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Nord-Ghoubbet Geothermal Site, Djibouti Republic

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ABSTRACT

Resulting from a regional consideration of the whole Afar, for ranking the best geothermal sites combining geodynamic and hydrogeological approach (J. Varet, Argeo meeting, 2011), the area located to the north of the Ghoubbet Rift appeared to be the most promising for geothermal energy developments in the Djibouti Republic. This "block", 10km long and 6km wide, covered at the surface essentially by the recent basalts of the gulf that is, emitted during the early stage of penetration of the Aden Ridge through the Gulf of Tadjourah, 4 to 2 My ago (O. Richard and J. Varet, 1979) benefits from unique geological conditions:

- The immediate vicinity of the Ghoubbet active spreading segment, with a shallow anomalous (partially melting, 1300°C) upper mantle at 7km depth, providing an important and safe (regularly renewed, hence renewable) heat source for the geothermal field.
- A tremendous fracturing of the whole block (made at the surface of recent basalts of the gulf) with at least 3 directions of open faulting with transverse components (NW-SE, NNW-SSE and NE-SW), providing a good fracture permeability of the reservoir. This particular tectonic setting is of course due to the vicinity of the transform faulting linking Ghoubbet and Tadjourah oceanic rift segments. But it also results (as shown by Manighetti et al. 2011) from the fast rotation of this brittle block. Numerous fumaroles and hot springs, some with important silica deposits, affecting the whole block, testify to the leakage of the geothermal reservoir due to the fairly active tectonics of the site.
- Good reservoir conditions are also expected from the geology itself, as very important detrital deposits accumulated there, for the last 5My, underneath the more recent basalts, due to the up-rise and concomitant faulting and erosion of the whole area located North before and since the early stages of opening of the Gulf (up to 1000m high Dalha basaltic plateau and the famous Day mountain).
- This reservoir should also benefit from relatively low salinity fluids – certainly the best for Djibouti Republic - due to the long lasting flow of water from the Day Mountain downstream towards the Gulf for the last few My.

Preliminary geochemical and geophysical studies were undertaken in the area by BRGM, and more recently MT and geo-electric surveys have been conducted by the CERD. Through this proposals were made for locations of exploration wells. However the investigation, presently limited to the immediate surroundings of the major surface hydrothermal manifestations should be extended to the whole area down to the sea shores.

1. INTRODUCTION

Among the geothermal sites in Djibouti Republic considered as suitable for high enthalpy geothermal energy development, the area located immediately north of the Ghoubbet Rift is listed at the top because of its intrinsic quality. Located near to Asal Geothermal Site, it may not benefit from the same exceptional shallow heat source (i.e. the Fiale caldera, at a very shallow depth of 5 to 2km), but clearly benefits from both an intense multiple fracturing as well as a feeding by meteoritic waters from the nearby Day Mountain drainage, an exceptional situation in this arid climate (Figure 1).

Figure 1: Location of the Nord Ghoubbet geothermal site (red oval) relatively to Asal 1-3 « BRGM site» and Asal-Fiale « World Bank site» (orange ovals).

Moreover, the site is located at a similar distance from Djibouti as Asal and the construction of an electric transmission line is being planned for on the southern side of the Ghoubbet pass for an Aeolian farm aimed at powering a future desalinization plant. Preliminary geochemical and geophysical investigations carried by BRGM (1992) and more recently by CERD (2011) helped in elaborating a first model for this geothermal field and in proposing sites for exploration drillings. Although the surface exploration, presently limited to the vicinity of the major hydrothermal emergences and deposits, needs to be completed in order to cover the whole block, the Nord-Ghoubbet Geothermal Site already appears as a new objective for another geothermal project - in addition to Asal - presently selected for drillings by a banking consortium led by the World Bank (Abdilahi et al. this volume). This could be done either at a successive stage to respond to the growing needs of Djibouti Town and Port, or as an alternative in case of difficulties encountered in Asal, where specific risks are considered (such as crossing shallow magma body or brines difficult to manage in this environment).

The present paper describes the state of knowledge of the site and proposes successive works to be carried out in order to ascertain its quality in terms of commercial electricity production.

2. APPLYING A GUIDE FOR GEOTHERMAL EXPLORATION IN AFAR

At the last ARGEO conference in Djibouti, a guide to geothermal exploration was proposed for Afar (Varet, 2011) focusing on the following condition - a combination of the occurrence of the following parameters:

- A high heat flow, linked with either a very shallow anomalous mantle or a superficial magma chamber;
- A highly fractured area, eventually combining several tectonic influences, allowing for good reservoir permeability;
- The recharge of the reservoir by meteoritic water or sea water, or a combination of both; and
- The development of a mineralised hydrothermal system.

2.1 A favourable Geodynamic Environment

In the context of Afar, such sites were shown to offer suitable conditions for development in areas of junction between the axial ranges and the transverse tectonic systems. As described by Barberi et al. (1970) transform faults are not observed in Afar - like in Iceland. Nevertheless, Tapponier and Varet (1974) showed and Barberi and Varet (1977) confirmed more precisely that large oblique fracture systems are in many places the surface expression of a transform fault linking two distant axial ranges. Such a tectonic structure is particularly well developed north of Asal, in the junction area with the Manda-Inakir Axial Range. It is also well developed – symmetrically - in the Nord-Ghoubbet block where the NW-SE trending normal faults of the northern side of the Ghoubbet Ridge interfer with the transform fault ensuring the link under-sea with the Tadjoura and Aden oceanic ridge (Figure 2).

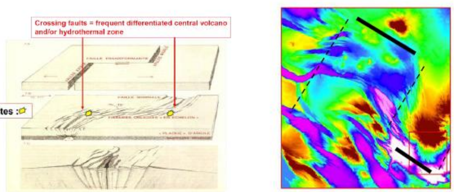


Figure 2: The surface expression of transform faults in Afar is characterized by fault systems oblique with respect to the direction of the transform movement. Such features, conform to analogical models are particularly well developed on both extremities of Manda-Inakir axial range in Makarassou and Dobi regions (treatment by BRGM from NASA/SRTM, in Varet, 2011). Nord-Ghoubbet site is indicated with a red rectangle.

2.2 The Feeding with Meteoritic Water

Although similar to Iceland in terms of many geological features, Afar suffers from a major handicap: the composition of the geothermal fluids. Whereas in the North Atlantic climate, geothermal reservoirs are predominantly fed by meteoric water due to high rainfall, Afar is characterized by a rather dry tropical climate. Annual rainfall there is one of the world's lowest and brines predominate over fresh meteoritic water both at and below the surface (Kebede et al. 2008), notably in northern and eastern Afar. The Nord-Ghoubbet block benefits from specific hydrogeological conditions in which the highlands of the Dalha plateau – with the well-known Day Forest – act as a meteoritic water source for the geothermal site (Figure 3). Even if the annual rainfall does not exceed 200 to 300mm, the small basin feeding the Nord-Ghoubbet site allows not only for occasional flooding, but also for recharging deep aquifers developed in the unconformity between the deeply faulted and tilted basaltic trap series of the Dalha, with additional circulation within this trap series and in the underlying unconformity with the underlying Mablarhyolitic unit. Since these successive geological units are characterized by different tectonic regimes (Marinelli and Varet, 1972), we can infer the development of well fractured reservoirs at depth.

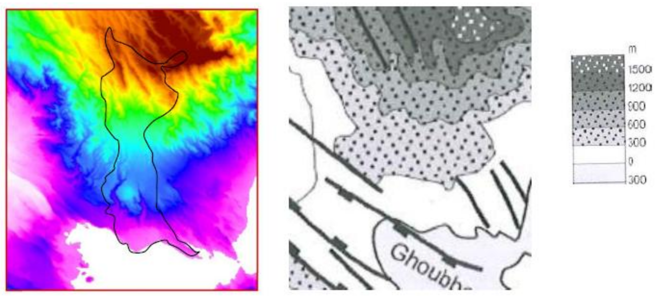


Figure 3: The North Ghoubet site is fed by an hydrological basin with the head in the Day mountain (Dalha basaltic trapp series), the region in Djibouti Republic with the highest rainfall (processed NASA/SRTM data and current topographic map, from J.Varet, 2011)

2.3 Brief Recall of the History of the Site

In the Republic of Djibouti, following extensive surveys of the whole country, the Asal site was first selected for geothermal developments (Farah, 2010). During three successive phases, led by BRGM (France) in the 1970s and by UNDP and Aquater (Italy) in the 1990s, the geothermal resource potential of the Asal site was tested with deep drilling operations. When the proposal of developing Hanlé was submitted by Aquater, Nord-Ghoubbet was proposed by BRGM as an alternative, but this offer was not considered (BRGM, 1983). A new approach that was recently developed led to the proposal of industrial development of a 50 MW plant centered on the Fiale Caldera in the Asal Site (ISOR, 2008; Hjartarson et al., 2010).

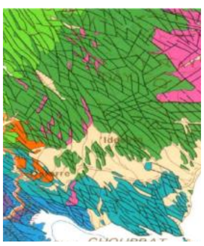
The major problems encountered on the Asal Site is not the heat source, which has already been certified by previous drilling campaigns (with temperatures ranging between 260°C-360°C), but the permeability at depth and the fluid composition. Located between the marine gulf of Ghoubet and the halite-saturated Lake Asal, the geothermal fluid prevailing in the deep reservoir is highly salty brine (Battistelli et al., 1990). Currently available technologies make it possible to exploit such geothermal brines, as shown in the Salton Sea basin (USA). But mastering these technologies in a local environment that is quite different from the Californian environment is not so easy, and finding nearby a geothermal site where a less salty fluid could be tapped would be a real advantage.

2.4 Geological Setting

The Nord-Goubbet block is bounded by the Goda Mountainto the north, Makarassou transverse fault system to the East, and by the sea of the Ghoubbet Gulf to the South. The geology is characterized by the Dalha basalts dipping towards south and faulted, covered by the more recent Gulf basalts after erosion and deposition of pleistocene detrital sediments. The area, situated under the influence of several different tectonic patterns is affected by several fault systems:

- The Asal-Goubbet rift normal faults trending NW-SE;
- The Makarassou N-S trending transverse faults;
- Older trends identified in the in the Dalha and older Mabla formations;
- Active faults resulting from the transform system linking Ghoubbet with Gulf of Tajoura ridge; and
- The fracture network is well developed.

The Nord-Ghoubbet site would merit more consideration from investors. Located near the Asal-Ghoubet NW-SE trending axial volcanic range, it is also affected by transverse faulting resulting from the transition zone between the Asal Range and Ghoubet submarine rift segment and the oceanic ridge identified along the axis of the Gulf of Tadjura (Figure 4). This multiple faulting should be favorable for fracturation at depth and hence the development of hydrothermal reservoirs. Indeed, fumaroles have developed along faults in this area, with the development of recent silica deposits indicating the continuous exhaust from an active hydrothermal reservoir (CFG, 1993).



...bet block ... salts (pale ... t younger basalts (deep blue and violet). The Dahla basalts (7 to 3 My) in deep green are intensively faulted and eroded. They are covered to the west by the basaltic stratoid series (2 to 1 M y, colored in pale green). MNT of the same area showing the different morphology of these units.

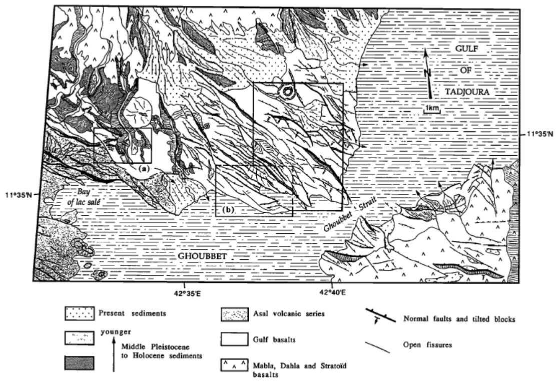


Figure 5: Tectonic sketch map of the Nord-Ghoubbet block drawn by Manighetti et al. (2000) from Spot Image. Rectanges indicate more detailed photo-interpretations on Fig. 6 (a) and 7 (b).

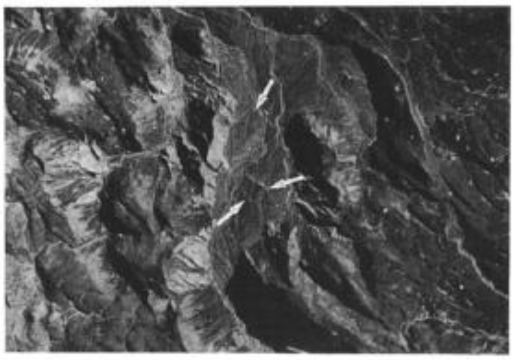


Figure 6: Aerial picture (box a in fig.5) showing 3 recent fault scarps (white arrows) cutting holocenene alluvial terraces a few meters above present river beds. These normal faults frequently display hot grounds, showing leakage from deep geothermal reservoir.

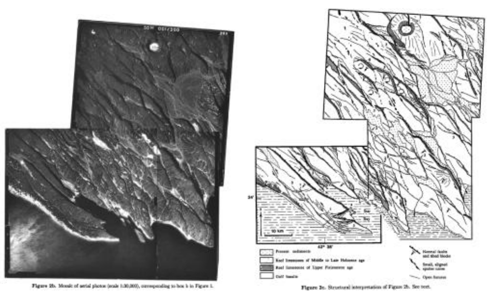


Figure 7: Aerial photo assemblage and structural interpretation of the central part of the Nord-Ghoubbet block (after Manighetti et al. 2000).

2.5 Hydrothermal Manifestations

Along the scarped valleys of the Wadis several fumaroles and one boiling spring are found located in the detrital terraces or along the volcanic cliffs. These fluids were sampled and analysed. Different methods were applied to the chemical data from the water condensate of the fumaroles, and provide estimations for the possible reservoir temperature of 220°C and 170°C (Gadalia et al. 1992; Correia et al, 1983). Stable isotopes analysis of the fumaroles assisted in assessing the origin of the waters. Compared to the fumaroles of the Asal Rift Zone, Nord-Goubhet fumaroles display significantly lower Deuterium and Oxygene18. It suggests that these emergences do not represent primary steam from geothermal reservoirs. Fumaroles would eventually result from a secondary process from previously condensed steam or boiling groundwater (Geothermica 1987).

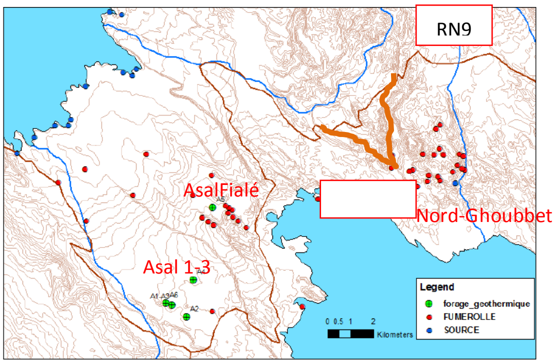


Figure 8: Topographic map of the eastern part of Nord-Ghoubbet block showing the numerous fumaroles surrounding waddiAfaï. The asphalted road (RN9) is reported as well as the track reaching the fumarolized area. Fumaroles and springs, as well as drilling sites (A1 to A5) of Asal geothermal field are also mapped.

2.6 Geophysical Surveys

Three geophysical surveys were conducted in the area of Nord-Goubhet: gravimetry, AMT and electric using rectangle method (Puvilland, 1983). The gravimetric map (Figure 8) point out several heavy and light anomalies not regularly distributed. Although these anomalies are of low amplitudes they are more or less clearly delimited by the different linear trends, and correlate with the major tectonic feature of the area. From their analysis, three main guidelines were proposed. First, the Southern Asal rift system delimits light density anomalies. To the North and parallel to it, a large axis includes a succession of heavy and light anomalies. In the central part, a similar axis is identified along a NNW-SSE trend. The authors noticed that the major part of the hydrothermal activity is located between these two axes. Finally, light anomalies cover the Eastern part of the prospect. The geoelectrical survey globally demonstrates three main zones of low resistivity. The first is located on the Eastern part of the prospect. The second is located to the South-West, while the last and very conductive area is located in the North-Western part. Higher resistivities are observed along a NNW-SSE axis. The bottom of the conductive zone was estimated to reach around 1000m depth. An uplifted conductive body was identified thanks to AMT survey in the central zone of the prospect. Results from the three geophysical surveys did not show direct simple inter-correlations. However, findings from the gravimetric and the electrical methods provided useful data on the underground reservoir structures in relation with the surface hydrothermal activities.

A new phase of geophysical exploration was completed by CERD in 2010 comprising of the application of TDEM and MT methods. Surface manifestations such as fumaroles and hot springs were also sampled for geochemical and isotopic analysis. A conceptual model was proposed for the geothermal site of North Goubhet according to the data collected. Beneath the Moudoud horst, a negative gravity anomaly is observed, and MT revealed very low to moderate resistivity for a thickness of several hundred meters throughout the area. These can be interpreted as resulting from alteration of the Dalha basalts due to hydrothermal activity. Low to moderate resistivities encountered below this impervious zone are suggested to be possible targets for the geothermal reservoir.

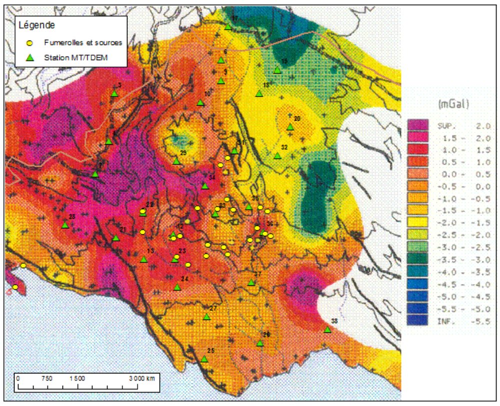


Figure 9: Gravimetric anomalies map (in milligals) obtained by Puvilland et al. (BRGM, 1993) with indication of fumaroles (yellow dots) and the position of CERD(2011) MT stations (green triangles).

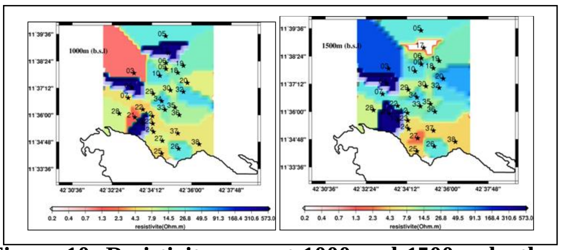


Figure 10: Resistivity map at 1000 and 1500m depth, resulting from MT survey by CERD (2011)

3. ELABORATION OF A CONCEPTUAL MODEL FOR NRD-GHOUBBET GEOTHERMAL FIELD

From the above mentioned data, it is possible to elaborate a first conceptual model for the Nord-Ghoubbet Geothermal Field, which will help in determining the next phase of geothermal exploration to be conducted in this favorable area. Before discussing the geothermal model itself, it is important to highlight the very specific geodynamic setting that prevails and that led to the development of the extraordinary intense fault system in the Nord-Ghoubbet block.

3.1. The Development of the Intense Fault System of Nord-Ghoubbet Block

The development of the fault system in Nord-Ghoubbet block is a major feature from the geothermal point of view, as it results from the interaction of the normally faulted spreading axis with the shear dominated transform fault system. The immediate proximity of the oceanic ridge allows for a sustained heat source to influence the whole area, whereas the intense and multiple faulting allows for the development of a fracture permeability in a geological environment already benefitting from geological permeable layers (due to the inter-bedding of detrital deposits with basaltic flows). This intense and complex tectonic setting is explained, according to Manighetti et al. (2001) by the rotation of the Nord-Ghoubbet block between the two oceanic spreading axes of Tadjoura and Asal-Ghoubbet, as seen in Figure 11.

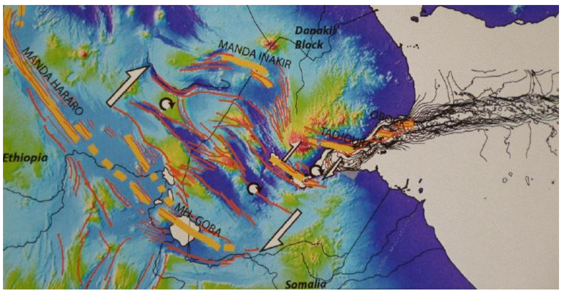


Figure 11: Rotation of the Nord-Ghoubbetblock according to Manighetti et al. 2001.

This phenomenon was recently explained by Doubre et al. 2012, using the deformation measured from satellites images from different dates, that is, 1997 and 2008. The Nord-Ghoubbet block appears to be subject to an intense horizontal deformation along the N35° direction. Figure 12 shows the variation of the speed field on this 11 years period.

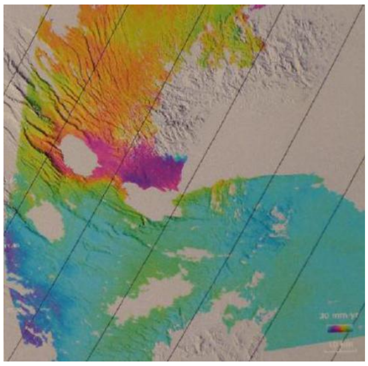


Figure 11: Deformations measured from satellites images in the central part of the Djibouti Republic, between 1997 and 2008. The most intense appear in red and violet colours, reaching 30 mm/year in the Nord-Ghoubbet block (Doubre et al. 2012

3.2 Proposed Conceptual Model of the Nord-Ghoubbet Geothermal Field

As a whole, Nord-Ghoubbet site is gifted with all the elements expected for a geothermal site:

- A heat source, provided by the two nearby ridges of Ghoubbet and Tadjoura. Even the transform zone linking these two segments may provide a heat source as it is certainly a “leaky transform” due to the oblique spreading of the whole area (Dauteuil et al. 2001).
- A permeable reservoir, gifted with both a permeability of formation (due to the numerous recent detrital inter-bedding with the basalts) and themselves partly permeable. The presently active nature of the deformation of the block, along several crossing fault systems, resulting from the rotation of the block and its deformation by spreading, allows for the development of geothermal reservoirs confirmed by geophysical surveys.
- Leakage from the geothermal reservoir appears as important in the block, particularly in its western part, but also to the eastern extreme, along the sea, where several hot-spring occurrences are reported. Fumaroles and hot grounds, developed even in the recent quaternary alluvial terraces and silica deposits along faulted basalts are the most evident aspect of theses leakages, with an extension certainly wider than the mapped area.
- A cover is provided by both hydrothermal deposits and alteration of the basalts in the upper part of the system. Deeply hydrothermally altered basalts are observed along the major faults in the upper part of the block, showing that this alteration zone is probably quite superficial.

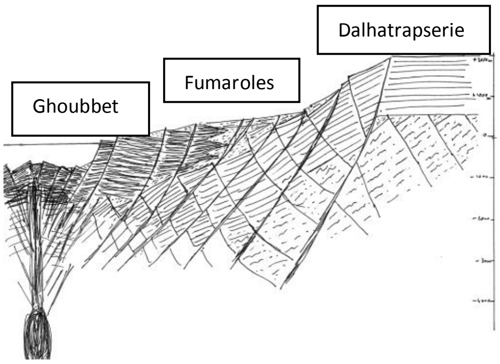


Fig. 12 : Geological qualitative model of the Nord-Ghoubbet geothermal site. Meteoritic water descending from the Dalha plateau penetrates through the numerous permanently reactivated faults in the basaltic Aquifer, heated at depth by the recurrent basaltic magma intrusions and anomalous hot mantel along the Ghoubet and Tadjoura accreting oceanic ridges. In the immediate vicinity of the Gulf, sea water infiltration may mix with meteoritic water in the fractured geothermal reservoir. (From Varet, 2011)

4. CONCLUSION: PROPOSAL FOR A FEASIBILITY STUDY AFTER COMPLEMENTARY WORKS

The Nord-Ghoubbet site has favorable geological parameters. Its geographic location is also in favor of proceeding with the feasibility study of its industrial development:

- A rather easy access road (through the present asphalted RN1 and older tracks crossing the hydrothermal zone);
- The proximity of the sea with adapted shores for shipping the equipment with barges directly from the Port of Djibouti;
- The vicinity of the towns and ports of Djibouti capital and Tadjoura prefecture; and
- Planed electrical transmission line to be built for the Aeolian farm projected south of the gulf for the future desalinization plant.

However, although demonstrated as highly favorable, the site still needs further field and laboratory works, in order to propose the best location for the exploration drilling program (at least 3 wells 200m deep) and better quantify the technico-economic feasibility study. These should include:

- Geological and structural field works at 1/10.000 scale on the whole block, including the sea coasts with neo-tectonic measurements and sampling for petrographic, mineralogical analysis and age determinations;
- Hydrogeological and hydrothermal field sampling of the fluids and deposits with the aim of determining the water circulation system and its recent history based on present and fossil hydrothermal deposits;
- Mineralogical, geochemical and isotope analysis to be carried on all liquid, gaseous and solid hydrothermal expressions;
- Detailed cartography of the heat manifestations and thermal anomalies and analysis in view of their geological and tectonic environment; and
- Complementary geophysical surveys, notably gravimetric, electrical and magnetotellurics in order to cover the whole block, with interpretation.

This complementary work should facilitate the quantifying (notably in terms of depth of the reservoirs, temperature for the geothermal fluid and optimal well location) of a 3D model of the whole block. The work is to be developed with professional geothermal experts, and should allow for training Djiboutian staff from CERD and MEERN. Through it the precise characteristics of the drilling and testing program should be determined.

This complementary prefeasibility work should be be completed within a short time (6 month) so that the results are available for the feasibility study to be conducted just after the drilling program of Asal is completed. This will increase the benefits arising from the mobilization and demobilization conditions for the drilling equipment and staff.

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