

Geothermal resource along the border: The Ethiopia-Djibouti case

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Keywords: *Geothermal resource, Dama Ale volcano, Lake Abhé, Tendaho-Gobaad graben*

ABSTRACT

Boundaries may happen to develop along certain geographic features that eventually correspond to geothermally significant geological structures. In the case of the Ethiopia-Djibouti border, two active volcano-tectonic systems are extending on both the northern and southern side of the border:

- The Manda Inakir volcanic range to the north
- The Gobaad graben to the south, which include Lake Abhe and Dama Ale volcano.

Manda Inakir volcanic range was shown by Haga et al. (2012) to be a site of potential geothermal interest, with a well-defined rift structure, as it is one of the active spreading segments in Afar, having encountered at least one historical eruption. The site is however rather remote and is not given a high priority on any side of the border at present. Nevertheless, the railway line project to link Dallol and Mekele to the port of Tadjourah, if engaged, would renew the interest for this potential geothermal site. The recent evolution of the diplomatic relations between Eritrea and Ethiopia may also change the game, as this is the nearest geothermal site to the port of Assab.

More mature appears to be the Lake Abhé geothermal prospect, which was recognized long ago (BRGM, 1972) as a target of geothermal interest, due to the spectacular travertine chimneys found on the Eastern shore in the Djibouti Republic, which – besides being a touristic attraction, still draw the interest of geo-scientists (see f.i. Dekov et al. 2014). The site was reconsidered recently and taken as a priority target by the Office Djiboutien de Développement de l'Energie Géothermique (ODDEG) (Awaleh et al., 2015; Kaireh et al., 2016) and it benefitted from the support of ICEIDA in the frame of a project of ODDEG's capacity building.

However, the geothermal conceptual model that can be deduced from the surface studies that have so far been done imply that the heat source of the geothermal system is located to the West; that is at the level of the Dama Ale volcano found on the Ethiopian shore of Lake Abhé. In fact, the Lake Abhé geothermal system is located on the Eastern extremity of the Tendaho-Gobaad graben, which bears several active volcanic units including Gabilema to the south. Both Gabilema and Dama Ale are located at the northern tip of the Main Ethiopian Rift at the place where it hits against the Red Sea – Gulf of Aden oceanic ridge crossing through Afar (Tazieff et al., 1972, Barberi & Varet, 1977, 1978). Their respective volcanic evolution shows magmatic series ranging from basalts to rhyolites, expressing the presence of magma chambers, i.e. shallow heat sources.

Considering the location of the heat sources, and the hydrogeological context - with surface and groundwater flow from West to East, a sound exploration programme of the area should rely upon a cross-border survey including both Ethiopian and Djiboutian partner organizations. A joint geothermal exploration project would enable the identification of the heat sources, the hydrogeological context and the nature and extension of the reservoirs – located in both sedimentary and stratoid series layers and bearing fluids of economic interest. It is not excluded that relevant financial agencies would be interested to support this kind of project, which would ultimately be of strategic interest for the sustainable development of the region.

1. Introduction

The Afar depression develops at the northern extremity of the East African Rift System (EARS), in Ethiopian, Eritrea and Djibouti. It is not simply the northern extension of the EARS, but also the place where this continental rift meets the oceanic ridge of the Gulf of Aden and the Red Sea. Afar is characterized by the existence of the axial volcanic ranges which formed in the last 1My, recognized as spreading segments by Taziell et al., (1972) and Barberi & Varet (1977), whereas important deformation implying bookshelf faulting and block rotation develops between these spreading segments (Tapponnier et al., 1990, Manighetti et al. 1998). Two of them occur along the Ethiopia-Djibouti border: Manda Inakir and the Tendaho-Goba'ad graben, southern extension of Manda Harraro (Fig.1). This last volcano-tectonics unit ends at the level of Dama Ale volcano, that developed at the level at which the Main Ethiopian Rift (MER) ends. The triple junction was not fixed with time (Dobre et al., 2016; Varet, 2017). The MER is presently active in the Adda'do graben and cross the Tendaho-Goba'ad southern wall at the level of Gabillemma, a complex volcano showing both WNW-ESE and NNE-SSW feeding fissures, with both a rhyolitic stratovolcano and basaltic fissural lava fields (Varet, 1975).

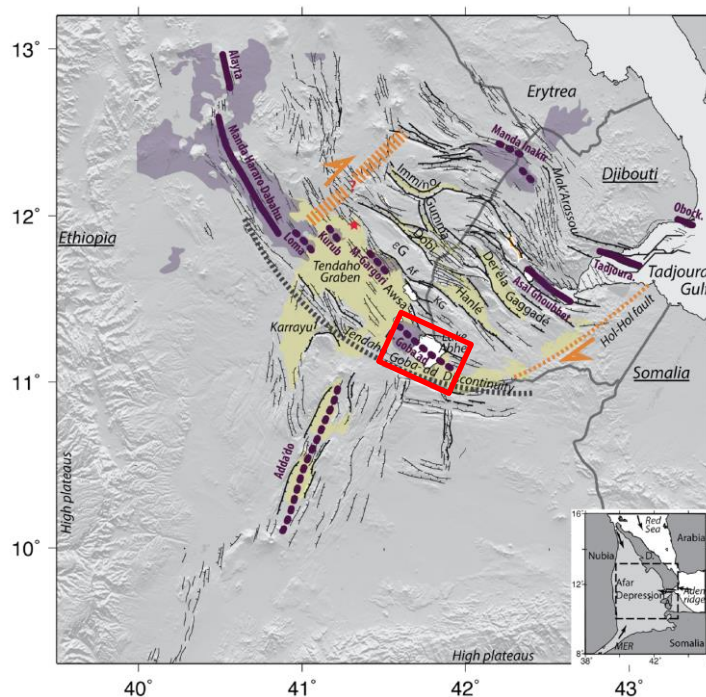


Fig. 1 : Location proposed for the Ethio-Djiboutian borderline project Dama Ale – Abhé (red square), superimposed on the volcano-structural map of the central Afar depression (Dobre et al., 2016).

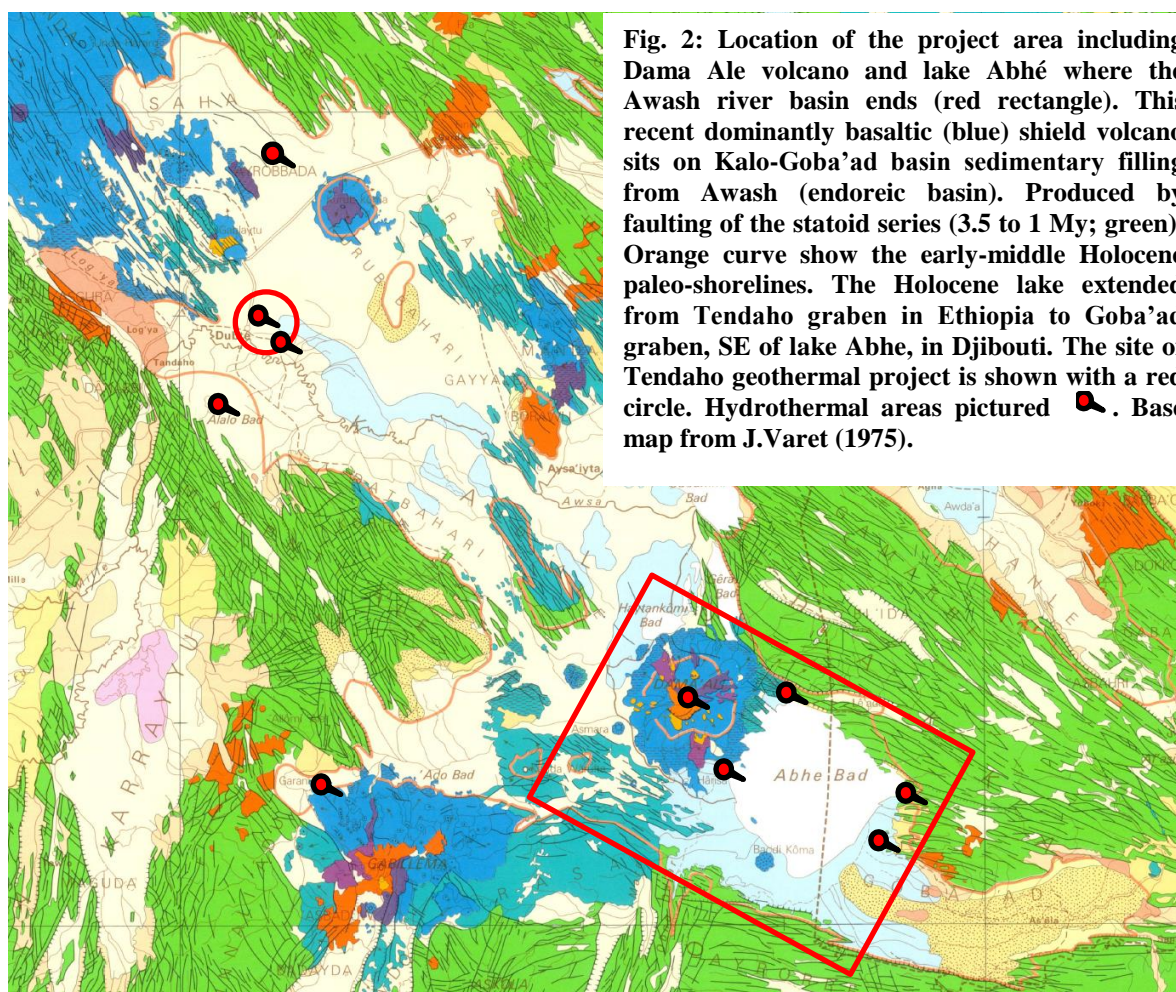
The active basaltic spreading segments (of NNW-SSE to NW-SE i.e. Red Sea – Gulf of Aden direction) are indicated in deep violet, and sediment filled basins in yellow.

The Adda'do (NNE-SSW) graben marks the northernmost segment of the Main Ethiopian Rift.

Dama Ale volcano sits in the middle of the Tendaho-Goba'ad graben at the intersection with an earlier “dry” MER graben (Fig.2). Differing from Gabillemma (that display characteristics of the MER volcanoes and Afar marginal units, Varet, 2017) and from axial Afar ranges, this is a circular dominantly basaltic shield volcano showing fumarolic activity in its summit crater and hot-springs in its surroundings. This thermal activity is particularly well developed on the Eastern side of Lake Abhé with the spectacular travertine chimneys (Fig.3), a touristic attraction in Djibouti (Fontes & Pouchan, 1975).

The eastern side of Lake Abhé was considered as a geothermal target since the early exploration work engaged in Djibouti by BRGM (1972) and it was investigated since with detailed mapping of the lacustrine deposits (Varet, 1975; Gasse, 1977; Gasse et al., 1987) and mineralogical and geochemical studies of the travertine (Dekov et al. 2014). Abhé was reconsidered recently and taken as one of the countries priority target by the Office Djiboutien

de Développement de l'Energie Géothermique (ODDEG) and benefitted from the support of ICEIDA in the frame of a project of ODDEG's capacity building (Awaleh et al., 2015; Kaireh et al., 2016). On the Ethiopian side, the western shore of the lake was identified for its thermal activity by the UNDP (1973), but the site of Tendaho located to the NE was taken as a priority target and was studied by AQUATER (1986) including exploration drilling. A geothermal reservoir at 250°C was met at 500 m depth and a deeper reservoir is expected to reach 290°C (Battistelli, 1998). It is at present investigated by GSE (Ethiopian Geological Survey) and EEP (Ethiopian Electric Power) with the support of AFD, EU and ICEIDA. Tender for drillings at up to 2500m depths was emitted in march 2018.



2. Arguments for a Dama Ale – Abhé geothermal site

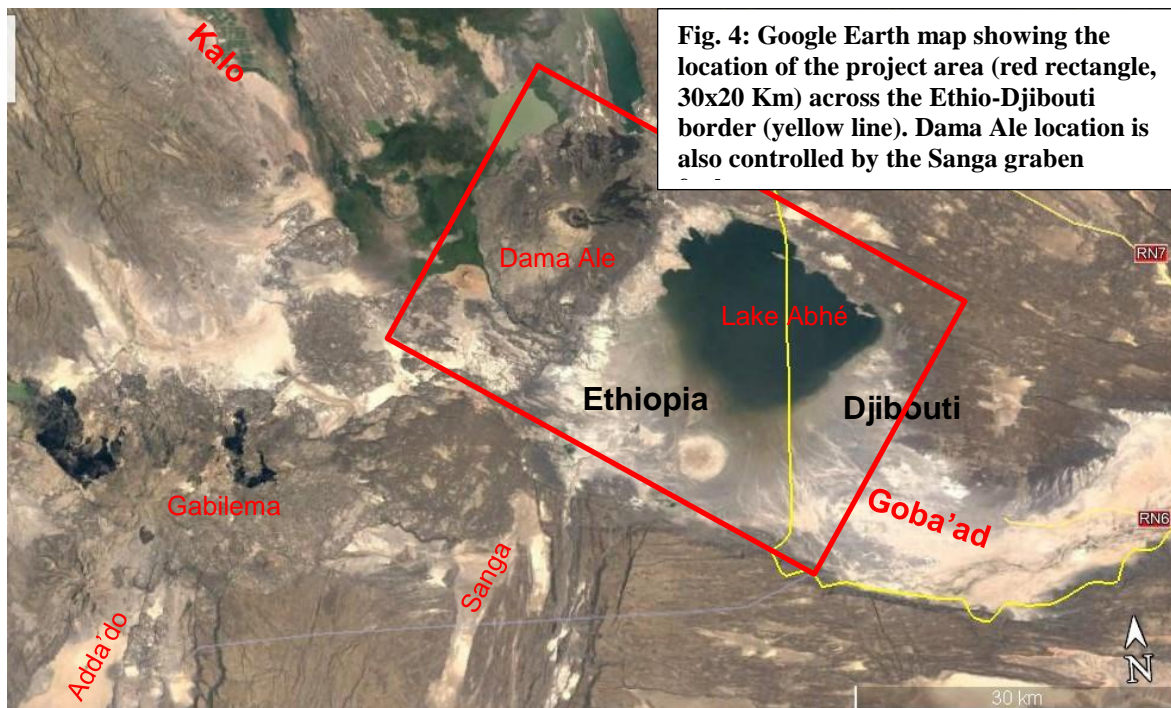
The proposed area display all the necessary geological characteristics for a high enthalpy geothermal site:

- It is located in middle of the Goba'ad graben trending NW-SE (Red Sea Aden trend) at the intersection with an NNE-SSW trending graben (MER trend, Fig.4). This dike crossing determined the location of the vertical axial magma conduit of the volcano. This important multiple fracturation should favour the permeability of the reservoir expected to be found in the underlying statoid series.

- The Awash river basin is ending at Lake Abhé (alt. 245m), providing an important surface and groundwater inflow from NW (where a wet zone with 3 lakes surrounded and wide swamps formed when the recent Dama Ale volcano dammed the basin) to SE (Fig.5), hence a good recharge of the geothermal reservoir.



Fig.3: Travertine chimneys on the eastern shore of Lake Abhé (Djibouti) were formed when the lake level was higher, some of them still active (hotspring at the bottom of the chimney). As seen on the satellite image, the chimneys are aligned along fissures of the two dominant tectonic direction, the emissive ones (see wetland) at lower altitude (photos J.Varet).



- Thermal manifestations are well developed around Lake Abhé, on both the Ethiopian and Djibouti sides. Hit-springs clearly emerge from faults and fissures of NW-SE direction, and eventually the NNE-SSW (MER) (Fig. 3, and 6) affecting even the very recent unconsolidated sediments near lake shoreline (Fig. 7). Fumaroles are well developed along the Dama Ale crater walls, particularly along the northern (trending WNW-ESE) and western rim (trending NE-SW) as seen on Fig.8. These manifestations have occurred since long, and the name itself (Abhé means “rotten” in Afar language).

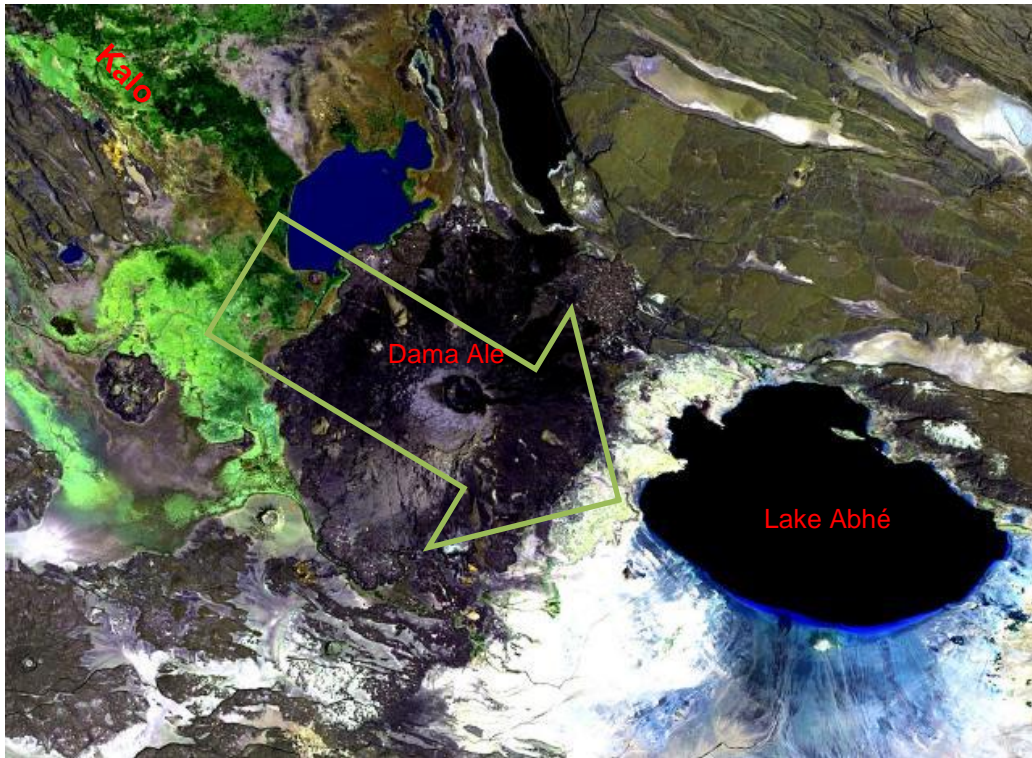


Fig. 5: This colour satellite image show the contrast between the swampy Kalo region West of Dama Ale volcano and the arid surroundings of Lake Abhé. The green arrow shows the general trend of the ground water, flowing through the root of the shield volcano and feeding the hydrothermal manifestations along the rim of the Dama Ale crater (fumaroles) and (hot-springs) along the NW-SE faults crossing through Lake Abhe. It is expected that these manifestations are also active underneath the lake surface.

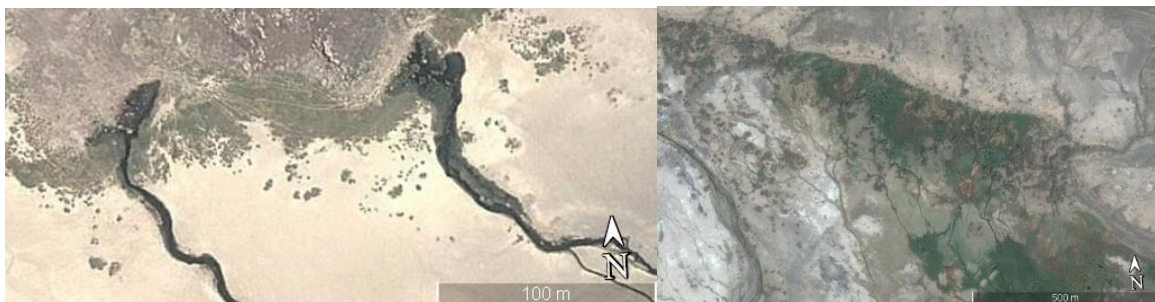


Fig. 6: Thermal springs at the foot of Dama Ale volcano (Ethiopia) emerging form the basis of the earliest flows (south, on the image left) and from the bottom of a normal fault (north, on the image right).

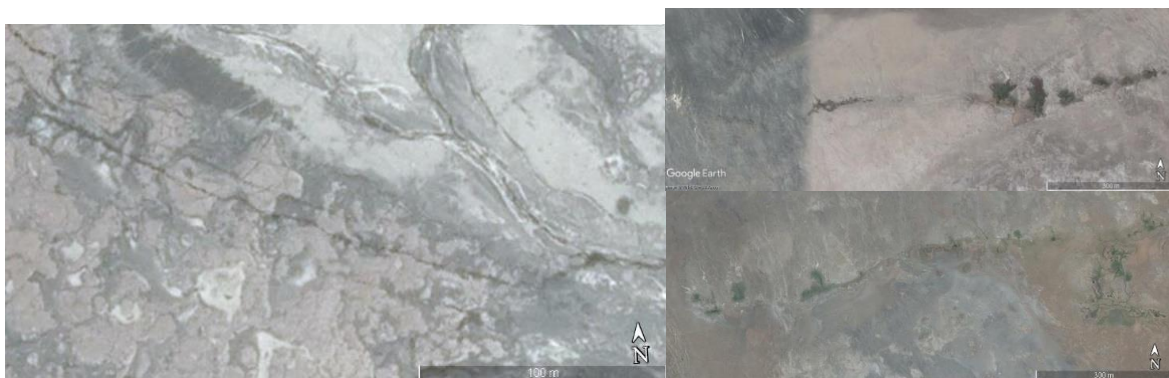


Fig.7: thermally emissive fissures affecting the recent unconsolidated sediments surrounding Lake Abhé West (300 m long, left on the Ethiopian side) and East (two fissures each over 1 Km long, right, on the Djibouti side)



Fig. 8: sites of fumarole emissions on the northern side of the Dama Ale crater. These thermal emissions are particularly well developed along the NNW-SSE and NE-SW trending border-faults.

- Dama Ale (11.28°N, 41.63°E, altitude 1068 m) is a 25-km-wide shield volcano. The place and unusual circular (in Afar) shape of this shield volcano is clearly determined by the intersection of the Sanga graben (of NNW-SSE direction, i.e. Main Ethiopian Rift) with the NNW-SSE trending Tendaho-Gobaad graben (Red Sea-Aden rift). This double extension could explain the higher degree of partial melting and hence the very tholeiitic nature of the initial magma (Ferrara and Santacroce, 1980). It is dominantly basaltic, and the earliest activity was subaqueous, as shown by several hyaloclatite cones (including the large Asmara guyot) and the well-developed pillow lavas observed all along the front of the lower flows (Fig. 9).

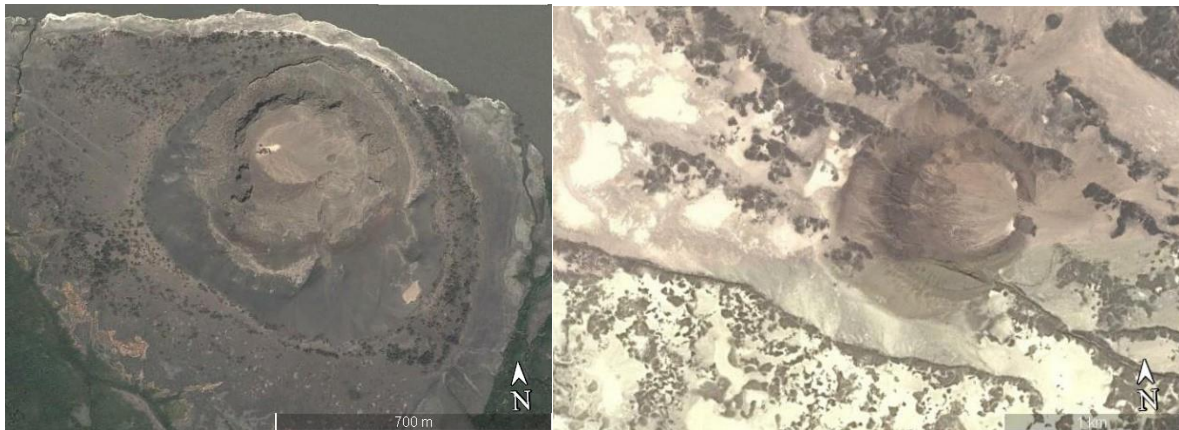


Fig. 9: Hyaloclatite cones on the NW (left, eroded) and SE flanks (right, faulted) of Dama Ale volcano.

- Intermediate terms (ferrobasalts and dark trachytes) occur on the flanks, where obsidian domes are also observed. These rhyolite domes are located at mid-slope around the volcano and may result of the combination of radial and ring dikes (cone sheets) linking to a shallow magma chamber where magma differentiated by crystal fractionation. If most evolved, they are not the most recent products, as younger flows emitted from the central crater surrounded and partly covered them (Fig. 10).

- Observation of the summit show that the 2,5 Km wide multiple rimmed crater was produced by the sinking of a wide lava lake that did overflow the rims (in 1631? Gouin, 1979) before it collapsed.
- The floor of the crater is occupied by a wide lava lake that remained active after the sink and was fed by several fissures, before it solidified during several successive periods.
- Traces of a 6 Km wide caldera are observed on the southern flank (Fig. 11), associated with a few pyroclastic products, within which several blocks displays fine, medium up to coarse grained crystalline structures: gabbros, diorites and granites. They are considered as intrusive equivalents of the surface lava, interpreted as testimony of former differentiated shallow magma chambers.
- These different petrological and volcano-structural arguments support the presence of a long-lasting and still active magma chamber at a few Km depth underneath the volcano that acts as an efficient heat source for the geothermal system.



Fig.10 (left): Recent basaltic lava flow emitted from the central crater surrounding one of the rhyolite dome found on the flanks (resulting from former cone sheet?) of Dama Ale volcano (Google Earth image).

Fig. 11 (right): Southern rim of the Dama Ale caldera (underlined red) with pyroclastic products observed south from the double-rimmed crater, occupied by a lava lake that partly overflowed the crater rim and consequently sunk. Fumaroles are observed in several places, in particular along the inner crater walls (also seen in Fig.8).

We have all the arguments: shallow magmatic heat source, multiple fractured reservoir in the underlying basalts of the steroid series, groundwater recharge and circulation from NW to SE and hydrothermal upwelling in lake Abhé basin. Surface studies undertaken – particularly on the Djibouti side – confirm this view.

3. Main outcomes of the recent surface exploration on the Djibouti side

The eastern part of the site, located at 5 h drive from Djibouti (with 75 Km of earth road from Dikhil), has been extensively studied by ODDEG with the support of ICEIDA (Awaleh et al., 2015; Kaireh et al., 2016).

Hot-springs were studied in the field, together with the hydrothermal alteration products surrounding them. A temperature of 99.5°C was recorded in two springs along WNW-ESE normal fault at Gamboli. Most hot-springs occur at the base of some of the travertine chimneys (Fig.3). Generally aligned on faults of the same direction, their average height is 5 to 10 m but some may reach 18 m; these reversed stalactites were formed when the lake level was higher (up to 30 m). They may show steam vents at the top. Hot springs and hot wet grounds are also observed along E-W fault lines affecting the most recent sediments (see above Fig.7).

Chemical analysis shows slightly alkaline thermal waters, with pH ranging from 8.1 to 8.7. Silica concentration is quite low (97-125 mg/l), and their salinity is surprisingly low (830-2170 mg/l) compared to the rather saline Lake Abhé (39 g/l). The salinity of the springs increases closer to the lake, but even at the lowest sampling point (which was under the lake surface a few years ago), the Cl concentration is only 2170 mg/L. This indicates that the reservoir feeding the springs is not connected to the lake. Notable is also the extremely low concentrations of CO₂ of the thermal waters (16.5 – 29.2 mg/l) compared to the cold groundwater (572 mg/L). This is also the case for Mg, and H₂S is equally very low. Cl-SO₄-HCO₃ ternary diagram commonly used shows mature thermal waters with volcanic influence. Compared to the cold groundwater, The Na-K-Mg ternary diagram also show equilibrium with respect to these three components.; The gas comprised mostly CO₂ (58 %V) and N₂ (39 %V), CH₄ (about 1.6 %V) O₂ and Ar (< 1 %V), and H₂S (0.03 %V). We still lack good analysis of the gas components which would allow for gas geothermometers.

Calculated silica temperatures indicate temperatures between 107 – 145 °C, depending on the geothermometer is used. This is consistent with the results obtained on the western side of the lake in Ethiopia by UN (1971). Reservoir temperatures calculated with cation geothermometers (Na/K and Na-K-Ca) are similar, in the range of 114 – 134 °C.

A gravimetric survey was conducted, with 86 gravity points, allowing to produce a Bouguer gravity anomaly map. With the good density contrast between the basaltic stratoid series and the lacustrine deposits, this allows to map the thickness of the sedimentary cover, shown to deepen towards the lake. Combined Magneto- telluric (MT) and Time Domain Electromagnetic (TDEM) investigations were conducted in 2011 and 2015. The first conducted by CERD included 34 MT soundings and 35 TDEM. The second was conducted jointly by ISOR with 26 new MT soundings and ODDEG geophysical team with another 24 MT soundings. As a whole, a total of 84 MT soundings and 53 TDEM soundings were performed. The resistivity models from the 1-D joint inversion and 1-D inversion of each sounding were interpolated into cross sections and maps shown in Fig. 12.

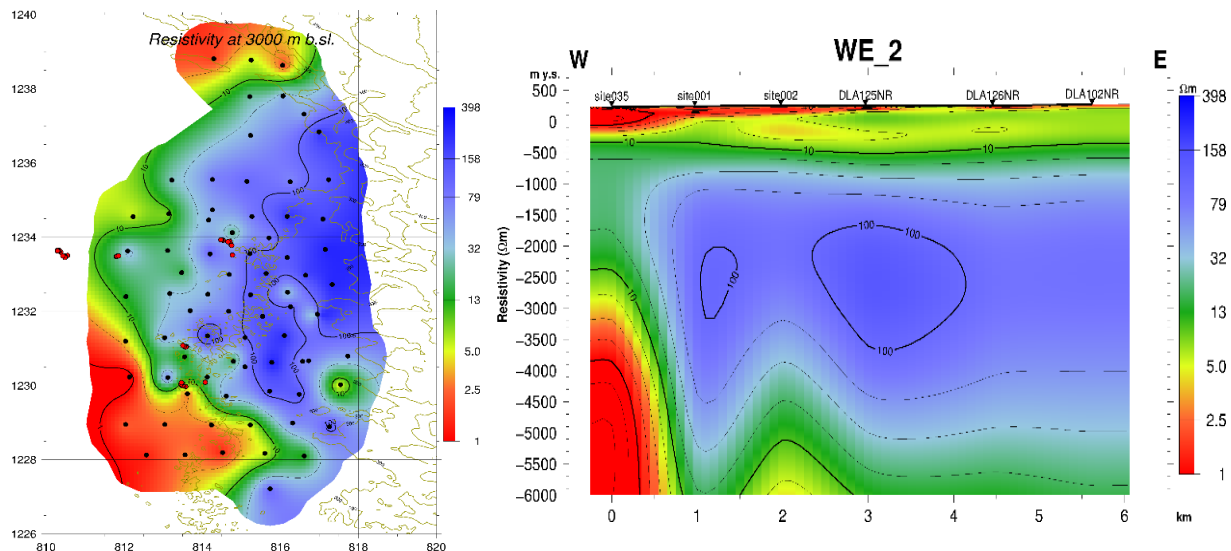


Fig. 12: Map of the resistivity measured at 3.000m depth on the eastern side of Lake Abhé (Djibouti Republic). Red dots show the main surface hydrothermal manifestations. On the right, is shown the W-E corresponding vertical section. To the east, high resistivities correspond to the stratoid series whereas both shallow and deep low resistivities are found on the lake side. These anomalies may characterize a geothermal system extending west in Ethiopian and developed on both sides of the border. (source: courtesy of ODDEG)

CONCLUSION: Proposal for a cross-border project

It appears from the above data – geological considerations as well as geothermal results already obtained – that a geothermal system developed in the Dama Ale – Abhé Lake area with all the necessary components: a well defined magmatic heat source at Dama Ale active volcano, a multiple fractured reservoir in the underlying stratoid series, and good groundwater circulation through NW-SE fault from the Kalo plain in Ethiopia to the Goba'ad graben in Djibouti. A geothermal field is hence expected to have developed on both sides of the Lake Abhé, and despite the high salinity of the lake, the geothermal fluid is shown to be rather unsalty. At present, the main incertitude is the temperature of the reservoir, but further geochemical survey and analysis are necessary, on both sides of the lake and in the Dama Ale massif, particularly on the gas components which could not be analysed until now.

It is suggested to undertake a cross-border survey in the project are pictured in Fig. 4, including:

- A detailed geological survey including Dama Ale volcano, Lake Abhé basin, and the surrounding stratoid series north and south with attention paid to the recent tectonic features. Attention should be paid to the study of the inclusions in the hyaloclastites and of the blocks found in the pyroclastic products around the caldera, that will provide information on both the magma chamber and geothermal reservoir (hydrothermal alteration affecting ejected blocks of underlying formations).
- Systematic mapping of the geothermal manifestations, using drone-borne IR technology with field controls and fluid sampling (liquid and gas) as well as mineralogical analysis of the hydrothermal deposits and alterations. Geochemical analysis – including isotopes – and interpretations should be engaged at regional level.

- A geophysical survey including gravimetry, microseismicity and TEM/MT should cover the area surrounding the Lake Abhé including the eastern slope of Dama Ale volcano.
- A bathymetric survey of Lake Abhé (recorded 37 m deep) should allow to precise the deep structure of the lake, and the active tectonic and hydrothermal features expected to be found on the lake floor.
- A socio-economic and environmental study allowing to precise the local demand and development perspective (cattle breeding and agriculture, domestic needs, tourism...).
- A geothermal conceptual model should result from this comprehensive survey. A preliminary hypothetical sketch is proposed in Fig. 13. Once precised in light of the above mentioned survey, this quantitative model should allow to engage a feasibility study of the site that could be considered in two perspectives:
 - A local development based on the exploitation of a shallow, medium temperature reservoir using ORC technology (1 to 5 MWe) also allowing to produce unsalty water, with a cascade use of the fluids, answering local needs of the population on both sides of the lake.
 - Larger development based on deeper wells with larger plant feeding the regional grid if the prefeasibility study confirms the expected high temperature reservoir.

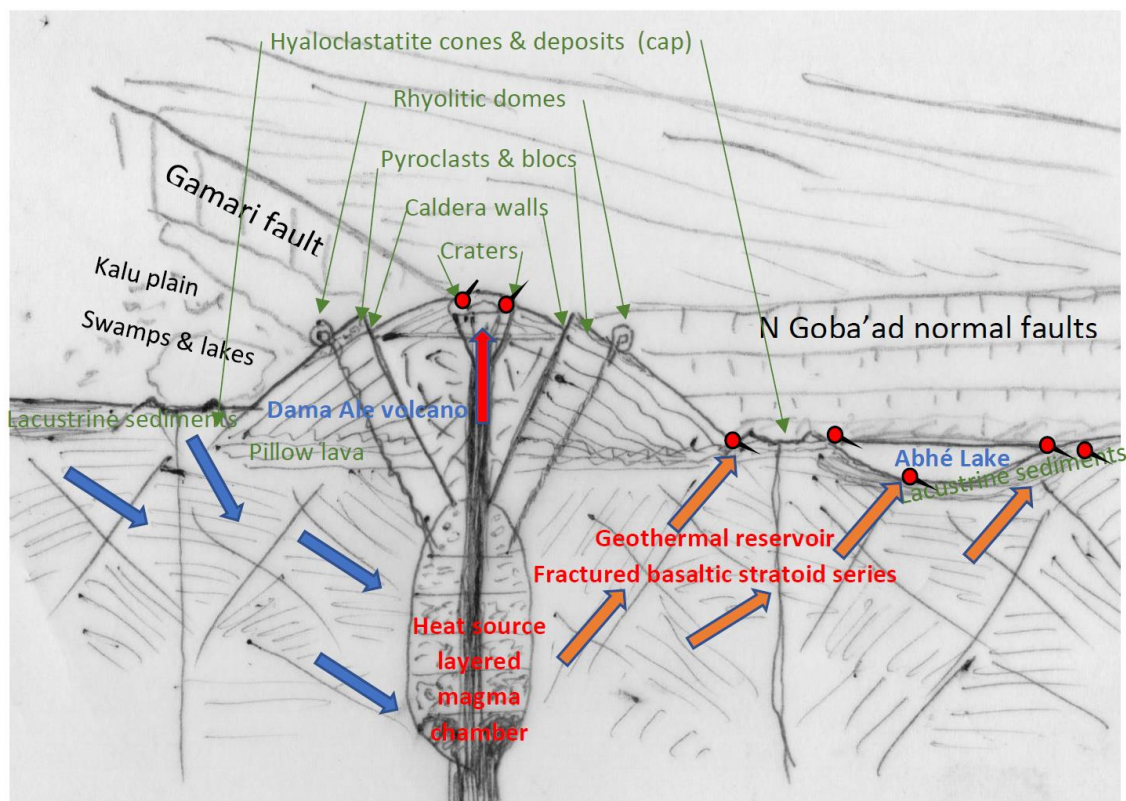


Fig. 13: Hypothetical qualitative conceptual model of the Dama Ale – Lake Abhé geothermal system (author's view, with NW-SE section through Dama Ale and Lake Abké in black, background faulted stratoid series in grey).

Acknowledgments

The author thanks ODDEG for providing the geophysical data on Lake Abhe and the reviewer for its enrichment.

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