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Geology and Conceptual Model of the Tulu Moye Geothermal Project, Oromia, Ethiopia

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ABSTRACT

Tulu Moye is a geothermal prospect area in the Main Ethiopian Rift, located around 70 km SE of Addis Ababa, in the Oromia region and Arsi Zone. The area is characterized by NNE-SSW aligned normal faults belonging to the Wonji Fault Belt, the most tectonically active segment of the Main Ethiopian Rift. On the eastern flank of the Wonji Fault Belt numerous recent scoria cones and rhyolitic/obsidian domes rise from the same eruptive segments, showing a bimodal volcanic activity. The Wonji Fault Belt and recent volcanic formations cross a large caldera, suggested to exceed 177 km^2, that is likely to have formed in later Pleistocene or ca 117 ky. The surface geothermal manifestations in the area are characterized by large areas of hydrothermally altered surface, often associated with weak fumarolic activity and steaming grounds. No surface waters are within the area and the groundwater level is likely to be closely connected to the water level of Lake Koka in the north and Lake Ziway in the south, standing in 1600 m a.s.l. Five temperature gradient wells were drilled in 2002 by the Geological Survey of Ethiopia, all reaching down to 90 – 120 m depth and > 90 °C. Gas samples collected from fumaroles and the steam from temperature gradients suggest reservoir temperature in excess of 230 °C. The resistivity survey suggests a clay cap within the large proposed caldera, possibly covering >200 km^2. Tulu Moye shows the characteristics of a large high-enthalpy geothermal system complete with recent volcanism, extensive surface activity and accompanied with a high estimated reservoir temperature beneath an extensive clay cap, all of which suggests high geothermal potential. Reykjavík Geothermal and Meridiam, a French investment fund formed Tulu Moye Geothermal Operation (TMGO) in 2018 to continue the project of drilling and building a geothermal power plant in the Tulu Moye area.

1. INTRODUCTION

Reykjavík Geothermal (RG) is a development company that has been active in developing geothermal projects in several areas in the world over the past decade. The focus projects of RG have been in Ethiopia, where currently involved are major shareholders in both Corbetti Geothermal Ltd. and Tulu Moye Geothermal Operation, the companies that are building geothermal powerplants in Ethiopia. Both have signed a PPA with the government of Ethiopia for 520 MWe each.

Tulu Moye is in the Main Ethiopian Rift (MER), just 70 km SE of Addis Ababa. 75 km N of the Aluto Langano geothermal powerplant is the Tulu Moye geothermal concession (Figure 1). The license area includes part of the Gedemsa caldera to the north, and the Bora-Bericha rhyolitic formations to the west, along with the volcanically active segment of the Wonji Fault Belt (WFB). Within the area a proposed large caldera is located with a visible caldera wall to the east and reaching south west to Bericha with several rhyolitic formations. The main water bodies in the area are Lake Koka and Lake Ziway in the south. No rivers, apart from some seasonal drain paths are within the concession and the only body of water is Lake Bite, a small lake that dries during the longest stretches of dry season.

In the eastern part of the license area, the WFB is present and trends from north to south across the entire concession. This eastern segment is characterized by active faulting, where in the eastern half of the segment there is no volcanic activity present, and on the western half resides a volcanically active feature called the Salen Volcanic Ridge (SVR). Recent formations, such as large obsidian domes as well as lava flows are clearly visible from aerial images, both within the SVR as well as west of the SVR. These formations have not been dated but have been suggested to be as recent as from the late 1800s from historic accounts (Wadge et al. 2016). In addition, large surface hydrothermal alteration areas are visible and are found on a south western segment of a proposed caldera, covering approximately 170 km^2 and located in the east of the concession (Figure 2).

Geothermal manifestations in the Tulu Moye concession consist mainly of weak steam rising within a hydrothermally altered surface, with temperatures ranging from 37- 95 °C near the surface. These manifestations are aligned to the SVR and the southern segment of the caldera. Locals have used this steam by constructing steam baths on top of the manifestations and use them for bathing; over thirty steam baths have been visited. In 2002 five shallow temperature gradient wells were drilled and all reached >90 °C at less than 150 m depth, indicating a shallow boiling system. Gas samples collected in Tulu Moye indicate a reservoir temperature >250 °C.

The focus of the surface exploration was concentrated towards the obsidian dome of Gnaro, located on the southern intersection of the proposed caldera and the Salen Volcanic Ridge (Figure 3). This area has surface alteration associated with the structural features of the WFB, recent rock formations of felsic composition suggesting central volcanism and resistivity anomaly at a suitable depth.

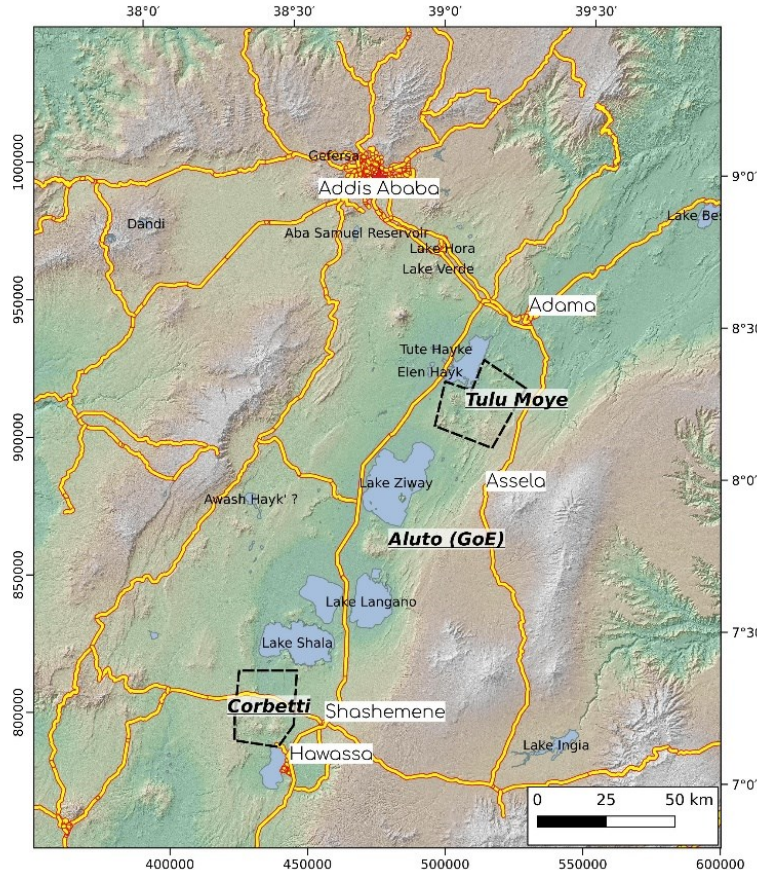

Figure 1. Tulu Moye and Corbetti geothermal areas in Oromia region, Ethiopia. The only current geothermal power plant in Ethiopia is Aluto Langano, located between Corbetti and Tulu Moye, around 60 – 70 km from each.

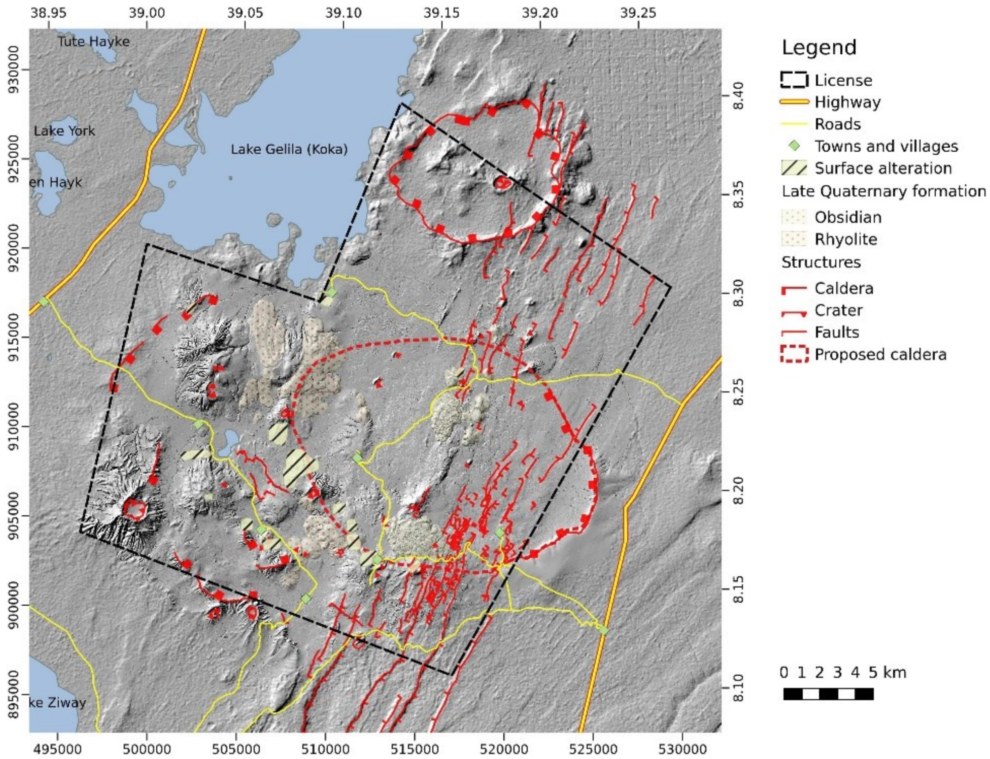

Figure 2. Tulu Moye geothermal concession. The Gedemsa caldera in the north and the large proposed caldera with the caldera walls to the east, and traced southward and to the west along structure, alteration and felsic lava formations towards the Boricha mountain in the west. No physical properties are observed at the northern caldera wall to the north. Koka, Bite and Ziway lakes from north to south are the important water bodies in the area. The post caldera rift, the WFB, with its NNE-SSW normal fault direction and the volcanically active western faults are visible in the middle of the proposed caldera.

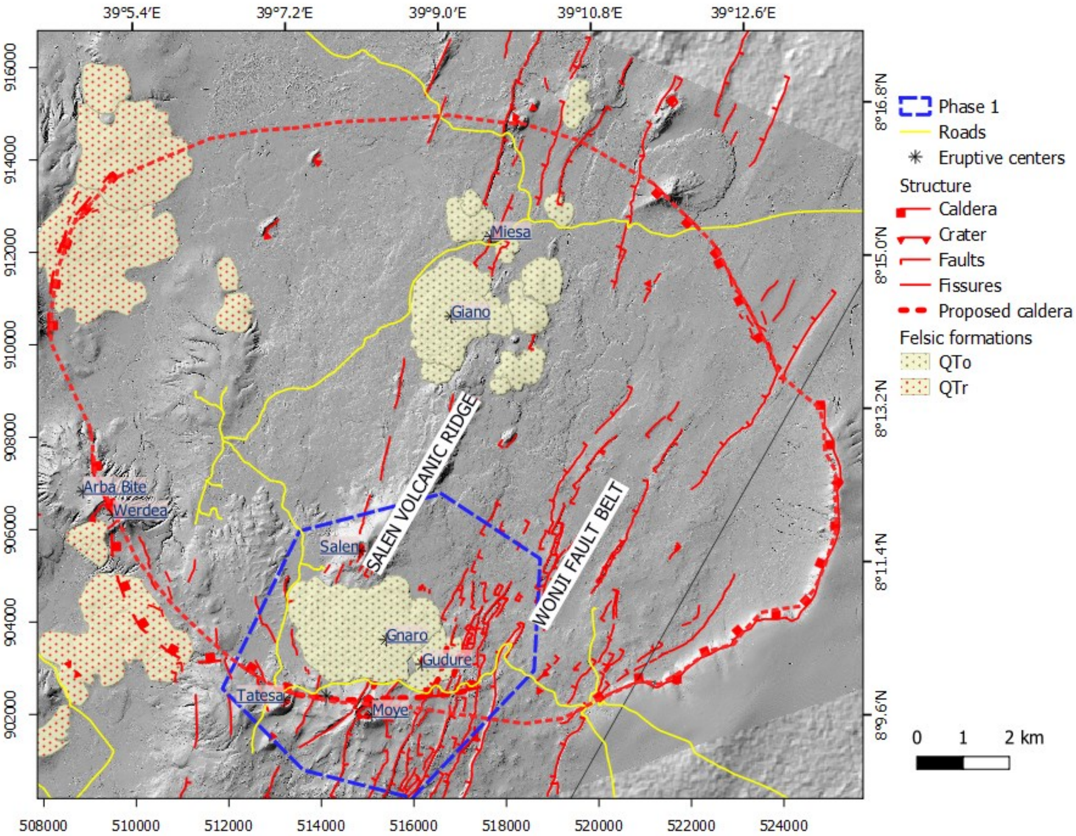

Figure 3. The proposed caldera in Tulu Moye. The red dotted polygon represents the recent rhyolitic formations at the caldera rim, the green dotted polygons are the obsidian formations associated with the Salen Volcanic Ridge, the volcanically active segment of the WFB. The black-dashed box indicates the Gnaro exploration focus area.

2. SURFACE EXPLORATION

Reykjavík Geothermal and TMGO have carried out extensive surface exploration in the area since 2014. These studies along with recent geological and geophysical studies carried out in the rift suggest a potentially large geothermal reservoir within the Tulu Moye concession.

2.1 Structure and surface manifestations

The volcano-tectonic activity of Quaternary to Recent MER is associated with the Wonji Fault Belt, as observed in the alignment of caldera structures, cinder cones and volcanic fissures. In general forms a close network of faults characterized by fresh, steep fault scarps. The eastern margin is characterized by closely spaced sets of horsts, graben and half graben fault planes that have high angle geometry with dip generally >65˚ (Corti, 2009).

The WFB is a post caldera rift segment, running through a large caldera that is visible in the east of the concession and can be traced along the southern rim by structural and petrological features, to the western rim that is the rhyolitic formation of the Bora-Bericha mountain complex in the west (Figure 4).

The geothermal manifestations within the Tulu Moye geothermal concession are characterized by weak fumarolic activity, mostly located within large surface hydrothermal altered areas, where temperatures at 50 cm depth ranges from 40–100 °C. Geological Survey of Ethiopia (GSE) drilled 5 temperature gradient wells in the region in 2002, ranging from 90 – 120 m in depth that all reached >90 °C, or boiling temperatures at 2000 m a.s.l. The manifestations are closely associated with the structural features in the area, aligning mainly along the southern rim of the proposed caldera, west of Gnaro obsidian dome and north from Gnaro on the SVR.

2.2 Geology

The petrochemical composition of the rock formations in the area suggests a bimodal volcanic system with mafic and felsic formations forming from the same eruptive locations as is frequently found in the MER (Mazzarini et al., 2004; Gasparon et al 1993). This is seen especially on the western flank of the WFB in the area, were the most recent volcanic activity in the area is located. There, numerous fresh scoria cones and basaltic flows are observed along various sized rhyolitic (obsidian) domes, all located on the same volcanic ridge and named after the highest scoria formation, Salen Volcanic Ridge. The dating of these formations are limited but according to Fontjin et al. (2018) the caldera collapse dates back 117 ky, suggesting all formations on the WFB being younger. The most recent eruptions reported by Wadge et al. (2016) are possibly as recent as 1775 and ~1900. These findings suggest that the area hosts several active eruptive centers as well as the high probability of a central volcanism (Figure 5).

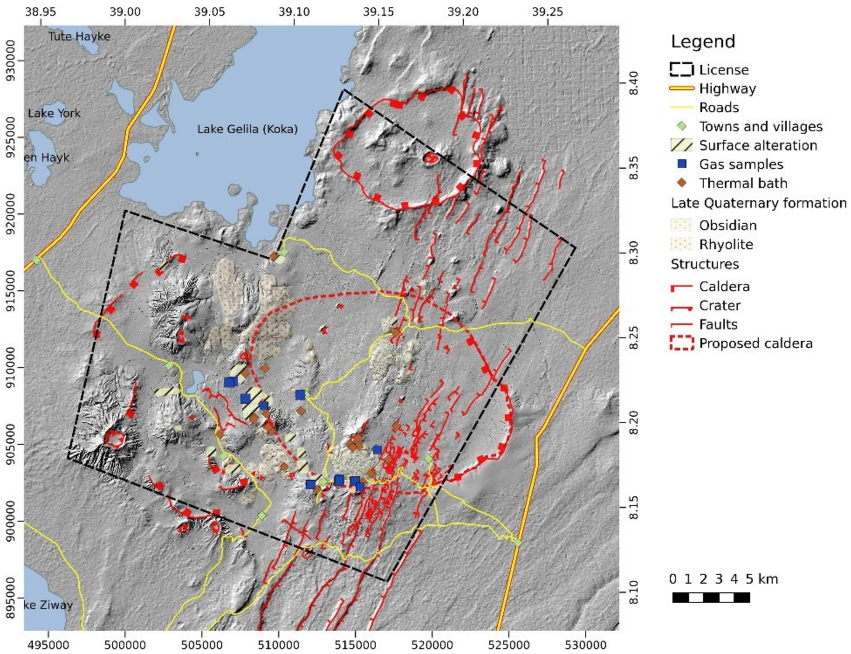

Figure 4. Structural features, hydrothermally altered ground and geothermal manifestations in Tulu Moye. A large proposed caldera south of the Gedemsa caldera in the north. The dominating NNE-SSW WFB is a post caldera rift, and is currently the active segment MER. The hydrothermally altered surface, thermal baths and collected samples align on the southern rim of the proposed caldera.

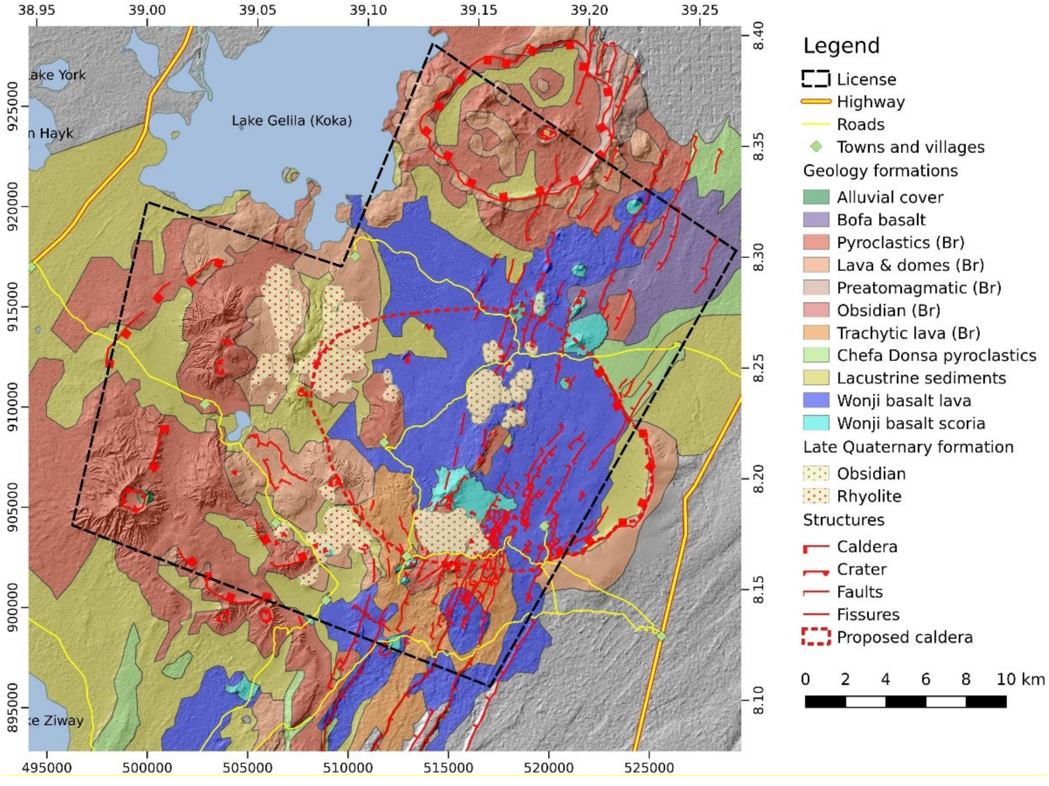

Figure 5. Updated geological map of the Tulu Moye geothermal concession. The felsic formations on the west and south west caldera rim (red dotted polygons) are associated with the proposed caldera, whereas, the green dotted polygons (south central and central caldera) are associated with the eastern flank and volcanically active segment of the WFB. The proposed caldera is <117 ky suggesting that the area is all late Pleistocene to recent (Adjusted from Abebe et al., 2005).

2.1 Seismicity

Prior to the Greenfield et al. (2018) seismic survey no seismic activity was known in the area, based on the GSE seismic survey catalogue. This is due to the limited coverage of the Ethiopian seismic network. Greenfield et al. (2018) show the image of a seismically active area, characterized by low magnitude, but frequent seismicity in the area. The seismicity is focused on the southern rim of the proposed caldera and even more intense is a cluster south of the rim (Figure 6). Greenfield et al., (2018) suggest that the seismic activity in Tulu Moye is possibly reflecting the hydrothermal fluid flow in the area. This also suggests that subsurface permeability is present, which is likely connected to the surface manifestations in the area.

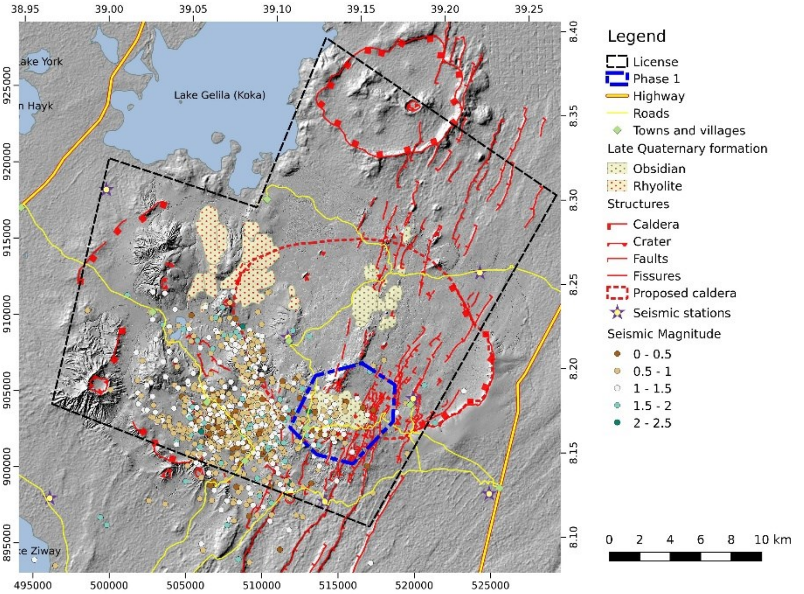

Figure 6. Seismic activity in the Tulu Moye geothermal concession. The seismicity is characterized by low magnitude, <2.5, events but frequent. The seismicity is focused on the southern rim of the proposed caldera and south-east of the caldera rim.

2.2 Geochemistry

No water samples were collected in the area due to absence of water boreholes as well as surface streams and springs, only steam samples from fumaroles and temperature gradient wells. The gas samples were collected in Giggenbach flasks where possible and pulled into bulbs through a solution of caustic soda when the steam flow was not suitable for a Giggenbach sample, see Arnórsson et al. (2006). The dissolved gases, H_2S and CO_2 were analyzed according to standard procedure in a field laboratory and the head space gas was analyzed at the Iceland Geosurvey for major elements using Gas Chromatography. The samples have all high concentration of CO_2 but H_2S was below detection limits in all samples. The results were used to calculate reservoir temperatures using gas geothermometers from Arnórsson (2000). The estimated reservoir temperature from the samples were a more than one geothermometer can be applied suggests a reservoir temperature in excess of 230 °C (Figure 7).

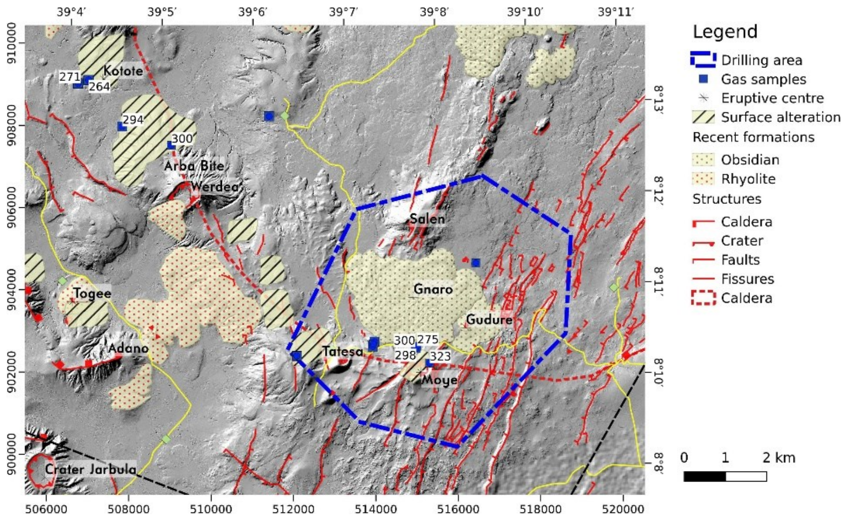

Figure 7. The proposed drilling site in Tulu Moye, blue polygon. The sampling locations, blue squares and the estimated reservoir temperatures based on gas geothermometers. Red dotted polygons are rhyolites associated with the caldera rim and green dotted polygons are obsidian formations within the volcanically active segment of the WFB.

2.3 Resistivity

An extensive resistivity survey with over 150 stations measured suggests a 500 to 1000 m thick clay cap being present at depth from 500 m to 800 m. The clay cap coverage as not been determined to the north but current studies indicate a clay cap in the license area exceeding 200 km^2; the full extent of the clay cap yet to be mapped as its boundary exceeds the concession area of interest. Under the southern part of the Salen Volcanic Ridge a shallow low resistivity anomaly is found that has been suggested to be a magma chamber at shallow depth, and the heat source of the geothermal system in Tulu Moye (Samrock et al., 2018).

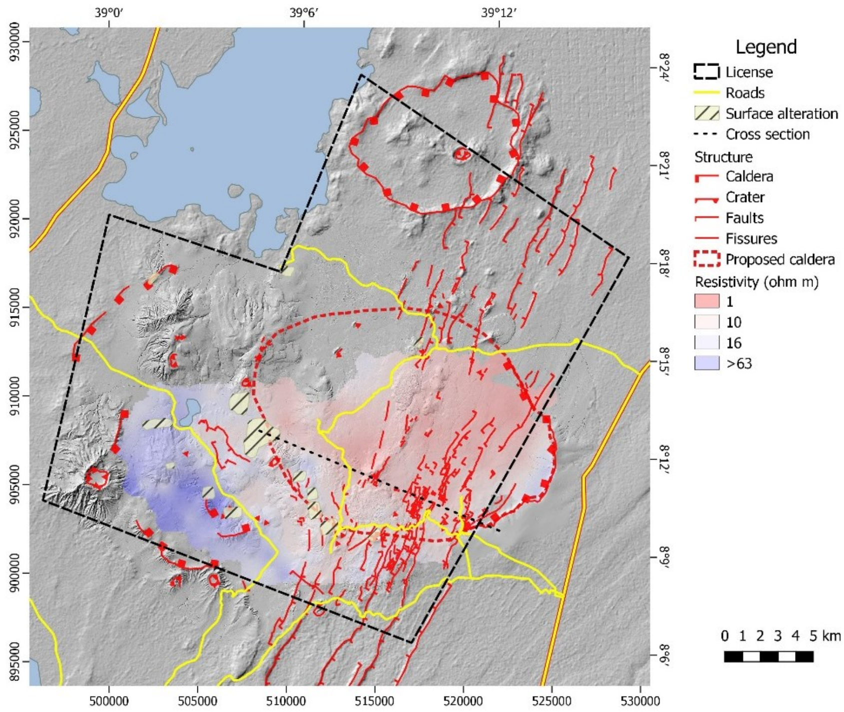

Figure 8. Resistivity map at 1500 m a.s.l. The identified clay cap (red surface) is focused inside the proposed caldera, whereas the clay cap is not visible west of the caldera. The dotted line represents the cross section that is displayed in the conceptual model.

3. CONCEPTUAL MODEL

Based on these findings a conceptual model has been proposed. Suggesting that the water recharge zone to be in the high plateaus in the east, Mt. Chilalo, infiltrating into the area from the east and being heated up below the Salen Volcanic Ridge, where the suggested heat source is located. The geothermal fluids rise to the surface through the faults in the west segment of the Wonji Fault Belt, the Salen Volcanic Ridge. The SVR is both seismically and volcanically active, ensuring the subsurface permeability and pathways of the geothermal fluids from the reservoir to the surface, observed in the fumaroles and hydrothermal alteration in the area.

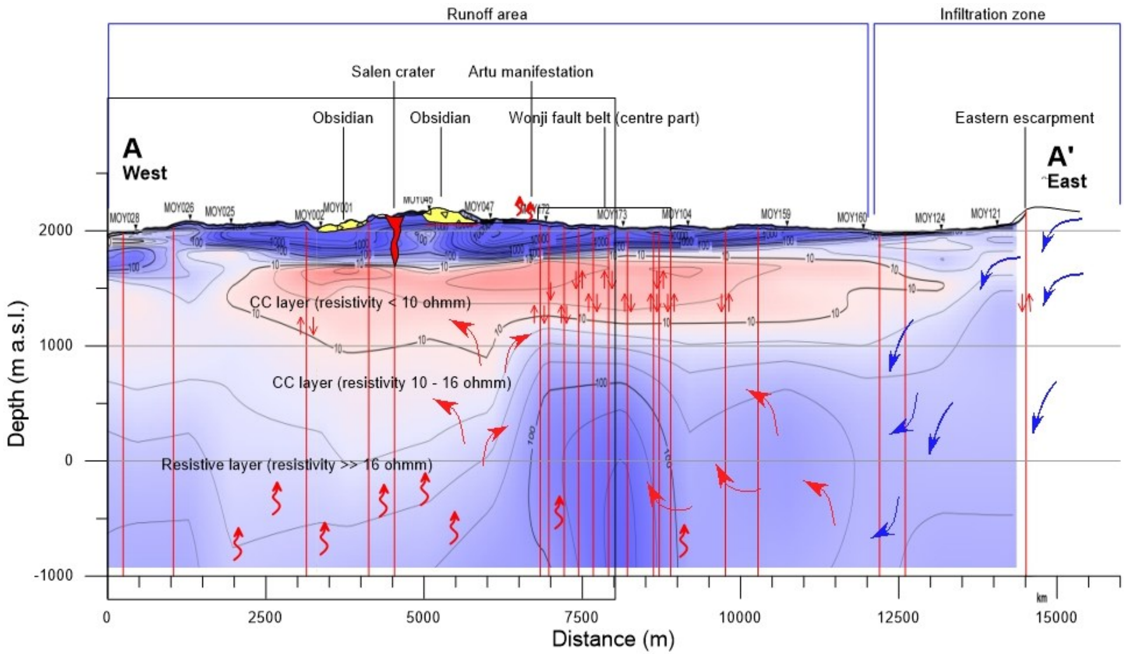

Figure 9. Proposed 2D conceptual model for the Tulu Moye concession. The section is W-E over the Salen Volcanic Ridge and Gnaro Obsidian dome. The infiltration zone in the east is recharged with water from the Mt. Chilalo, further in the east. The low resistivity layers (clay cap) is found in from 1600 to 1000 m.a.s.l. in the area, with the low resistivity anomaly below the Salen crater, indicating the heat source of the geothermal system.

3. CONCLUSION

The Tulu Moye area in the MER bears all characteristics of hosting a high enthalpy geothermal system, being in a tectonically active segment of the EARS, displaying recent volcanic activity, with an area of over 200 km^2 of low resistivity reaching to a suitable depth for production, where a geothermal reservoir in excess of 230 °C is estimated to be found. Tulu Moye Geothermal Operation plans to drill for the first phase in the winter of 2019-2020 for the first phase of 50 MWe.

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