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Tulu Moye Geothermal Project (Oromia, Ethiopia)

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ABSTRACT

Meridiam engaged with Reykjavik Geothermal (RG) in the development of the Tulu Moye geothermal site (Oromia Regional State, Federal Republic of Ethiopia) with the objective of installing 520 MWe within eight years (i.e. by 2025). Within the first four years of the project, a unit of 50 MWe is planned to be completed (i.e. by 2022), following the feasibility engaged by RG in 2008-2009 (including deep exploration drilling and tests) while complementary surface studies will be conducted in parallel for subsequent phases.

Meridiam is a global investor and asset manager specializing in public and community infrastructure with a long-term view. Founded in 2005 by Thierry Déau, the company is an independent player committed to aligning the interests of public, private and community stakeholders. Projects are developed by working closely with public authorities at every stage, from design through long-term management (25 years). Meridiam promotes a hands-on approach with a strong focus on technical, environmental and social aspects as well as an active engagement with all project stakeholders. Its business model is built exclusively on the equity financing of projects sponsored by public authorities for the benefit of the community.

Meridiam joined Reykjavik Geothermal and co-created a dedicated project company (Tulu Moye Geothermal Operations Plc, i.e. TMGO) to acquire the concession/lease rights secured 8 years ago from the Ethiopian Federal Authorities by RG. Meridiam also signed a geothermal assistance agreement with SARL Géo2D. TMGO signed a Power Purchase Agreement (PPA) and Implementation Agreement (IA) with the Ethiopian Electric Power and the Government of Ethiopia (GoE) in December 2017 and is established in Ethiopia with its own staff.

The Tulu Moye lease is located in the Main Ethiopian Rift (MER) inside a set of successive calderas of recent Quaternary age, covering a surface several hundred Km wide, crossed through by one of the active segments of the Wonji Fault Belt trending NNE-SSW called Salen Range. The area also appears to act as a leaky-transform zone between two rift segments, with transverse (NW-SE) magmatic and thermally emissive faults. Complete sets of differentiated magmas of fairly recent age (the last emitted circa two centuries ago), ranging from transitional basalts to peralkaline rhyolites show the presence of a heat source confirmed by geo-electric models, which also reveal the typical low-high-low resistivity profiles characterizing high temperature geothermal reservoirs. The surface extension of the reservoir already mapped in the southern part of the lease largely exceeds 200 Km2. Gas geothermometry indicate temperatures of 360°C to the south and 240°C to the north of the lease.

Drilling sites and characteristics are designed for the exploration wells to be engaged at the end early 2019, whereas complementary field works are planned to delineate the extension of the reservoir further north. The full project will channel private investments to Ethiopia of

more than $USD 2 billion. It represents an important milestone in Meridiam's commitment to sustainably supporting Ethiopia's infrastructure development efforts.

Although its limits are not yet fully investigated, Tulu Moye already appears to be one of the most promising sites in the East African Rift Valley, with a potential that place it in the category of the world geothermal giants, over 1GWe.

1. Background and main findings

The TM project aims at addressing Ethiopia's national electric grid needs. With a population of over 100 million and a fast-growing economy (about 10%/year) the country has an increasingly growing power production demand, particularly to cover the base load. Presently, the production is mainly covered by hydroelectricity, the development of which was the priority of the Federal Government for the last 20 years. Despite huge advantages, hydro depends on the fluctuation of the climate and the resource is also affected by climate change.

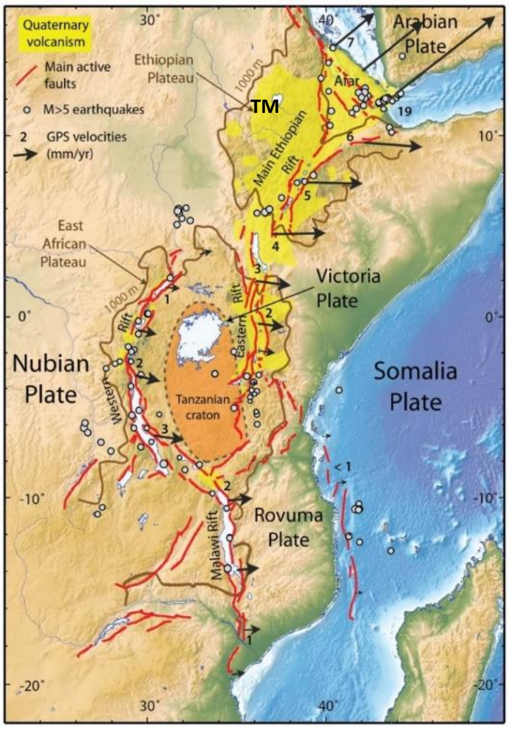
Ethiopia is particularly rich in geothermal energy, due to its geodynamic position. Although its location along the active EARV (with spreading rates increasing from 4 to 7 mm/y from south to north and reaching 2 cm/y when reaching the Red Sea and Gulf of Aden oceanic rifts emerging in Afar, Fig. 1) allow for the highest terrestrial heat flows in Africa, geothermal was not really developed yet. After pioneer's works by CNR (Italy) and CNRS (France), inventories were engaged (UNDP, 1972; ELC, 1987), a pilot plant was built at Aluto-Langano (1998, 7MWe), and since 2016 a new legal framework was defined to favor private and foreign investments through resource licensing and Power Purchase Agreements (PPAs).

RG was among the few foreign enterprises who anticipated this evolution and pioneered geothermal development in the Main Ethiopian Rift (MER) with the Federal Ethiopian Ministry of Mines nearly 10 years ago, and more recently engaged negotiation for a rewarding partnership with the Federal Ministry of Energy and Water. PPAs and feed-in tariffs were defined in December 2017, allowing to reactivate the investments in geothermal exploration in the country.

Meridiam has embarked in the project at this stage; when the geothermal resource has been defined from surface exploration, but not yet confirmed by production drilling - a necessary step to precisely define the reservoir parameters and all production devices - namely the production and injection wells, fluid conduits as well as the power plant characteristics. This paper hence aims at showing the quality of TM's geothermal resource based on RG's surface exploration studies carried in 2015-2017 with the support of GRMF as well as new field observations based on scientific works recently published in this portion of the MER.

2. Geographic and volcano-structural context

The Tulu Moye site is located in the middle of the MER, south of Adama, not far from the main axis linking the capital Addis Ababa to the main port Djibouti (highway, railway, powerlines, communication…Fig. 2). This corresponds with an area where the rift valleys enlarge as several NNE-SSW active volcano-tectonic segments co-exist, with in particular the two "en échelon" spreading and diking segments of Tulu Moye (Salen Range) and Koka-Boku-Adama (Fig.3).



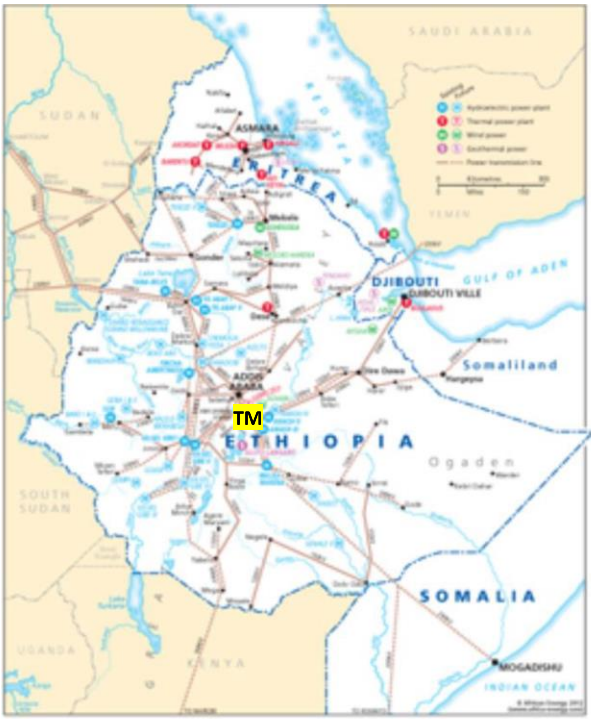


Fig. 1(left) : The East African Rift system, with major fault systems (in red), major earthquake location (white dots for M> 5), manifestations of Quaternary volcanism (in yellow) and plate-motion vectors with GPS velocities (black arrows, with numbers in mm/y). Observe the progressive decrease of the spreading rate from South to North along the EARV (from 5 to 7 mm/y along the MER; up to 2 cm/y in Afar). Plate motion is of 5 mm/year at the level of Tulu Moye (TM blue square), (base map from Calais, 2016).
Fig. 2 (right): location of Tulu Moye geothemal site (TM in yellow) with respect to the electric grid in Ehiopia and surrounding countries (base map from African Energy Atlas 2012).

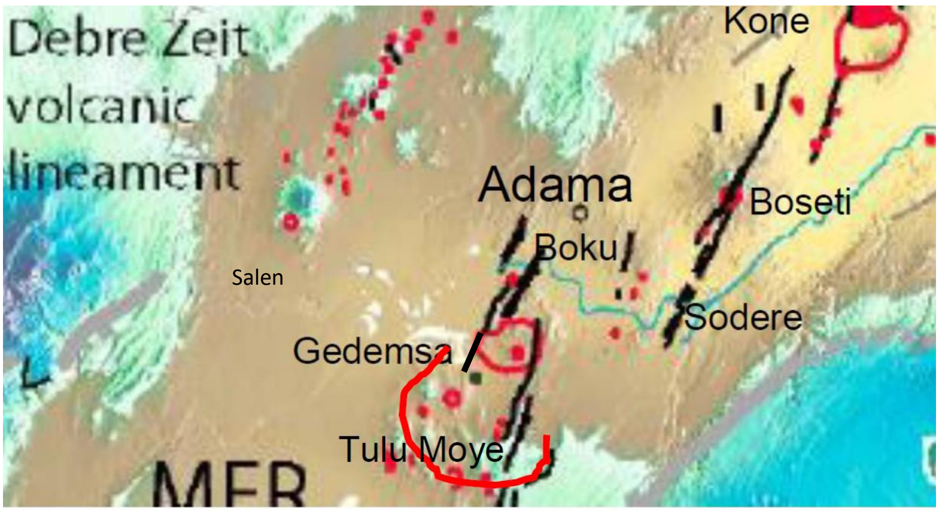


Fig. 3 : Geo-structural map showing the location of the active spreading segments along the MER floor, with major tectonic lines (open faults) in black and active volcanic units in red. The TM concession is located in the area where the rift floor widens, with several segments allowing for the development of large size magmatic bodies with calderas. The Salen segment is replaced north by the Koka-Boku-Adama segment. TM and Gedemsa calderas developped earlier in this TFZ environment.

From a volcanological point of view, it is characterized by the presence of at least two calderas:

- the earliest exceptionally large (at least 25 Km in diameter, i.e; 500Km2 in surface), largely determined the volcanic history of the area;
- the youngest (340ky), called Gedemsa located on its northern edge, of more classical size (10x8 Km, i.e. a surface of 63 Km2);
- both displaying post-caldera activity along caldera ring faults as well as along faults of MER (NNE-SSW) and transverse (NE-SW) directions.

But also by the presence of the very recent and eventually historic Salen range occupying the eastern part of the mega-caldera, with a continuous set of vents aligned on NNE-SSW faults and feeding fissures having produced a variety of magmas ranging from basaltic cones and flows to viscous domes of peralkaline rhyolites (Fig. 4).

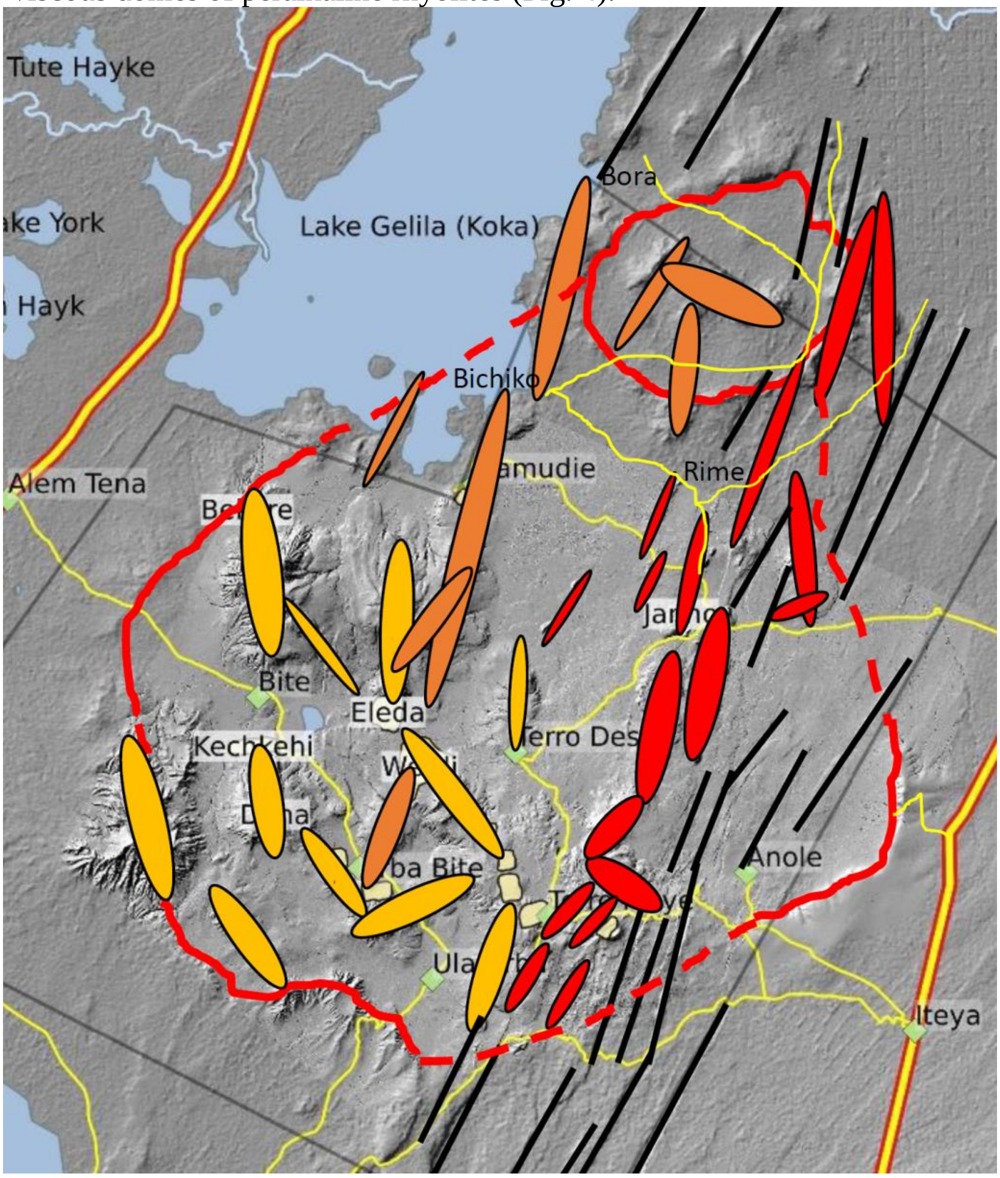


Fig. 4 : Schematic volcano-structural interpretation of the lease area (grey polygon) : visible caldera rims (red lines); first post-caldera eruption centres frequently transverse (yellow); later post-Gedemsa-caldera events (orange); presently active Salen range (emissive axis in red); the "dry" normal faults (black) show the E-W displacement of the rift from S to N of the TM caldera, the area acting as a hidden leaky transform fault zone. (Varet, 2018). In the area of junction between the two calderas a wide surface covered by recent basaltic flows do not allow to observe earlier structures.

The 785 Km2 exploration licence includes all these features, although cutting through the middle of the Gedemsa Caldera. Having noticed that the surface studies engaged by RG in 2016 concentrated on a limited (SW) part of the lease (122 Km^2, i.e. 15% of the surface of the exploration licence), hopefully complemented in 2017 (up to nearly 30%), Géo2D engaged a larger approach of the whole area, with a focus on the Salen range (the active rift segment of the MER crossing through the eastern part of the lease). The survey covered the major objectives assigned, and allowed to elaborate interpretations and to issue recommendations:

- Understanding the active tectono-magmatic rift structure (Salen range[1]), that cut through the eastern part of the lease, and define the complementary work to be undertaken around the exploration drilling sites in priority;

- Visiting the most visible rims (East, West and South) of the early Mega-caldera, which draw the limits of the volcanic and geothermal system in view of checking the possibility to better define its age and characteristics;

- Have a first insight view of the post-caldera activity of the central part of the lease, where the most spectacular hydrothermal manifestations (fossil and still active) are observed, in order to precise which further works would allow to evaluate the geothermal perspective of this part of the lease.

3. A persistent magmatic heat source within the caldera presently reactivated along the Salen range

From our observations results that the Salen range acts as an active rift segment, with normal faulting over a width of 4 to 5 Km (locally up to 10), frequently limiting an axial graben, where the most recent activity (volcanic, tectonic as well as hydrothermal) concentrates (Fig.5).

This magmatically active rift segment is observed all across the calderas over a length of 30 Km. It extends further south, but with different characteristics: important normal faults and basaltic fissure eruptions (Fig.6).

To the north, this rift appears to weaken and diapers while reaching the eastern border-faults of the Gedemsa caldera, where only a few domes are still aligned along the same direction. This is the effect of the crypto transform fault zone[2] that allow for a shift of the spreading, displaced “en echelon” to the west, with the Koka-Boku-Adama spreading segment replacing the Salen rift north of Koka Lake (Fig.7).

Within the TM caldera limits, our observation (see Varet et al., 2018) show that the Salen range is characterized by a variety of magma types ranging from basalts to peralkaline rhyolites (pantellerites), essentially lavas (domes and flows) with limited pyroclastites (Fig.5 to 10). Such a variety of magmatic products, all linked along a fractional crystallisation line[3]

[1] From the name of its highest relief in the range, a trachytic volcano

[2] Marked by the NW-SW faults and volcanic ranges visible in the south-central part of the TM caldera (Fig. 4)

[3] Need to be confirmed by more complete sampling of the eruptive centres along the Salem range, further petrological studies and chemical modelling. The abundance of the feldspar porphyritic lavas,

is not usual in such fissural environment. Our interpretation is that it results from the rejuvenation of the wide magma chamber (of the size of the mega-caldera), which was associated with the construction of the TM stratovolcano. This recent E-W extension of the rift axis allowed to sample magmas at different levels of the chamber.

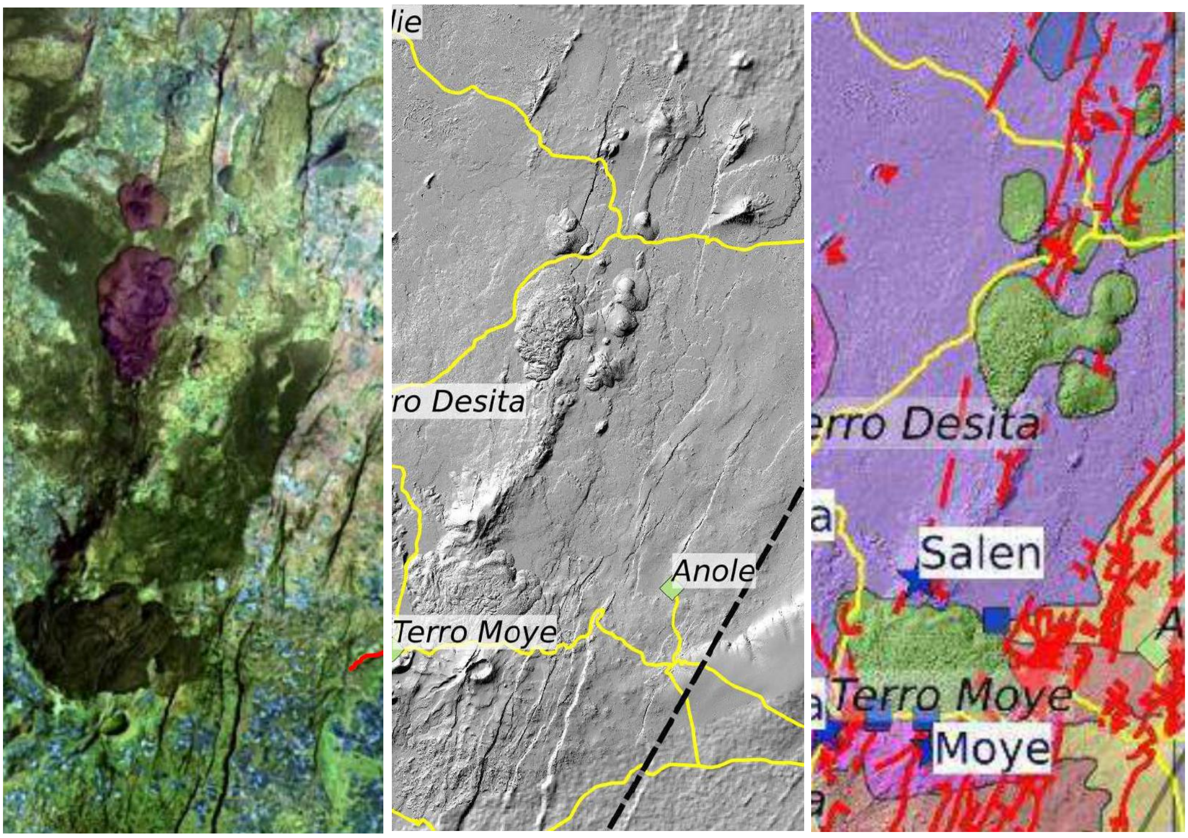


Fig. 5 : Views of the Salen range, from Landsat satellite imagery (left), Digital Elevation Model (Jonson, 2016, centre) and geological map (Gudbrandsson et al. 2017, right). Note that this geological map is limited to two magma types (basalts in violet and obsidians in green) when a large variety of differentiated products are found. Proposed drilling site locations are shown in blue squares. All maps show the combination of tectonic and magmatic activity along this active rift axis.

Fig. 6 : southern extension of the Salen rift axis south of TM caldera, characterized by normal faults and basaltic volcanism. A temporary lake occupied the floor of the rift at the bottom of the fault (seen from east, photo J.Varet, 2018).

If the post-caldera activity that immediately followed the caldera collapse produced gas-rich silicic pyroclastics along the caldera walls, a few hundred thousand years later the Salen rift produced a wider sampling of the rather degassed magmas by thermal reactivation of the

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from the basalts to the rhyolites (Fig. 10 & 11), support the hypothesis of a fractionation process in a shallow magma chamber.

cooling chamber (Fig.13). The most favourable geothermal conditions for high temperature resources are therefore found along the Salen range, as a shallower, hotter heat source underlies a fractured area with a high permeability resulting from the numerous open fissures where steam vents are observed (Fig.14).

Fig. 7 (left): Satellite image of the northernmost extension of the Salen range, along the eastern flank of the Gedemsa caldera.

Fig. 8 (right): north-central part of the Salen range where it enlarges with an axial graben and trachytic and rhyolitic domes aligned along feeding fissure parallel to the normal faults, and several basaltic spatter-ramparts of same direction are feeding basaltic flows west of the range.

Fig. 9 : Obsidian dome overlying a viscous rhyolite flow in the north-central part of the Salen range (Photo J.Varet, 2018)

Fig.10: Highly viscous pantelleritic obsidian dome in the northern part of the Salen range (photo Varet, 2018)

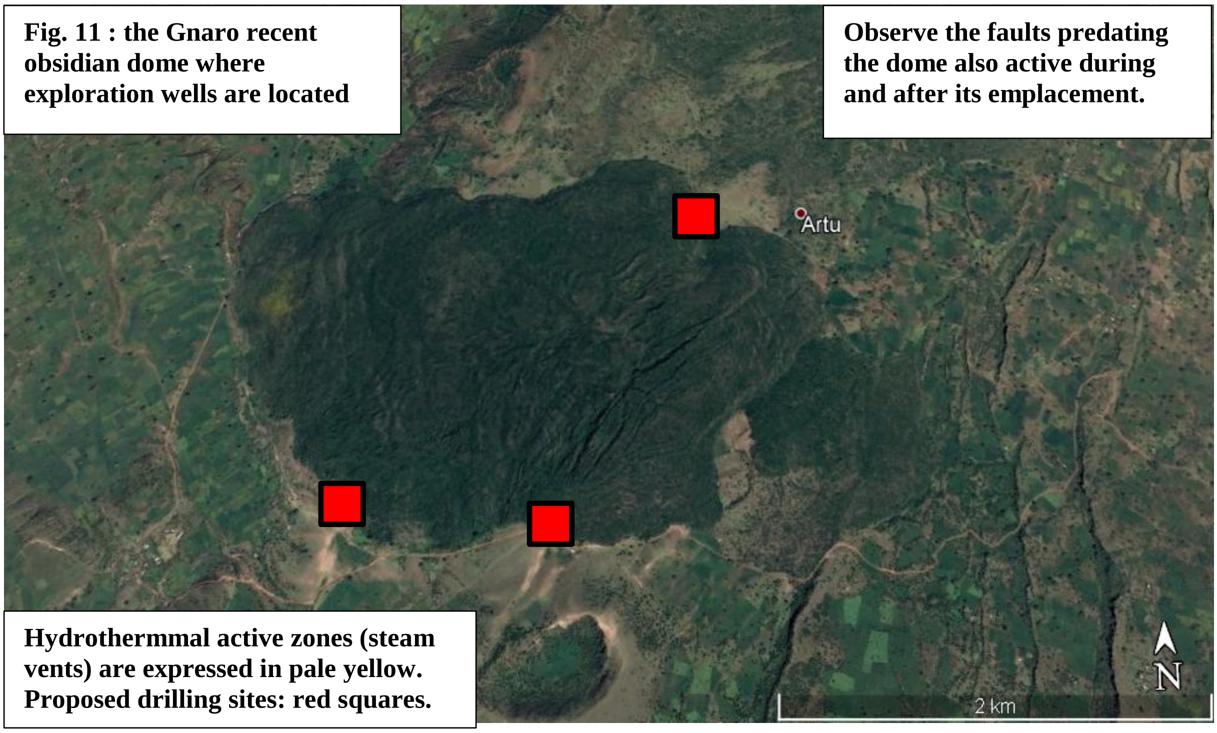

Fig. 11 : the Gnaro recent obsidian dome where exploration wells are located

Observe the faults predating the dome also active during and after its emplacement.

Hydrothermmal active zones (steam vents) are expressed in pale yellow. Proposed drilling sites: red squares.

Fig. 12 : Highly porphyritic basalt (left) and rhyolitic obsidian (right). The basaltic plagioclase crystal mesh was sampled from a thick faulted flow covering the caldera floor in the SE Salen rift area. The feldspar porphyritic obsidian is from the most viscous dome N Salen range. (Photos Varet, 2018*)*

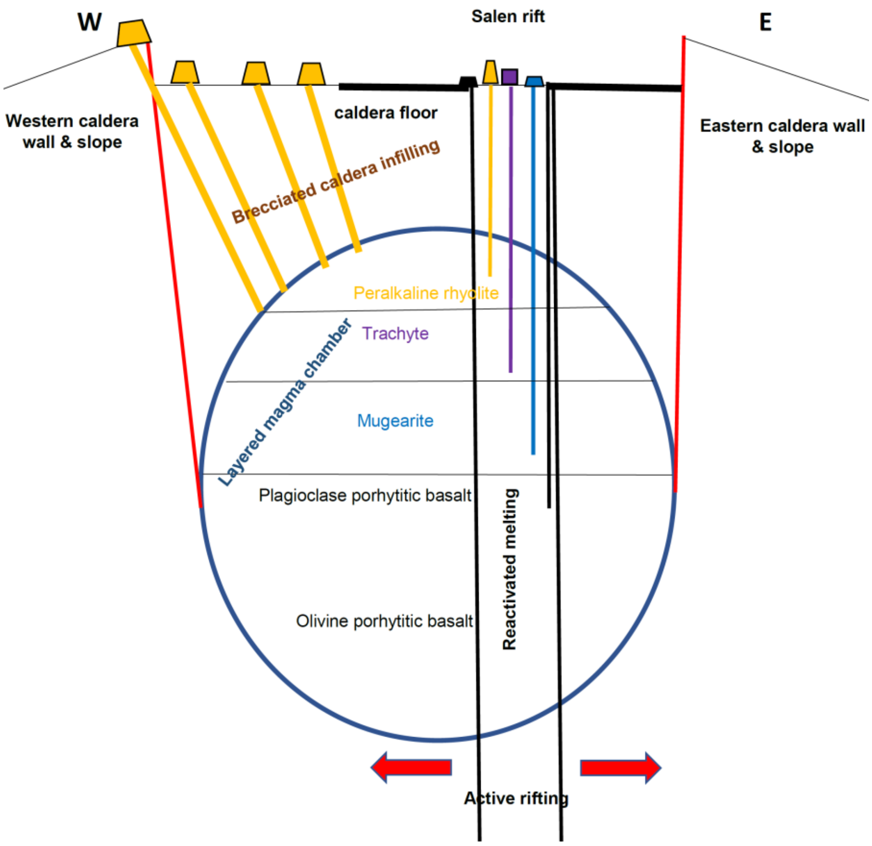

Fig. 13: Schematic interpretative W-E volcano-tectonic section through the TM mega-caldera (Varet, 2018). A large magma chamber developped at a few Km depth underneath the huge stratovolcano that produced the ignimbrite layer covering the region (circa 1My?). The meag-caldera (25 Km) collapse resulted from this eruption and was followed by silicic pyroclastic emissions along the W and S walls and along fractures on the SW caldera floor. To the north, the Gedemsa caldera (340ky) developed along the flank of the mega-caldera. A layered magma chamber was maintained active underlying the fractured caldera infilling. Lately (sub-historic) the Salen rift reactivated the magma chamber and favoured the eruption of degassed differentiated magmas of various compositions, providing an efficient geothermal heat source.

Fig. 14 : Steam emissive rift fault affecting the Tulu Moye pumice dome south of Gnaro (Photo Varet 2018). Such steaming faults are numerous along the Salen range and need further mapping (IR drone survey planed)

4. Hydrogeology and hydrogeochemistry supporting a powerful geothermal system.

The Tulu Moye caldera geothermal system comprises (Marini, 2018):

a) an *upflow zone* positioned along the Salem range, well identified in Gnaro area with
- steaming grounds along open fissures;
- high CO2 concentration of the gas mixtures emitted from these manifestations,
- the δ2H and δ18O values of the steam condensates, consistent with relatively high vapor/liquid separation temperatures, and
- the anomalous CO2 flux values from soil and soil temperatures measured in this area, indicating a high thermal power, naturally released.

b) A wide area of *outflow*, west of Gnaro as suggested by:
- the CO2 concentration of the fumarolic gas mixtures collected in this area;
- the close-to-boiling temperatures measured in the thermal gradient wells drilled there;
- the distribution of the steam baths (Guðbrandsson et al. 2016).

In fact, most steaming grounds and thermal gradient wells are positioned at the eastern termination of the conductive unit marking the clay cap, as geothermal fluids are able to flow up towards the surface where the clay cap ends or becomes thinner. The most reliable estimation of the *reservoir temperature is ~360°C* as suggested by H_2-Ar, H_2-N_2, and CH_4-CO_2 gas geothermometers for sample TG-02 collected in 2012.

The reservoir liquid is expected to have Na-HCO_3 composition and TDS of 3100 mg/L, with HCO_3 = 1740 mg/L, Cl = 256 mg/L, SO_4 = 190 mg/L, F = 12 mg/L, and Na = 870 mg /L. The absence of oxygen isotope shift and the high reservoir temperature imply that the geothermal reservoir has relatively good permeability.

5. Geophysical structure and geothermal reservoir model

The choice made to locate the first exploration drilling in the southern part of the range (Gnaro dome, see Fig.9 above) results from the exploration strategy which focused on SW side of the TM caldera (Gudbrandsson et al. 2017). Hopefully the 2017 extension of the TDM-MT survey allowed to hit the southern part of the Salem range, and to confirm the geothermally favorable resistivity structure at depth (low-high-low) in the Gnaro area in the southern part of Salen range (Fig. 15).

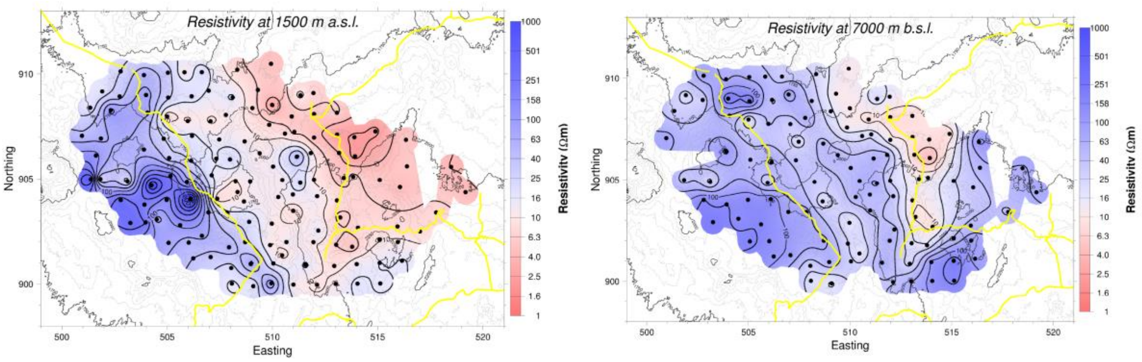

Fig. 15: Resistivity maps at 1500 and 7000m bsl computed from MT survey data processing (Gislason et al., 2016) showing the upper (hydrothermal) and the deeper (magmatic) low resistivity zone in the eastern part of the survey area (south Salen range)

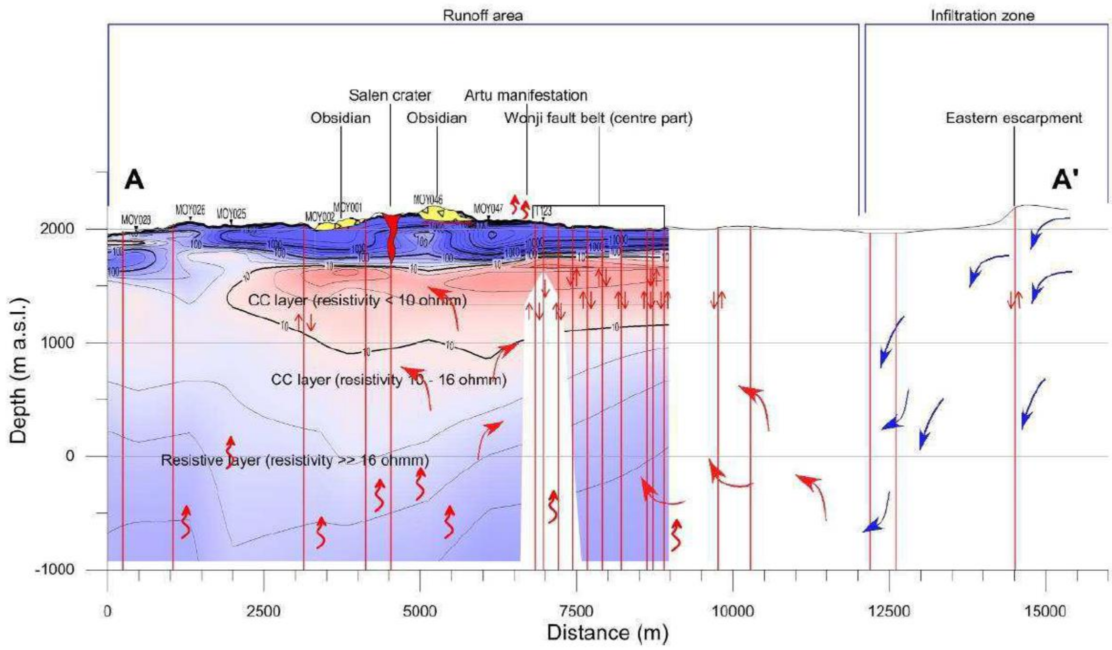

Fig. 16 : Geothermal conceptual model proposed by Gislason et al. (2016) along a E-W profile crossing the Salen range at the level of Gnaro. Same resistivity colors as on the maps Fig. 14. Inflow zones along the eastern escarpment (in blue) and upflow zones (in red) along the Salen range are pictured.

Conclusion

The capacity of TM geothermal system was estimated to reach 500 MWe according to VSO Consulting (2016). This appears as a conservative figure, as the surface exploration was carried on part of the lease only and the geothermal reservoir identified was not fully investigated yet. New geophysical survey engaged in 2017 allowed to extend the low resistivity zones towards North, but not closing the “anomalies” over a wider surface reaching 200 Km^2.

Together with convergent geological data, this confirms the existence of a wide HT geothermal system (up to 360°C according to gas geothermometry), with a well-defined magmatic heat source and an extensive reservoir as well as cover. Given that the southern limit has already been well mapped, and the northern extension is not yet constrained, we may be considering a geothermal field of a capacity of over 2,000 MWe.

As confirmed by new surface investigations, the geothermal system extends with promising geological characteristics northwards up to the Gedemsa caldera in the northern part of the lease. Surface studies for subsequent phases of the project should focus on this area in order to close the reservoir limits north (Fig.17).

These studies can be engaged during the stage of the preparation of the exploration drilling phase, and while drilling and tests are progressing, that is in the dry season end2018-early 2019. This will allow Meridiam to have a better view of the development perspective of Tulu Moye which already appear as one of the world giant geothermal site.

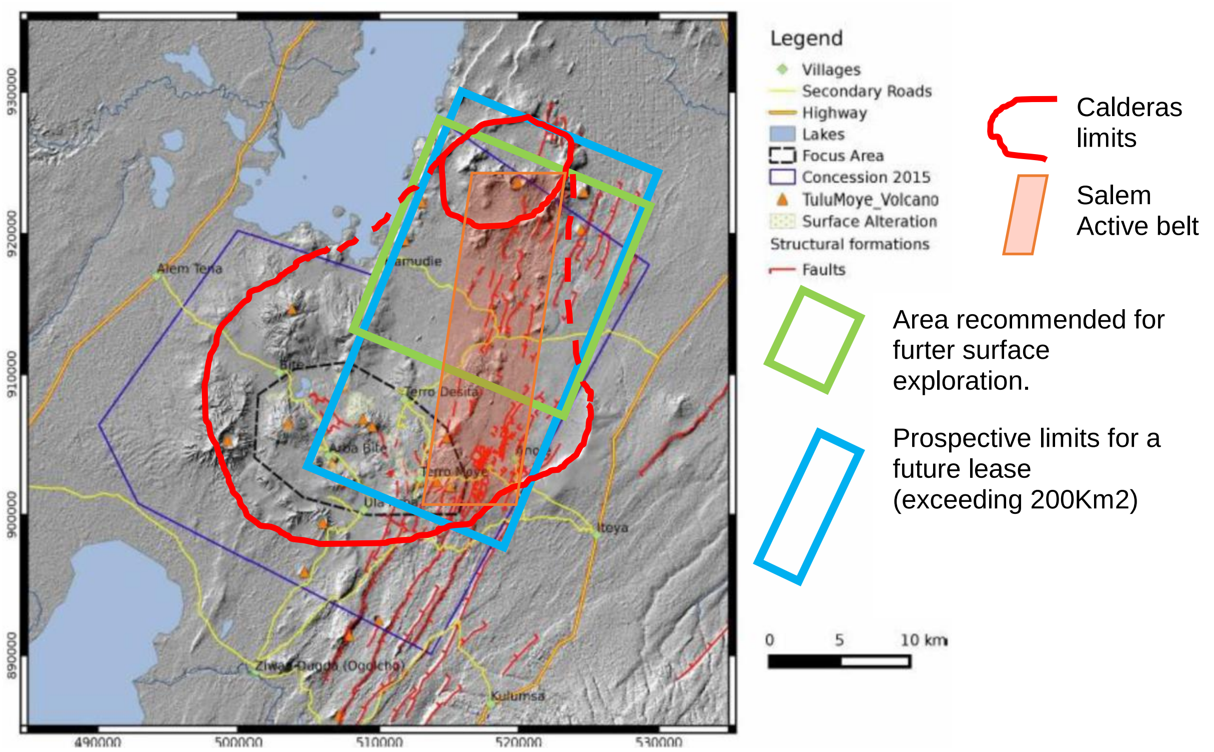

Fig. 17: Proposed extension for further surface studies of TM site: the green area located NE of the limits of the "focus area" (black dotted) as defined by RG may well be the most promising reservoir of the concession (in Violet). Redrawn from original map from VSO Consulting (2016). The hypothetical limits of the TM mega-caldera, and the limits of the Gedemsa caldera are shown in red. The Salem active range is shown in orange. (Varet, 2018)

Acknowledgments

The geoscientific interpretations exposed in this paper reflect the opinion of one of the authors (J.V.) and not necessarily the views of Meridiam and RG. The authors thank Tadesse Mamo, Aklilu Hailu Tekka, Tomas Gudmarsson, and Darrell Boyd from TMGO for their support, and the team from Reykjavik Geothermal (RG) for their expertise and availability, as well as Luigi Marini (consultant in geochemistry). They also express their gratitude for the reviewer's contribution.

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