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Proposal for New Geothermal Models and Sites Hierarchy in Djibouti Republic

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ABSTRACT

An update of available geological geochemical and geophysical data, together with new field works undertaken by the Ministry of Energy, Water and Mineral Resources of the Djibouti Republic have allowed for an attempt to propose new geothermal models for several sites identified for their geothermal potential from previous general surveys and specific studies. 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 the central and south-western part of the Republic of Djibouti.

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 and Obock.
- The geothermal systems relying on 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 that 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, as is the case in Asal, Obock and MandaInakir, or result from transverse faulting with the eventual association of block rotation, 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 from meteoritic water in MandaInakir, Abhé, or Nord-Ghoubbet, to dominant sea water component in Obock and Rouéli. Continental brines will probably dominate in other sites of endoreïc basins and strong evaporation (such as Allol-Sakhalol) which have not yet been identified as geothermal sites at present due to insufficient knowledge.

As a whole, our approach helps to provide a first hierarchy of the geothermal potential of Djibouti in terms of perspective for future power production. Ridge located sites have the best heat source and therefore the largest quantitative potentials. But transverse fracturing and block rotation will allow for development of the best reservoirs, and water composition will directly influence the costs of systems and maintenance. Of course, real quantitative figures will be possibly approached only after feasibility drilling and production tests will have been undertaken. There is also need to develop an overall prospective and strategy for the country, that the present approach, further works and confrontation of experts views will help to finalize.

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, which showg 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).

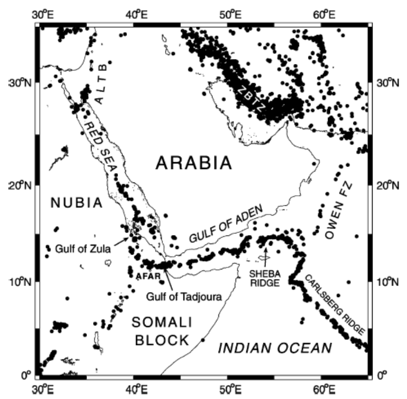

Figure 1: Seismicity (M more than 5) of the Afar region and surroundings

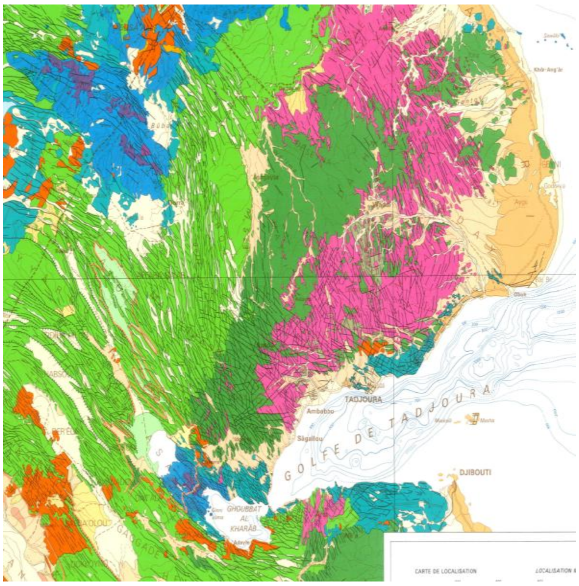

Figure 2: Abstract from the geological map of central-southern Afar (Varet, 1975) showing the active axial volcanic ranges of Asal and MandaInakir as well as the Gulf basalts (blue), and the intensively faulted stratoid series in Afar (pale green). The older Dalha basalts (dark green) covering the previously 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 cut 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)

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 in-land 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).

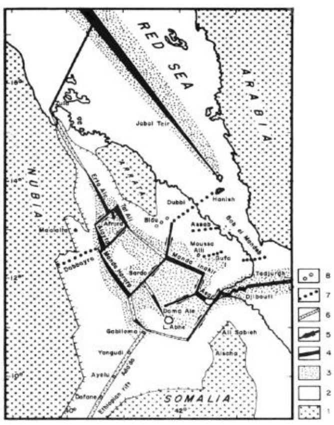

Fig 3: Reconstitution of the present Afro-Arabian plate boundaries from geological data in Afar after Barberi& Varet (1977). A succession of axial ranges, dominantly basaltic (transitional basalts) is observed from Erta Ale range in northern Afar down to Manda-Inakir and Asal ranges in Djibouti Republic, 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 volcanics 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 volcanoes of the Afar margins and Rift

Typically, 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).

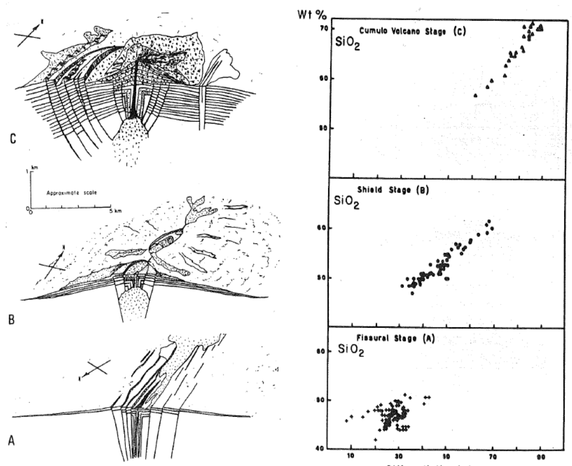

Figure 4: Possible evolution of axial ranges from: A) Fissural stage with rift-in-rift structure, characterized by more recent dyking and basaltic flow emissions only along the axis, to B) shield volcano with lava lake, with magma evolution towards iron rich trachytes by crystal fractionation of plagioclases 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 works have confirmed the presence of an uplifted anomalous (low velocity) mantle underneath these axes, the depth of which is 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 stratoidseries, is 15km deep under the Manda-Inakir range, 10km under Asal Rift, and even at a shallower depth underneath the Gulf of Tadjoura (Hebert, 2008, Figure 6).

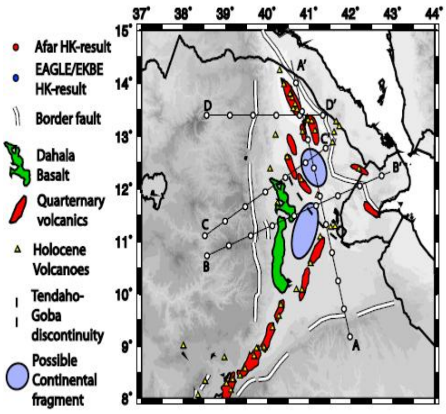

Figure 5: Deep profiles of the Afar lithosphere through axial ranges (in red), stratoid series and older Dahale basalts in Ethiopia (equivalent to Dahlain Djibouti) obtained by Hammond et al (2011).

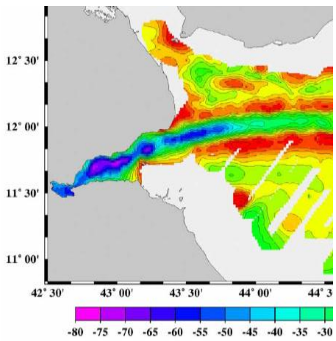

Figure 6: Free air bouguer anomaly map (from Hebert, 2008)

The uplift of the anomalous, hot mantle (around 1300°C) should provide a thermal gradient of 130°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 chamber 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 1km 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.

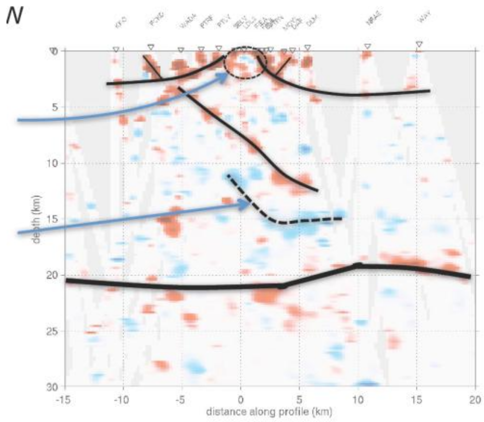

Fig.ure 7: Seismic section showing low velocity zones (in red) across the Asal Rift (Vergne et al. 2012). The presence of a magma chamber at a depth of 2km is inferred under Fiale Caldera.

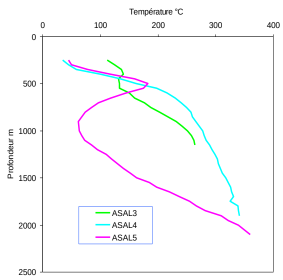

Figure 8: Thermal profiles for deep geothermal wells A3 to A5 (from Jaludin, 2010). The temperature gradient in the 250-500m interval observed for A5 would fit with a basaltic magma chamber at 1200°C located at 2000m depth in a conductive model in the absence of cold sea water circulation.

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 MandaInakir 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 more detailed works on these active sites.

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

1.3. The Graben Resource Illusion

A point should be stressed here, that is the idea, which prevailed in the years 80' 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 looking 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.

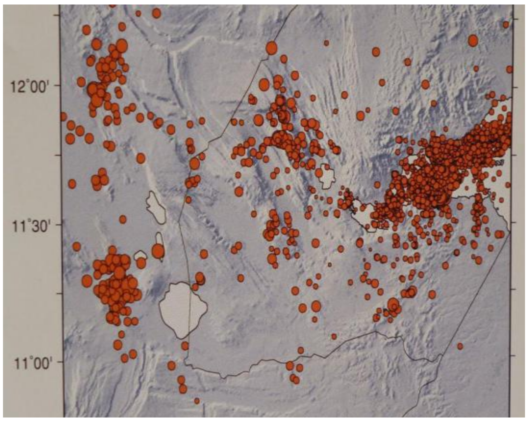

Figure 9: Map of the recent seismic activity in the Djibouti Republic and adjacent regions. Note the important activity in the gulf of Tadjoura, at Asal-Fiale and in the horst structures NW and W from Asal axial range.

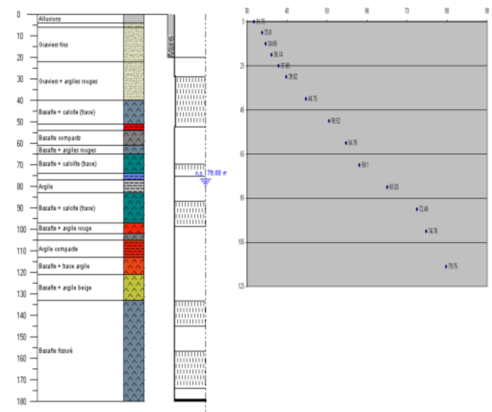

Fig. 10: Geological and temperature log of well drilled at Karapti San, a village located in the northern extension of the Asalgraben. A temperature of more than 80°C was observed at a depth of 120m, and the drilling was stopped at 180m, with no possibility to undertake other temperature measurements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

2. THE RESERVOIR ISSUE: FRACTURATION BY ACTIVE FAULTING IN MULTIPLE TECONIC 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. Notably when the presence of hydrothermal manifestations confirm the development of a nearby geothermal reservoir.

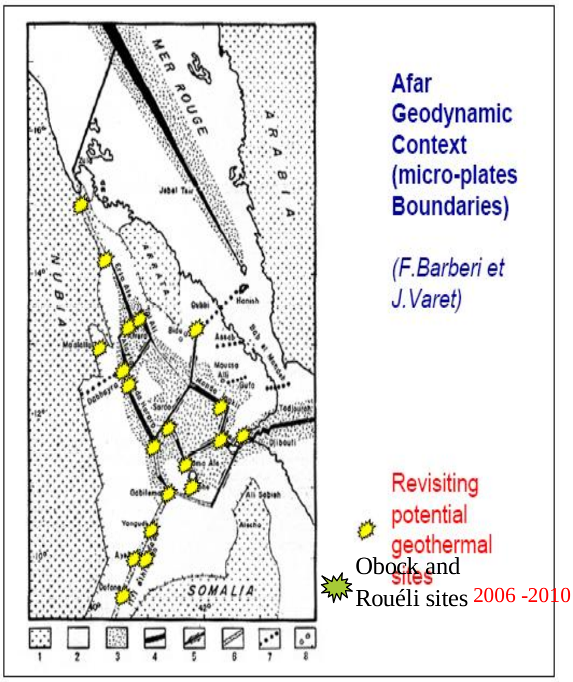

Figure 11: Proposal for geothermal sites identification in Afar on the basis of volcano-tectonic considerations (after J.Varet, 2006, 2010). The most efficient heat sources should be looked for along the active axial range, preferably at the extremity where normal and open faults cross with transverse 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 looking for sites along the gulf of Tadjoura was not yet considered, but the same reasoning apply 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 grounds 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.

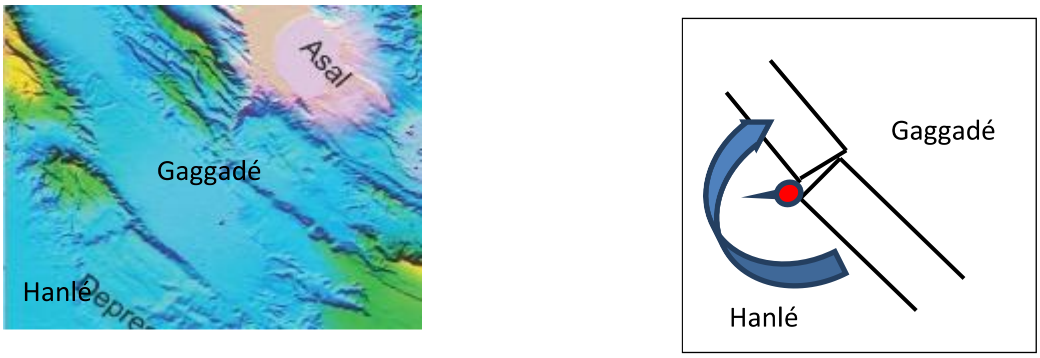

Fig.12: Schematic interpretation proposed for the presently active Garabbayis fumaroles (in red) along transverse faults opening affecting the horst south of Baba Alou between Hanlé and Gaggadé plains. This open fracture is to be linked with the rotation of the area (from Abdourahman et al., this volume)

2.3. Block Deformation Under Rotation

An efficient mean 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 were 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).

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 15).

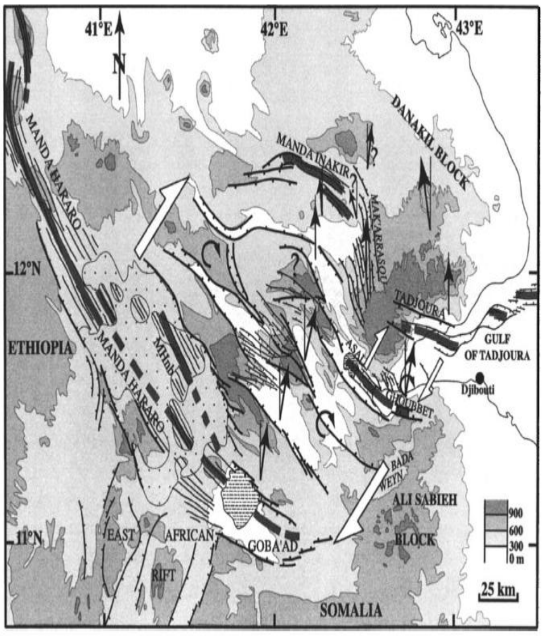

Figure 22. Simplified, synthetic structural map of central Afar, showing measured paleomagnetic rotations. Only major faults and first-order blocks are represented. Active rifts are shaded; MHnb, Manda Hararo northern branch. Solid arrows indicate the measured declination anomaly (from Table 4) relative 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.

Fig. 13: Simplified synthetic structural map showing the paleomagnetic rotations measured by Manighettti 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.

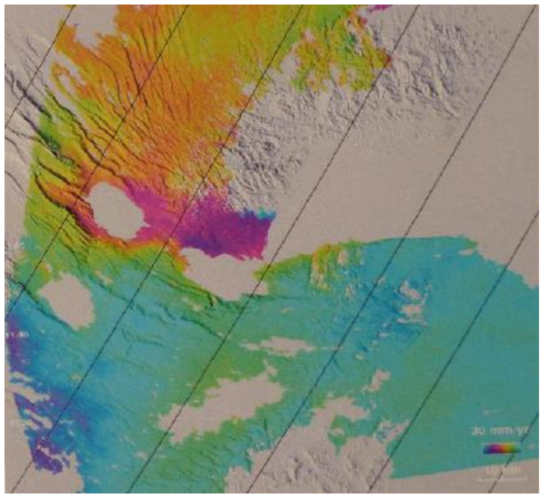

Figure 14 Deformations measured from satellites images in the central part of the Djibouti Republic, between 1997 and 2008. The most intense appear in red and violet colours, reaching 30 mm/year in the Nord-Ghoubbet block (fromDoubre et al. 2012)

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

3.1. Endoreic 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 endoreic 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). With 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 these 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 endoreic basins located away from this inflow, salty waters and brine dominate. This is notably the case in Asallake, saturated in halite, with a continuous feeding by sea-water 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 A1-A3 location displayed hyper-saline brines which posed serious problems of scaling during production texts, and would create difficult future exploitation conditions.

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 in 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 inter-bedded 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 eastern 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.

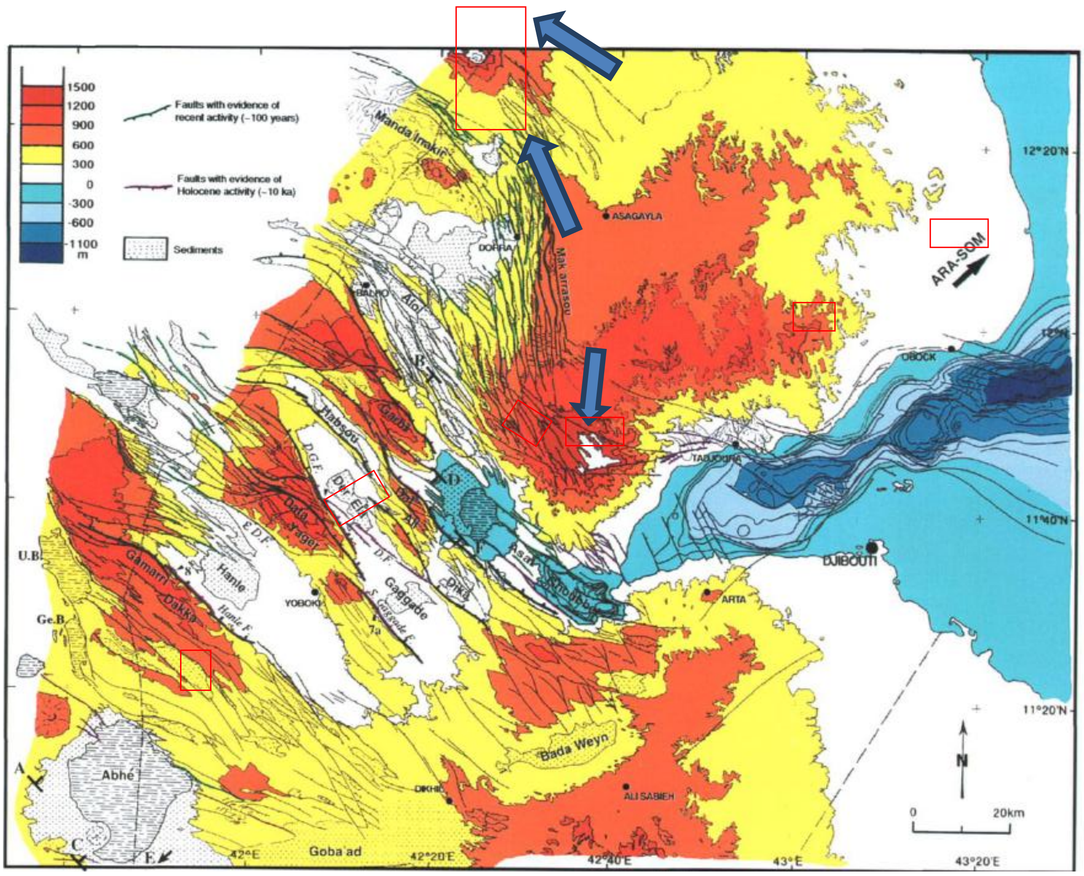

Figure 15: The meteoritic water feeding of the geothermal sites of Nord-Ghoubbet and Manda-Inakir, on a topographic and bathymetric base map with major tectonic structures from Mainighetti et al (2001). All the sites mentioned in this paper are reported with a red quadrangle.

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 Awash endoreic basin. It will therefore display a good water recharge, from continental water 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 by tectonic only, i.e. no resource of high enthalpy, but rather hot water ascending through normal faults affecting the eastern side of the lake (Figure 16)

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. SYNTHESIS: A FIRST QUALITATIVE HYERARCHY 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 ManadaInakir

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

1) Asal
2) Nord-Ghoubbet
3) MandaInakir
4) Rouéli
5) Obock

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

1) Nord-Ghoubbet
2) MandaInakir
3) Rouéli
4) Obock
5) Asal

In terms of permeability:

1) Nord-Ghoubbet
2) MandaInakir
3) Asal
4) Rouéli
5) Obock

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

1) Asal
2) Nord-Ghoubbet
3) MandaInakir
4) Obock
5) Rouéli

In terms of proximity and importance of the demand:

1) Asal
2) Nord-Ghoubbet
3) Rouéli
4) Obock
5) MandaInakir

In terms of knowledge of the geothermal field:

1) Asal
2) Nord-Ghoubbet
3) Rouéli
4) Obock
5) MandaInakir

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	++	++	++	++	-	-

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 develop (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.

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**
Obock	**High**	**Future high**	**Small**	**Large**	**-**	**5 MW 2015**
Manda-Inakir	**High**	**Small**	**Small**	**Large**	**-**	**1 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**
sites to be identified (W)	**Medium**	**Small**	**Small**	**Small**	**-**	**1 MW 2020 Up to 10**

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 field works, 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.

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