethiopian Rift and is the furthest south of the Reykjavík Geothermal projects in Ethiopia.

The concession is cut across by a NNE-SSW trending fault swarm and is also the setting for three prominent graben structures, the Salewa Dore - Hako Graben in the west, which hosts an array of scoria cones and active fissures, the Chewkare Graben in the east, and the Abaya Graben in-between. Surrounding and within the license area are various volcanic centers, with what is known as the Salewa-Dore and Hako rhyolitic eruptive complex accommodating the most recent volcanic activity in the area and providing several minor geothermal manifestations. Most geothermal surface manifestations are found on the northwestern Abaya fault, a large ignimbrite escarpment on the western part of the Chewkare Graben. These manifestations consist of thermal springs, ranging from moderate 35 °C to boiling as well as steaming ground/fumarolic activity, at close to 100 °C at 20 cm depth.

Through numerous and extensive field campaigns, Reykjavík Geothermal has been compiling GIS, geological, geochemical and geophysical data of the Abaya geothermal prospect in the aim of creating a scientific foundation to characterize the geothermal production potential of the area. Geochemical sampling of thermal manifestations, subsurface fault characterization, rock sampling, soil-gas analysis and a geophysical MT/TEM survey provide the data to create a conceptual model. The compiled data ultimately suggests the Abaya region to be a high-enthalpy geothermal prospect.

1. INTRODUCTION

Reykjavík Geothermal (RG) has been active in Ethiopia since 2011. Prior to the Abaya geothermal project, RG has been instrumental in the Corbetti and Tulu Moye geothermal projects, both located in the Main Ethiopian Rift. The Corbetti and Tulu Moye geothermal projects are signed into a Power Purchase Agreement with the Ethiopian Government, with each project signed on for 520 MWe. Abaya is therefore the third area that RG is investigating in Ethiopia. Surface exploration has been conducted by RG in the high-temperature prospect of Abaya. The concession area is labelled in Figure 1 below, along with the two other RG geothermal concessions in Ethiopia: Corbetti and Tulu Moye. The concession is located directly north of Lake Abaya in the Southern Nations, Nationalities and Peoples' Region, and has an area of 513 km^2 (2019).

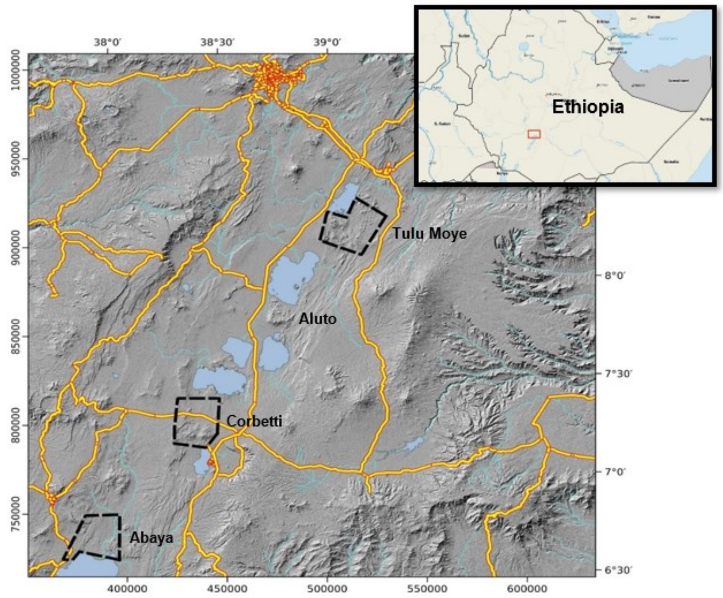

Figure 1: The Reykjavík Geothermal concessions in Ethiopia. The reference map in the upper right-hand corner shows the location of the Abaya concession.

2. GEOLOGICAL SETTING

2.1 Regional Tectonics and Geology

The EARS is a 50-60 km wide geographic phenomena about 6,400 km long and bounded by opposed and steeply dipping normal faults. It is relatively young rifting which started approximately 20-30 Ma ago when the African continental plate split into two separate plates: the Nubian plate to the west and the Somalian plate to the east (Ebinger et al., 1993). These plates interact with the Arabian plate to the north, meeting at a "triple junction", known as the Afar Triple Junction. South of the Afar Triple Junction begins the MER, which hosts the Abaya geothermal prospect and continues to the south through Ethiopia and Kenya. The most recent volcano-tectonic activity within the MER began in the Pleistocene and continues to present day and is related to the axial extensional zone denoted as the Wonji Fault Belt (WFB). The WFB is a NNE-SSW trending series of faulting along the rift floor, found widely in an "en-echelon" arrangement and resulting in bimodal basalts and rhyolitic volcanic products accumulated on the rift floor (Chernet, 2011; Electroconsult (ELC), 1987; Kazmin and Berhe, 1978).

The MER is divided into three sections based on surface geology and geomorphology, as shown in Figure 2. The Abaya area is in the western half of the Southern Main Ethiopian Rift (SMER), which extends from Lake Hawassa and slightly past Lake Chamo, in a southwestern direction. The SMER is the youngest part of the MER and is thought to be comprised of less-evolved rifting in comparison to the Central and Northern MER (Corti et al., 2013). The SMER area is characterized by the absence of a major rift escarpment as might be expected from a rift margin setting, and instead the topographic transition is gentle between the rift floor and highland plateau (Minissale et al., 2017).

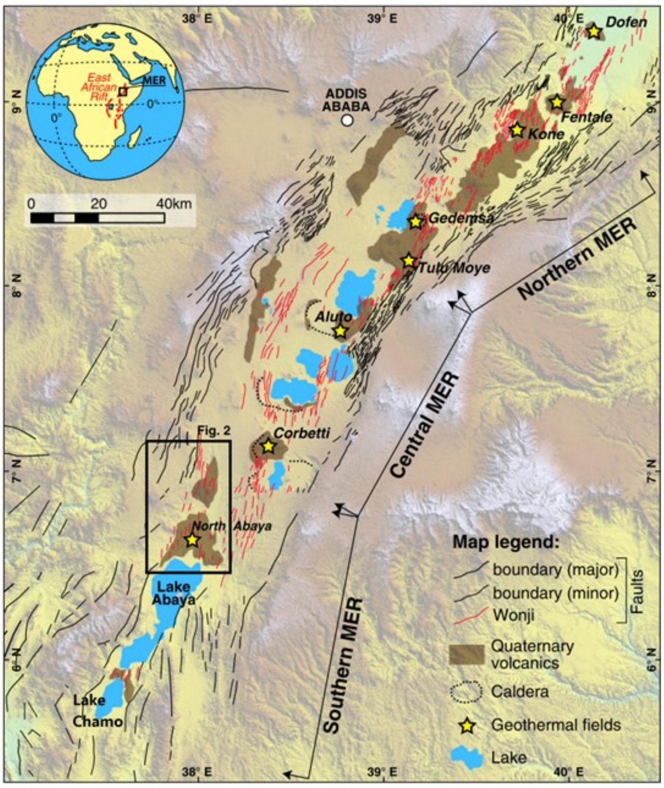

Figure 2: Tectonic map of the MER superimposed on a digital model (SRTM) data. Inset show en-echelon right-stepping arrangement of the volcano-tectonic segments of the Wonji Fault Belt. The Abaya geothermal concession is located within the black rectangle (Minissale et al., 2017).

2.2 Local Geology

<u>2.2.1 Structural Faulting</u>

The faulting in the area were identified by RG using a combination of methods and resources. High-resolution DEMs were initially used to delineate faults on the surface, and from this a total of 168 faulting traces were mapped with 69 of these faults ground-verified during three different field campaigns that took place between 2018-2019. The structural faulting observed from these methods are in good agreement with the cited works described in this section. An NNE-SSW trending fault swarm can be observed in the western area of the concession, which is intersected in the NW corner by the ring faults of what is known as the Obitcha Caldera. The numerous normal faults are closely spaced, have limited vertical offset and often present themselves in an en-echelon pattern, as seen in Figure 3 (Corti et al., 2013). A well-recognized fault providing permeability for major thermal manifestations is known as the northwest Abaya Fault, located north of the northwest corner of Lake Abaya. The base of the fault scarp strikes NNE-SSW and has a dip of 75-80° to the east (Ayele, Teklamariam, and Kebede, 2002; Mamo and Abtew, 2008).

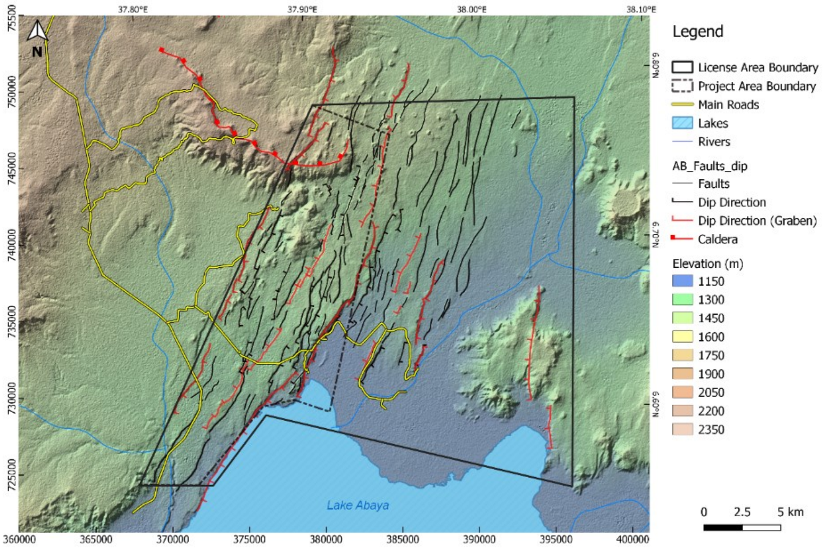

Figure 3: Structural faulting seen in the RG Abaya concession.

There is a lack of consensus within scientific literature as to whether the fault swarm in the western Abaya region is classified as an extension of the WFB, or rather what is known in some previous studies as “boundary faults”, which are faults that reside at the rift boundaries (Corti et al. 2013). As the Abaya concession is located in a transition zone between the western rift shoulder and the rift floor, it may be that the faulting of the area is indeed characterized more by boundary faulting, rather than Wonji faulting. Though it is generally agreed that the volcano-tectonic activity of the Quaternary period is associated with the WFB, the analysis of historical seismic activity of the SMER in particular suggests that it is the boundary faults that are responsible for the largest part of recent active deformation, while axial deformation is practically negligible in the SMER (Corti et al., 2013). This is likely due to the SMER being the youngest part of the MER, comprises of less-evolved rifting in comparison to the Central and Northern MER (Corti et al., 2013).

2.2.2 Major Geological Structures

Overall, the area within the concession can be recognized as a series of grabens and corresponding horst structures from west to east. Figure 4 displays the major structures in Abaya, which are three grabens: The Salewa Dore – Hako Graben, the Abaya Graben and the Chewkare Graben, as well as what is known as the Obitcha Caldera. The Salewa Dore – Hako Graben and the Abaya Graben are the most significant geological structures to the study at this time.

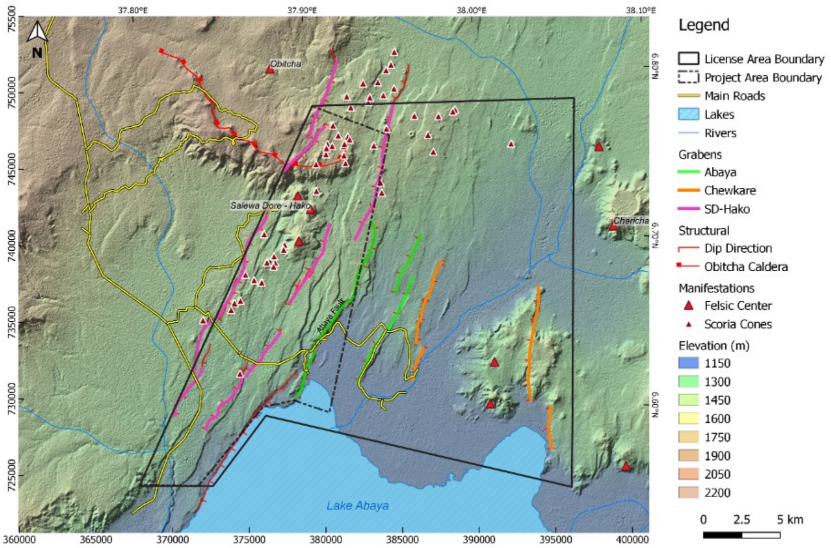

Figure 4: The Obitcha caldera structure of Abaya seen in the northwest of the concession, along with the outlines of the Salewa Dore – Hako (pink), Abaya (green), and Chewkare (orange) Grabens. The locations of known scoria cones and eruptive centers are also shown.

The Salewa Dore – Hako (SD-H) Graben is located in the western area of the Abaya concession. It is a NNE-SSW trending graben about 3 km wide and 5km long (Chernet, 2011). Scoria cones that relatively delineate faults are found within and around the length of the graben and scatter toward the northeast when moving northward along the graben length. Situated within the SD-H Graben are the eruptive centers Salewa Dore and Hako, known as the Salewa Dore-Hako rhyolitic complex.

Following the SD-H Graben, towards the east, is another graben feature recognized by RG as the Abaya Graben. Like the SD-H Graben the Abaya Graben trends NNE-SSW and is around 11 km long and 2.5 km wide. The western boundary flank of the Abaya Graben is the northwest Abaya Fault, a major ignimbritic escarpment. This escarpment is the location for prominent thermal manifestations, including high-temperature outflow, high-temperature drainage and warm (> 40° C) ground.

The Chewkare Graben is located in the southeast area of the Abaya concession. It is an axial graben of approximately 8 km at its widest and is partly occupied by the north-eastern tip of Lake Abaya (Chernet, 2011). The western boundary flank of the Chewkare Graben is located 1-2 kms to the east of the eastern flank of the Abaya Graben.

The Obitcha was a prominent rhyolitic volcanic center that is presently a horseshoe-shaped caldera with a diameter of approximately 10 km (Corti et al., 2013). The earliest phase of rhyolitic volcanism in the area is associated with the Obitcha volcanic center, and exposed on the flanks and rim of its caldera are large volumes of lava and pyroclastic material from past eruptions (Corti et al., 2013). Two major segments of the caldera can be in the northwest of the RG Abaya concession, with the southernmost segment intersecting the concession boundary.

2.2.3 Lithological Units

The local geology of the Abaya area consists of igneous and sedimentary lithologies. Most of the rift floor and margins in the area are covered by volcanic and volcano-sedimentary rocks associated with main rifting events (Corti et al., 2013). The most recent lithologies in the concession area consist of scoria, basalt, rhyolite, trachyte, ignimbrite, pyroclastic material and alluvium and fluvial deposits. The map in Figure 5 presents a compilation of the lithological information found in various studies (Ayele, Teklamariam, and Kebede, 2002; Chernet, 2011; Corti et al., 2013; Minissale et al., 2017).

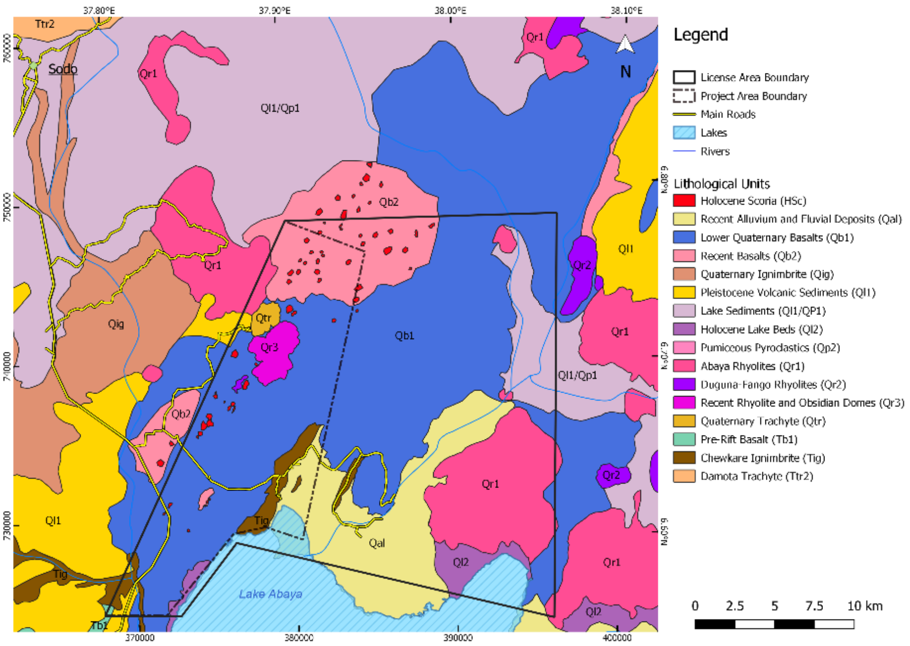

Figure 5: Lithological units seen in the RG Abaya concession.

3. SURFACE EXPLORATION

3.1 Geochemistry

3.1.1 Water and Gas Chemistry

Water chemistry for the Abaya area has existed since the 1970s. To add to this collection, RG collected gas and water samples during field excursions in 2018 and 2019 from springs and fumaroles in the area. The geothermal manifestations in Abaya are found in two areas: the Salewa Dore – Hako rhyolitic complex and on the northwest Abaya fault. Around the Salewa Dore – Hako rhyolitic complex several weak, moderate-temperature steaming areas are found at 30-45˚C, and on the northwest Abaya fault boiling mud pools and abundant fumaroles are found with temperatures ranging from 50 – 100 ˚C. Furthermore, several springs and hydrothermally altered surface rocks with weak fumarolic activity can be found on the northwest Abaya fault. The springs range in temperature from 40 ˚C to close to 100 ˚C, with the temperature increasing from north toward the south. Audible subsurface boiling can be heard in this area.

The waters collected from the springs show high concentrations of SiO_2, CO_2, and relatively low SO_4 and chlorine. The anion ternary diagram for the sampled waters along compositions of springs recorded in literature can be seen in Figure 6. All of the samples are plotted as peripheral waters with the exception two samples plotting as steam heated water. It is suggested that the high CO_2 concentrations and lack of H_2S, as also observed in the Corbetti and Tulu Moye RG concession, might eschew the characteristics of the water, plotting them as peripheral waters.

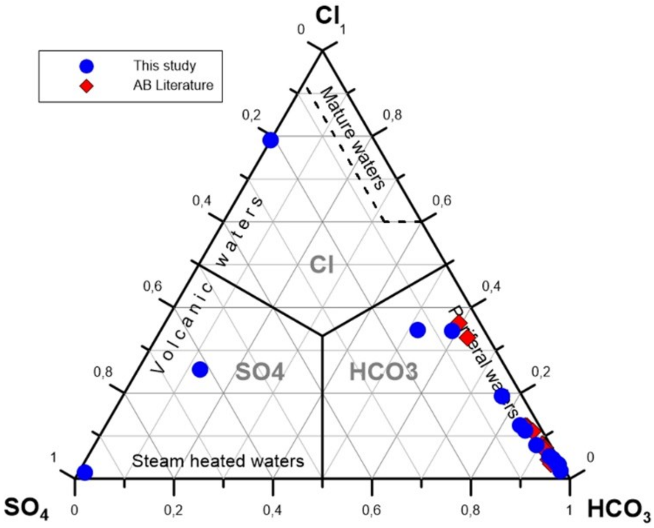

Figure 6: An anion diagram of the waters sampled from the springs in Abaya. All waters, apart from two, are suggested to be surface waters with CO_2 dominant species.

The concentration of sodium in the water samples ranges from 5 to 1370 ppm, potassium 3 to 174 ppm, calcium 0.4 to 53 ppm and magnesium 0.1 to 56 ppm. The Giggenbach ternary diagram and therefore the geothermometers suggests that most of the collected waters are regarded as immature, or partially equilibrated. However, one sample from this study and two from literature suggest partially to fully equilibrated water and reservoir temperatures exceeding 200 ˚C, as seen in Figure 7 below.

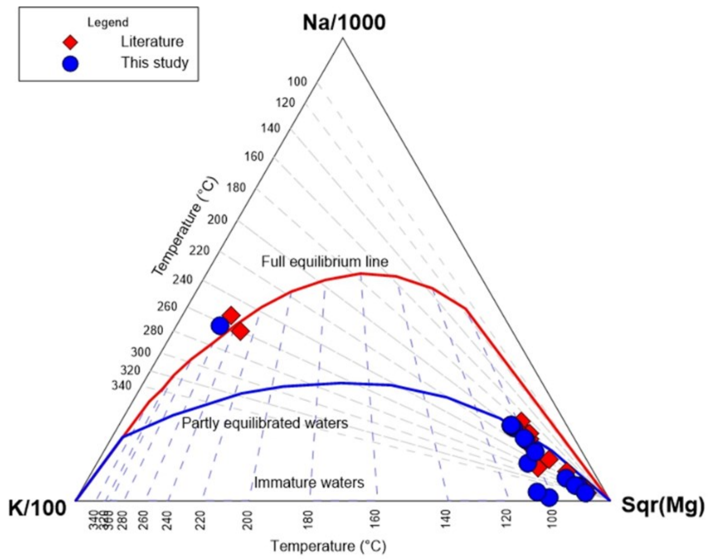

Figure 7: A Giggenbach diagram suggests most water samples collected in the area are of unequilibrated to partially equilibrated waters. Samples collected from Spring 6 show water of partially to fully equilibrated waters with reservoir temperature > 200 °C.

The high silica concentration measured in all springs results in estimated reservoir temperature of >140 °C. The highest silica temperature estimation is in agreement of the highest cation reservoir estimated temperature from samples collected from Spring 6, which both show a reservoir temperature estimation of 260 °C. The results of Spring 5 are close to a match, with the silica temperature estimation at 243 °C and cation estimated temperature at 252°C.

3.1.2 Soil-Flux Survey

RG with the participation of the University of Addis Ababa conducted a soil-gas and temperature survey in the Abaya concession with the aim to distinguish the permeable zones within the faulting. The distribution of gas flux in the areas around the surface manifestations of Abaya has been established in accordance to standard practice. The same applies for the temperature survey at 50 cm depth. A regional background value for the gas flux was established and geothermal anomalies were mapped in four main areas. The anomalies, as seen in Figure 8, are centred on the observed faults that are associated with the SD-H graben (Site 3), the northwest Abaya fault (Site 4), and the Salewa Dore – Hako rhyolitic complex (Sites 1 and 2), the most recent eruptive mechanism in the area. There is a clear agreement with the flux of CO_2 and the temperature anomalies in the region. Not all mapped faults were found with anomalous heat or gas flow. The methods are therefore useful to identify the permeable fractures, and possible drilling targets. The most obvious anomaly is along the northwest Abaya fault, where there are high temperature manifestations and shallow, boiling thermal waters (Site 4 in Figure 8).

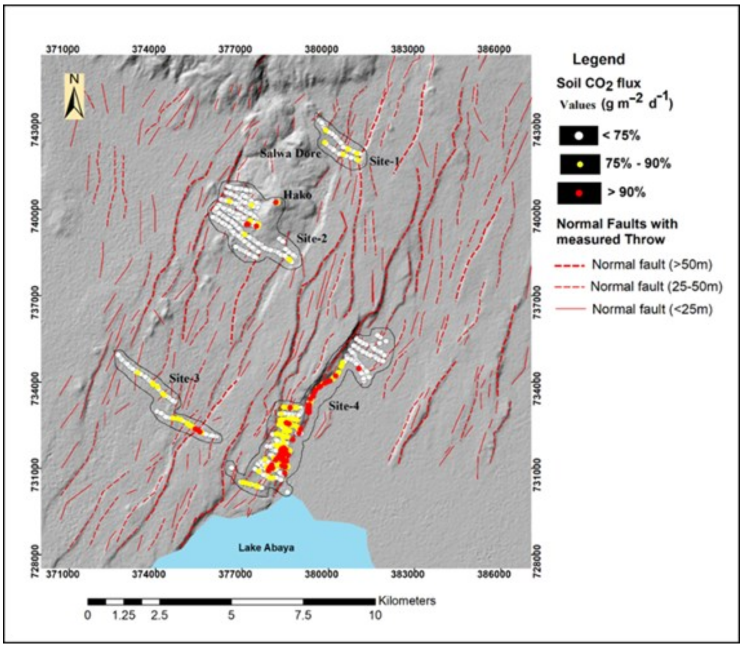

Figure 8: Location and spatial distribution of soil CO_2 flux. Spatial distribution of soil CO_2 flux is reported in cumulative percentage, with white circles representing a background value, yellow representing a transitional value and red representing a geothermal anomaly.

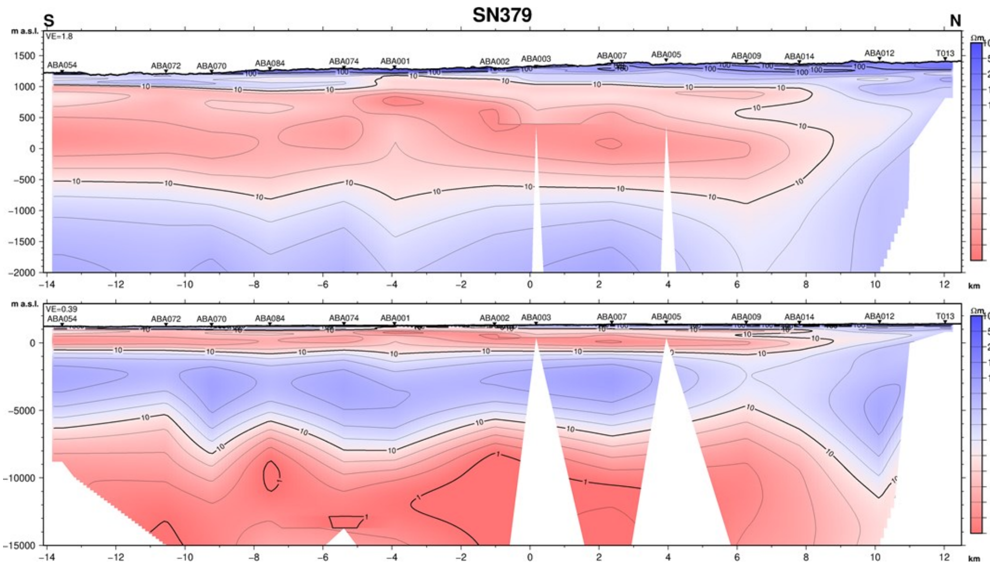

Figure 9: Resistivity profile SN379 from SW – NE. The upper figure is shown down to 2 km b.s.l., while the lower figure is down to 15 km b.s.l. The red indicates resistivity of < 10 Ωm.

3.2 Geophysics

A geophysical surface resistivity study in Abaya was conducted by RG in late 2018 and early 2019. A total of 88 Time-Domain Electromagnetic Soundings (TEM) and 82 Magnetotelluric (MT) soundings were set up in an area of approximately 300 km^2 in the western part of the concession area.

The results showed a subsurface resistivity structure that is consistent with the expected characteristics of high enthalpy geothermal systems. The most pronounced signature is located close to the northern Abaya shoreline, where a major NNE-SSW fault is located, and main surface geothermal manifestations are observed. Two low resistivity layers are observed: the first shallow layer at few hundred meters depth to roughly 2 km depth which is interpreted as thermally altered zone of temperatures up to 230°C and the second conductor is found to be at roughly 8 km depth and interpreted as a heat source for the active geothermal system in Abaya.

The area which shows the greatest resistivity signature of a high enthalpy system (indicated as the alteration layer with resistivity <

10 Ωm) is around 250 km^2. However, this area is only confined towards the north, thus 250 km^2 can be considered the minimum area coverage.

4. SUMMARY AND CONCLUSION

The Abaya geothermal prospect has been studied extensively by Reykjavík Geothermal. The overall geological structure presents surface thermal manifestations hosted by permeable fault systems, as indicated by thermal springs and altered ground which has been confirmed further from the results of soil-flux analysis. The fluid chemistry analysis indicates fluid sources derived from a geothermal reservoir, with geothermometer measurements suggesting temperatures >230 °C. The results from MT/TEM surveying of the area present the presence of a low-resistivity layer at a few hundred meters of depth, and a deeper conductor at roughly 8 km depth, being the heat source for the system. All these combined factors strongly suggest the presence of a high-enthalpy reservoir suitable for geothermal power production in the Abaya area.

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