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# A Revised Approach to the Hanlé - Gaggadé (Djibouti Republic): The Garabbayis Geothermal Site

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**ABSTRACT**

The central part of Afar, between the active basaltic axial ranges of Asal and MandaInakir to the east and MandaHarraro to the west, is characterized by large horst-and-graben structures deeply affecting the stratoid series, 2.5 to 1 My old. This series is essentially made of trap basalts and a few rhyolitic centers outcrop in the upper part of the sequence. While the sequences in the hosts are essentially volcanic, the grabens are filled with sedimentary strata of detritic, lacustrine,and more recent evaporitic and eolian deposits.

Hot springs and fumaroles are observed in several locations along the major faults limiting the grabens, both in Hanlé and Gaggadé, as in the whole area (both in Djibouti and in Ethiopia). Considering the fact that permeable reservoir could be well developed in detrital layers of the lower part of the sedimentary sequence, the exploration team considered the grabens as good geothermal targets. The Tendaho Graben in Ethiopia and the Hanlé Graben in Djibouti both looked as good candidates for geothermal feasibility studies.

In the years 1980-1984, a significant geothermal exploration program was undertaken in Djibouti Republic under Italian and World Bank cooperation. The Hanlé and Gaggadé grabens were identified as targets of prime interest, with the hope of finding less salty fluids than in Asal, but at similar depth. Geological, hydro-geochemical and geophysical investigations, and a few gradient wells were used to locate deep exploration wells in the Hanlé gGaben. No sufficient geothermal gradient was however found, the Hanlé target was abandoned and the continuation of the drilling program was transferred to the Asal site.

New site investigations, together with updates of the geological and geophysical data and geodynamic interpretations of this part of Afar led to the proposal of a new model for the geothermal fields, which the authors see as present in this area, not located in the graben but in the horsts. The Garabbayis site, where fumaroles above 100°C are present, appears to be located along a transverse fault, cutting through the whole horst along the southern limit of the Baba Alou rhyolitic massif. Fumaroles, hot grounds, deeply altered basalts and hydrothermal deposits (silica, zeolites, calcite) are found along this fault line, and are particularly well developed when crossing the cliffs bordering the Gagagdé and Hanlé grabens. Significant seismic activity characterizes these NE trending faults, which are much less spectacular in the landscape but most active at present.

The geodynamic model proposed for the area by Barberi and Varet (1977), précised by more recent geophysical considerations including geomagnetism and summarized by Tapponier et al. (1990), shows that the whole area is subject to dextral rotation. This allows the development of intense bookshelf faulting and transverse fracturing. At Garabbayis, we observe that this rotation produces a significant extensional movement along the transverse faults.

The following interpretation and propositions are made in terms of the geothermal model:

- A high temperature geothermal reservoir was produced by transverse fractures, rejuvenated by present seismicity, with a significant extensional component at Garabbayis;
- The heat source is uncertain, but could be magmatic and related to the presence of an important magma chamber underneath Baba Alou volcano, presently fossil but eventually still hot. It could equally be just produced by hydrothermal fluids circulating from deep in the mantle. Gas compositions in fumaroles show significant magmatic component; and
- Further geochemical, geophysical, detailed geological surveys and civil engineering studies on the upper part of Garabbayis hydrothermal site should be conducted to locate places for geothermal exploration and production wells. They should be located on the volcanic horst and not in the sediments, and be drilled with the correct inclination in order to cross the NE trending faults at the suitable depth for high temperature steam production.

## 1. INTRODUCTION

The present paper describes the justification for implementing a small-size geothermal plant in the south-central part of the Djibouti Republic, a rural area, including the towns of Dikhil and Yobouki, where the demand is high due to a fast growing development linked with the major highway linking Ethiopia (80 M ha) to the port of Djibouti. It highlights the characteristics of the energy sector, presently totally dependent from imports, the potential geothermal resources of the country, the characteristics of the proposed geothermal site and the work to be carried in order to check the feasibility of the project and implement it under optimal conditions.

## 2. THE ENERGY SECTOR

### 2.1 Overview of the Energy Sector

Energy consumption in Djibouti is characterized by the following features:

- Heavy external dependence: About 85% of the final energy consumed is based on imported refined petroleum products, and since last year electricity from Ethiopia. The rest is consumed in the form of fuel wood and charcoal.
- Few directly productive activities: consumption by industry and construction is estimated at 5% and agriculture 0.3%, the rest is used in transport (42%), households (38%) and services (15%).
- Limited consumption: The per capita energy consumption is estimated to be 0,2 Toe.
- Large urban-rural disparity in terms of quality of energy consumed: about 90% of consumption of oil and electricity in Djibouti-ville, and 99.5% biomass fuels in rural areas.
- High cost: approximately 68% of energy is consumed in the form of petroleum products, 17% in the form of electricity and 15% in the form of biomass fuels.

In reality, about half of the country's population meets its energy needs from fuel wood and kerosene. The country being arid with an annual rainfall of about 140mm, fuel wood is in short supply. The use of animal waste is not known. Modern energy supply in Djibouti is based on refined petroleum product imports, which are primarily used in the transport and for electric power generation. The external dependence on petroleum products and the price fluctuation in the international oil market impose serious difficulties.

An estimated 50% of the population has access to electricity, of which population 99.5% is urban. Electricity cost averaged at an equivalent of US$ 0.32/kwh in 2009. The high cost of electricity is considered to be the main barrier to investment in industry and economic production in general, since the investment climate is otherwise good. The high cost of electricity also imposes a barrier against the population fully using electricity for household and social consumption. The state owned power utility, Electricite de Djibouti (EdD), had only 40750 clients in 2009. The annual per capita electricity consumption was 288kwh (including the high per capita consumption of the French army stationed in Djibouti).

As a whole, high electric power cost is the key cause of the prevalent slow pace of socio-economic development and that of poverty in the peri-urban and rural areas. The availability of an adequate and reliable supply of energy in various forms and at affordable cost is the key to the development of small and medium industries. It is also essential for the improvement of water supply to the disadvantaged by reducing the cost of production and treatment. With respect to health and sanitation such adequate and low cost energy supply should contribute to improved conditions by enabling provision of health services to the pastoral population and their livestock. It would also contribute towards the improvement of access to education and furthering literacy. In brief the availability of a reliable and adequate supply of low cost energy will contribute to economic development as well as improvement in the quality of life.

In light of the above priority should be directed to the promotion of alternative solutions by replacing fuel burning generation with geothermal and wind energy, strengthening of management and technical staff training and developing a program of energy management to be implemented by the new Energy Efficiency Agency (ADME).

### 2.2 Potential for Renewable Energies and Energy Efficiency

The energy resources available are wind, geothermal, and solar (high rate of insolation: 21.6 MJ/m2/day). Wind speed measurements have been carried out in various parts of the country and the results are encouraging, with constant wind speeds of 4-7m/sec.

Geothermal exploration has shown the existence of a number of potential areas suited for electric power development. Drilling at in Asal Rift has encountered high temperature fluids from zones of high permeability. The field awaits development, and several other sites suitable for further development, have been identified..

### 2.3 Government Energy Policy

The availability of and access to clean, adequate and low cost energy is expected to significantly contribute to economic growth, re-enforcement of the competitiveness of the country, improved of the quality of daily life of the population and consequently to the reduction of poverty. The government's aim is thus to develop all available alternative and renewable energy resources giving priority to geothermal resources for which the country is believed to have a good potential. This will be carried out through private sector participation in the development of the resource and the generation of electricity for supply to EdD.

## 3. UPDATE OF GEOTHERMAL EXPLORATION IN DJIBOUTI

### 3.1 Summary of the Past Explorations in Djibouti Republic

The geothermal exploration can be divided in two 3 phases. The first phase is concerned with the exploratory survey conducted by BRGM (1970), which identified possible potential geothermal areas as such as Lake Asal, Lake Abhé, Allols, Nord-Ghoubet, Arta and Obock to be prospected by drillings. The two initial drillings in the rift of Asal in 1975 (BRGM) recognized a deep reservoir at 1000m depth with a high mineralisation (180 g/l) fluid and 260°C. The production of the well Asal 1, located in the southern area of Asal Rift, decreased quickly because of mineral deposits in the wellbore casing and in the surface tubings.

The second phase started in 1981 with the exploration of the Hanlé-Gaggadé area, recent tectonic basins, located between Abhé and Asal by AQUATER under Italian and

World Bank assistance. Results from Hanlé plain drillings reported a low temperature fluid (AQUATER 1989) and the exploration continued in the Asal area with four new wells. Asal 3 located nearby Asal 1, revealed a well head pressure of 21 bars and a discharge rate of 350 ton/h at 12.5 bars, still accompanied by scaling and decreasing of the discharge rate. Except Asal 6 located in Asal 3 area, the other wells located toward the axial rift area, did not meet a reservoir.

The third phase started in 2008 with new exploration activities initiated in cooperation with the Iceland Government, and the involvement of a private enterprise, Reykjavick Energy Invest, REI. The programme realized a new geophysical coverage of Asal Rift using TEM and MT methods. Through the analysis of the results, REI proposed a more targeted area - known as Fiale and represented by a collapsed large caldera - for exploration within the Asal Rift. Based on those results, a feasibility study programme was prepared including deviated exploratory wells.

The next immediate step for the Asal Rift prospect is the feasibility study for at least three deviated wells in the Fiale area. Such exploration drillings are presently being implemented under a new financial arrangement, by a consortium of public banks, including World bank, African development Bank, OPEP funds and AFD, with the objective of developing a geothermal 50 MW power plant under p.p.p.

### 3.2 Other Suitable Geothermal Sites in Djibouti Republic

Other sites suitable for geothermal development have been identified in several locations. Besides Asal, North Ghoubbet (near Asal), Abhé (to the extreme south), Obock and MandaInakir (in the north) have been recognized (Figure 1). In the central part of Djibouti Republic, the Garrabayis site – located between the towns of Dikhil and Yobouki – appears to be of the most urgent, in terms of demand for energy and in terms of resources for small to medium size development (2.5 MW).

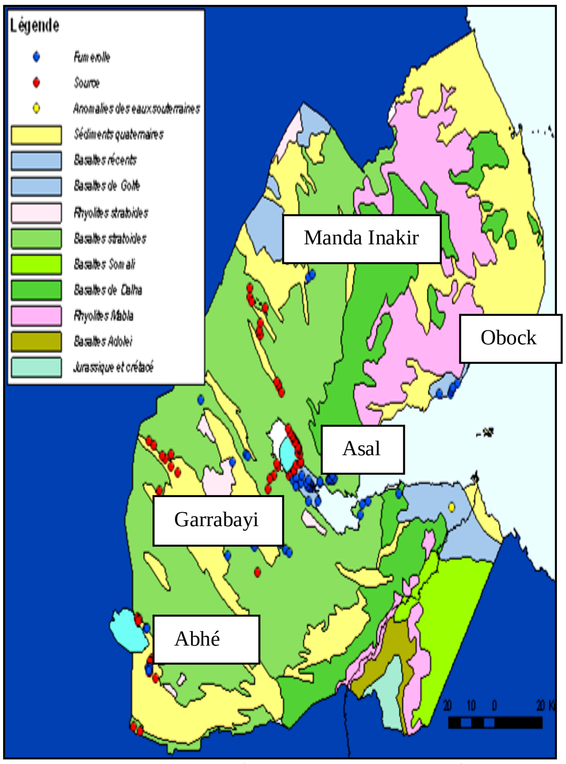



**Figure 1: Simplified geological map of Djibouti Republic with location of major fumaroles and hot spring sites.**

## 4. THE GARRABAYIS GEOTHERMAL SITE

### 4.1 A fast Growing Rural Area in Dikhil Prefecture

The region located in the south-central part of Djibouti Republic is developing fast, notably due to the intense road traffic on N9, the road linking Djibouti to Addis-Ababa. The port of Djibouti is presently the only access to the sea for Ethiopia (80 million inhabitants). Several villages are located along this axis; with the town of Dikhil as Prefecture. The area, mainly rural, is relatively densely populated, the Hanlé plain being relatively fertile. The development of this axis is however handicapped by the lack of an electric grid, as the region is presently deprived of indigenous energy resource. Dikhil is presently fed by a small diesel plant, located away from the electric line interconnecting Djibouti and Ethiopia (Figure 2).

**Figure 2: Map of the south-eastern part of Djibouti Republic, with the location of the site proposed for geothermal medium-enthalpy development (red square)**

### 4.2. Geographic and Gelogical Setting

From Dikhil to Yoboki, the last Djiboutian city before the frontier with Ethiopia, the asphalted road is located along the floor of a wide Hanlé graben. This quaternary tectonic structure is bounded by faults trending in the NE-SW direction, which correspond to the spreading of the Red Sea – Gulf of Aden plate boundary between Africa and Arabia. If no recent volcanic activity was identified in this part of the Republic, as in Asal-Ghoubbet further north, important fumaroles sites are present on both sides of the graben (Garabbayis and Dalahammallou). Fumaroles also occur at Awdaea and Dimbir on the southern flank of the Bab'Alou Massif, an important rhyolite center located on the top of a horst of Dokkoyno separating the Hanle and Gaggade grabens. They extend, along the same NE line, down to the northern flank of the horst (southern fault of the Gaggade graben).

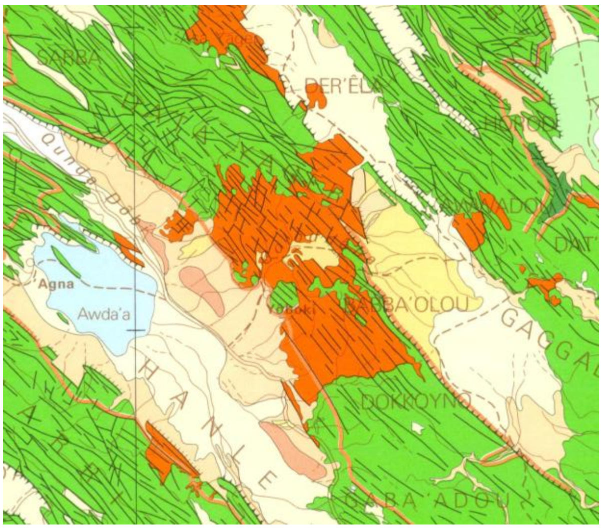



**Figure 3: The Hanlé and Gaggadé (recent sedimentary fillings in pale colour) and the Dokkoyno horst, made of basalts of the stratoid series and of the Baba'Alou rhyolite massif. (From Map of Central and Sptentrional Afar, 1/500.000 scale, J. Varet 1977**

### 4.3 Analysis of the Previous Geothermal Exploration Failure

The Hanlé Plain was considered as a potential geothermal site, and an intensive exploration program was thus developed from 1981 to 1987, led by Italian experts and enterprises under bilateral assistance with the support of the World Bank. Geological, geochemical and geophysical surveys led to the implementation of 3 geothermal gradient drillings at depths of 450m as well as 2 deep exploration wells (at 1620 and 2038 meters).

The studies undertaken by AQUATER (1981) recognized 3 water types representative of different aquifers. In the low depth waddi bed alluvium, i.e. with direct recharge from intermittent surface water, springs are bicarbonated-earth-alkaline with low mineralisation. All the boreholes catching the regional volcanic aquifer show chlorinated-alkaline waters, the same as the springs located in Hanle plain fault along the fault scarps at the contact of basalts with the sediments. In the sedimentary aquifers of the Hanle Plain, water is the chlorinated-bicarbonated-sulfated-alkaline type. Geochemical anomalies in $CO_2$, $NH_3$ and $H_3BO_3$ identified deep ascending fluids. This hydrochemical approach used a water circulation model with important undergroud flow through the stratoid series recharged from the Awash River basin located south. Through geoelectrical prospection the thickness of the sedimentary filling was assessed - with low electrical resistivity due to clays - and the surface of the stratoïd series was mapped. Aeromagnetic data and a seismic activity were also used in the interpretative model. Below the sediments, an upper resistant layer and a lower conductor was identified, with a thickness exceeding 200m, interpreted as signs of hydrothermal alteration or intercalated layers of fluviatile sediments with paleosoils in the upper part of the stratoid series. Deeper, a resistant substratum was considered as the lower part of the Afar stratoïd series.

3 gradient wells at an average of 450m depth were drilled (Teweo1, Garabayyis 1 and Garabayyis 2) to confirm the geothermal model and the precise temperature at depth before undertaking deep drillings (GEOTHERMICA 1985; GENZL 1985). They showed heterogeneous sedimentary sequences with sandy aquifers overlying the stratoid series. Measurements gave up to 121,7°C at Garabayyis 1 and a maximum temperature of 87°C on Garabayyis 2. Two deep wells drilled in the plain reached 1623 and 2038m respectively (Hanlé 1 and Hanlé 2, AQUATER 1989). Hanlé 1 recorded a maximum of 72°C at 1420m, i.e. lower than normal gradient in continental environment! Under the lacustrine deposits, a rhyolitic sequence was crossed between 94 m and 307m (probably from Baba Alou centre) with permeable layers overlying the sequence of basaltic flows from the stratoid series, impervious below 800m. A maximum temperature of only 124°C was reached at the very bottom of Hanlé 2, 2020m deep. Highly permeable levels were observed down to 450m (with fluid TDS 2 g/l) and the rest of the well remains impervious with a dominantly basaltic lithological sequence from the stratoid series (AQUATER 1989; Jalludin, 2003).

This attempt was a failure, considering the objective of high enthalpy geothermal production. One must say that the site suffers from a major handicap, well expressed in the geology: no magmatic heat source is present in this area, as the volcanic activity in the surroundings is rather old (more than 2 My). The active volcanic ranges of Asal, Manda-Inakir and Manda-Harraro are far away, and if the seismic activity occur, it is rather shearing than extensive, with no evidence of magma injection!

The composition of the gases however, although incomplete, clearly indicates leakages from a steam reservoir (with the presence of B and $H_2$). The exploration revealed a high permeability, as the gradient was null on two sequences (1600 and 2000m), showing a circulation of low temperature fluids at great depth underneath the graben. Note the exploration work, in particular the geophysics and the drillings, was developed exclusively in the plain inside the graben, and not in the horst part, where the active fumaroles occur. Hence, one could conclude that the wells were not located in an appropriate position, and did not intersect the geothermal system, which is clearly not regional, but local and linked to localized hydrothermal circulations. If a wide geothermal field could have existed in the past, as shown by the important hydrothermal deposits (carbonaceous travertine in the Hanlégraben, silica rich in the Baba'Alou Horst and along the southern fault), it is no more presently the case. This justifies the proposal for a small size, medium enthalpy geothermal system.

### 4.4 Proposal for a New Geothermal Model for a Small Size Medium Enthalpy Target and Consequent Exploration Scheme

The geological observations carried out by Jacques Varet, Abdu Mohamed Houmed and Abduraman Omar Haja, in April 2012 at the request of Dr. Fouad Aye, Minister (MEERN) proposed a new interpretation of the geothermal system. If the hydrothermal deposits, notably carbonate and silica, are widespread and clearly linked with structural systems related to the graben NW-SE normal faulting; then the fumaroles, steam vents and hot grounds in all the visited sites are all clearly linked with N70 trending faults. That is perpendicular to the regional normal faulting.

The occurrence of such faults was already observed from previous studies. In their small scale plate tectonics interpretation of the Afar region, Barberi& Varet (1977) inferred the presence of a transform fault system linking the Northern Asal Rift with the Manda-Hararo/Dama Ale rift (Figure 6). In a more recent approach, Manighetti et al. (2007) - Figure 7 - confirmed the idea, already developed by these authors 30 years earlier, of the rotation of the block located between the two spreading segments.

The present seismic activity (Doubre et al., 2012) shows several events in the period 2005-2010, with an apparent NE trend (Figure 8). Our present interpretation is hence that the southern border of Baba'Alou rhyolite massif is affected by a transverse fault trending N70, well visible in the geology at various scales, that represent both a transform fault and a break in the horst that accommodates a rotation of the northern part (Baba'Alou) with respect to the southern segment (Dokkoyno horst) (Figure 9).

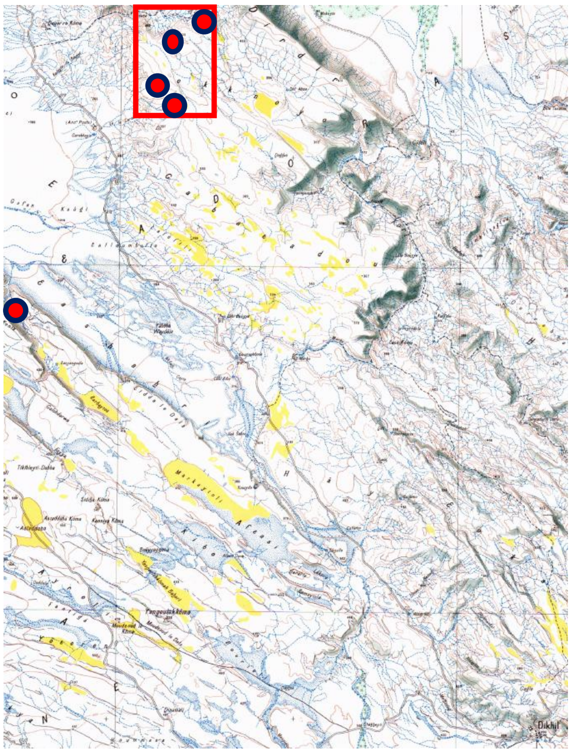


**Figure 4: Topographic map of the area proposed for the project, at a distance of 30Km to the north from Dikhil. The major active fumaroles are indicated with red dots. The project area is the red rectangle.**

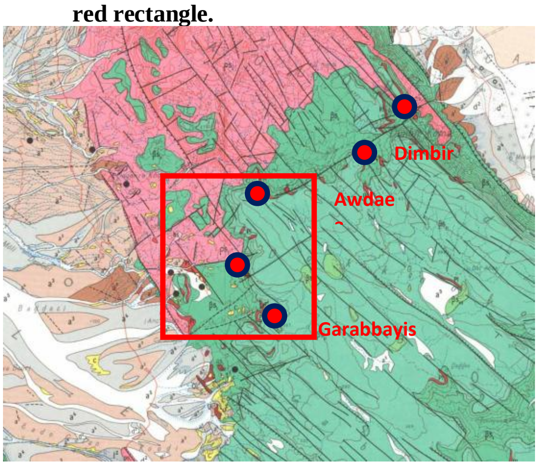



**Figure 5: The geothermal area selected for the feasibility study and further development of a small-size ORC geothermal plant, on the detailed geological map (ISERST-ORSTOM, 1987). Red dots indicate the main fumarole sites. Black dots indicate travertine deposits.**

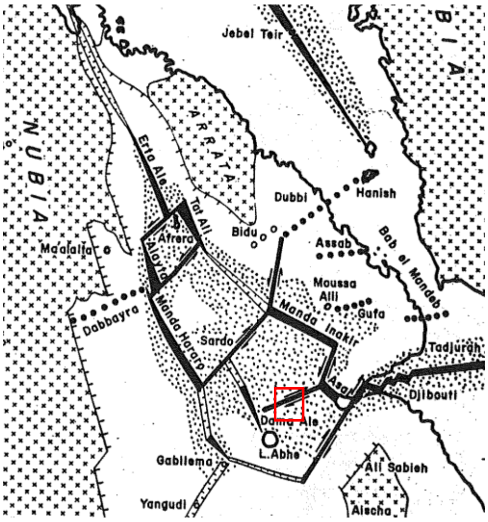



**Figure 6: Small scale plate tectonics interpretation of Afar (Barberi& Varet, 1977), inferring the existence of a transform fault in the site of interest (in red).**

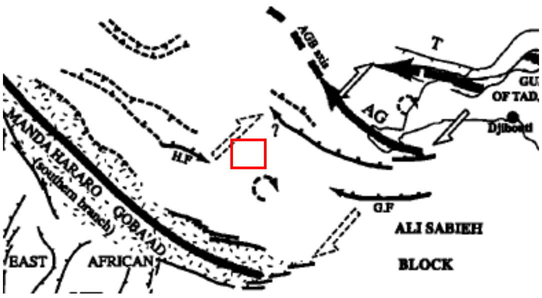



**Figure 7: Rotation of the block located between Asal and Abhé (Manignetti et al. 2007) in the project area**

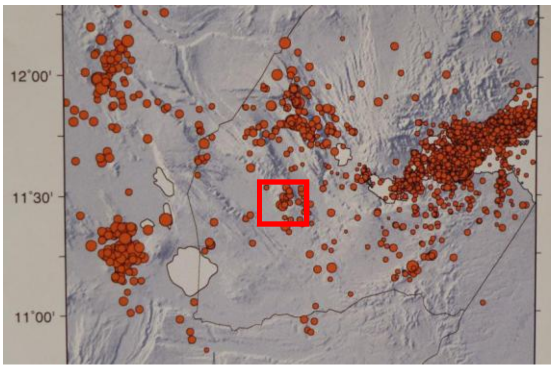



**Figure 8: Present seismic activity in Central Afar (in the 2005-2010 period); the Dokkoyno horst appears as seismically active, with an apparent NE trending direction (Doubre et al, 2012) which fits with the geological observations of the faults and fumarole sites.**

## 5. PROPOSED GEOTHERMAL FEASIBILITY AND DEVELOPMENT PROGRAM

Although the area was subject to important geothermal studies in the years 1981-1987, new field and modern work is necessary, as the target of the exploration undertaken at that time was centered on the plain of the Hanlé graben only, and neglected the Dokkoyno – Bab'Alou horst where the major hydrothermal manifestations occur, and the real geothermal target is located on the basis of our geodynamic model. The work to be undertaken should be developed in 3 steps:

e) Surface exploration using geological, geochemical and geophysical methods, centered in the Dokkoyno – Bab'Alou horst,with the aim of locating the geothermal wells.
f) Geothermal drillings,for geothermal fluid production at expected medium temperature (130-170°C)
g) Construction of a small-sized geothermal plant on well head site and an electric line connecting Yoboki with Dikhil, as well as rural villages located in-between .

### 5.1 Surface Exploration

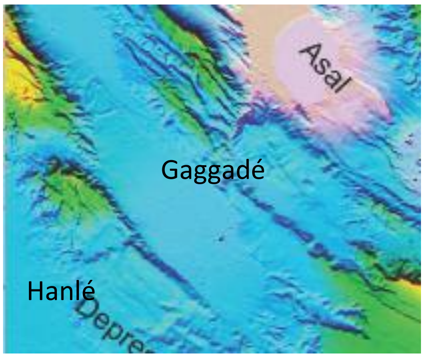
On the basis of a detailed analysis of the available data, resulting from previous geological surveys, geothermal exploration work and more recent data (notably registered seismic activity), a complementary surface exploration program will be undertaken. The program will be centered on the area including the 3 active fumaroles sites (red square on the maps Figures 3 and 4). Using geological, geochemical and geophysical methods, with the aim of identifying the active fissures and faults feeding the surface manifestations from the depth, this step will help in locating the sites of the geothermal wells.

Work will consist of neo-tectonic field studies, with attention focused on the faults and fissures where present fumaroles activity develops as well as those where hydrothermal deposits are observed. Photo-interpretations and field measurements will be conducted by specialized personnel.

An infrared survey of the area is also proposed in order to obtain a map of the hot grounds, which will help in revealing the trends of the faults and fissures that transmit hot fluids from depth to the surface. Such features are not always visible, on surfaces covered with basaltic blocks - the usual characteristic of the plateaus in Afar.

Complementary geochemical analysis, including isotopes will be carried on the fumaroles and mineralogical studies of the hydrothermal alteration products and deposits will also be conducted to determine precise fluid characteristics (composition and temperature).

Geophysical survey will be undertaken on the plateau and across the fault, using both geo-electric and magneto-telluric methods to trace at depth the conductive layers characteristics of the hydro-thermalized system as well as eventual resistant bodies which could sign steam conduits or even reservoirs.



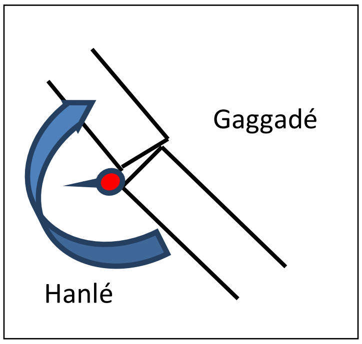




**Figure 9: The schematic interpretation we propose for the presently active Garabbayis fumaroles (in red) along transverse faults opening affecting the horst between Hanlé and Gaggadé plains. This fracture results from the whole rotation of the area located between the two major spreading segments of Asal-Ghoubbet and MandaHarraro-Dama'Ale.**

### 5.2 Geothermal Drillings and Well Testing

The exploration phase will help in locating the sites for geothermal production drillings. 3 wells will be drilled, with directional drilling to maximize the chances of intersecting productive fractures and faults, although we noticed that some of them are inclined and therefore can be intersected by a vertical drilling.

No real deep well will be undertaken. The depth of the productive zone will be looked for in the interval of 500-1000m, sufficient for a geothermal fluid production at medium temperature (130°C -170°C). These wells will be drilled with a diameter (at least 9 inches for the final production casing) sufficient for a significant flow rate (of about 30 - 100t/h).

Long lasting production tests with proper well-head pressure avoiding deposits in the casing will also help in determining the physico-chemical characteristics of the fluids so as to optimize the production scheme.

### 5.3 Implementation of Small-size (2.5MW) Geothermal Plant

The characteristics of the fluid produced from the wells will assist in determining the characteristics of the first small-size geothermal unit to be built on one of the well heads site. If the parameters of the geothermal system allow for further developments, other wells and geothermal units will

Note that while the first phase should be non-refundable, the second phase could be partly refundable (in case of success, for production wells only) and the third phase could be covered with a soft loan.

## 7. CONCLUSION

Although the poor results of previous exploration works discouraged further geothermal development in the area, a new approach, based on a completely new target (horst instead of graben) and model (fracture zone inherited from block rotation rather than normal faults), is proposed with a realistic target eventually able to fulfill the needs of electrical power of the surrounding rural and small town inhabitants, along this fast growing economic axis linking Addis-Abeba and Djibouti capitals.

be added, depending on the local demand, which will certainly increase if electricity is on offer.

An electric line will have to be built, to connecting Yoboki and Dikhil, and eventually all villages and houses located along the National Road linking these two cities.

## 6. ESTIMATED BUDGET AND FINANCING

The total cost of the project is estimated at 15M$, broken down as follows:

- Complementary exploration work for an optimal drilling location :
  - 1M$ (including training of the Djiboutian personnel for the 3 phases of the project).

- Drilling works, drilling equipment, including civil works (road and platform building):
  - 9M$ (for 3 deviated wells at 500-1000meters depth, i.e. up to 1500m length each)

- Implementation of a geothermal plant, 2.5MW (electric transmission lines and transformer for distribution in cities and villages not included):
  - 5M$ (eventually financed with a soft loan)

- Total budget:
  - 15M$

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