Proceedings of the 4th African Rift Geothermal Conference 2012

Nairobi, Kenya, 21-23 November 2012

The Obock and Rouéli Geothermal Sites, Djibouti Republic

Abdourahman Omar Haga, HamoudSouleimanCheik, Jacques Varet

Ministry of Energy, Water and Natural Resources, Djibouti Republic

bilane24@yahoo.fr; hamoudsoulei@yahoo.fr; j.varet@brgm.fr

Keywords: Geothermal, exploration, Djibouti, Obock, Gulf, Tadjoura, Aden, ICDP

ABSTRACT

The western extension of the Aden Ridge penetrates the African continent through the Gulf of Tadjourah, an active oceanic ridge elongated in an East-West direction, but made of NW-SE rift segments and NE-SW transform faults, emerging from the Asal-Ghoubbet westernmost segments where two geothermal sites have been identified (see Abdourahman et al. this volume). While looking at the bathymetric or seismicity maps of the area, a striking feature appears: the active ridge is not located in the middle of the Gulf of Tadjourah, but on the northern part, very close to the coast, which itself appears to be parallel to the ridge. This means that an important heat source is available from the shallow anomalous mantle and there is active volcanism on the spreading sea floor (1500m deep in Tadjourah trough) very near to the coast.

Near the town of Obock, the dominantly coralline coastline, uplifted and affected by E-W faults, is very close to the ridge itself, whereas in Rouéli - a recent basaltic plateau ("gulf basalts", emitted 1 to 2My ago, at the early stage of opening of the Gulf of Tadjourah) forming a promontory above the sea level and deeply affected by both WNW and NE fault systems – it gets very close to the transverse faulting linking the Obock and Tadjourah troughs at depth.

While the surface geology is rather well known (Marinelli& Varet, 1973, Richard & Varet, 1979, Manighetti et al. 1998), the marine side was studied by at least two oceanographic cruises: SUDMEROUAD in 1977 (Choukroune et al. 1986) and TADOURADEN in 1995 (Hebert, 1998). The latest studies have shown that the direction of spreading is oblique with respect to the rift as well as to the transform faults, and hence that both have an opening component (Dauteuil et al. 2001). It means that a shallow hot, anomalous, and magma generating mantel, is also present along transverse structures. This geophysical interpretation corroborates the field observations at Rouéli where both WNW and NE faults look extensional.

As a matter of fact, several hot springs are encountered at both sites and steam vents are also present at Rouéli. Available hydro-geochemical data indicate a temperature of 210°C for the geothermal reservoir at Obock (Houssein et al. 1993, Sanjuan, 2010).

The high degree of recent faulting and the currently important seismicity indicate a good permeability at depth, also linked with the expected geological nature of this talus continental made of detrital formations interbedded with coral reefs and faulted basalts.

Of course, the geothermal reservoir should be looked for by deviated wells, towards south in Obock and towards South-east in Rouéli.

The presence of an attractive geothermal resource in the area is of interest at two stages: at present, to answer the needs of the local population, currently (only very partly) addressed by diesel engines in Obock and Tadjourah, and in the future, to serve the railway line and port linking central-northern Ethiopia to the sea through central Afar.

In addition to such promising prospects for geothermal power production, these sites appear particularly appropriate and unique in the world in regard to the attempt to drill deep them (with ICDP) in an oceanic ridge from the continent, an approach to future exploitation of the huge energy potential of mid-oceanic ridges in general.

1. INTRODUCTION

Iceland and Afar are the two regions of the world where geologically oceanic sites have been reached on land. While several geothermal sites are exploiting conventional high temperature fluids, one ICDP well was drilled in Northern Iceland on this emerged Mid Atlantic Ridge, and another is being planned in Southern Iceland (Reykjanes Ridge) in order to reach super-heated steam. In this paper, we describe the Obock and Rouéli sites located along the northern coast of the Gulf of Tadjourah (Djibouti Republic). The authors believe that the area is suited for both conventional high temperature geothermal exploitation - to be undertaken in the coming years -, as well as for a future research program under ICDP with the aim of reaching the internal part of an oceanic ridge by drilling a deep inclined well from the coast. To the best of our knowledge, this is the only place in the world where this can be achieved. This would pave way for a sustainable exploitation of Mid-Oceanic Ridges in the future.

2. GENERAL ENVIRONMENT OF THE GEOTHERMAL SITES

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 represents 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 (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 Obock district, located in the northern half of the country, faces Yemen along the NE coast of Djibouti Republic.

With a population of circa 40,000 inhabitants and a surface of 5.700km^2, the Obock prefecture is dominantly a pasture land for the nomadic Afar population. However, it also offers possibilities in the field of fisheries and eventually mineral resources which is still to be prospected in the dominantly volcanic hinterland. In the near future however, the situation in Obock and Tadjourah will change radically with the opening of a new railway line linking Central and Northern Ethiopia to the Sea through the port of Tadjourah. Both towns are accessible from the capital by the asphalted road, with a long detour around the Gulf through Ghoubbet-Asal Rift, or directly by boat. With this proximity these coastal sites can be considered as suitable candidates for the delocalization of part of the activity of the port of Djibouti, notably trans-boarding (Fig.1).

Of course, in such a perspective, the water and energy issues are capital. Although gifted with an arid climate, the town of Obock is located on the delta of the large OuaddiSadai, flowing from the Dalha and Mabla mountains extending north and feeding a wide groundwater reservoir located in the detrital sediments and coralliferous plateau constituting the surrounding plains, up to a few tens meter above sea level. But the most attractive potential is the geothermal energy resource. Not only are good hydrothermal indices present along the coast, but the geodynamic environment, in the vicinity of the active oceanic ridge of the Gulf of Aden prosecuted by the well documented Gulf of Tadjourah ridge is particularly attractive. However, no real geothermal exploration has been carried on this site yet.

The objective is first to develop a conventional high enthalpy geothermal energy project (2013-2015), in order to serve the local present and future needs, and at the same time prepare an ICDP project to be undertaken later on this site (2016-2020). Coupling both projects would help in evaluating and proceeding to the optimal development of the area’s geothermal potential by starting with a small well head plant, allowing for further conventional high enthalpy developments and later catching superheated technologies.

3. GEOLOGICAL FRAME OF THE OBOCK REGION

3.1. Previous Geological Studies

Although located in an arid, under-developed region, the area is already well known due to field geological works undertaken mainly in the years 1960-1990. More recent (last 10 years) geophysical and oceanic scientific researchers are also available. Some previous studied include: geophysical electric survey (CGG, 1960), geological mapping at 500.000 and 100.000 scales, volcanological, structural, petrological and sedimentary studies (Marinelli & Varet, 1973; Varet, 1975; Varet &Gasse, 1978; Richard & Varet, 1979;Gadalia, 1980; ISERST, ed. ORSTOM, 1983), several marine surveys: SUDMEROUAD in 1977 (Choukroune et al. 1986), and TADOURADEN in 1995 (Hebert, 1998; Dauteuil et al. 2001); a geothermal report (Aquater, 1981, 1982) completed by water geochemistry (Houssein et al., 1993, Sanjuan, 2010) and regional geophysics (Friedman, 1990). A continuous monitoring is also ensured by the permanent seismic regional grid (CERD and IPGP)

The geophysical survey carried by CGG in 1960 around Obockused Schlumberger electric profiles allowed a penetration depth of 200m. It allowed mapping of the major shallow conductive and resistant layers (a still valid view of superficial geology and water aquifers) on the shore. The geological works undertaken in the year 1970 were the first systematic survey. Supported by the French CNRS and the Italian CNR, the major geological units were identified, their composition and origin described and absolute dating provided, allowing for a geodynamic interpretation of the evolution of the whole Afar and southern Red Sea region (Marinelli& Varet, 1973). Several theses were written, with a view to understanding the origin of the Mabla and Dalha series (now stable) and to date the progressive and active opening of the Gulf of Tadjourah (Richard & Varet, 1979). This provides a good geological knowledge of the geological formations to be encountered at the intermediate depth by the proposed deep scientific drilling.

The first real geothermal investigation was provided by Aquater in 1982, but the scientific approach was limited to preliminary reconnaissance of the hydrothermal manifestations along both sides of the Gulf and inland. The idea expressed at that time was to develop a thermal station with a therapeutic objective near Obock. The thesis by Dr. Housseinprecise: the rock-water interactions using the chemistry of the thermal waters, show that the hot component at the origin of Obock thermal water is at a temperature of nearly 200°C, at (unknown) depth. Through oceanographic surveys, mapping the extension of the oceanic ridge of the Gulf of Aden trough and the Gulf of Tajourah was newly interpreted by Dauteil et al. (2001) in terms of oblique spreading.

A more recent geothermal investigation carried under MEERN facilitated the identification of the precise location of two sites that would allow for the tapping of a high temperature geothermal resource by inclined drillings from the coast, both at Obock and Rouéli. Further field surveys are needed to locate and engineer the exploration wells better (Abdouahman et al. 2012).

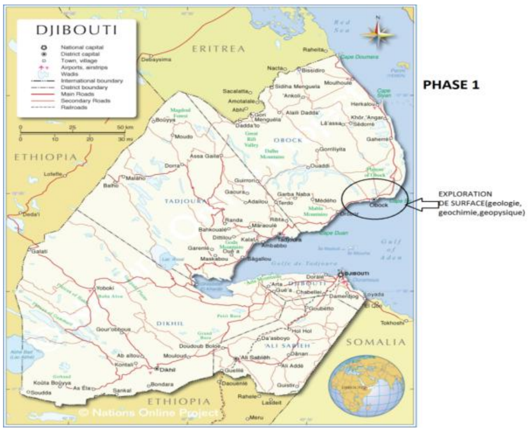

Figure 1: Main geographic features of the Djibouti Republic. The Obock region and its two potential geothermal sites: the Obock linear shore (black) and/or the Roueli cape (blue)

3.2. Main Geological Formations

The geological formations present at the Obock and Rouéli areas are both volcanic and sedimentary, but all of rather recent age (recent Pleistocene). This clearly relates to the very young nature of the Gulf of Tadjourah - the opening does not date more than 3Ma and the process is still active (at an average speed of 2 cm per year). It is necessary to recall the nature of the older geological sequences that outcrop north, in the nearby mountains, as they will most probably be present in the intermediate depth, underneath the recent quaternary sediments and basalts immediately surrounding the Gulf and the production resulting from its initial opening. These are:

- The important rhyolites event of Mabla, which dominate the immediate surroundings, on the hills North and West of Obock. These are pyroclastic layers and massive flows, dating back 11 to 16 Ma, and affected by extensive tectonics in the NNW-SSE (Red sea) direction. The lava is characteristic of the early stage of opening of the Red sea (of continental rift type, according to Marinelli and Varet, 1973).

- The basaltic trap series of Dalha cover the Mabla unit with a discordance following strong erosion, with thick detrital deposits in the paleo-valleys. These are regular basaltic flows, well visible in the highest part of the mountains of the Northern half of Djibouti Republic. These build a plateau that is gently dipping NW, with a sequence that was dated 8 to 4 Ma. These basalts were probably emitted from the area located now in the gulf of Tadjourah, which was then an uplifted basaltic plateau developed due to mantle upwelling, preceding the opening of the Gulf of Tadjourah.

- The Dalha series is eroded and covered, along the Eritrean frontier, by the more recent basalts of the stratoid series. In the Makarassou area, north of the Asal rift, the basaltic sequence appears almost continuous from the Dalha to the stratoid series. To the south, along the Gulf of Tadjourah, the whole series (Mabla and Dalha) is deeply affected by normal faulting along E-W and SW-NE directions, that amplifies while approaching the coast (and certainly underneath the sea shore, as the relief is quite violent in the vicinity of the oceanic ridge located only a few kilometers from the coast).

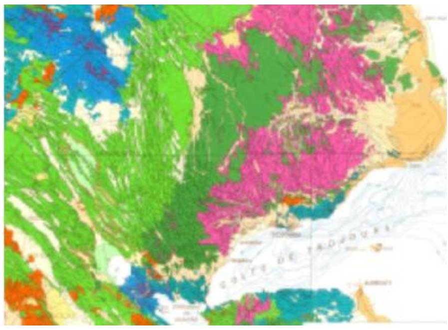

Figure 2: Extracted from the geological map of central and southern Afar (J.Varet, 1975). The Mabla rhyolites (violet), are faulted along the Red Sea direction and covered after erosion by the basaltic Dalha plateau (deep green), itself intensively faulted and tilted towards NW, eroded and covered by the Afar stratoid series (clear green). In the vicinity of the Gulf of Tadjoura, these faulted and eroded blocks are covered by the basalts emitted during the early stage of opening of the Tadjour oceanic ridge (blue-green),deeply faulted along Aden rift normal and transverse directions. Bathymetric contours in the gulf are also drawn showing the position of the ridge near the Obock coast.

- This important and still active faulting affects the volcanic as well as the sedimentary formations of quaternary age located along the gulf coasts. The initial basalts of the gulf were dated back 3 to 1Ma, depending on their position, with a regular decrease of the age towards the West, indicating a progressive penetration of the Aden Ridge into Afar along the gulf of Tadjourah (Richard & Varet 1979, Courtillot et al. 1980). These basalts are covered and partly inter-bedded with detrital sediments and coral reef deposits. If the coralliferous limestone of the Obock plateau were fist uplifted, they were also deeply faulted along the sea coast of the gulf.

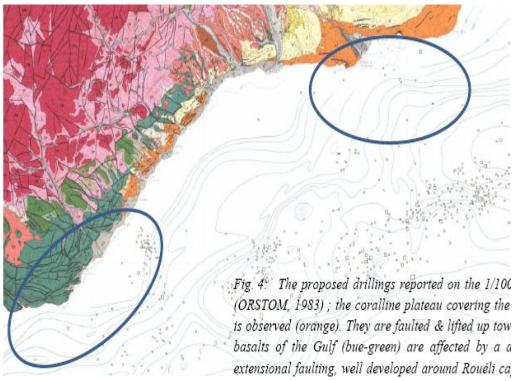

Figure 3: The proposed drillings reported on the 1/100.000 Djibouti sheet (ORSTOM, 1983) ; the coralline plateau covering the whole coastal zone is observed (orange). They are faulted& lifted up towards SE. The initial basalts of the Gulf (bue-green) are affected by a double ENE & NW extensional faulting, well developed around Rouéli cape, well fitting with the ridge tectonics (see bathymetry). Ellipses are 5Km long & 3Km large.

- The outcropping coralliferous plateau of Obock (orange on the map) was dated between 100.000 to 150.000 years. It extends up to 4km inland. This carbonate formation is well developed and underlies the town. It is a good building material, eventually suitable for cement production.

- The latest geological formations are detrital and eolian sediments covering the madreporiclimestones.

-

3.3. Oceanographic and Geophysical frame

In view of the vicinity of the active geodynamic axis of the Gulf of Tadjourah and the lack of surface volcanic manifestations, attention should be drawn to the submarine areas bordering the Obock coast.

Figure 5 shows the main characteristics of the geology of the active part of the Gulf drawn as a result of the oceanographic TAJOURADEN campaigns carried in 1977 and 2000 (Dauteuil et al. 2001). Oblique spreading explains the extensional nature of the transform faults and transverse tectonics in general.

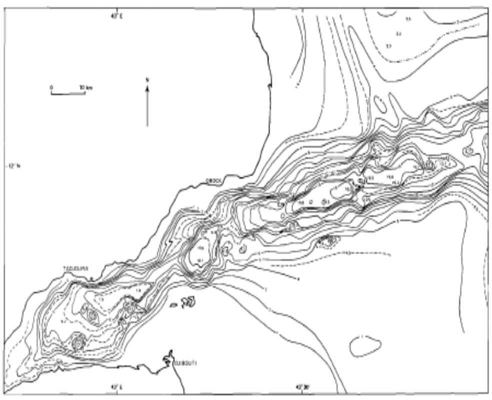

Fig. 17 : Carte bathymétrique du golfe de Tadjoura (profondeurs en centaine de mètres).

Figure 4: Axial valleys of the Aden Gulf extend in the Gulf of Tadjourah in the vicinity of Obock and Tajourah.

A number of troughs are observed bordered by symmetrical faulting in NE-SW and WNW-ESE directions that extends towards the west the axial valleys of the Gulf of Aden (Figure 5). Near Obock, 3 such rifts trending WNW-ESE are separated by transform faults of SW-NE direction. The most important is the Obock Trough, whose depth reaches 1500m. These axial valleys' floors are carpeted with basaltic volcanoes aligned along the axis. 375 craters were noted, 50 of which had calderas. A central volcano 8km in diameter was identified south of Obock. The faults bordering the Obock Rift to the north extends inland and directly determine the coastline. Similarly, the transform fault linking that rift to the next one located SW (north of Dalhac islands) extends north and determines the shape of the coast towards the Red Sea and Bab-El-Mandeb straight. The coast line at the west of Obock, towards Tadjourah is strictly determined by the succession of WNW-ESE rift and NE-SW transform directions. In greater detail, this double combination of faults is well expressed in the small basaltic plateau of Rouéli, marking the prominent cape on the coast between Obock and Tadjourah (Figure 4).

As observed in Figure 6, the Gulf of Tadjourah, which marks the present active plate boundary between Africa and Arabia, is subject to intense and active seismic activity. It is located along the mid-gulf ridges, their subsea bordering faults and their extension on land. Most of the faults located north of the gulf, notably in the Roueli Plateau, are subject to intense tectonics presently active and directly linked with the oceanic rift system.

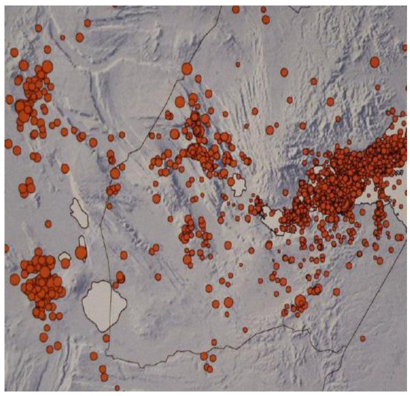

Figure 5: Intense seismic activity measured in the Gulf of Tadjourah between 2005 and 2010

4. PROPOSAL FOR DEVELOPPING GEOTHERMAL SITES AND FURTHER DEEP DRILLINGS

4.1. Observing Inside the Active Spreading Mechanism and Magmatic Heat Source

Following the above mentioned observations, it is possible to note that the western extension of the MOR of Gulf of Aden is at a sufficiently short distance that it can be reached by deviated drilling from the coast. It is proposed that deviated research wells should be undertaken with 2 objectives: first, to reach a conventional geothermal reservoir (200 to 250°C) at a depths of circa 2000m for geothermal power generation answering local future needs and secondly, while pursuing a deep under ICDP, help in understanding spreading mechanisms, magma generation in relation to extensive faulting as well as heat source development and heat transfer in oceanic systems.

In the Obock region, the final target should allow a reach to the base of the rift system whereas from Rouéli, a leaky transform fault can be crossed and allowed to touch from inside both the shear and extensional faulting. Two heat sources can be expected: the hot anomalous mantle (1300°C) located a few kilometers deep and more superficial magmatic chambers (above 1200°C) could be crossed underneath the ridge, the leaky transform faults and the central volcano mapped in the vicinity of Obock.

4.2. Hydrothermal Activity and Indices for a Geothermal Reservoir

The two sites, both are located along the coast, display hydrothermal emergences that were identified, though not all being reported on the geological sheet of Djibouti including Obock:

- The first is observed in the southern part of the town of Obock, in the intertidal zone (red points on Figure 7). Several hot springs are observed, located along an E-W trending normal fault, with temperatures ranging from 54 to 86°C, and a flow rate related to the movements of the sea.

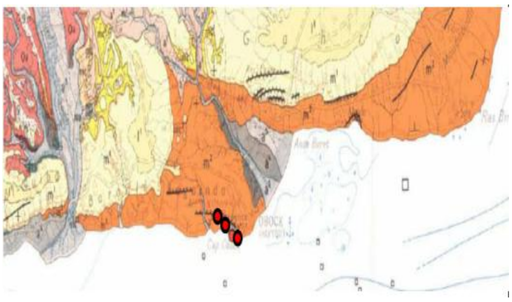

Figure 6: Zone of Obock thermal emergences (red dots) aligned along a normal fault parallel to the axis of the nearby mid-oceanic ridge.

- The second is located in the Roueli massif that marks a prominent part of the coast line between Obock and Tadjourah. Several sites of thermal emergences (mainly gas and steam vents), the surface temperature of which do not exceed 50°C were identified by Aquater (Vol.II, 1981), notably between the localities of Tanttako and Nieille. They all appear to be controlled by normal faults in both WNW and NE directions. Not all are reported in Figure 8.

As one would expect in such a context, the composition of the thermal springs appear to be very near to the sea water (Table 1). The most recent hydrogeochemical interpretations (Houssien, 1993; Sanjuan, 2010) show that the Obock waters result from the mixing of a hot component of deep origin with the sea water, together with a slight dilution by meteoritic water. The hot end member shows temperatures of 210°C, and on a few geothermometers up to 240°C, that could reflect the temperature of the geothermal reservoir feeding them from the depth (Figure 2).

The thermal manifestations of Rouéli are clearly controlled by the intersection of rift and transform faults both with dominantly extensional component according to observations by Richard and Varet (1979) and the more recent model of oblique spreading developed by Dauteuil et al. 2001). The water component at Rouéli is less salty than at Obock, expressing the influence of meteoritic infiltrations in the Rouéli basaltic plateau that overlies the emergences mostly located near to sea level. Steam vents that favor the development of the characteristic vegetation (Fiale) are also observed. The liquid part of the thermal emergences may also result from condensation of the stream at shallow depth. But the field observations did not allow for the identification of hydrothermal deposits. Geothermometers indicate temperatures of up to 170°C, i.e. lower than at Obock. But the important dilution of the hot component with meteoritic and sea water provides weaker evidence of the temperature of the hot component. As a whole, it may well be that the heat is largely provided by dry steam leakage from deep reservoir through superficial groundwater.

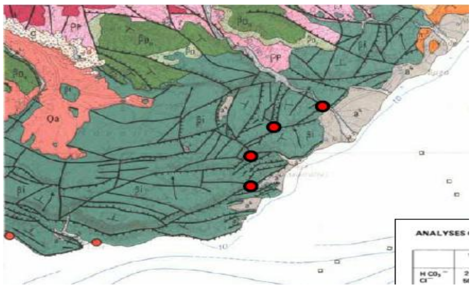

Figure 7: Geological context of the thermal emergences of Rouéli, between Obock and Tadjourah, with location of the springs reported on the Djibouti geological sheet (ORSTOM-ISERTS, 1984), from Aquater (1981) and our own observations.

Table 1: Chemical Analysis of the Thermal Waters of Obock

ANALYSES CHIMIQUES DES EAUX HYDROTHERMALES D'OBOCK

	1	2	3	4	5	6	7	8 eau de mer
HCO_3^-	2.4	2.5	2.5	2.7	2.5	2.6	2.8	2.5
Cl^-	507	511	497	511	501	513	562	587
SO_4^{--}	31.6	33.5	29.4	32.4	29.7	29.9	35.0	58.5
Ca^{++}	50	48	52	49	51	52	52	21
Mg^{++}	60	64	55	64	58	58	65	114
Na^+	424	428	412	432	424	436	486	524
K^+	15.5	14.9	15.3	15.2	15.6	16.4	17.8	11.1

Les concentrations sont exprimées en meq. 1^{-1}.
La température des différentes sources varie de 57° à 86° C.
Les prélèvements ont eu lieu en juin 1981.
Les analyses ont été faites au Laboratoire des Sciences de la Terre de l'ISERST (Djibouti), sous la responsabilité de H. BUTZ.

Source: B.Sanjuan, 2010

Table 2: Chemical Analysis and Geothermometric Interpretation of the Thermal Waters of Obock, cCmpared with Icelandic Geothermal Waters

Table 2: Measured temperatures, temperatures of deep geothermal fluid estimated using chemical geothermometers and values of temperature selected for this study.

Geothermal area	Sample	T °C	$T_{Na/KM}$ °C	$T_{Na/KF}$ °C	$T_{Na/K/Ca}$ °C	$T_{K/Mg}$ °C	T_{Qz} °C	$T_{Qz\ vapor}$ °C	$T_{Chalc.}$ °C	$T_{Na/Li}$ °C	$T_{sel.}$ °C	$1000/T_{sel.}$	log(Na/Li) molar
Djibouti													
Asal wells	Asal 1	255	262	267	251	278	255			263	260	1.88	2.82
	Asal 3	260	268	271	253	277	256			287	260	1.88	2.75
	Asal 3 (BH)		261	266	251	274	256			286	260	1.88	
	Asal 6	260	268	271	254	280	266			277	260	1.88	2.78
Ghoubbet Channel thermal spring (Tadjourah)	G2	60	107	140	166	98	62			64	60	3.00	3.83
Tadjourah hot end-member	HEMGC	?	122	153	163		152			171	160	2.31	3.23
Obock thermal spring	O3	74	150	177	193	118	133			148			
Obock hot end-member	HEMO	?	213	229	223		201			240	210	2.07	2.90
Iceland													
Svartsengi wells	SV-07	244	243	253	240	310	258	230		235	243	1.94	2.92
	SV-07	244	230	242	233		246	221		242	235	1.97	2.89
	SV-18	244	248	256	243	309	264	234		248	245	1.93	2.87
Reykjanes wells	H2	260								279	260	1.88	2.77
	H2	?	247	255	246	241	245			275	250	1.91	2.78
	H8	?	250	258	249	252	318			281	292	1.77	2.77
	H8	283					265			284	283	1.80	2.76
Reykjanes wells	RN-10	319	239	250	245	292	328	283		265	283	1.80	2.82
	RN-21		234	245	246		298	261		256	261	1.87	2.84
	RN-22	305	243	252	245	288	298	260		250	260	1.88	2.86
	RN-22	305	224	237	240		300	262		255	262	1.87	2.85
	RN-24	286	241	251	243	310	292	256		251	256	1.89	2.86
Seltjarnarnes wells	SN-04	114	73	109	104		142	137	113	113	114	2.58	3.49
	SN-05	114	68	105	103		140	135	111	107	114	2.58	3.53

Source: B.Sanjuan, 2010

4.3. Tentative Elaboration of a Hypothetical Geothermal Model

The hypothetical geothermal model we have to work with at Obock and Rouéli presents the originality of being largely underneath the ocean. Surface indices along the shore are limited, and the most active part of the system clearly lies to the south and east, underneath the Gulf of Tadjourah, as the northern emerged part clearly belongs to more ancient, presently (and since 4Ma) inactive geological setting (now part of the Arabian plate). A hypothetical interpretative scheme is proposed in Figure 11, where the relations between the submarine active rift segments and the surface manifestations are underlined.

- **The active ridge axis and related heat source,** at nearly 1300°C, is mantellic or magmatic, located at a few kilometers depths south of Obock in the oceanic axial valley of WNW-ESE direction, that is oblique to the direction of the opening, which is N37°E according to Dauteuil et al. (2001). It should be noted that the NE-SW transverse faults, well developed along Obock and Rouéli coast lines, are also of extensional character. They appear as the northern extension of the transform faults linking the Obock and Tadjourah rift segments through the small Maskali Rift. Hence they also generate magmatic heat of mantellic origin (leaky transform faults). Nearby anomalous mantle at 1300°C, located - according to seismic evidence - at a depth not exceeding 6 to 7 kilometers is therefore expected on both sites of Obock and Rouélia. Moreover, more superficial magma chambers are expected underneath nearby submarine central volcanoes. A geothermal gradient of 20°C/Km at depth may therefore be expected in the wells.

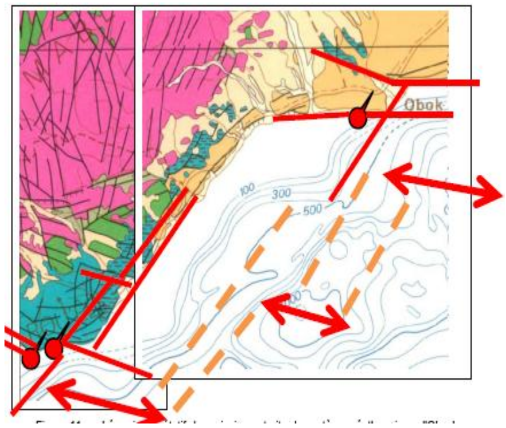

Figure 8: Interpretative scheme of the major determinants of the Obock geothermal system: heat source located along the axial (WNW-ESE) volcanic rift zones of the oceanic floor (double red arrows), transverse fractures (NE-SW) of the transform faults (orange discontinuous lines) that are equally leaky. Major sites of hydrothermal surface manifestations (red bordered black)and visible faults at the surface along the coastline (red).

- **A geothermal reservoir,** the temperature of which is above 210°C at Obock may well be located at a depth of about 1.000 meters, and should be develop in the faulted basaltic formations resulting from the early gulf opening (with a good fracture permeability), but also in the interbedded detrital deposits, displaying a good matrix permeability. The intense fracturing developed along both WNW and NE directions, reactivated by the present seismicity offers a particularly favorable context for the possible development of a geothermal reservoir. Higher temperature supercritical reservoirs are expected to be found at a greater depth

- **The cover** is made of quaternary formations detrital and coral reef deposits and most probably hydrothermally altered units to be encountered at a few hundred meters depth. The self-sealing process may have allowed the development of impermeable clay and silica rich layers, although the active seismicity and faulting may regularly re-open these plugging. Surface manifestations are more abundant in the rejuvenated fractured basaltic plateau margins of Rouéli than in the sedimentary plains of Obock where rapid sedimentation of the Sadai delta may obliterate the eventual leakages anyhow less abundant in these softer units.

- **The feeding** of the reservoir is ensured by both meteoritic water flowing from the upper faulted formations and oceanic water, which is certainly dominant at depth below sea level.

5. PROPOSAL FOR A GEOTHERMAL DEVELOPMENT PROGRAM

Before geothermal fluids can be used for electricity and heat generation, preliminary studies should be conducted to determine the precise physic-chemical characteristics of the geothermal field, to be reached by drillings. This implies the need to undertake more detailed geochemical sampling of the thermal springs (including new emergences identified in the vicinity underneath the sea), concerning gas and liquids, with new and more precise hydro-chemical and isotopic studies. Geophysical survey with a good penetration – gravimetric, geo-electric and magneto-telluric - should be undertaken to identify the geometry of the geothermal reservoir and its cover. In addition, a few seismic profiles should be undertaken at sea, perpendicular to the coast, as the objective of the drillings lies underneath the sea. At the feasibility stage, the exploration wells will be drilled from the coast with a deviation towards the ridge axis underneath the bottom of the gulf. The deviation will also allow for better intersections with faults (improving permeability). The most favorable objectives will be looked for where the rift crosses with the transform faults, as important heat and permeability can be expected.

These studies should aim at determining the following elements:

- Establish a provisional geological section (for the determination of the technical drilling program);
- Fix the objective for the exploration wells (i.e. estimate the depth of the reservoir from geological, geochemical and geophysical data);
- Determine the possible physic-chemical characteristics of the geothermal fluids; and
- Precisely locate the wells and determine their characteristics (directional drilling notably).

We have shown above that although based on available it is possible to make hypothesis on the existence of a geothermal potential and to draw a hypothetical model, the necessary information to facilitate the establishment of a sound drilling program is still. Specific studies need to be conducted, namely specialized geological, geochemical and geophysical investigations to assist in planning the drilling and production test program. The geothermal exploration will be handled in 2 phases:

5.1. Phase 1 - Prefeasibility

Detailed synthesis of all available data on land and off shore and undertaking of surfaces studies to determine the 3D characteristics of the site subsoil in order to plan the drilling program.

Djiboutian staff as well as geothermal experts of international reputation will mobilized to asses available data, determine and carry out specific field and marine works and establish and validate models and drilling options to be undertaken in phase 2.

Geology: 1/100.000 maps are available. The study will establish provisional geological sections for the wells sites. Precise stratigraphic logs will be set up in order to launch the drilling program and in particular the geothermal reservoir (physic-chemical parameters and production depth).

Geochemistry: Fumaroles, hot springs and other water emergences will be sampled and analyzed. This will help in establishing the nature of the aquifers and their link, and in deducing the temperature of the reservoir from geothermometers. Isotopic studies will also be undertaken to determine the origin of the geothermal fluids.

Bathymetry and submarine littoral studies: As thermal emergences are located along the marine shore, and the model we propose indicates that the heat source and geothermal reservoir are located in the submarine part of the geothermal site, further oceanographic work will need to be carried out in the off-shore zone. This will involve reinterpretation of data from previous campaigns, cartography of the faults and of the geological formations located between the coast and the mid-oceanic ridge of the gulf, and sampling of under sea's geothermal emergences. New bathymetric and seismic profiles will need to be prepared. Their interpretation will be essential in establishing the drilling program.

Geophysics: Geothermal exploration is capital for geothermal project, as it allows for mapping of the extension and structure of the formations at depth, thus helps in determining the location and the depth of the reservoir and cover. The most suitable tools for this are gravimetric and electrical methods, coupled with magneto-telluric surveying. Data will need to be obtained both on shore and off shore.

Phase 1 is to be considered as a research project, and to be financed under non-refundable source.

5.2. Phase 2 - Feasibility

This will entail undertaking at least one, and up to 3 exploration wells of up to 2km depth, and consequent production tests, in order to determine the characteristics of the fluid for geothermal production (flow rate, temperature, composition, producible electrical power). The results of phase 1 will determine the characteristics of the exploration drilling and test program for phase 2. From the interpretation of the data collected during phase 1, the number and characteristics – namely the location and depth of the reservoir to be tested by the exploration wells will be proposed.

This phase is still at high risk, and the financing scheme should be adapted: either non-refundable, or refundable in case of success only.

5.3. Phase 3: Construction of the Power Plant

If the exploration wells are drilled with a diameter sufficient for geothermal production (7 to 9 inches), the producing ones will be used directly for the production of electricity to feed the plant. In a first step, a light well-head turbine could be installed (with an electricity production of 2 to 5 MWe). If necessary, other wells will be drilled to meet the demand for electric power.

Differing from the 2 previous phases, the risk is here much lower and the financing of the project can be ensured under classical refundable funding, as the sales of the energy produced will pay for the geo-thermo-electric unit.

6. PREPARING FOR THE ICDP PROJECT

6.1. How the Obock-Rouéli Site Fulfills the ICDP Criteria

Global Criterion: The unique geodynamic environment in the area located around Obock, on the northern shore of the Gulf of Tadjourah (Djibouti Republic) can be tackled through the possibility of directly touching a real oceanic ridge, by direct drilling onshore from a continent. This will solve problems of global significance. Although unique, this is without doubt an opportunity for better understanding the actual geological structure of mid-oceanic ridges (MOR). Moreover, this would be an attempt in building the first steps towards further prospective industrial developments off-shore and in-situ along these major energy producers from the inner earth as future sources of geothermal power. In this respect, this is a real “World-Class” Geological Site!

International Criterion: Afar region as a whole is already a geological site of major international significance, with important works developed there by German, Italian and French scientific teams since the years 1970-1980s, with a renewed interest in the last 6 years due to the MandaHarraro – Dabbahu event (2005-2011) leading to the “Afar Rift Consortium”, international conference in Addis Ababa in January 2012, and continuous works by several scientific teams in the region extending from Afar to the Gulf of Aden. Hence the international collaboration is already broad, implying the best possible science teams as well as local scientist. In the context of the present project, this would be a real opportunity for pooling of resources and technology towards off-shore exploitation of MOR geothermal resources.

Societal-Needs Criterion: Geothermal power production is of relevance to the people of the country itself, as an immediate solution to the presently unsatisfied energy needs. In the long-run, however, the incidence is of course much larger and concerns everybody/the whole world in its capacity to rely upon renewable, reliable an clean energy sources. In such circumstances collaboration with industry will represent an attractive target although, at present, the site is not located in an industrial environment, but rather to-be-developed region. Nevertheless, the site is open to a bright future due to the future railway link between central and northern Ethiopia with the sea through the future port international of Tadjourah.

Need-for-Drilling Criterion: Although the approach from the surface – already well developed through previous scientificc works (geology, fluid geochemistry, geophysical hydrographic and oceanographic studies) - still needs to be fine tuned, there is no doubt that deep deviated drilling is the only way to directly touch the actual problems yet to be understood and solved. We have hence a clear proof of necessity for drilling!

Depth-to-Cost Criterion: It is clear that, if one accepts the idea that looking after the actual functioning of MOR is of major scientific interest, and that approaching this question with a view of future economic developments (notably power production, but also eventually several minerals) is also valuable, then the site proposed is optimal in terms of depth-to cost criterion. This point however still needs to be well quantified through further engineering and economic studies. Balancing of costs and drilling design is yet to be established although preliminary approach is made available in the following pages.

6.2. Specific Works to be Engaged Before Deep Drilling

Before deep research drilling is commissioned in the Obock and Rouéli areas, specific complementary work should be done. Some could be done under exploration programs to be developed for geothermal resource assessment. As seen in part 4, partners are at present being searched for by the Ministry for a prefeasibility (surface exploration to locate exploration wells) to be followed by a feasibility study (drilling in order to assess the geothermal reservoir) if surface exploration confirms the favorable perspectives.

As for the deep drilling project under ICDP, the preparation work will be determined by the panel in charge. It is clear that besides the above described works, supplementary oceanographic investigations will have to be carried along the coast lines, as the present data provide a rather good knowledge of the ridge itself, but information are lacking concerning the talus (between 0 and 500m depth): geology, tectonics, hydrothermal manifestations and volcanic features.

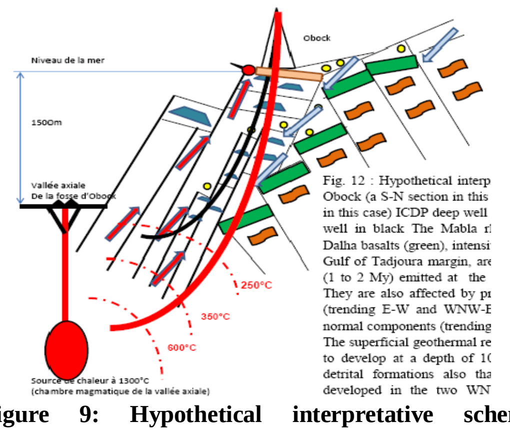

Figure 9: Hypothetical interpretative scheme proposed for the Obock (a S-N section in this case) and Rouéli (a E–W section in this case) ICDP deep well (in red) & “ordinary” geothermal well in black. The Mabla rhyolites (marron) and overlying Dalha basalts (green), intensively faulted and eroded along the Gulf of Tadjoura margin, are covered by the younger basalts (1 to 2 My) emitted at the initial stage of the gulf opening. They are also affected by presently still active normal faults (trending E-W and WNW-ESE), and transverse faults with normal components (trending NE-SW) along the gulf margins. The superficial geothermal reservoir (up to

220°C) is expected to develop at a depth of 1000 to 2000m in the quaternary detrital formations also thanks to the important fractures developed in the two WNW and NE directions, Deeper supercritical fluids are expected to be met at 3000 to 4000m depth while approaching the spreading axis under the sea floor

These preliminary studies will allow for the precise determination of the physic-chemical characteristics of the 2 areas and the location the drillings sites and characteristics, with the aim of determining the following elements:

- Fix the objective for the deep wells;
- Determine the possible physic-chemical characteristics of the fluids to be met;
- Precisely locate the wells and determine their characteristics (depth, length, directionfor drilling notably), if these are not just deepening of the conventional geothermal wells;
- Establish provisional geological sections for the selected sites (to be used to determine the technical drilling program); and
- Define logging and sampling strategy.

6.3. The Deep Deviated Drilling (up to 5000m Length)

The deep wells sites under ICDP will be located and their characteristics defined on the basis of the above results. Up to 2 wells will be drilled - one at Obock, drilled with an inclination in a southern direction to penetrate underneath the axial valley of the MOR and the other at Rouéli with a eastern direction to cross a transform fault, both active extensional structures.

Of course, the program described above is a reminder - a first estimate of what, in any circumstances, should be done on these sites to develop better knowledge. But the action plan should be determined by a proper ICDP workshop, whose main goals should be to:

a) Formulate focused scientific objectives
b) Define specific operational targets
c) Form an active and convincing scientific team and project structure
d) Draft Plans including funding, Budgeting, operations and management plans
e) Write and submit a full frilling proposal to ICDP and other agencies

7. CONCLUSION

The Obock-Rouéli area is well suited for both conventional geothermal high enthalpy developments as well for basic research superheated systems in real oceanic ridge environment, opening the way for the future exploitation of the mid-oceanic ridge potential.

Besides producing the power needed for the inhabitants, and preparing further developments induced by ambitious regional projects (electrical railway line linking Centre-North Ethiopia to the Tadjourah port facility) the deep drilling project under ICDP fulfills the necessary criteria for success:

- A"bright scientific idea": to study in situ MOR processes (rifts and transform faults) and test important hypothesis concerning magma and heat generis, heat transfer and nature of the reservoirs, only accessible through deep drilling
- These sites are clearly of "global scientific importance" and deep drillings are not only scientifically sound but of important societal and economic relevance as it will help developing geothermal energy in Djibouti - which is key for the countries development - and establish a first step towards the exploitation of MOR economic potential in general.
- Rather good geophysical and geological site surveys are available. Together with complementary investigations to be undertaken, these surveys and 3D models will justify drilling targets and reduce drilling risks
- Technical feasibility and budget realities still remain to be polished up.
- Environmental and societal compliance will not pose a problem. The population expects that such developments will have a direct impact on the quality of their lives. Acceptance and support through national authorities is clear.
- A high degree of international cooperation will develop. Besides the Djibouti and French teams already at work, several members of the Afar Rift Consortium are likely to participate. This will help in establishing the best possible science teams and will contribute towards the educational potential, notably by supporting PhD thesis.

REFERENCES

Barberi F., Ferrara G., Santacroce R., Varet J. :Structural evolution of the Afar triple junction. In: A. Pilger, A. Rösler (edit.), AfarDepression ofEthiopia, Stuttgart (Schweizerbart),(1975) 38-54

Barberi F., Borsi S., Ferrara G., Mazinelli G., Santacroce R., Tazieff H. & Varet J.: Evolution of the Danakil Depression (Afar, Ethiopia) in light of radiometric age determinations a reply. J. Geol., 81(1973) 749-751.

Barberi F., Tazieff H. & Varet J.: Volcanism in the Afar Depression its tectonic and magmatic significance. Tectonophysics, 15 (1972) 19-29.

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

ChoukrouneP. et al. Tectonics of the westernmost: Gulf of Aden and the Gulf of Tadjoura from submersible observations. Nature 319 (1986) 396-399

Dauteuil, O., Huchon, P., Quemeneur, F., Souriot, T.: Propagation of an oblique spreading centre : the west Gulf of Aden. Tectonophysics,332 (2001) 423-442.

Friedmann E. & Brunel P.: Geophysicalstudy, Obock, Djibouti (1991)

Gadalia, A.: Les rhyolites du stade initial de l'ouverture d'un rift: exemple des rhyolites Miocène de l'Afar. Thèse 3e cycle, Université Paris-Sud.(1980)

Houssein, I., Sanjuan, B., Michard, G.: Indices géochimiques de l'existence d'un fluide à 210°C dans la région d'Obock (République de Djibouti). C.R. Acad. Sci. Paris316(1993) 771-776.

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.

ORSTOM: 1/100.000 geological map of Djibouti, Djibouti sheet (1985)

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)

Ruegg et al. : Campagne SUDMEROUAD. Sud Mer Rouge et Golfe d'Aden (1977)

Ruegg J.C., Lepine J.C. et Vincent C. : Sismicité et microsismicité de la dorsale de Tadjoura, tectonique et frontière de plaques. Bull. Soc. Géol. Fr.7. 22, 6 (1980) - 917-923.

Sanjuan, B. :Use of a new Sodium/Lithium (Na/Li) geothermemetric relationship for high-temperature (HT) geothermal fluids derived from seawater/basalt interaction processes : application to the Djibouti case. ArgeoConference, Djibouti, 21p.(2010)

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

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

Varet J. &Gasse F.: Geology of central arid meridionalAfar. Ed. CNRS, 140 p.(1978)

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

Varet J.: Proposal of Djibouti for ICDP: the Obock and Rouéli sites, ICDP workshop, Iceland, (2012)