Proceedings of the 4th African Rift Geothermal Conference 2012

Nairobi, Kenya, 21-23 November 2012

The Manda-Inakir Geothermal Prospect Area, Djibouti Republic

Abrourahman Omar Haga, Said Kaireh Youssouf, Jacques Varet

Ministry of Energy, Water and Natural Resources (MEERN), Djibouti Republic

abdou_med05@yahoo.fr; bilane24@yahoo.fr; sakayou@yahoo.fr; j.varet@brgm.fr

Keywords: Geothermal, hydrothermal, fumaroles, volcanic, tectonic, fault, Djibouti, Manda-Inakir, Moussa Ali

ABSTRACT

The northern half of Djibouti Republic is made of volcanic formations of late Miocene age, with the extensive and deeply faulted Mabla Rhyolites (12 to 8 My) partly covered (western side) by the Dalha Basaltic Plateau (7 to 4 My) gently dipping towards NW. This geologic block is rather stable and appears to be a part of the Arabic Plate since oceanic spreading stopped along the Bab-El-Mandeb straight of the Red Sea and developed inside Afar for the last 3 to 4 My (Marinelli& Varet, 1973). No real high enthalpy geothermal potential is therefore expected there. On the western flank of this block however, the Dalha Plateau sinks under the more recent basalts of the stratoïd series, itself deeply faulted. Near to the triple state boundary with Ethiopia and Eritrea (Moussa Ali central volcano, of quaternary age), an active axial range called Manda-Inakir was identified (La Volpe et al. 1974). Since then, the huge N-S fault zone linking Manda-Inakir and Asal Rift segments was interpreted as the surface expression of a transform fault (Tapponier and Varet, 1974). Hence an active plate boundary crosses through the westernmost part of this region, with related geothermal heat source.

The Manda-Inakir axial range extends ENE-WSW across the boundary with Ethiopia, and displays similar volcano-tectonic behavior, as the Asal and other axial ranges. However, a shift is noticed, the most recent volcanic activity having migrated from Inakir - an elongated and rifted shield displaying the whole petrologic sequence from basalts to trachytes - to the north, in the Manda range, where historical basaltic eruptions did occur. Open fissures affecting the most recent basaltic flows and nearby sediments in the rift direction show that the extensional phenomena is still active at present. This implies that there are the benefit of both a magmatic heat source and important fracture permeability. Although the climate in the area is particularly dry, any meteoritic water concentrates in these recent volcanic lowlands and nearby sedimentary plains, and quickly infiltrates deep in the basalts due to the open faults. Part of the large hydrographic basin of the Dalha Plateau also feeds these reservoirs.

A field study undertaken by the authors identify several sites where gas vents, hot-springs and fumaroles occur, mainly located in the faulted formations surrounding the plains of Andaba and Awda'a near the villages of Dorra and further south towards Malaho and Balho. They are mostly located in sites where the NW-SE open faults cross with the N-S trending transverse faults. Suitable sites for geothermal development are hence certainly present in this district.

However, geochemical and geophysical investigations should be undertaken to enhance the location of sites for geothermal exploration wells. Although no geothermal gradient drilling has been undertaken, it is important to note that several sites drilled for water production in the area and its surroundings display high temperature gradients (up to 60°C/100m).

At present, the local consumption of electricity is very low. The nearby villages rely on small diesel engines. There is no doubt that such a local energy source would boost the demand, notably for groundwater pumping. In addition, future needs will increase due to the development of transport. An important highway is under construction and will be followed by a railway line linking Makalé, the capital of Tigré regional state in the Federal republic of Ethiopa, to the sea port of Tadjoura in the Republic of Djibouti. The modular character of power production development on geothermal sites should ,provide - once the resource have been proved by exploration drilling – a solution to these successive needs (from a few MW initially to a few ten or more if needed).

1. INTRODUCTION

Djibouti is a low-income country located in a key regional Afro-Arabic geopolitical context coupled with an exceptional geodynamic base, making it favorable for geothermal energy development. Besides covering the people's need and contributing to stabilizing the region, geothermal may also be in itself attractive for energy intensive industries. In the present paper, we describe a rather remote area, located in the Northern part of the Republic near the triple point of boundaries with Ethiopia and Eritrea. We show that the south-eastern side of the Manda-Inakir Volcanic Range – unidentified as such until now – appears to be a potentially promising zone for geothermal energy research and developments, provided it starts with the objective of covering the local needs. The aim of this paper is to provide enough evidence on the geothermal resource in that area and hence convince bilateral and/or multilateral agencies interested in the socio-economic development of the country to take advantage of and asses the geothermal potential of the northern part of the Republic.

2. SOCIO-ECONOMIC BACKGROUND

2.1 The Djibouti Republic

Djibouti Republic is presently a low income country, located in one of the most arid climatic environments. It is also located at the intersection of several major economic routes of the planet, linking the Red and Mediterranean seas with the Indian Ocean, as well as large African countries with the outside world. This original position presents a major advantage in a world-open economy and offers a real opportunity for the country to respond to the needs of the growing regional economic development.

Wide open on the Gulf of Aden at the southern end of the Red Sea, Djibouti is in a geostrategic position touching Ethiopia (over 80 million inhabitants), Eritrea (4 million) and Somalia (10 million), and in great proximity with Yemen (15 million) through the narrow Bab-El-Mandeb straight. The current population of the Republic of Djibouti is estimated at about 850 000, of which about 600 000 live in the main town of Djibouti-Ville, 95 000 in secondary towns and the remaining, 155 000 in the rural setting, including a substantial nomadic population. The country’s electrification rate is about 50%. Demand in the Djibouti-Ville area is currently supplied from two main power stations operating on fuel oil with an installed capacity of 100.3 MW.

The availability of and access to clean, adequate and low cost energy is expected to significantly contribute to economic growth, reinforce the competitiveness of the country and improve the quality of daily lives of the population thereby reducing the poverty. At present, the lack of a distribution network or even isolated generators, and the high cost of electricity in Djibouti-City and other towns makes it unaffordable to many citizens, small scale commerce and light industry. Access in the rural areas is very limited and electricity is unknown to the pastoralist population. This of course imposes triggers limited access to water - a real handicap in this arid country - where although groundwater is available it is inaccessible due to lack of power to pump it.. This is a major issue in the northern part of the Republic where the Afar tribes are nomadic but attached to defined areas.

The energy policy of the government is to diversify the primary source of energy for conversion to electricity on a commercial basis at affordable prices. At present, Djibouti has no indigenous coal, oil of gas. There is very little vegetation for the supply biomass energy and no rivers for hydro-power generation. The government’s aim is thus to develop all available alternative and renewable energy resources with a priority on geothermal resources which the country is believed to have a good potential. This is intended to be carried out with all potential partners including private sector participation for the development of the resource and the generation of electricity.

The unavailability of a reliable and adequate supply of low cost energy is viewed as the main constraint on communication, artisanal, transport, and industrial development – all determinants of economic growth and social well-being of citizens. The increasing cost of importing petroleum products not only by far surpasses the level of the negative trade balance, but import dependency also subjects the country to uncertainties arising from tensions in oil producing regions. The risk of social instability – and simply the survival of human life itself - arises from the constraint that the high cost and inadequate availability of energy imposes on the effort at sufficiently and rapidly reducing poverty.

2.2 Focus on the North - The Tadjoura District

With a population of circa 50.000 inhabitants and a surface of 8.000km^2, the wide Tadjoura prefecture is dominantly a pasture land for the nomadic Afar population. Besides Tajoudra city and port, several small cities are under development in the hinterland, notably Randa, AsaGayla, Dorra, Andaba, Balho, Manda and Karabti-San. The area also offers potential in the field of agriculture (with the populated plains of Hallol and Sakalolgrabens), tourism (with a combination of highlands, remarkable telluric sites and sea shores), fisheries and mineral resources yet to be prospected in the dominantly volcanic hinterland. A new road axis, linking northern Ethiopia (Tigray regional state) with Tadjoura and Obock seaport facilities (to be developed) is presently being built and the construction of an electric railway line is projected by the Ethiopian Railway Authority.

Apart from the city of Tadjoura, there is no real electricity supply service in the District. Even the water supply service is handicapped by the lack of energy supply, and any economic activity is limited due to this deficiency. The recent effort in terms of development of schools and rural hospitals also faces this difficulty. The development of a locally produced and mastered, renewable energy supply would definitely play a major role in eradicating poverty and stimulating social and economic development.

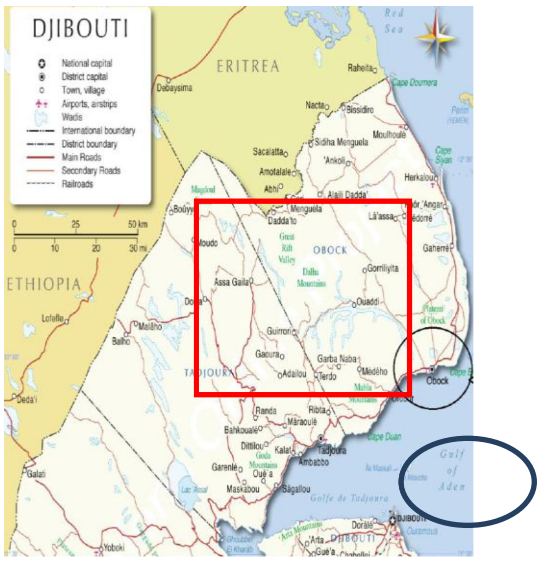

Figure 1: Simplified geographic map of the northern part of Djibouti Republic - the districts of Obock and Tadjoura. Red Square: the area studied in this paper.

3. *THE* GEOTHERMAL POTENTIAL AND THE ENRGY DEMAND IN THE AREA

3.1 A Favorable Geodynamic Context

The Djibouti Republic is located in the western corner of the Afar Triangle, in an exceptional geodynamic context in continental environments, in which a major oceanic ridge enters land and meets with an active continental rift. The Aden Ridge enters Djibouti through the Gulf of Tadjoura, extends inland through the Ghoubbat-el-Kharab and emerges along the same axis with the Asal Rift (Barberi& Varet, 1977, Richard & Varet, 1979). It then develops inland to the north though the Makarassou Transform Zone (Tapponier& Varet, 1974) with the Manda-Inakir Rift (which crosses the boundary with Ethiopia), before extending to central-western and northern Afar in Ethiopia and Eritrea (Figure 2).

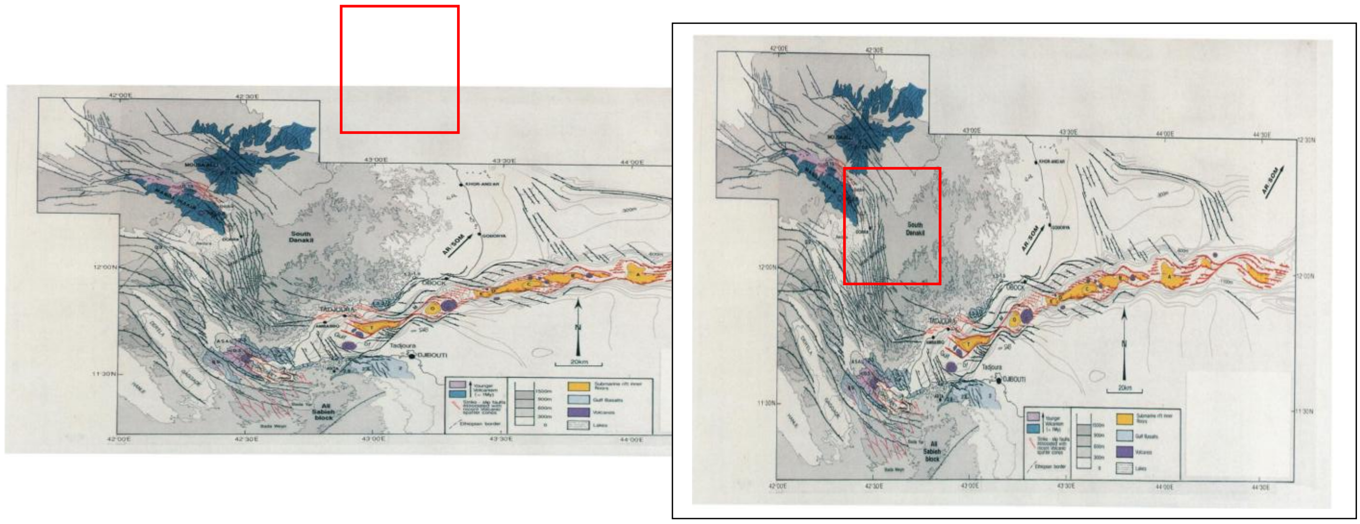

Figure 2: Structural sketch map of the active plate boundary system (Gulf of Aden ridge extension, though Gulf of Tadjoura and inland trough Asal-Ghoubbet, Makarassou and Manda-Inakir (Manighetti et al. 1998). The rectangle in red draws the area of interest considered in this paper.

A considerable amount of energy is dissipated along these spreading axes, mainly through the active ridge segments and along the transform faults, which are also partly extensive in nature. The hot anomalous mantle is located at shallow depth (a few kilometers only) with regular basaltic dike injection (2cm/year, i.e. 2 meters per 100 years) and in addition, shallower magma chambers develop locally, notably along the ridge axis and at the intersection with transverse structures (Varet, 2011). The presence of magma chambers is ascertained by the crystal fractionation observed in the volcanic sequence. The accumulation of Plagioclase, with the production of iron rich trachytes, indicates low oxygen partial pressure, and hence shallow magma chambers (Barberi and Varet, 1973).

The geological works undertaken in the year 1970 were the first systematic surveys of the Afar region and the present Djibouti Republic. Supported by the French CNRS and the Italian CNR, they helped identify the major geological units, their composition, age and origin, as well as a geodynamic interpretation of the evolution of the whole region and the progressive and active opening of the Gulf of Tadjoura to date (Marinelli& Varet, 1973; Varet, 1975; Richard & Varet, 1979).

A geothermal survey which identified the Asal site was undertaken by BRGM in the years 1970-1975. This was followed by another survey undertaken by Aquater (1982). However, this northern region was not included in these studies, probably due to its remoteness. The aim of this paper is to demonstrate this point - there are significant indices in favor of the presence of geothermal sites.

Our interpretation is that the area benefits from a geologic environment favorable for geothermal energy development with the presence of:

- Magmatic heat source (or sources) developed along the axis of spreading of the axial range (and sub-ranges) of Manda-Inakir, due to shallow anomalous mantle, basaltic dike injection and magma chamber (as shown by crystal fractionation and differentiated products).

- Fractured deep aquifers developed in the most intensively faulted part of the area, notably where NW to WNW extensional faults and open fissures cross with the fracture zone of Makarassou, a transform fault that also expresses an extensional nature.
- Although the area is quite arid, meteoritic water feeds the reservoirs from the southern slope of Moussa Ali Volcano and the wide watershed of the Dalha Basaltic Plateau gently dips towards NE, i.e. mainly north of the area (towards the Red Sea), but also partly the Buba and Andaba Plains (Said Kaireh, 2011).

3.2 Need for a Targeted Geothermal Development

It is clear that the very low income of the essentially pastoral and dispersed population of this arid area does not favor the immediate development of a centralized energy production and distribution system. Geothermal energy however can allow for a modulated development, starting with small size local units to respond to the present needs of the local population and increasing these in size when the demand justifies it - either due to the extension of local distribution network or stimulated economic activity.

Based on the present knowledge of the area, the active volcanic axial range Manda-Inakir can be pinpointed as a major potential heat source, where these axis crosses with the Makarassou Transform Zone. Note that hydrothermal leakages (fumaroles, gas vents and hot grounds) appear to develop along such intersections. This site can be viewed as suitable for standard, modular, high enthalpy geothermal approach.

The Hallol and Sakalol horst-and-graben structure extending towards south down to north the Asal Rift, displays numerous hot springs in the lowlands along the bordering faults, as well as fumaroles and hot grounds on the upper part of the horsts. A systematic mapping and consequent geochemical and mineralogical sampling and analysis of these hydrothermal sites should be conducted for a better understanding of the regional geothermal regime of this wide area located between two active spreading segments of Asal and Manda-Inakir, especially considering the relatively high population density in these wide plains favorable to palm trees culture and cattle breeding.

According to our knowledge and views of the local conditions concerning geothermal resources and possible technological development schemes adapted to local socio-economic conditions, four models/steps can be considered, from micro units for rural villages (20-200 kW) to small-size units for little towns or local specific economy (0,2-2MW), up to medium size unit for district cities (2-20MW). In the most favorable sites, this will lead, in the future, to the deployment of larger modular units (20-50MW) for more important plants serving an expanding interconnected network and newly attracted consumers (such as industry).

It will be a long time before an interconnected electrical network can cover the whole country - it may even never be the case considering the low population density in such remote areas. The priority target is to meet the local needs of this first category of users (production units catering for the demand of a population in the range of 100 to 1000). Responding to such needs from geothermal sources is feasible by just capturing naturally occurring hot springs or drilling shallow wells. Small size binary plants with adequate characteristics are available on the market.

Differing from classical geothermal developments, initial geological risk is quite limited in such conditions, and explorations costs are reduced if a valid and well documented inventory is availed.

Attention should be paid to maintenance (due to scaling and/or corrosion) and this will necessitate the availability of a specialized team able to intervene on all sites and train the local workforce. The inventory will confront hot springs or wells occurrences and nearby village's size and number.

We recommend that the feasibility studies should be carried on 3 sites representative of the diversity of the demand and resource conditions in this small-size category and that one to three sites should be selected for demonstration. At least one demonstration plant should be built to check the operationality of the scheme from early conception and local negotiation to long-term maintenance. Development should then be carried out on the concerned villages relying on local motivation, with a financial scheme to be determined with local banks involved in project financing for local public authorities or cooperatives. Local ad hoc PPPs should be established when possible, involving public local authorities as major partners, with the participation of both local enterprises and investors and larger industries and banks.

A classical geothermal exploration strategy should be applied to the Manda-Inakir area, with geological, hydro-geochemical and light geophysical surveys. More significant wells (1000 - 2000m deep) should also be drilled. With the objective of building a first well-head unit with a capacity of 1 - 5 MW, multi-purpose plants applications will be studied, implying various types of energy and geothermal fluid uses, including drinkable water production, thermal applications (such as drying or freezing) as well as balneo-therapic or touristic further developments. Later on, the development should then evolve to modular units for large plants serving the expanding interconnected network (20-50MW), linked to the projected communication routes (highway under construction and projected railway line linking the Tigré capital of Makalé in the Federal Republic of Ethiopia to the port of Tadjoura in Djibouti Republic).

4. GUIDELINES FOR THE GEOTHERMAL EXPLORATION OF THE AREA

4.1 Identification of the Magmatic Heat Source

A field work was carried in the area in May 2012 at the request of Dr. Fouad Aye, Minister of Energy, Water and Natural Resources. 4 staff took part in the field work:

Abduraman Omar Haja, geologist and director for natural resources, Said KairehYoussouf, hydrogeologist and resources projects coordinator at the water division, Jacques Varet counselor of the Minister and M. Baalah, driver of local Afar origin. The aim was to complete the information already known to the members due to previous field work done in the area. The geological map of Moussa Ali Volcano and Manda-Inakir Range and related petrological and volcanological studies was established by one of the staff, whereas several drilling sites were implemented after hydrogeological studies of the whole area by Said Kaireh (2008, 2011, 2012). This confirmed the very young nature of the axial part of Manda-Inakir north-eastern extremity on the western end of Andaba sedimentary plain. As observed by De Fino et al. (1973), and confirmed by new age determinations by Manighetti et al. (1998) - see Figure 3 - the range is divided in two segments: the northernmost – basaltic and fissural - being the most active at present (with ages ranging from 140 to less than 25kA) and a differentiation series produced by crystal fractionation (up to alkali trachytes) is observed in the Inakir range (an elongated shield volcano with axial graben).

Hence the most active heat source of ridge type (vertical basaltic dike injection) is available in the Manda area whereas the Moussa Ali (500kA at the basis) and Inakir (350-190kA) volcanoes are slightly older but display more evolved petrologic sequences (up to trachytes), allowing for the formation of shallow magma chambers, the thermal effect of which should not have disappeared.

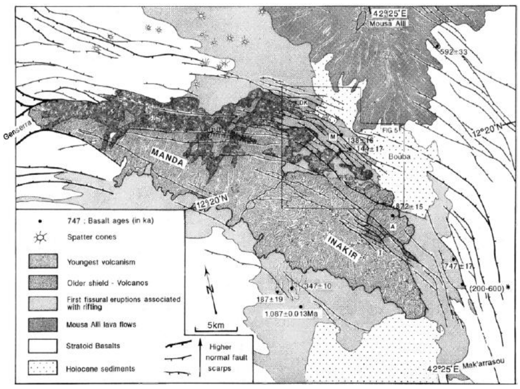

Figure 3: Schematic geological and structural map of Manda-Inakir interpreted from Spot and aerial images (Manighetti et al, 1998)

With a closer look at the most recent volcanic and tectonic events, from field observations crossed with satellite and airborne images, one can notice that direction of rifting rotated from NW to WNW directions in the recent years (Figures 4and 5), with well- defined extensional structures (symmetrical normal faults and open fissures).

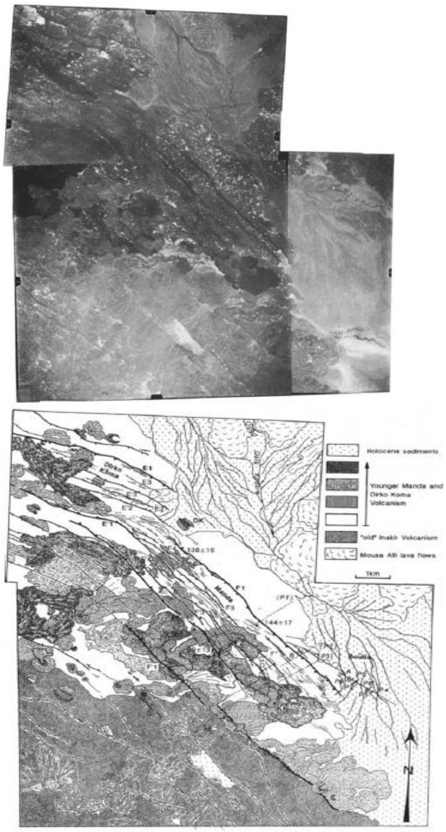

Figure 4: aerial photo mosaic of MandaHararo (1/50.000, IGN, 1950) and geological and tectonic interpretation (Manighetti et al, 1998)

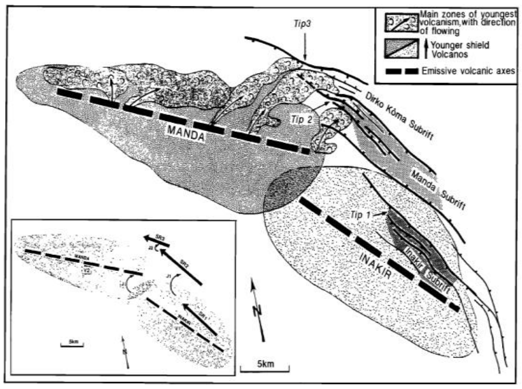

Figure 5: Interpretation of the structural evolution of the rifts and sub-rifts systems in the Manda and Inakiraxial range system. (Manighetti et al, 1998)

4.2 Hydrothermal Manifestations

The thermal manifestations in the northernmost part of the surveyed area, where these most recent tectonic and volcanic features are observed, are not spectacular but significant. All are located along faults and open fissure of dominant spreading rift direction (NW-SE). They are of 3 kinds:

- Fumaroles generally developed in the high part of faults scarps affecting the stratoid series, along small open fissures, with an intense alteration of the basaltic substratum (development of clay, silica, zeolites and carbonate deposits). The temperature generally gets up to 100°C when the steam flux is not too dispersed in the blocky surface (see map Figure 6).
- Hot springs occurring in sedimentary plains, near the foot of fault scarps, frequently at the intersections of transverse faults, with rather high flow rates and temperature ranging from 45°C - 62°C (Said Kaireh, 2011). Such features are characteristic of Hallol and Sakalol graben floors, but also occur locally in the sedimentary plains at the foot of the above described recent volcanic systems (see map Figure 6).
- Gas flux emitted from several sites in the surroundings of Manda-Inakir. One can feel the gas emission (not necessarily hot) and hear the bubbling of gas from a (not visible) groundwater lever. Four such sites could be visited. 3 of them located along recent (apparently historic) fault of open fissure of the most recent sub-rifts of the Manda-Inakir Range, and one in the productive well operating in the Andaba and/or Awda'a plain.

In addition to these active vents, there is the discovery of anomalous hot water occurrence in certain wells drilled for water production (Said Kaireh, 2008, 2012, Figure 7). Although most of the wells display temperatures of circa 45°C for the water table, two wells, in Balho and Karabti San have temperatures of 70°C and above 80°C respectively, the last showing a geothermal gradient of 45°C/100m (see Figure 8).

Also to be considered is the presence of paleo-hydrothermal alterations and deposits, frequently quite wide, and also linked with extensional fissures along faults of the dominant direction of spreading. These should be mapped and analyzed to establish their age and origin. Such features are notably well developed along the margins of the Hallol and Sakalol graben, in the southern part of the investigated area, but also elsewhere. Time did not allow for a visit to all the sites reported by the local tribesmen or inferred from the air photographs. A more detailed investigation should be done to establish an exhaustive coverage of these various types of hydrothermal vents. In this respect, an airborne infrared survey of the whole area would be a welcomed idea. In addition, chemical and isotopes analysis of the gas vents, spring waters and deposits as well as age determination and paleo-thermal conditions of the carbonate deposits should be conducted.

Although we cannot adequately describe a precise geothermal model for the area, it is clear that this place should undergo further geothermal exploration, as we believe the present surface investigations and preliminary model interpretation provide sufficient convincing evidence of the presence of real geothermal resources, which can eventually be adapted to meet the needs of the local population.

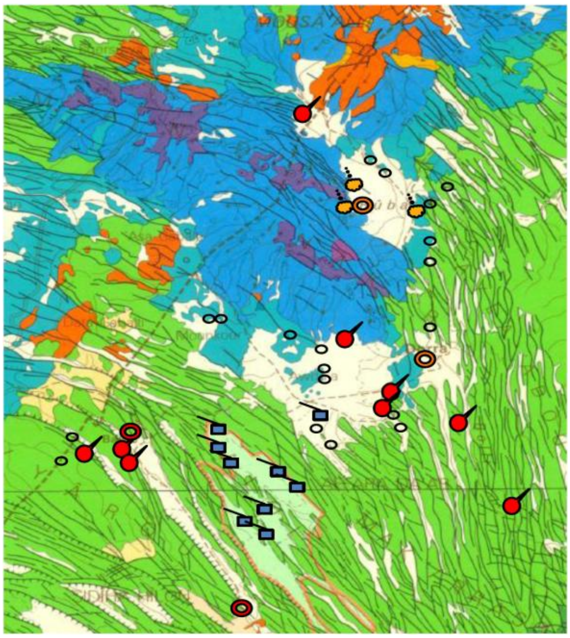

Figure 6: Main hydrothermal vents identified in the Northern part of the Tadjoura district during the field survey organized by MEERN in the area in may 2012. Blue squares are hot springs (ranging in temperature from 36 to 60°C). Red rounds are fumaroles and hot grounds (with temperature circa 10°C). Double circles are water wells drilled by the water division of MEERN, with orange colors when normal temperature (circa 40°C) and red color (when temperature exceeds 70°C). Orange rounds with dotted lines are vents in which gas are emitted with a bubbling water noise. Black spheres are potential springs or fumarole sites to be confirmed by future observations. The base map is the geological map of central and eastern Afar (Green: stratoid series, deep orange:alkalitrachytes and rhyolites, blue: recent basaltic flows well developed in the Manda-Inakir axial ranges, clear colors: sedimentary fillings, former lake shore: orange line; J. Varet, 1975)

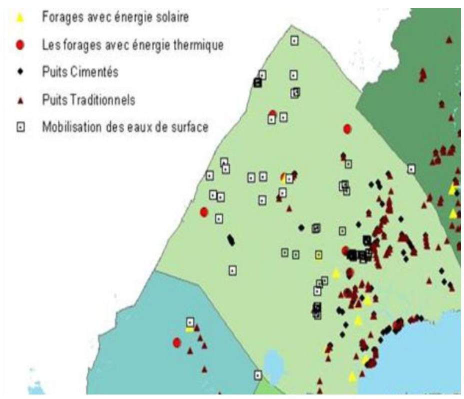

Figure 7: Location of water used by local population in the district of Tadjoura according to the

capture type (source: Said Kaireh, Water direction, MEERN, 2012)

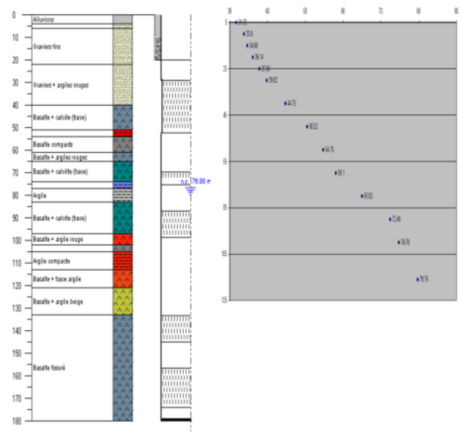

Figure 8: Geological and temperature log of well drilled at Karapti San, a village located in the northern extension of the Asalgraben. A temperature of more than 80°C was observed at a depth of 120m, and the drilling was stopped at 180m, with no possibility to undertake other temperature measurements due to the limitation of the instruments and rig facilities (from Said Kaireh, water division, MEERN, 2012).

5. PROPOSED EXPLORATION AND DEVELOPMENT PROGRAM

Apart from our preliminary field investigations and interpretations, the area had not yet been subject to a real geothermal exploration program. New field works should be undertaken define the sites of serious geothermal potential better. Actions should be developed in the following steps:

a) Surface exploration using geological, geochemical and geophysical methods, to locate the geothermal exploration wells;
b) Geothermal drillings, either shallow or deep, for geothermal fluid production at medium (100-170°C) or high (150-250°C) temperature;
c) Feasibility study and implementation of a few micro-ORC geothermal plants (a few kW up to 100kW in size), with the size adapted to the local need, on shallow well head appropriate sites; and
d) Construction of a well-head geothermal plant on a deep well located in the Manda-Inakir vicinity in the Andaba and/or Awda'a plain to serve the needs of local villages of Dora and Buba, and the development of local electric grid.

5.1 Exploration and Prefeasibility

On the basis of a detailed analysis of the available data, resulting from previous geological surveys, geothermal exploration works and more recent data (notably registered seismic activity), a complementary surface exploration program will be carried out. The program will be developed on the areas including the most recent volcanic structures, the active fumaroles sites (red dots on the maps Figure 3) and gas vents as well as hot springs and hot wells, (plus the various suspected vents sites which could not be checked during the May 2012 field work), using physical measurements (GPS, temperature, pH…), geological mapping, geochemical sampling and analysis and geophysical methods. The aim will be to identify the active fissures and faults feeding the surface manifestations from the depth, this step will assist in locating the sites of the geothermal wells.

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

An infrared survey of the area would also be welcomed in order to obtain a map of the hot grounds. This 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 characteristics of the plateaus in Afar.

Complementary geochemical analysis, including isotopes will be carried out on the emitted fluids (liquid and gas) and mineralogical studies of the hydrothermal alteration products and deposits conducted to determine precise fluid characteristics (composition and temperature) – both present and past.

Geophysical survey will be undertaken in the Andaba and Awda'a plains, and surrounding faulted zones on both recent volcanics of Manda-Inakir to the west and stratoid series to the east, using both geo-electric and magneto-telluric methods in order 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.

5.2 Feasibility

The exploration phase will be important in locating the sites for geothermal production drillings, where production wells will be implemented. .

In a first step, no real deep well drilling will be undertaken. The depth of the productive zones will be looked for in the interval 350-500m, sufficient for a geothermal fluid production at medium temperature (100-170°C), aimed at serving micro-geothermal binary plants in the range 10 to 100kW. About 10 wells will be drilled with a diameter (at least 8 inches for the final production casing) sufficient for a significant flow rate (about 30 to 100t/h). Long lasting production tests will also help in determining the physico-chemical characteristics of the fluids so as to optimize the production scheme.

In the Manda-Inakir area, one or several deeper well(s) will be drilled, up to 2000m depth, depending on the results from the shallow wells, to test the presence of a classical high-enthalpy geothermal field. According to the geological (and tectonic context) directional drilling may be needed (in the open fissure axial zones) in order to maximize the chances of intersecting productive fractures and faults, although we noticed that some of them - particularly on the eastern side in the Makarassou surroundings - are inclined and therefore can be intersected by a vertical drilling.

5.3 Further Development: Implementation of an ORC Geothermal Plant

The characteristics of the fluid produced from the various wells will help in determining the characteristics of the first ORC micro-geothermal unit - in the 10 - 100MW range - to be built on the shallow well heads sites displaying positive results.

In the Manda-Inakir area, if the geothermal model of a high-enthalpy geothermal field is confirmed by earlier phases, deep wells will be drilled to obtain a production with a well-head turbine in the range 1 - 5 MW.

If the parameters of the geothermal system allows for further developments, other wells and power units will be added, depending on the local demand, which will certainly increase with the electric offer. Local electric lines and grids will be progressively developed, linking villages and housing located in this remote region, to allow for the optimization of the geothermal development at district and national levels.

5.4 Budget and Financing

The total cost of the project is estimated at around 20 M$, broken down as follows:

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

- Drilling works, drilling equipment, including civil works (road and platform building):
    - 9 M$ (for 9 exploration wells at 350-500m depth and 1 well at a depth up to 2000m)

- Implementation of a demonstration micro-geothermal plant based on ORC technology (in the range 10 - 100MW), and of a well-head high enthalpy plant (1MW capacity). Electric transmission lines and transformer for distribution in cities and villages not included:
    - 10 M$ (eventually financed with a soft loan)

- Total budget:
    - 20 M$

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

NB: This proposal identifies the total geothermal potential of the area. The target could be reduced to a smaller number of units (for example, 2 - 3 instead of 5), with a budget reduced accordingly.

6. CONCLUSION

The area of Manda-Inakir appears as a zone of high enthalpy geothermal energy potential, which was not identified as such until recently. In addition, small units exploiting fault-related hydrothermal sites at shallow depth could serve local electric power needs with micro-geothermal ORC plants in the range 10 - 100kW.

A coherent exploration program is proposed for the whole area, including geological, geochemical and geophysical surveys to allow for the implementation of shallow exploration wells (350 to 500m depth) and development of one or more demonstration sites.

In addition, the Manda-Inakir area, and more precisely the Andaba and Awda'a plains and surrounding faulted volcanic zone whether very recent open faults in the axial ranges or double fracture zones affecting the stratoid series along the same axis have to be considered as serious candidates for high enthalpy geothermal energy exploitation. Deeper wells are proposed to be drilled there, up to 2000m deep, with the objective of installing a first demonstration plant of the size order of 1 MW.

This program should provide data on the whole area, and allow for further development to be undertaken in the longer run while accompanying the development of the demand for energy emerging from the qualitative and quantitative knowledge of this potential.

REFERENCES

Barberi, F., Borsi, S., Ferrara, G., Marinelli, G., Santacroce, R., Tazieff, H., Varet,J. :Evolution of the Danakil depression (Afar, ethiopia) in light of radiometric age determinations. J.Geol.80(1972) 720-729.

Barberi, F.& Varet,J. : Volcanism of Afar : small plate tectonics implications. Bull. Geol. Soc. Amer. 88(1977)1251-1266.

BRGM : Reconnaissance géothermique du TFAI. 70SGNGTM.59p. (1970).

deFino M., La Volpe L., Lirer L. Varet J. : Geology and petrology of Manda-Inakir range and Moussa Alli volcano, central eastern Afar (Ethiopia and T.F.A.I.). Rev. Geog. Phys. Géol. Dyn.,(2) 15 (1973) 373-386.

Farah,A.A. ;Djibouti potential status and prospectives in geothermal resources development. Proceedings WGC, Bali (2010)

ISERST : Etude géophysique dans les districts. Rapport, Djibouti (1989)

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

Landsystem-Tecnosol : Prospection géophysique: Annexe à l'étude hydrogéologique (15 forages). Rapport Djibouti(1989)

MAEM-RH : Catalogue des forages réalisés en RDD, 3ème édition, Djibouti (1994)

Manighetti, I., Tapponnier, P., Gillot, Y., Jacques, E., Courtillot, V., Armijo, R.,Ruegg, J.C. &King, G. Propagation of rifting along the Arabia-Somalia plate boundary Into Afar. J. Geoph. Res.103(1998) 4947-4974

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, Republique de Djibouti. Int. Symp. Geodyn. Evols. Afro-Arabian System, Roma (1979)

Saidkaireh : rapport technique du Forage de Balho. MEERN, Djibouti (2011)

Saidkaireh : rapport technique du forage de Margoyta.MEERN, Djibouti (2012)

Saidkaireh : rapport technique du forage de Awrlofoul. MEERN, Djibouti (2008)

Tapponier,P. &Varet, J. : La zone de Mak’arrasou en Afar : un équivalent émergé des « failles transformantes » océaniques. C.R. Acad. Sci., D 278 (1974) 317-329.

Varet,J.et al. :Geological map of central and southern Afar (Ethiopia and Djibouti Republic) 1/500.000 scale. Edition Technip, CNR-CNRS, Paris-Pisa(1975)

Varet, J.: Contribution to favorable geothermal site selection in the Afar triangle, Argeo Meeting, Djibouti, 17p.(2010)