

## The Obock and Rouéli Geothermal Sites, Djibouti Republic

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### 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 in 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 as paralleling the ridge. This means that an important heat source is available from the shallow anomalous mantle and active volcanism on the spreading sea floor (1500m deep in Tadjourah trough) very near to the coast.

Near to 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 - gets very close to the transverse faulting linking at depth the Obock and Tadjourah troughs.

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 TADOURED in 1995 (Hebert, 1998). From the latest studies, it was shown that the direction of spreading is oblique with respect to the rift as well as to the transform faults, and that both have hence an opening component (Dauteuil et al. 2001). It means that a shallow hot, anomalous, and magma generating mantle, 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 temperature of 210°C for the geothermal reservoir Obock (Houssein et al. 1993, Sanjuan, 2010).

The high degree of recent faulting and the currently important seismicity let envisage 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 need of the local population, presently (only very partly) answered by diesel engines in Obock and Tadjourah, and in the future in order to serve the railway line and port linking central-northern Ethiopia to the sea through central Afar. In addition to such promising perspectives for geothermal power production, these sites appear also particularly appropriate - and eventually unique in the world to this respect - for attempting to drill deep (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.

### INTRODUCTION

Two regions of the world allow reaching on land geologically oceanic sites; that is Iceland and Afar. 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 superheated 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 our knowledge, this is the only place in the world in which this can be achieved. This would pave the way for a sustainable exploitation of Mid-Oceanic Ridges in the great future.

### 1. GENERAL ENVIRONMENT OF THE GEOTHERMAL SITES

Djibouti Republic is presently a low-income country, located in one of the most arid climatic environment. 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 if it can answer 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 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 strait. 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<sup>2</sup>, the Obock prefecture is dominantly a pasture land for the nomadic Afar population, but it also offers perspectives in the field of fisheries and eventually mineral resources 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 both by the asphalted road, with a long detour around the Gulf through Ghoubbet-Asal rift, or directly by boat. This proximity allows to consider these coastal sites as suitable candidates for the delocalization of part of the activity of the port of Djibouti, notably trans-boarding (figure 1).

Of course, in such a perspective, the water and energy issues are capital. Although gifted with a quite arid climate, the town of Obock is located on the delta of the large Ouaddi Sadai, 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 good hydrothermal indices are 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 was carried on this site yet. Our objective is at first to develop first (2013-2015) a conventional high enthalpy geothermal energy project, in order to serve the local present and future needs, and to prepare in the same time for an ICDP project to be undertaken later on this site (2016-2020). Coupling both projects would help to better evaluate and proceed to the optimal development of this geothermal potential, starting with a small well head plant, allowing for further conventional high enthalpy developments, and later catching superheated technologies.

## 2. GEOLOGICAL FRAME OF THE OBOCK REGION

### 2.1. Previous geological studies

Although located in an arid, underdeveloped region, the area is already rather well known due to field geological works undertaken mainly in the years 1960-1990, whereas more recent (last 10 years) geophysical and oceanic scientific researchers are also available: A 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), regional geophysics (Friedman, 1990). A continuous monitoring is also ensured by the permanent seismic regional grid (CERD and IPGP)



**Figure 1: main geographic features of the Djibouti republic (obock geothermal field and roueli geothermal field in blue and black)**

The geophysical survey carried by CGG in 1960 around Obock used Schlumberger electric profiles allowing a penetration depth of 200m. It allowed mapping 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, they allowed identifying the major geological units, to describe their composition and origin, and to provide absolute dating, allowing for a geodynamic interpretation of the evolution of the whole Afar and southern Red Sea region (Marinelli & Varet, 1973). Several theses were undertaken, allowing to understand 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 offers a good geological knowledge of the geological formations to be encountered at 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 to Obock. The thesis of Dr. Houssein precise the rock-water interactions using the chemistry of the thermal waters, and show that the hot component at the origin of Obock thermal water is at a temperature of nearly 200°C, at (unknown) depth.

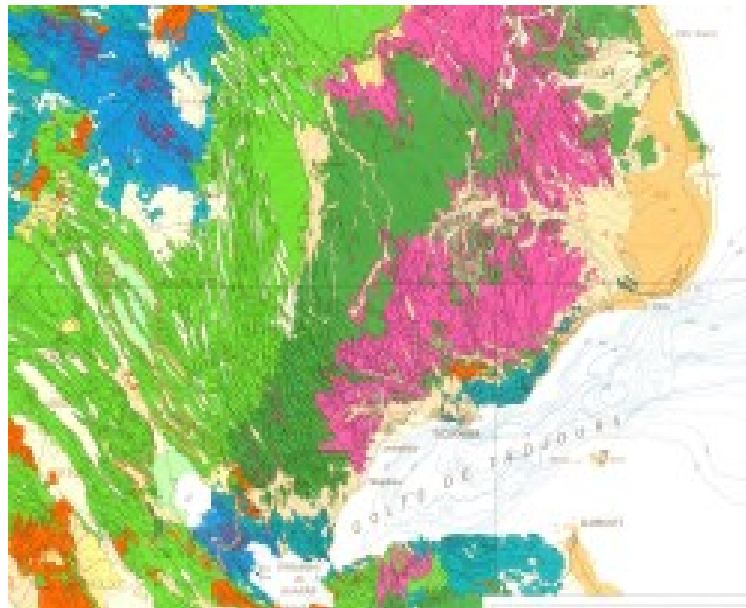
Oceanographic surveys allowing mapping the extension of the oceanic ridge of the Gulf of Aden through the Gulf of Tadjourah, and were newly interpreted by Dauteil et al. (2001) in terms of oblique spreading.

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

## 2.2. Main geological formations

The geological formations present in Obock and Rouéli area 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 of which not dating more than 3Ma, and the process being 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 at intermediate depth, underneath the recent quaternary sediments and basalts immediately surrounding the Gulf and the production of which is resulting from its initial opening. These are:

- The important rhyolites event of Mabla, which dominate the immediate surroundings, in the hills North and West of Obock. These are pyroclastic layers and massive flows, dating back 11 to 16 Ma, and affected by an extensive tectonics in the NNW-SSE (Red sea) direction. These lavas are 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 a 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. This 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.



**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 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.

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) are 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).

- 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 upon 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 first 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); coralline plateau covering the whole coastal zone is observed (orange). They are faulted & lifted up toward SE. The initial basalts of the gulf (blue-green) are affected by a double ENE & NW extensional faulting, well developed around Roueli cape, well-fitting with the ridge tectonics (see bathymetry)**

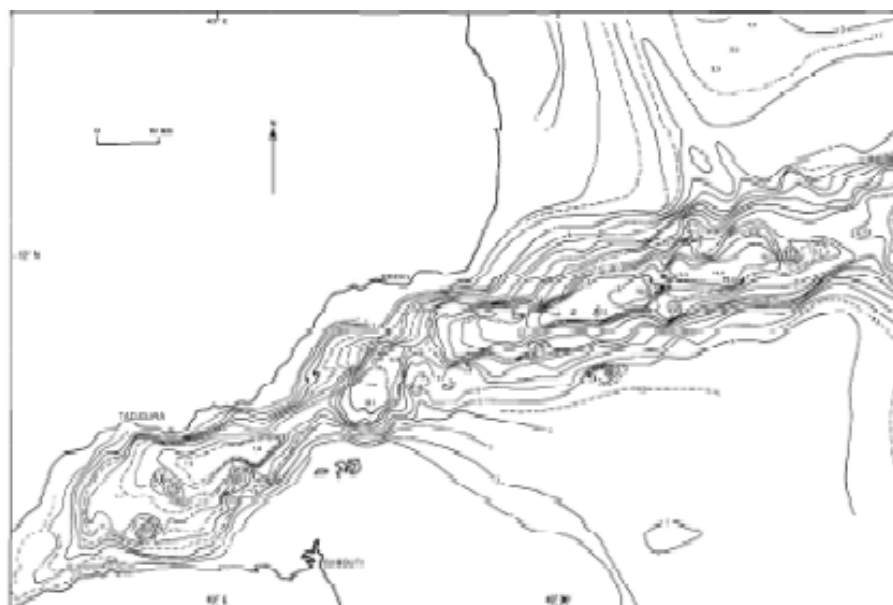
The outcropping coralliferous plateau of Obock (orange on the map) was dated 100.000 to 150.000 years. It extends up to 4 Km inland. This carbonate formation is well developed and underlies the town. It is a good building material, eventually suitable for cement production.

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

### 2.3. Oceanographic and geophysical frame

According to the vicinity of the active geodynamic axis of the Gulf of Tadjourah, and to the lack of surface volcanic manifestations, our attention needs to be drawn on the submarine areas bordering the Obock coast.

The oceanographic TAJOURADEN campaigns carried in 1977 and 2000 (Dauteuil et al. 2001) allowed drawing the main characteristics of the geology of the active part of the Gulf (figure 4). Oblique spreading explains the extensional nature of the transform faults and transverse tectonics in general.

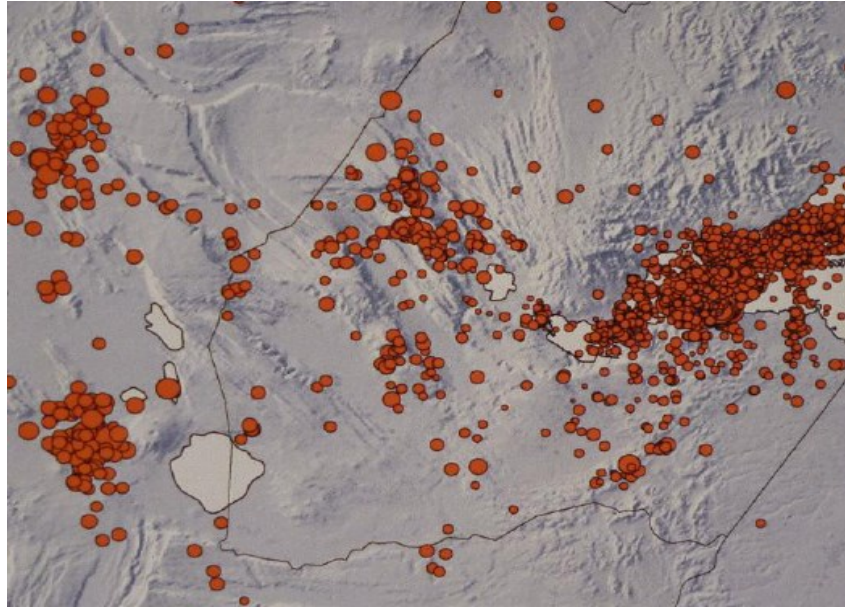


**Figure 4: Axial valleys of Aden Gulf extend in the Gulf of Tadjoura in the vicinity of Obock and tadjoura**



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 4). Near to Obock, 3 such rifts trending WNW-ESE are separated by transform faults of SW-NE direction. The most important is the Obock trough, the depth of which reaches 1500m. These axial valleys floors are carpeted with basaltic volcanoes aligned along the axis. 375 craters could be numbered, out of them 50 with calderas. A central volcano 8 Km in diameter was identified south of Obock. The faults bordering the Obock rift to the north extends in land 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 determine 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 (see figure 3).

As observed in figure 5, the Gulf of Tadjourah, which marks the present active plate boundary between Africa and Arabia, is subject to intense and active seismic activity, 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 Rouéli 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 Tadjoura between 2005 and 2010**

### **3. PROPOSAL FOR DEVELOPPING GEOTHERMAL SITES AND FURTHER DEEP DRILLINGS**

#### **3.1. Observing inside the active spreading mechanism and magmatic heat source**

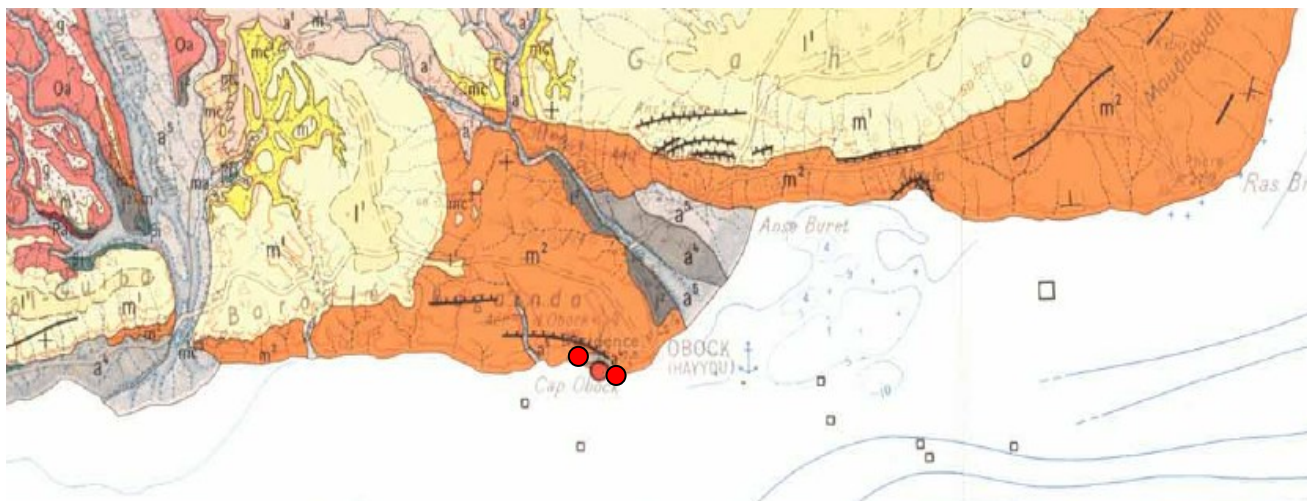
Following the above mentioned observations, it is possible to assess that the western extension of the MOR of Gulf of Aden is at a sufficiently short distance that it can be reached by deviated drilling from the coast. Deviated research wells are proposed to be undertaken with 2 objectives: 1. Reach a conventional geothermal reservoir (200 to 250°C) at a depth of circa 2000m for geothermal power generation answering local future needs. 2. While pursuing a deep under ICDP, help understanding spreading mechanisms, magma generation and 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 to reach the base of the rift system whereas from Rouéli, a leaky transform fault can be crossed allowing to touch from inside both the shear and extensional faulting. Two heat sources can be expected: in addition to the hot anomalous mantle (1300°C) located a few kilometers deep, 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.

#### **3.2. Hydrothermal activity and indices for a geothermal reservoir**

The two sites, both are located along the coast, display hydrothermal emergences that were identified, 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 6). 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.

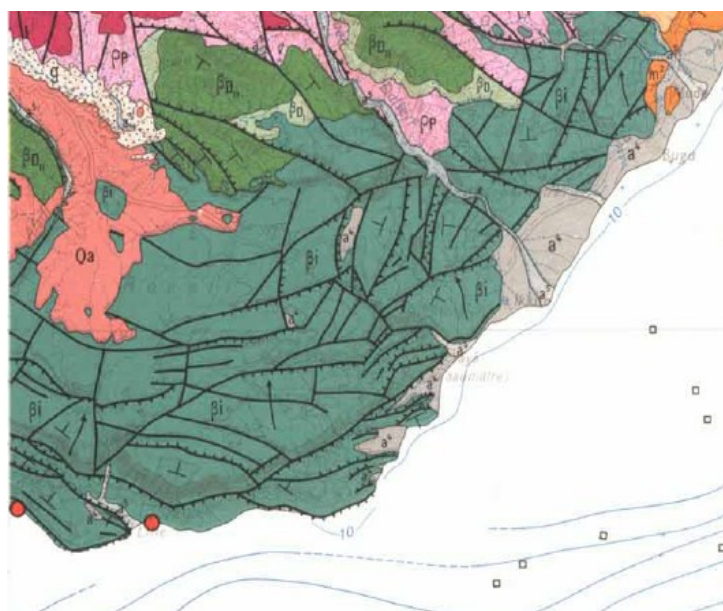
The second is located in the Rouéli massif that marks a prominent part of the cost line between Obock and Tadjourah. Several sites of thermal emergences (mainly gas and steam vents), the surface temperature of which do not exceed apparently 50°C were identified by Aquater (Vol.II, 1981), notably between 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 on figure 7.



**Figure 6: Zone of Obock thermal emergences aligned along a normal fault parallel to the axis of nearby mid-oceanic ridge**

As one can 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 show temperatures of 210°C, and 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). Water components are 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 are also observed that favors the development of the characteristic vegetation (Fiale). The liquid part of the thermal emergences may also result from condensation of the steam at shallow depth. But the field observations did not allow yet for hydrothermal deposits to be identified. Geothermometers indicate temperatures 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 evidences for 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 thermal emergences of Rouéli between Obock and Tadjoura, with Location of springs reported on the Djibouti geological sheet (ORSTOM-ISERST, 1984), From Aquater (1981) and our own observations.**

## ANALYSES CHIMIQUES DES EAUX HYDROTHERMALES D'OBOCK

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

Les concentrations sont exprimées en meq. l<sup>-1</sup>.

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.

Table.1: Chemical analysis of thermal waters of Obock (Sanjuan2010)

Geothermal area	Sample	T °C	T <sub>Na/KM</sub> °C	T <sub>Na/KF</sub> °C	T <sub>Na/KCa</sub> °C	T <sub>K/Mg</sub> °C	T <sub>Qz</sub> °C	T <sub>Qz vapor</sub> °C	T <sub>Chalc</sub> °C	T <sub>Na/Li</sub> °C	T <sub>sol</sub> °C	1000/T <sub>sol</sub>	log(Na/Li) molar
<i>Djibouti</i>													
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
<i>Iceland</i>													
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

Table.2: Chemical analysis and geothermometric interpretation of thermal waters of Obock compared with Icelandic geothermal waters (Sanjuan, 2010)

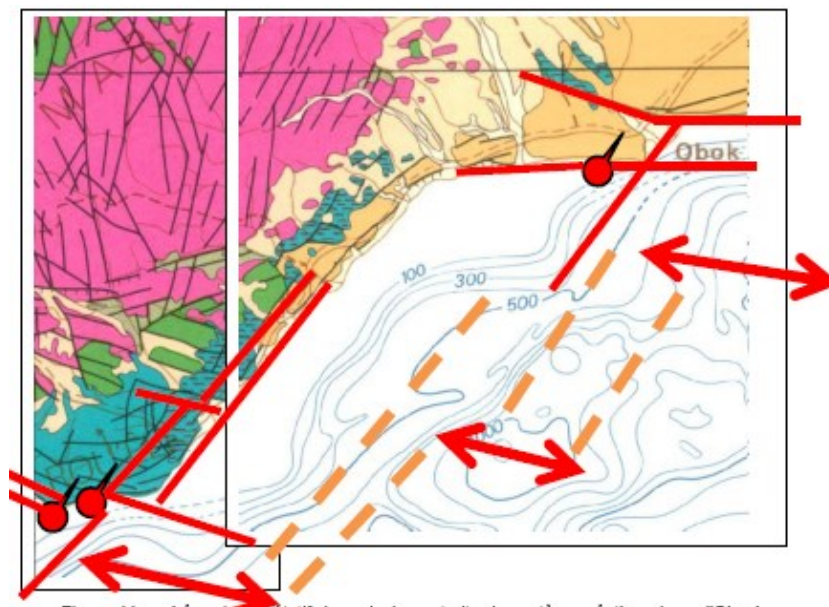
### 3.3. Tentative elaboration of a hypothetical geothermal model

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 8, 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). One should note 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. They are hence also generating magmatic heat of mantellic origin (leaky transform faults). Therefore we expect on both sites of Obock and Rouéli a nearby anomalous mantle at 1300°C, located - according to seismic evidence - at a depth not exceeding 6 to 7 kilometers. 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: Interpretation scheme of the major determinants of the Obock geothermal system: heat source located along the axial (WNW-ESE) volcanic rift zones of oceanic floor (double red arrows), transverse fractures (NE-SW) of transform faults (orange discontinuous lines) that 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 hence well be located at a depth of the order of 1.000 meters, and should 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 fracture developed along both WNW and NE directions, reactivated by the present seismicity is offering a particularly favorable context for the possible development of a geothermal reservoir. Higher temperature supercritical reservoirs are expected to be found 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 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.

#### 4. PROPOSAL FOR A GEOTHERMAL DEVELOPMENT PROGRAM

Before geothermal fluids can be used for electricity and heat generation, preliminary studies need to be conducted in order to precisely determine the physico-chemical characteristics of the geothermal field, to be reached by drillings. This implies to undertake notably more detailed geochemical sampling of the thermal springs (including new emergences to be 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 in order to better 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 aim to determine the following elements:
- Establish a provisional geological section (to be used to determine 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 physico-chemical characteristics of the geothermal fluids.
- Locate precisely the wells and determine their characteristics (directional drilling notably).

We have shown above that if according to data available allow to emit hypothesis on the existence of a geothermal potential and to draw a hypothetical model, the necessary information is still lacking in order to establish a sound drilling program. Specific studies need to be conducted, namely specialized geological, geochemical and geophysical investigations in order to plan the drilling and production test program. The geothermal exploration will be handled in 2 phases:



#### 4.1. Phase 1 (prefeasibility)

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

These will mobilize Djiboutian staff as well as geothermal experts of international reputation; in order to assess 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 allow establishing provisional geological sections for the wells sites. Precise stratigraphic logs will be established in order to establish the drilling program and in particular the geothermal reservoir (physical-chemical parameters and production depth).

**Geochemistry:** fumaroles, hot springs and other water emergences will be sampled and analyzed. This will allow to establish the nature of the aquifers and their link, and to deduce the temperature of the reservoir from geothermometers. Isotopic studies will also be undertaken in order 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: 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 carried out. Their interpretation will be essential for establishing the drilling program.

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

*This phase 1 is to be considered as a research project, and to be financed under non-refundable source*

#### 4.2. Phase 2 (feasibility)

Undertaking at least one, and up to 3 exploration wells at up to 2 Km 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 the phase 1 will allow determining the characteristics of the exploration drilling and test program of 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.

#### 4.3 Phase 3: construction of the power plant

If the exploration wells were drilled with a diameter sufficient for geothermal production (7 to 9 inches), the producing ones will be used directly for the production of electricity in order 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 need to be drilled in order to reach the requested 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.*

### 5. PREPARING FOR THE ICDP PROJECT

#### 5.1. How the Obock-Rouéli site fulfills the ICDP criteria

**Global Criterion:** The area located around Obock, on the northern shore of the Gulf of Tadjourah (Djibouti Republic) allows to tackle a unique geodynamic environment which will allow to solve problems of global significance: the possibility to directly touch an real oceanic ridge, by direct drilling onshore from a continent. Although unique, this is without doubt an opportunity for better understanding the actual geological structure of mid-oceanic ridges (MOR). This would moreover be an attempt for 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. To these respects, this is a real “World-Class” Geological Site!

**International Criterion:** Afar region is already as a whole a geological site of major international significance, with important works developed there by German, Italian and French scientific teams since the years 70-80', with a renewed interest in the last 6 years due to the Manda Harraro – 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 concept of the present project, this would be a real opportunity for pooling of resources and technology towards off-shore exploitation of MOR geothermal resources.

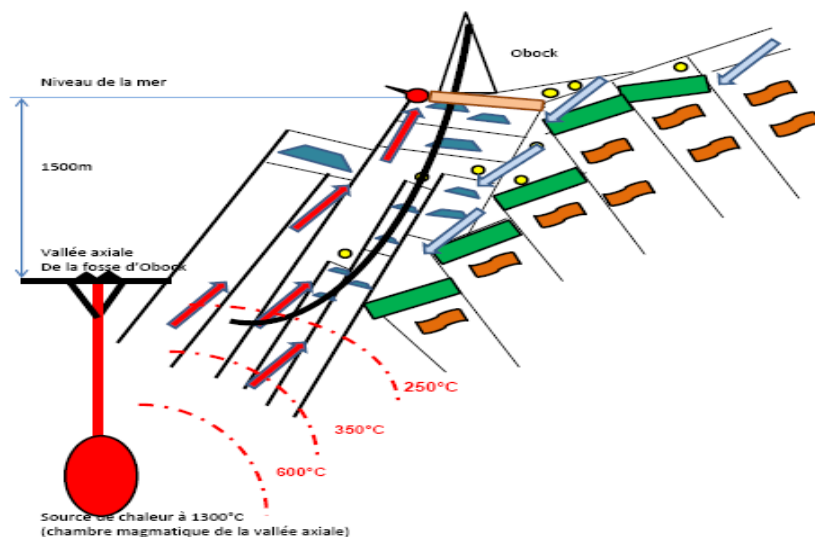
**Societal-Needs Criterion:** The relevance of the problem of geothermal power production to society is of no doubt for the people of the country itself, as an immediate answer to presently unsatisfied needs. But in the long run, the incidence is of course much larger and concerns the people of the earth as a whole in its capacity to rely upon renewable, reliable and clean energy sources. No doubt in such circumstances that the collaboration with industry will represent an attractive target even if, 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 scientific works (geology, fluid geochemistry, geophysical hydrographic and oceanographic studies) still needs to be précised, there is no doubt that deep deviated drilling is the only way to directly touch the actuality of the problems remaining 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 really after the actual functioning of MOR is of major scientific interest, and that approaching this question with view of future economic developments (notably power production, but also eventually several minerals) is also valuable, there is no doubt that the site proposed is optimal in terms of depth-to cost criterion. This point however still needs to be better quantified through further engineering and economic studies. Balancing of costs and drilling design remains to be established although preliminary approach is made available in the following pages.

## 5.2. Specific works to be engaged before deep drilling

Before deep research drilling is engaged in Obock and Rouéli area, specific complementary work need to be engaged. Some could be done under exploration programs to be developed for geothermal resource assessment. As seen in part 4, partners are at present searches for by the Ministry for a prefeasibility (surface exploration allowing 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 to be developed 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-SE) 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 is under the sea floor

## 5.3. The deep deviated drilling (up to 5000m length)

The deep wells sites under ICDP will be located and their characteristics defined on the base of the above results. Up to 2 wells, one at Obock, drilled with an inclination in a southern direction, in order to penetrate underneath the axial valley of the MOR, and the other at Rouéli with a eastern direction, in order 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 a better knowledge. But the action plan should be determined by a proper ICDP workshop, the main goals of which should be:

1. Formulate focused Scientific Objectives
2. Define specific Operational Targets
3. Form an active and convincing Scientific Team and Project Structure
4. Draft Plans incl. Funding-, Budget-, Operations-, Management- Plan
5. Write and Submit a Full Drilling Proposal to ICDP and other agencies

## CONCLUSION

The Obock-Rouéli area is 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 fulfill 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, a 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 allow to justify drilling targets and to reduce drilling risks

Technical Feasibility and Budget Realities still remain to be precise.

Environmental and Societal Compliance will not pose problem. The population is expecting such developments directly impacting the quality of their lives. Acceptance and Support through National Authorities is early 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 like to participate to such. This will allow to establish Best Possible Science Teams and to contribute to the Educational Potential, notably by supporting PhD thesis.

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