Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Proposal for New Geothermal Models and Sites Hierarchy in Djibouti Republic (Update -2014)

Djama Robleh Djama, Abdou Mohamed Houmed, Abrourahman Omar Haga, Saida Abdillahi, Jacques Varet

Ministry of Energy, in Charge of Natural Resources, Djibouti Republic

jamajama3@hotmail.com; abdou med05@yahoo.fr; bilane24@yahoo.fr; saida.omar.abdillahi@gmail.com; j.varet@brgm.fr

Keywords: Djibouti, geothermal, energy, exploration, hierarchy, heat source, reservoir, hydrology

ABSTRACT

An update of available geophysical, geochemical and geological data, together with new field work and research undertaken by the Ministry of Energy in Charge of Natural Resources of the Djibouti Republic and CERD have allowed proposing new geothermal models for several sites identified by their geothermal potential from previous general surveys and specific studies for the upcoming geothermal plans. While other contributions describe in detail the characteristics of each site, this paper aims at proposing a synthetic view of the different components and an overall concept, mainly based on the geodynamic and hydrogeological environment of this eastern portion of the Afar triangle.

Concerning the heat source, two major cases occur:

- The geothermal systems located at the top or in the immediate vicinity of the oceanic ridge, whether submarine or emerged. That is the case of Asal, Nord-Ghoubbet, MandaInakir, Rouéli, Obock and lastly Arta.
- The geothermal systems relying upon deep faulting, frequently transverse to the dominant rift system (NW-SE) without evidence of active volcanic heat sources. This is the case of Garrabayis and eventually Abhé.

For the geothermal reservoir, we also consider it relies directly upon the geodynamic environment of the site. It may either result from simple extension and be produced by normal faulting and open fissures, that is the case in Asal, Obock and MandaInakir, or result from transverse faulting with the eventual association of block rotation, such as in Nord-Ghoubbet, Rouéli, Garrabayis and Abhé.

The composition of the geothermal fluid in the reservoir will directly rely upon its hydrogeological environment. From marine brines at Asal, it will vary up to meteoritic water in MandaInakir, Abhé, or Nord-Ghoubbet, to dominant sea water component in Obock, Rouéli and Arta. Continental brines will probably dominate in other sites of endorheic basins and strong evaporation (such as Hallol-Sakhalol, or the fumarole Qiqleh site of Arta), not yet counted as geothermal sites at present due to insufficient knowledge.

As a whole, our approach helps to provide a first hierarchy and structural plan of the geothermal potential of Djibouti in terms of perspective and objectives for future power production. Ridge located sites have the best heat source, therefore the largest quantitative potentials, and were proven by the result of research studies. But transverse fracturing and block rotation will allow for development of the best reservoirs, while water composition will directly influence the costs of systems and maintenance. Of course, real quantitative figures will be possibly approached only after feasibility drilling begins at the end of last quarter of 2014 and after production tests are undertaken in the following years. But we also need to develop an overall prospective and strategy for the country geothermal plan, that is the present approach, and further work and discussion of experts views will help to finalize the progress of geothermal drilling that will be held through the next years based on the results of the research study.

1. INTRODUCTION: THE HEAT SOURCE ISSUE/ANOMALOUS SHALLOW MANTLE, REGULAR DIKING AND MAGMA CHAMBERS ALONG SPREADING RIDGES

1.1 The Ridge along Gulf of Tadjoura and inside the Continent

Djibouti benefits from an exceptional geodynamic situation, in which a mid-oceanic ridge, i.e., the Aden Ridge, penetrates into a continent. This situation is well expressed while observing the present seismic activity (Figure 1) or from geological mapping, that show that the southern Red Sea axis and margins have been stable for the last few million years whereas the Gulf and Afar areas were subject to intense volcano-tectonic activity (Figure 2).

This change in spreading regime 3 million years ago became particularly spectacular with the opening of the Gulf of Tadjoura and the prosecution of the ridge axis inland through axial volcanic ranges. These characteristic volcano-tectonic structures described by Barberi et al., 1970 for the whole Afar, concentrate at present the major spreading mechanism (Figure 3).

'I'ypically, basaltic magma is emitted from a median axis located in the middle of a "rift in rift" structure, in which the lava flows become younger and younger towards the center, whereas the older first emissions are located on both sides (Figure 4). These axial ranges started being active 1 My ago, after a phase, which lasted 2 million years, in which the spreading was operated through dispersed fissures affecting the central Afar floor, with the emission of basaltic trap series now constituting the piles of the so called "stratoid series" (Barberi et al. 1975; Varet, 1985).

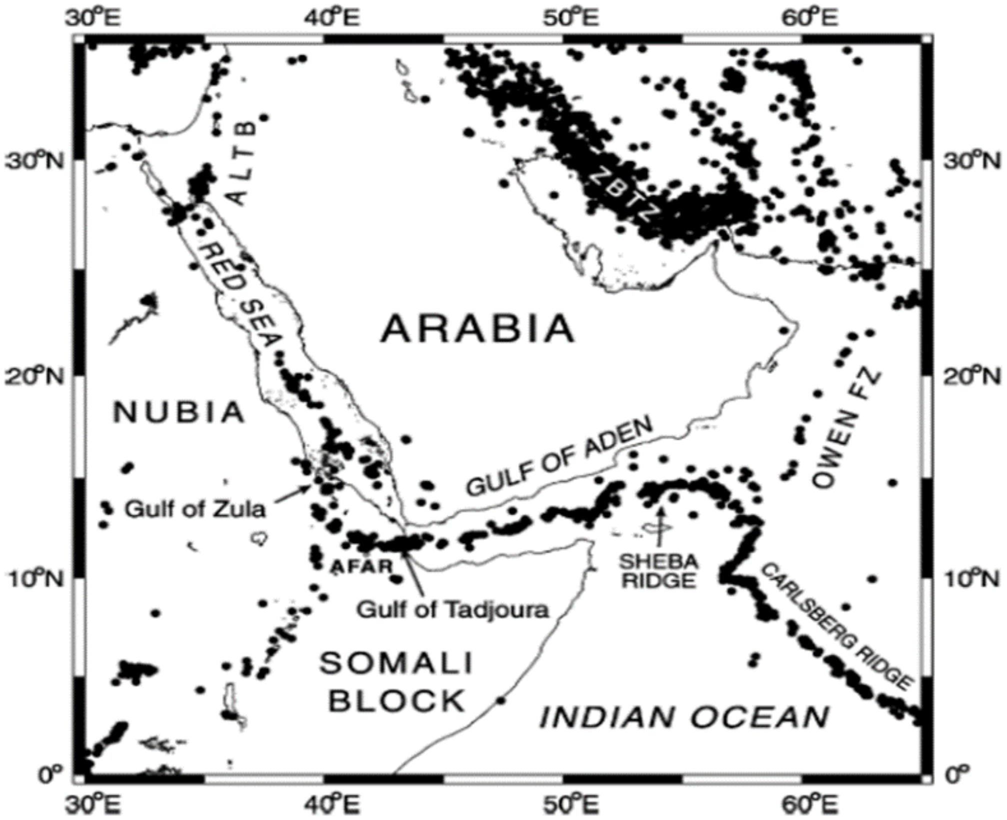

Figure 1: Seismicity (M more than 5) of the Afar region and surroundings.

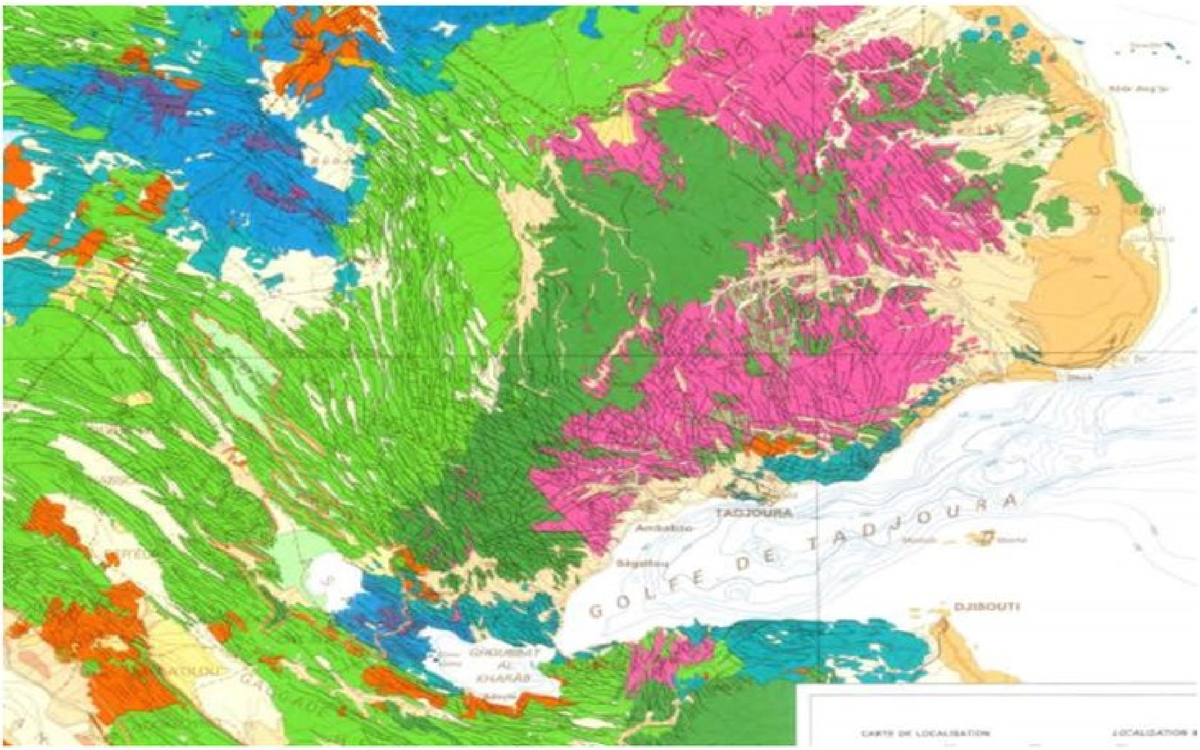

Figure 2: Abstract from the geological map of central-southern Afar (Varet, 1975) showing the active axial vo1canic ranges of Asal and Mandalnakir as well as the Gulf basalts (blue), and the intensively faulted stratoid series in Afar (pale green). The older Dalha basalts (dark green) covering the previously faulted rhyolites in the Red Sea direction (purple Mabla series) were tectonically stable along the Red Sea for the last 8My, whereas affected by intense faulting north of Asal range. The gulf of Tadjoura ridge is observed from bathymetry, with deep trough out by transform faults, down to the Ghoubbet-Asalrfit segment, The N-S faulted Makarassou area was interpreted as the surface expression of a transform fault (Tapponier & Varet, 1975).

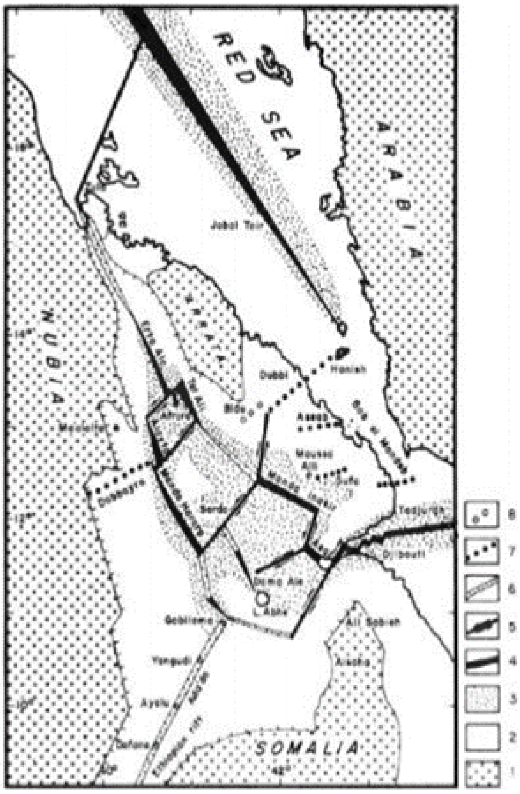

Figure 3: Reconstitution of the present Afro-Arabian plate boundaries from geological data in Afar after Barberi & Varet (1977). A succession of axial ranges, dominantly basaltic (transitional basalts) is observed from Erta Ale range in northern Afar down to Manda-Inakir and Asal ranges in Djibouti Republic, ensuring the link between the Red Sea and the Gulf of Aden oceanic ridges through the Gulf of Tadjoura ridge, 1 - Crystalline basement, 2 - Continental rift vo1canies and sedimentary filling, 3 - The Afar stratoid series (3 to 1 My), 4 - Axial active volcanic ranges (active spreading plate boundaries), 5 - Relative motion along transform fault zones, 6 - Extensional faulting with no or limited active magma emission, 7 - Transverse alkali-basaltic fracture zones, 8 - Central dominantly silicic vo1canoes of the Afar margins and Rift.

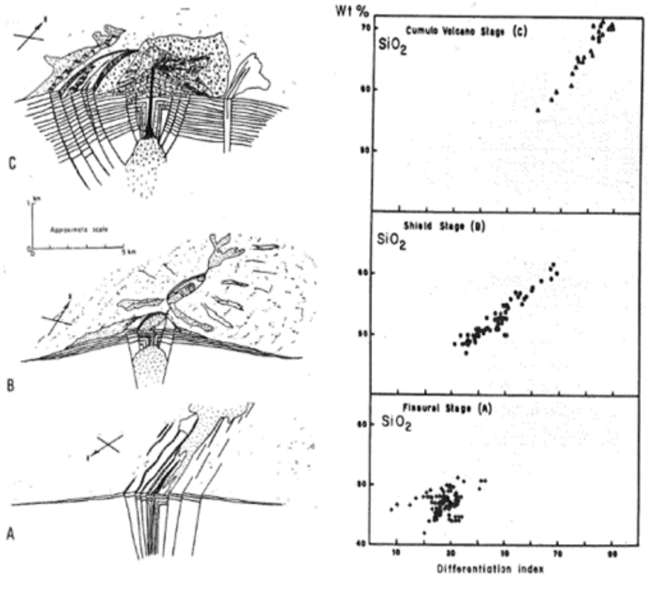

Figure 4: Possible evolution of axial ranges from: A) Fissural stage with rift-in-rift structure, characterized by more recent dyking and basaltic flow emissions only along the axis, to B) shield vo1cano with lava lake, with magma evolution towards iron rich trachytes by crystal fractionation of plagioclases mainly, up to eventually C) small topping central volcanoes silica-rich end-members (commendites) at the final stage when superficial magma chambers develop. The Asal range reached stage B but was subject to later rifting episodes due to intense extensional faulting (this volume). The Manda-Inakir range is left at stage 1, with a motion of the axis from south (Inakir) to north (Manda) together with a rotation of the spreading axis. The stage B was reached at Inakir, with a trachyte dome observed in the central part of the volcano.

We have shown (Varet, 1975, Barberi & Varet, 1977) that these axial ranges can be considered as the present surface expression of the Afro-Arabian plate boundaries (see Figure 3). More recent geophysical studies have confirmed the presence of an uplifted anomalous (low velocity) mantle underneath these axes, the depth of which are shallower underneath the Gulf of Tadjoura Ridge and increases while progressing inland in Afar as shown by Vergne et al. (2012) while comparing results obtained in Asal with those obtained in Afar by Hammond et al. (2011), as shown in Figure 5. The depth of the low velocity zone marking the bottom of the lithosphere averages 20 - 26km in Afar under the stratoid series is l5km deep under the Manda-Inakir range, l0km under Asal Rift, and even at a shallower depth underneath the Gulf of Tadjoura (Hebert, 2008, Figure 6).

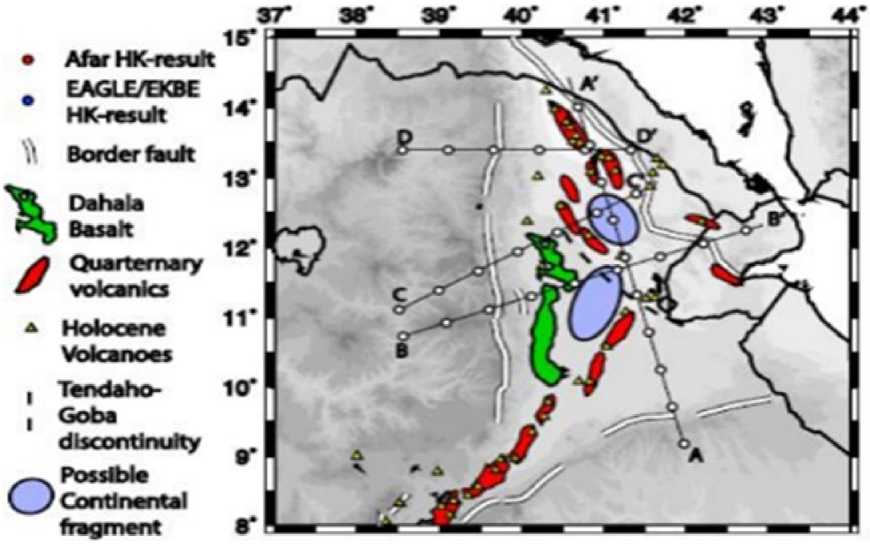

Figure 5: Deep profiles of the Afar lithosphere through axial ranges (in red), stratoid series and older Dahale basalts in Ethiopia (equivalent to Dahlain Djibouti) obtained by Hammond et al (2011).

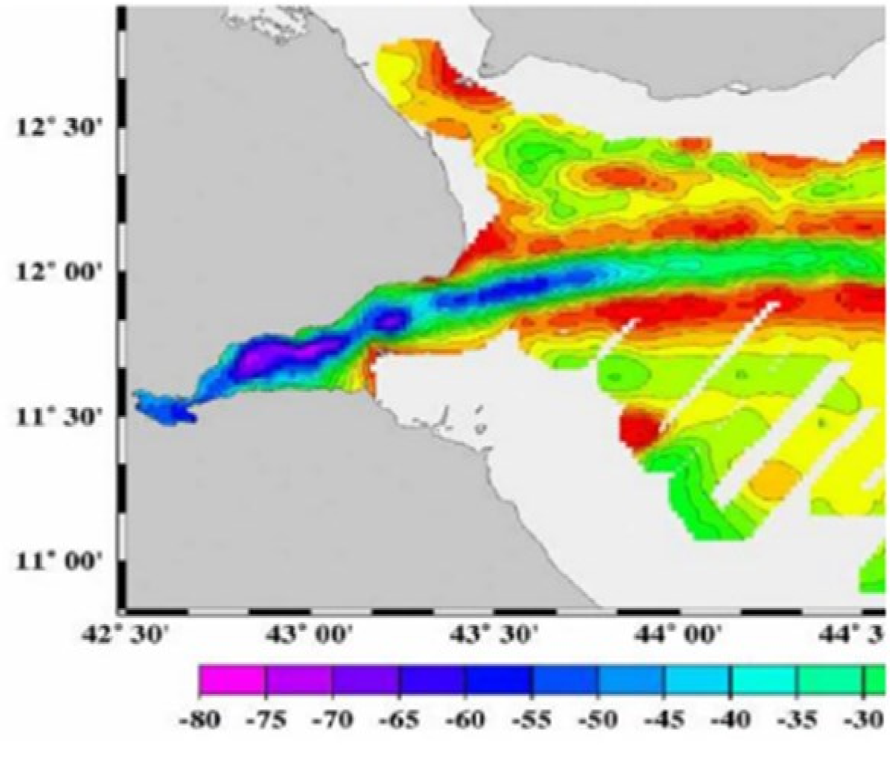

Figure 6: Free air Bouguer anomaly map (from Hebert, 2008).

The uplift of the anomalous, hot mantle (around l300°C) should provide a thermal gradient of l30°C per km at Asal and along the Tadjoura Ridge, that is, appropriate heat source conditions for high enthalpy geothermal power production (300°C at 2000m with a 40°C surface temperature, in good agreement with the results from the average deep wells results). At Manda-Inakir, the same calculation provides a gradient of 81°C per km, that is, 200°C at 2000m, an interestingly high enthalpy objective. Note that, in addition to this, one should add the effect of diking and the eventual presence of magma chambers at shallower depth, which should provide even higher temperature gradients along the axial range axis. At Asal, the identification of a magma chamber at 5 or even 2km depth under the Fiale Caldera (Vergne et al., 2012, Figure 7) would provide supercritical fluids at only 1 km depth. Very high temperature gradients were observed in the upper part of the A5 well located near to Fiale Caldera, consistent with such magmatic shallow magmatic sources (Figure 8). If we note that the A5 well was drilled prior to the major magma injection episode of Fiale Caldera, one should expect such hyper-thermal conditions to occur in the Fiale site retained for the next drilling phase to be carried out under the World Bank's leadership.

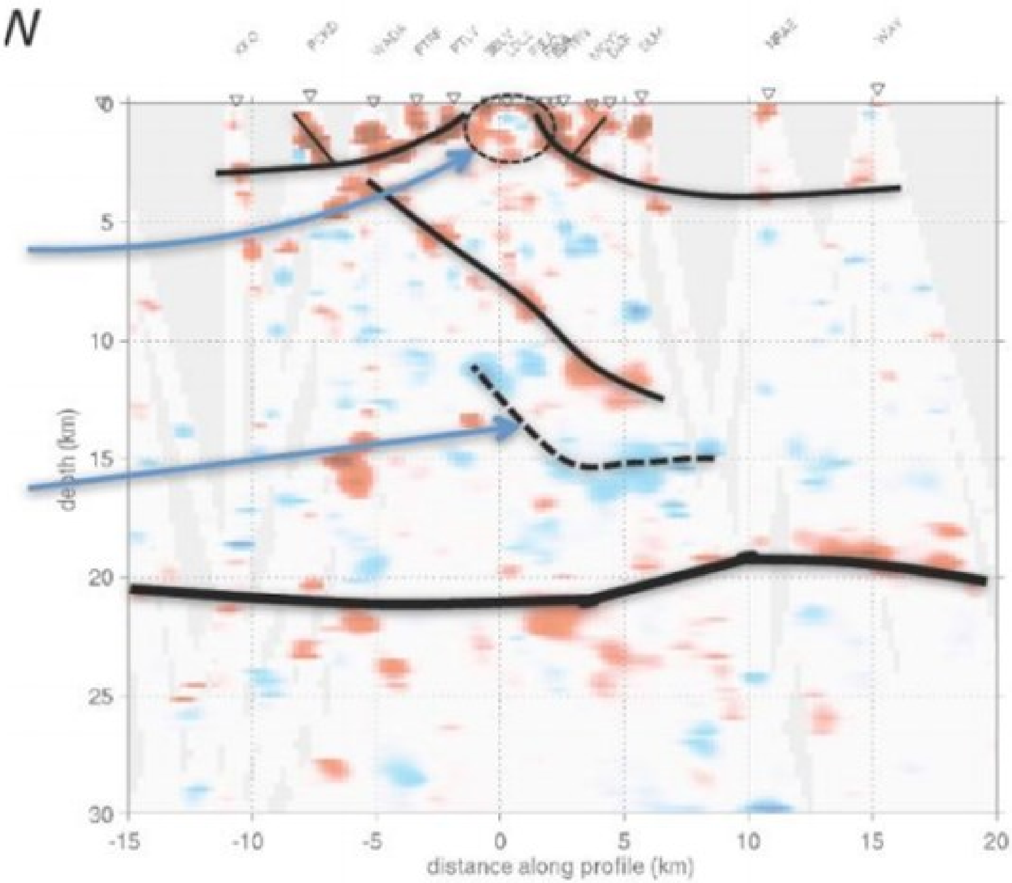

Figure 7: Seismic section showing low velocity zones (in red) across the Asal Rift (Vergne et al. 2012). The presence of a magma chamber at a depth of 2km is inferred under Fiale Caldera.

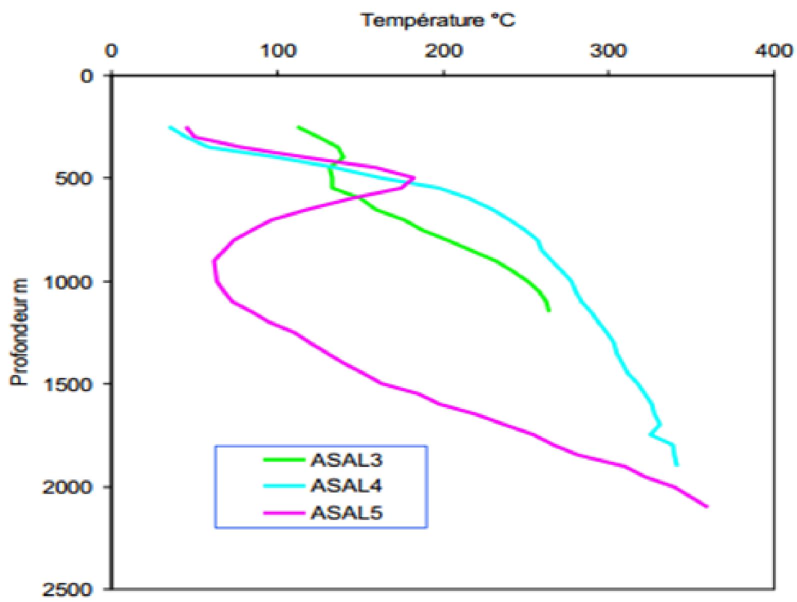

Figure 8: Thermal profiles for deep geothermal wells A3 to A5 (from Jaludin, 2010). The temperature gradient in the 250-500 m interval observed for A5 would fit with a basaltic magma chamber at 1200°C located at 2000 m depth in a conductive model in the absence of cold sea water circulation.

In the area covered by the stratoid series, that is the faulted zones with rift-and-graben structures found in central-and south-western part of Djibouti Republic, the average thickness of the lithosphere of 20-26 Km display less favorable conditions.

1.2 Non Magmatic Heat Sources

Considering the characteristics of the lithosphere outside the active spreading segments, averaging 20 - 26km depth, and the lack of recent volcanic products outside these areas, geothermal high enthalpy systems can be considered only if resulting from non-volcanic, active hydrothermal systems. Such systems may of course develop in the context of Afar, notably due to the transverse fault systems resulting from unexpressed transform faults.

Looking at the general seismicity (Figure 1) as well as at more precise and recent seismic history map (Figure 9), one can observe that the area located between the northern extreme of the Asal Rift segment and the active Manda-Harraro Rift segment in Ethiopia is at present subject to a more important seismic activity than the Makarassou Transform Fault and Mandalnakir Range. One can note that the fumaroles and hydrothermally altered zones appear as more frequent in these seismically active sites. This preliminary observation should of course be confirmed by further and more detailed work on these active sites.

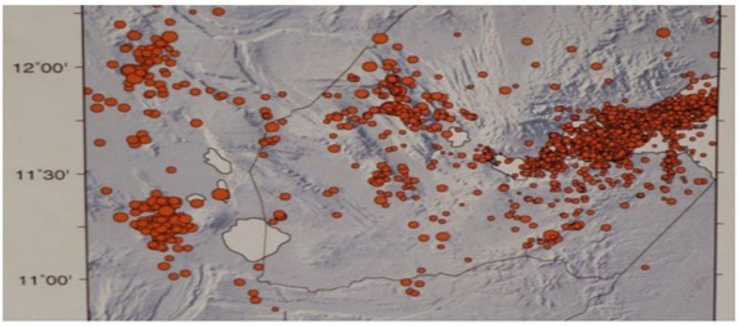

Figure 9: Map of the recent seismic activity in the Djibouti Republic and adjacent regions. Note the important activity in the gulf of Tadjoura, at Asal-Fiale and in the horst structures NW and W from Asal axial range.

Note also that one of the wells drilled for water production at Karapti San, a village located in the seismically active area at NE of Asal (Figure 10), showed high temperature but drilling had to be abandoned due to lack of proper instruments (temperature measurements and BOP).

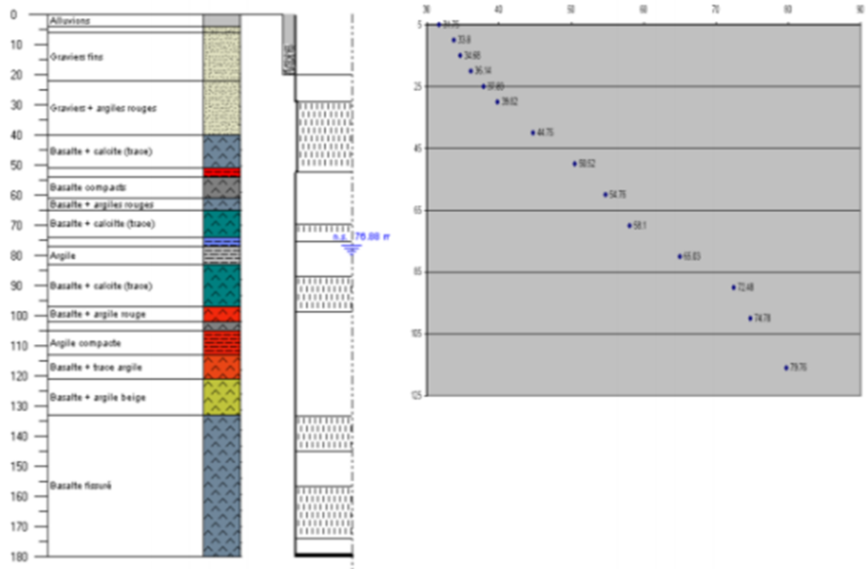

Figure 10: Geological and temperature log of well drilled at Karapti San, a village located in the northern extension of the Asal graben. A temperature of more than 80°C was observed at a depth of 120m, and the drilling was stopped at 180m, with no possibility to undertake other temperature measurements due to the limitation of the instruments and rig facilities (from Said Kaireh, water division, MEERN).

1.3 The Graben Resource Illusion

A point should be stressed here, that is the idea which prevailed in the 1980s, that graben structures affecting the stratoid series in Afar are suitable targets for the development of geothermal systems. This strategy was developed by Aquater both in Ethiopia (Tendaho graben) and in the Hanlé graben in Djibouti. The experience did show that such targets may not be appropriate. Such sites generally do not benefit from active magmatic heat source. Moreover, the sinking of the block may even provide thicker crustal conditions and hence lower geothermal gradients than the nearby horsts.

In fact, from the magma source point of view, one can observe that the differentiated rhyolitic products at the terminal phase of the stratoid series are rather located in the horst structures, as shown in the case of Baba-Alou volcano between the Hanlé and Gaggadé grabens. Although several hundred thousand years old, these are the most recent magmatic expression in the stratoid series, and may have kept some hydrothermal resources at depth due to the presence of large magma chambers, expected to have operated for a long period in order to develop such abundant differentiated materials.

And considering the hydrogeological conditions, it appears that water circulation may be important in some of the permeable layers of the sedimentary infilling. In the case of Hanlé, the very low gradient in the sediments was interpreted to be as a result of ground-water circulation from the Awash River Basin. And in the case of Tendaho, temperature inversions in some wells drilled in the middle of the sedimentary plain seem to indicate that such circulations also occur, and that the heat source is not located in the graben itself.

For these reasons, while 100 king for sites appropriate for geothermal development in the horst-and-graben structures of the stratoid series, we would rather recommend that focus is directed to the sites where complex faulting (with transverse faults as well as normal faults) coincide with active hydrothermal systems as well as with the vicinity of central differentiated volcanoes topping the stratoid series.

2. THE RESERVOIR ISSUE: FRACTURING BY ACTIVE FAULTING IN MULTIPLE TECTONIC ENVIRONMENT

2.1 Fracture Zone in-between Spreading Segments

In previous papers presented by one of us in the ARGEO conferences (J.Varet, 2006, 2010), the thesis was developed that, while looking for suitable sites for high enthalpy geothermal development, priority should be given to the Afar areas where the axis of the axial ranges cross with the transverse fracture zones. Moreover, where the presence of hydrothermal manifestations confirms the presence of a nearby geothermal reservoir.

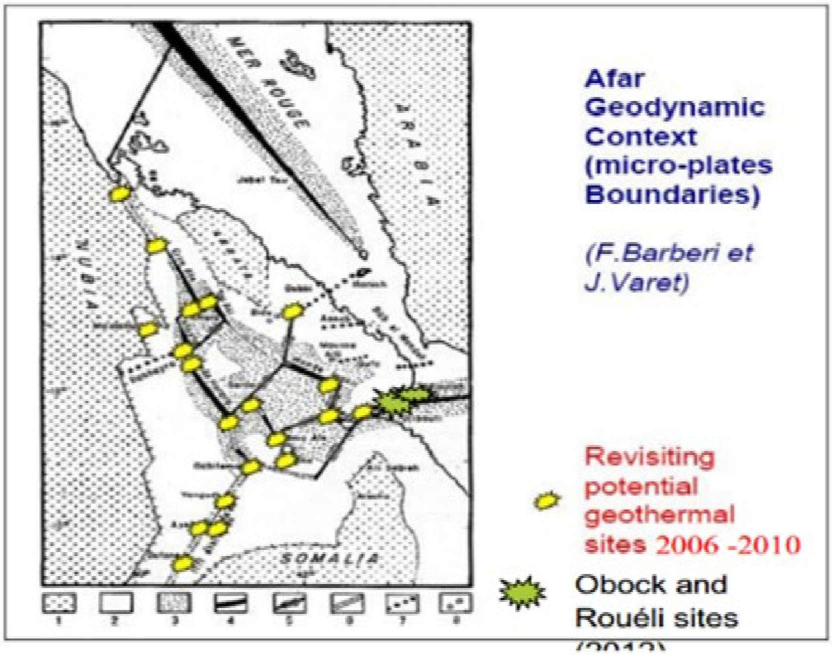

Figure 11: Proposal for geothermal sites identification in Afar on the basis of volcano-tectonic considerations (after J.Varet, 2006, 2010). The most efficient heat sources should be looked for along the active axial range, preferably at the extremity where normal and open faults cross. With transverse faults, central active volcanoes with calderas also represent suitable targets, notably along Afar margins and in the main Ethiopian rift. At that time, the idea of also 100 king for sites along the gulf of Tadjoura was not yet considered, but the same reasoning applies in recommending geothermal exploration in Obock and Roueli sites where transverse faults cross with normal faults whereas the oceanic ridge heat source is near to the coast.

2.2 Active Faulting Outside Axial and Fracture Zones

Whereas active micro-plate boundaries could be identified in Afar (Barberi and Varet, 1977), it immediately appeared that the movements do not concentrate on these linear structures only. First of all, these are not just thin lines, as classically reported from oceanic bottom structures, but always imply a certain width (a few kilometers large). Besides this, it is clear that outside these lines, the general crust in Afar is almost everywhere affected by normal faulting, with horst and graben as well as "bookshelf faulting", as shown by Black et al (1973) and Manignetti et al. (2001).

In the case of Garabbayis hydrothermal system, we could show (this volume) that the thermal activity (fumaroles, hot ground and hydrothermal deposits) develops along a transverse fracture located in the horst between Hanlé and Gaggadé plains, on the southern flank of Baba Alou rhyolitic massif, at a place in which the whole horst is broken allowing the fracture to leak hydrothermal fluids. It may well be that this active structure started being active several hundred thousand years ago at a time when the volcanic products were erupted, playing a role in the location of the central volcano having differentiated these pretty important final products in a long-lasting magma chamber. In this case, the hydrothermal activity may not be just of tectonic origin, but could also be the final hydrothermal stage of a past magmatic system still cooling underneath the Baba Alou old volcano. Preliminary gas geochemical indications - to be confirmed by further sampling and analysis could help in confirming this hypothesis.

2.3 Block Deformation Under Rotation

An efficient means for developing intense and complex faulting favorable for the development of fractured geothermal reservoirs is the rotation of the blocks located in-between spreading segments and transform faults. Such rotation was hypothesized by Barberi and Varet (1977) from tectonic considerations, and confirmed by Manighetti et al. (2001) from field measurements, notably paleomagnetic sampling and analysis (Figure 14).

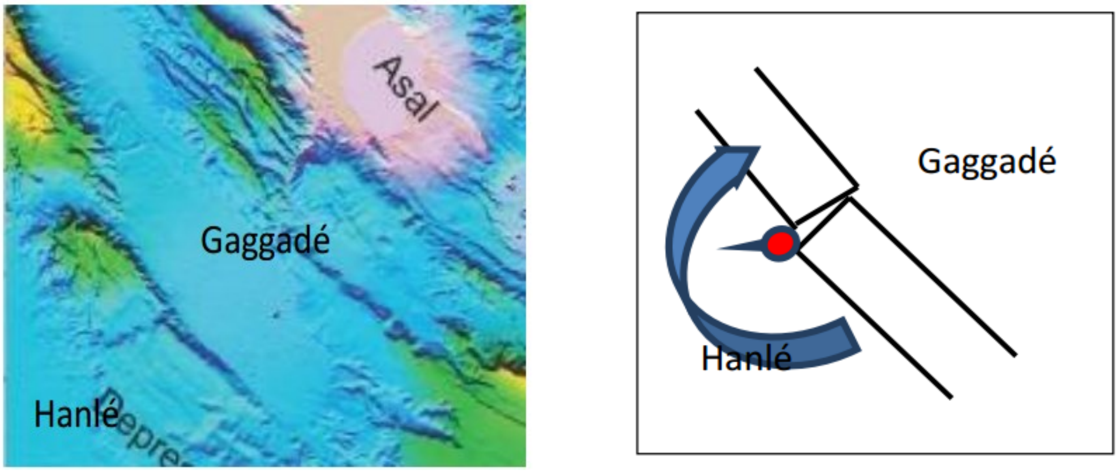

Figure 12: Schematic interpretation proposed for the presently active Garabbayis fumaroles (in red) along transverse faults opening affecting the horst south of Baba Alou between Hanlé and Gaggadé plains. This open fracture is to be linked with the rotation of the area (from Abdourahman et al., this volume)

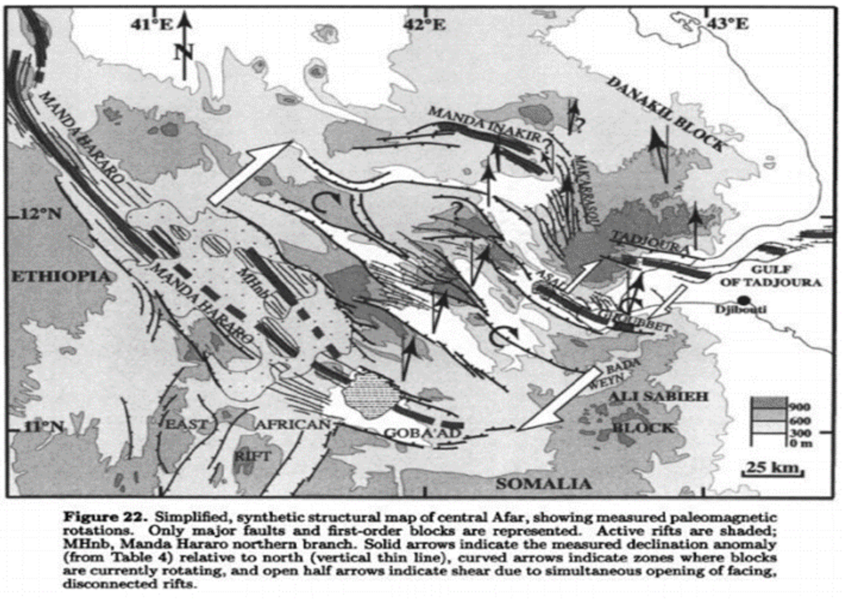

Figure 13: Simplified synthetic structural map showing the paleomagnetic rotations measured by Manighetti et al, 2001. Solid arrows indicate the measured declination anomaly relatively to north (vertical thin line), curved arrows indicate zones where blocks are currently rotating , and open half arrows indicate shear due to simultaneous opening of facing, disconnected rifts.

When occurring near to spreading segments, as in the case of Nord-Ghoubbet, the complex faulting induced by the block rotation provides particularly favorable conditions for fractured geothermal reservoir development. This case was particularly well documented using satellite image interferometry (Figure 14).

3. THE WATER ISSUE: METEORITIC, MARINE, OR BRINE WATERS IN EVAPORITIC BASINS

3.1 Endorheic Basins Dominating the Area on Land.

The Republic of Djibouti is gifted with one of the most arid climates in the world. Besides this, in the tectonic context of the Afar area, with its numerous graben structures, the low altitude favored the development of endorheic basins. Even if in past historical periods a wetter climate allowed for the development of rather large lakes, the traces of which are found in the widespread deposits (notably diatomite and lacustrine limestone). Over time, these basins accumulated elements dissolved by the meteoritic as well as hydrothermal inflows, so that evaporitic superficial crusts and interbedded layers are frequent in the bottom part of the grabens.

Although in the vicinity of the Awash River Basin, it appears that groundwater can be of low salinity (AQUATER, 1980), it is equally clear that in endorheic basins located away from this inflow, salty waters and brine dominate. This is notably the case in Asal Lake, saturated in halite, with a continuous feeding by seawater channeled through open fissures from Ghoubbet. Located between the sea influence of the Ghoubbet and the Lake Asal influence, the deep geothermal aquifer encountered in Al-A3 location displayed hyper-saline brines which posed serious problems of scaling during production tests, and would create difficult future exploitation conditions.

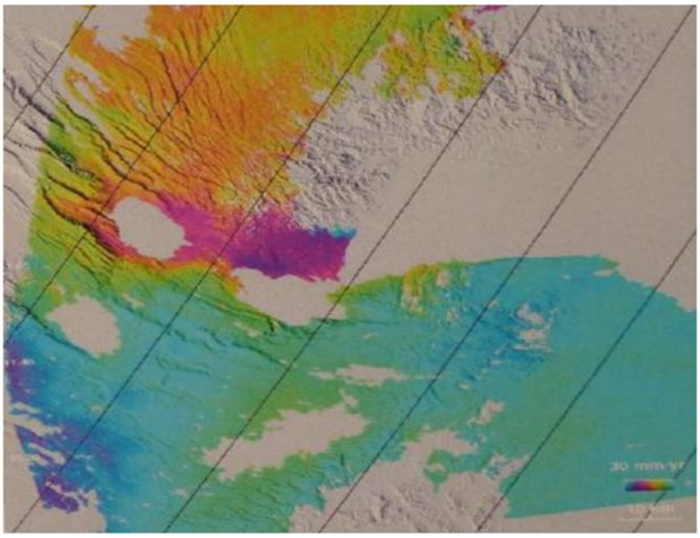

Figure 14: Deformations measured from satellites images in the central part of the Djibouti Republic, between 1997 and 2008. The most intense appear in red and violet colours, reaching 30 mm/year in the Nord-Ghoubbet block (from Doubre et al, 2012).

Therefore, looking for geothermal sites in which the meteoritic inflow may dominate in the geothermal reservoir was considered as a priority in siting future geothermal feasibility projects (J.Varet, 2010).

3.2 The Rare Cases of Meteoritic Water Feeding

A geological and hydrological study of the region helped identifying a unique area in the Republic of Djibouti in which a well-defined important heat source, as well as favorable fractured reservoir conditions, coincide with an important inflow from the nearby Day Mountain - a place which receives the most amount of rain in the country - where a relict forest could be maintained due to humid conditions. Important waddies directly flow from these elevations into the Nord-Ghoubbet Geothermal Site. The presence of good groundwater conditions is confirmed by the valuable results obtained from shallow wells drilled in the area.

The area was subjected to intense erosion due to the uplift of the Nord-Tadjoura block in the doming period preceding the gulf opening and rifting 3My ago. The combination of erosion terraces interbedded with basaltic flows - providing good formation permeability - and important faults affecting the block in several directions thus ensuring fracture permeability, provide good potential conditions in terms of water reservoir quality, even if sea water influence cannot be excluded notably in case of well location in the vicinity of the coast.

In the case of Manda-Inakir, the plains located on the eastem side of the rift axis affected by both normal and open faults as well as transverse faults of the Makarassou, appears equally favorable in terms of water quality due to the wide basaltic plateau of the Dalha formation dipping NW, and the smaller inflow from Moussa Ali volcano southern flank. The area is, however, located far away from the present consumptions centers and the geothermal objective would rather be to supply the needs of the surrounding villages.

In the case of Arta, from recent study and research, it was proven that the southern short of the gulf of Tadjoura and west from Djibouti was identified as significant or near past hydrothermal activity. The area has few fumaroles that are active and, in some cases, much altered. The geochemical studies in the area proved two chemical types, alkaline-bicarbonated groundwater that takes its recharge from the wadis bed, and alkaline-chlorine from shallow wells, related to the bed rock underlaying.

There is a slight connection with fresh sea water that recharges the magma in high temperature from 75 to 95ºC. This result was demonstrated in the country (bough 2006; Jalludin et al. 2006). Knowing also that the area has mostly formations that represent Miocene of Dalha basalt, Mabla Rhyolites, and finally with alteration of stratoid basalts with the Gulf basalt.

The Geophysical anomaly that was identified with gravimetry and electric survey delineates some area with positive anomaly that represents a rhyolite dome such as the fumarole Qiqleh that are on top of them. The main fracture trends from NE-SW and the conductivity from the sounding show several hundred meters thick conductive layer. It was proven that the area has a feeding zone by the Dalha basalts that constitute a highly altered volcanic rock and has a cap rock with relatively high thickness.

Perhaps to realize the idea of a geothermal field as it was mentioned in Geothermica (1982), it is most likely to drill a deep shallow borehole in order to cover the possible cap area of the geothermal reservoir. This area possibly also has a fresh water and sea water zone that has a better potential recharge than the Asal area.

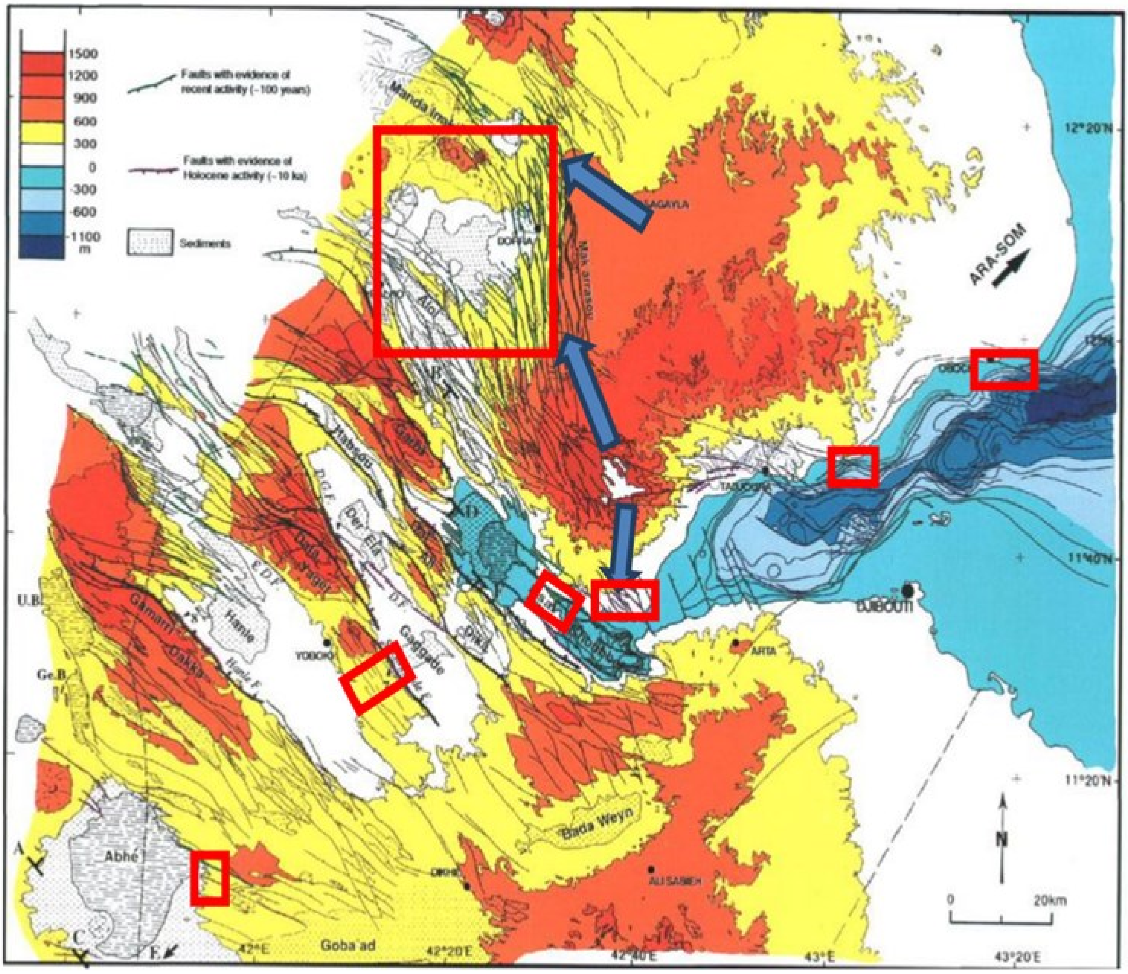

Figure 15: The meteoritic water feeding the geothermal sites of Nord-Ghoubbet and Manda-Inakir, on a topographic and bathymetric base map with major tectonic structures from Mainighetti et al (2001), AH the sites mentioned in this paper are reported with a red quadrangle.

The Abhé site is in a particular situation. Located in an area of low pluviosity and intense evaporation, it is fed by the water from Lake Abhé, itself the ultimate site of the A wash endorheic basin. It will, therefore, display good water recharge, from continental origin. But this site poses other unsolved questions, the most intriguing being the heat source, as the nearest volcanic unit, Dama Ale central volcano, is located on the opposite side of the lake, in Ethiopia, and its thermal influence is far from being evident. It may well be that the thermal manifestations are controlled tectonically only, i.e., no resource of high enthalpy, but rather hot water ascending through normal faults affecting the eastem side of the lake (Figure 15)

3.3 Sea Water Influence Along the Gulf

The geothermal sites identified along the Gulf of Tadjoura with the intention of drilling deviated wells from the coast in order to tap the geothermal fluid located in fractured reservoir fed by heat from the oceanic ridge (Abdourahman et al. this volume) would certainly be fed by sea water fluid, although marginal inflow from the continent cannot be excluded. Such fluids should not pose very difficult problems for exploitation, at least in terms of the medium and high temperature objectives. Of course, when developing future supercritical fluid exploration and exploitation, more aggressive conditions should be expected, with brines enriched in silica and metallic sulphides.

4. THE SYNTHESIS: A FIRST QUALITATIVE HYERACHY OF GEOTHERMAL SITES

From this logical overview of the potential geothermal resource of the Republic of Djibouti, two contracting types of development can be considered from the resources point of view:

- Classic high enthalpy sites located on land and offshore, aimed at serving the present or future electric grid, from eventually large thermal power units; and

- Smaller medium enthalpy development using ORC technologies on non-magmatic hydrothermal sites linked with fracture systems affecting the stratoid series.

4.1 Classic High Enthalpy Fields Along Ridge On land and Offshore, Serving the Present or Future Electric Grid

We have the following sites, from east to west along the ridge axis: Obock, Rouéli, Nord-Ghoubbet, Asal and Manadalnakir

In terms of magmatic heat source proximity at depth, the order is:

1) Asal
2) Nord-Ghoubhet
3) Rouéli
4) Arta
5) Obock

In terms of permeability:

1) Nord-Ghoubbet
2) Mandalnakir
3) Arta
4) Asal
5) Rouéli
6) Obock

In terms of knowledge of the geothermal field:

1) Asal
2) Nord-Ghoubbet
3) Rouéli
4) Obock
5) Arta
6) Mandalnakir

In terms of water quality in the reservoir, the score is the following:

1) Nord-Ghoubbet
2) Mandalnakir
3) Arta
4) Rouéli
5) Obock
6) Asal

In terms of the potential size of the site (in MWe):

1) Asal
2) Nord-Ghoubbet
3) Mandalnakir
4) Arta
5) Obock
6) Rouéli

In terms of proximity and importance of the demand:

1) Asal
2) Nord-Ghoubbet
3) Arta
4) Rouéli
5) Obock
6) Mandalnakir

As a whole, Table 1 presents the respective scoring of these sites in light of these various criteria:

Table 1: Scoring of sites for high enthalpy development in Djibouti Republic

Geothermal site along the ridge	Heat source	Permeability	Water recharge quality	Potential size of the site	Geothermal knowledge	Demand size grid proximity
Asal	+++	+	-	++	+++	+++
N-Ghoubbet	++	+++	+++	+++	++	++
Rouéli	++	++	+	+	+	+
Obock	++	++	+	+	-	-
Manda-Inakir	++	++	++	+	-	-
Arta	++	+++	++	+	+	++

4.2 Local opportunities for medium enthalpy ORC plants answering local needs

ORC plants can be developed in several sites, the size of which will depend on:

- The quality of the site
- The importance of the local demand

In this respect, some of the sites placed in the first category, i.e., suitable for eventual important high enthalpy development could justify the installation in a first step of a small-size medium enthalpy plant only due to the limited demand at present. In a few cases, the local demand may just be fed by the binary plant, due to the limitation of the resource parameters.

In the places located outside the above mentioned set, we have described in this paper one interesting site, due to the local demand, and its limited but still attractive potential, that is Garabbayis answering the need of development axis of Dikhil-Yoboki.

The Abhé site could be a significant site in size, but limited in terms of temperature to ORC technologies. However, due to the agricultural potential of the area, other direct applications of the geothermal fluid could be developed (drying, fish farming, cooling).

Besides those two places, several other sites are certainly suitable for small-size ORC medium enthalpy units exploiting local hydrothermal manifestations in response to local demand. We have seen several such sites during our first exploration work developed in this respect in the north-western part of the Republic. Such potential sites are notably encountered north-east of Asal along the major fault lines crossing transverse faults. We mentioned the case of Karapti San, where a water well already met such conditions, but several other sites certainly exist in the area as well as in the populated Allol and Sakalol sites to the north and Gaggadé to the east. There is a need for further exploration specifically for this purpose, combining the location of the villages and population concentrations in comparison to the fumaroles and thermal emergences related to transverse faulting systems. It may well be that up to 10 such sites could be identified. Table 2 tries to synthetize these present views by combining all site characteristics.

The Arta site could also be a significant site in terms of heating, electricity and heating water as it is close to the major small city of Arta. It has a huge advantage for the grid as it will be easier to attach the power plan directly to the main major grid that comes from the south.

5. CONCLUSION: TOWARDS A LONG TERM NATIONAL STRATEGY FOR GEOTHERMAL DEVELOPMENT

From the methodology proposed in this paper, it would be possible, after consultation with other experts, and complementary fieldwork, to develop a sound strategy for geothermal development in the country. This should of course, in addition to the improvement of the knowledge of the sites, also rely on a better approach of the appropriate technologies, adapting the costs of the exploration and drillings to the targeted size of the site. Moreover, the study should be carried with a prospective view of the evolution of the demand, not only resulting from standards figures already available concerning the Djibouti capital and port, but also considering the future development axis (for example, the Makalé-Tadjoura railway line and induced development). The attractiveness the Djibouti Republic for foreign industrial investments due to the potential located along the northern coast of the Gulf of Tadjoura (as in Iceland) for aluminum plant developments along the coasts of the Reyjanes peninsula should also be taken into account.

Table 2: First attempt to establish a hierarchy of potential geothermal sites of Djibouti Republic for development planning according to local geothermal potential and considering present and future demand (a base for discussion with experts, to be completed)

Geothermal site	Enthalpy	Future demand type	Present needs	Potential size of the site	Geothermal knowledge	Size order (short term)
Asal	High	High (grid)	50MW	Large	+++	50 MW 2016
N-Ghoubbet	High	High (grid)	Be prepared	Very large	++	50 MW 2020
Rouéli	High	Future high	Medium	Large	+	2 MW 2018
Manda-Inakir	High	Small	Small	Large	-	1 MW 2015
Obock	High	Future high	Small	Large	-	5 MW 2015
Abhé	Medium	Small	Small	Medium	++	1 MW 2015
Garabbayis	Medium	Medium	Medium	Small	+	1 MW 2015
Karapti San	Medium	Small	Small	Small	+	1 MW 2015
Balho	Medium	Small	Small	Small	-	1 MW 2015
Site to be Identified (W)	Medium	Small	Small	Small	-	1 MW 2020 Up to 10

REFERENCES

Abdallah A. Gérard, A., Varet, J.: Construction d'un modèle synthétique du champ géothermique d'Asal. BRGM/82-SDN-95l-GTH 25p. 10 cartes (1982) AQUATER: Geothermal exploration project. Republic of Djibouti. Final Report.ISERST.159p. (1989).

Barberi F., Borsi S., Ferrara G. Marinelli G., Varet J.:

Relationships between tectonics and magmatology of the Northern Afar (or Danakil) depression. Symp. Royal Soc., March, 1969, Philos. Trans. Royal Soc. London. A 267(1970)293-311

Barberi F., Ferrara G., Santacroce R. and Varet J.:

Structural evolution of the Afar triple junction. Afar Depression of Ethiopia, Bad Bergzarben, Germany, April 1-6 1974. A Pilger and A Rösler, 1 (1975) 38- 54.

Barberi F. & Varet J.: Volcanism of Afar: small scale plate tectonics implication. Bull. Géol. Soc. Amer.88 (1977) 1251-1266.

BRGM: Reconnaissance géothermique du TF AL BRGMI70-SGN-GTM. 59p. (1970)

BRGM: Territories Français des Afars et des Issas: rapport de fin de sondage, interprétation des données géologiques de Asal 1 et Asal 2. BRGM75-SGN- 443-GTH 19p. (1975)

BRGM: République de Djibouti, champ géothermique d'Asal: synthèse des données disponibles au 1er juin 1980. BRGM80-SGN-525-GTH42p. (1980)

CFG: Champ géothermique d'Asal. Djibouti. Synthèse des données. 93CFG06. 87p. (1993)

Correia, H., Demange, J., Fabriol, R., Gérard, A., Varet, J.: Champ géothermique d'Asal. Synthèse des données disponibles au 1er janvier 1983. BRGM/83- SGN-022-GTH. 7lp. 10 cartes. (1983)

Dauteuil, O., Huchon, P., Quemeneur, F., Souriot, T.: Propagation of an oblique spreading centre: the west Gulf of Aden. Tectonophysics332 (200l) 423- 442.

De Chabalier J-B. & Avouac J-Ph.: Kinematics of the Asal Rift (Djibouti) determined from the deformation of Fiale volcano. Science265 (1994) 1677-1681

Doubre C., Manighetti L, Dorbath L, Dorbath C., Bertil D., Delmond J.C.: Crustal structure and magmatotectonic process in an active rift (Asal-Ghoubbet, Afar, East Africa): 2. Insights from the 23-year recording of seismicity since the last rifting event. J. Geoph. Res. l2B05406 1029(2007) 32p.

Doubre C. & PeltzerG. Fluid-controlled faulting process in the Asal Rift, Djibouti, from 8 yr of radar interferometry observations. Geology35 (2007) 69- 72.

Hammond J.O.S, Kendall J.-M., Stuart G.W., Keir E., Ebinger C., Ayele A, Belachew M.: The nature of the crust beneath Afar triple junction: Evidence from receiver functions. Amer. Geophys. Union, G3-l2 (2011) 24p.

Hebert H. Thèse, Université Paris-Diderot (1998) Hjartarson, G., Gisladottir, V., Gislason, G., Olafsson, K.:

Geothermal Developenmt in the Assal Area, Djibouti. Proceedings World Geothermal Congress, Bali, 8p. (2010)

Jalludin M.: Synthèse sur le réservoir géothermique superficiel du rift d'Asal. Rapport CERD. (1992)

Jalludin M.: Interprétation des essais de production et des essais hydrodynamiques sur les forages géothermiques du rift d'Asal. Rapport CERD, 47 p. (1996)

Jalludin M.: An overview of the geothermal prospections in the Republic of Djibouti. Results and perspectives. Kengen geothermal conference, Nairobi (2003)

Manighetti, L, Tapponnier, P., Gillot, Y., Jacques, E., Courtillot, V., Armijo, R., Ruegg, J.C. and King, G.:

Propagation of rifting along the Arabia-Somalia plate boundary Into Afar. J. Geoph. Res.103 (1998) 4947-4974

Manighetti, L, P. Tapponnier.V. Courtillot.Y. Gallet, E.

Jacques, and Y. Gillot: Strain transfer between disconnected, propagating rifts in Afar, J. Geophys. Res. 106 (2001) l3, 6l3- l3, 665.

Marinelli G. et Varet J.: Structure et évolution du Sud du"horst Danakil" (TFAI et Ethiopie). C.R. Acad. Sci.D 276(1973) 1119-1122.

Richard, o. et Varet, J.: Study of the transition from a deep oceanic to emerged rift zone: Gulf of Tadjoura, République de Djibouti. Int. Symp. Geodyn.Evols. Afro-Arabian System, Roma (1979)

L. Stieltjes: Carte géologique du rift d'Asal, République de Djibouti, Afar, East Africa, CNRS, Paris, BRGM, Orléans (1980)

Tapponnier P. et Varet J.: La zone de Makarassou en Afar: un équivalent émergé des "failles transformantes" océaniques. C.R. Acad. Sc. ParisD- 278 (1974) 209-212

Tazieff H., Barberi F., Giglia G., Varet J.: Tectonic significance of the Afar (or Danakil) depression. Nature235 (1972) 144-147.

Varet J.: Carte géologique de l'Afar central et méridional, CNR-CNRS, 1/500 000 Géotechnip (1975)

Varet J.: L'Afar, un "point chaud" de la géophysique. La Recherche, 62(1975) 1018-1026

Varet, J.: Geology of central and southem Afar (Ethiopia and Djibouti Republic), 1/500.000 map and l24p. report, CNRS, Paris (1978

Varet J.: Contribution to favorable geothermal site selection in the Afar triangle, Argeo Meeting, Djibouti, l7p. (201O)

Vergne J., Doubre C., Mohamed K., Dujardin A., LeroyS: The lithospheric structure beneath mature continental rifts: New insights from a dense seismic profile across the Asal-Ghoubbet Rift (Djibouti). Addis Ababa Afar Rift Symposium, (2012) Jalludin M: State of Knowledge of the Geothermal Provinces of the Republic of Djibouti., Presented at Short Course VII on Exploration for Geothermal Resources, organized by Unu-gtp, gdc, and Kengen, 27 – Nov. 18, 2012 Geothermica (1982). Evaluation of Geothermal resources of the Arta region. Prefeasibility study. Final Report, 14p

Bouh H. 2006. Etude de l´aquifêre des basalts du Golfe et des aquifers adjacents (République de Djibouti). Approche Hydrochimique et Isotopique. Thèse de Doctorat, Université de Paris Sud, p; 117