

STATE OF KNOWLEDGE OF THE GEOTHERMAL PROVINCES OF THE REPUBLIC OF DJIBOUTI

JALLUDIN Mohamed

Centre d'Etudes et de Recherches de Djibouti (CERD)

P.O. Box: 486

Djibouti, Republic of Djibouti

Email: cerd@intnet.dj

ABSTRACT

Owing to an exceptional geodynamic situation, the Afar Depression, an emerged triple junction of the Red Sea, Gulf of Aden and East African rifts, where volcanic and tectonic activity occurs since 30 My, the Republic of Djibouti (23000 km²) is characterized by numerous current and past hydrothermal activities. Schematically, the country can be divided in two sectors, westward regions composed of plateaus and plains formed since 3.4 Ma and Eastward regions elevated and mountainous lands separated by the Gulf of Tadjourah ridge. Most of the current hydrothermal activities are located in specific zones of the recent western regions formed by the opening of the Afar Depression and the Danakil plate anticlockwise movement. Few other current and past hydrothermal activities are found in the Eastern part around the Gulf of Tadjourah ridge. Already in the early geological explorations these hydrothermal manifestations were described as a result of potential geothermal resources.

Surface explorations based essentially upon geological, tectonic and geochemical studies have identified the geothermal provinces of the country. All of the surface manifestations are fracture controlled and occur within the recent volcanic and sedimentary rocks or at the contact of recent and old formations. As a result, Asal rift, Nord Goubhet Hanle and Gaggade areas were determined as priority sites for geothermal explorations. Therefore, gradient wells and geophysical prospections were undertaken at different stages to assess geothermal reservoirs. Deep drilling programmes revealed a high enthalpy reservoir in Asal rift zone and a low enthalpy reservoir at medium depth. Results in Hanle plain demonstrated low temperatures caused by a high underground fresh water flux.

Although potential geothermal reservoirs have been recognized in the Republic of Djibouti, the power generation from geothermal energy is still to be achieved. The next step for the geothermal development programme is the regional ARGeo project. The first phase for this project is to complete the exploration in Asal rift area and begin the power generation. The next phases will focus on other geothermal sites as Obock and Gaggade first.

1. INTRODUCTION

The Republic of Djibouti is one of the several African countries located on the East African rift system where geology is also resulting from the two other ridges of Red Sea and Gulf of Aden. Such a particular geodynamical situation gives to the area a remarkable position for the development of the geothermal energy. Effectively, the underground heat sources are expressed on the surface by numerous hot springs and fumaroles mainly distributed on the Western part of the country and along the Gulf of Tadjourah ridge. In spite of the significant geothermal studies and the deep drilling explorations conducted

since 1970 on several geothermal prospect zones, the geothermal energy in Djibouti is still to be developed.

This paper summarizes exhaustively all the geothermal explorations undertaken in the Republic of Djibouti. The most advanced exploration prospects, recognized by deep drilling, are first described and analysed: Asal rift and Hanlé. Secondly, the Nord-Goubhet and Arta prospects are presented for their relatively complete surface studies. Finally, the other potential geothermal zones are summarized with a more detailed presentation for Obock and Lake Abhé prospects.

2. GEOLOGY

The volcanic series overlie the basement rocks (Jurassic limestone and Cretaceous sedimentary rocks) as a result of the Red Sea, Aden gulf and East African rifts triple junction system, related to plate tectonic movements in the last 25-30 Ma. Adolei basalts characterize the first rupture movement within the Arabo-Nubian block which occurred during the later Miocene period (Figure 1). During these first movements the area is under an Ethiopian rift tectonic pattern with N-S extension faults system (Gaulier and Huchon, 1991). There then followed a period of slow expansion during which the Mabila rhyolites outcrop formed (15 Ma) in a large sinistral shear zone. Oldest Ethiopian structure oriented N-S to N20°E is reactivated as sinistral strike-slip faults. Mabila rhyolite located in the Northern part of the country was then submitted to a diffuse extension phase with associated N160°E normal fault system. After an interval during which these rhyolites were eroded, the Dalha basalts were laid down with an angular unconformity (3.4 - 9 Ma). The Somali basalts outcrop was formed practically contemporaneously in the eastern part of the region. N160°E extension links to early movements during the emplacement of Dalha basalts. Progressively this extension turned to N20°E. Between 3.4 and 1.5 Ma, the Stratoid basalts and Gulf basalts poured out as the Gulf of Tadjourah opened (Black et al., 1974; CNRS-CNR 1973). At the early stage of the opening of the Gulf of Tadjourah the western border of Ali Sabieh horst acts as a wide dextral strike-slip zone with related N-S to N20°E extension which turned to N40°E. Recent volcanic formations are mainly located in the Asal rift and the Manda Inakir rift.

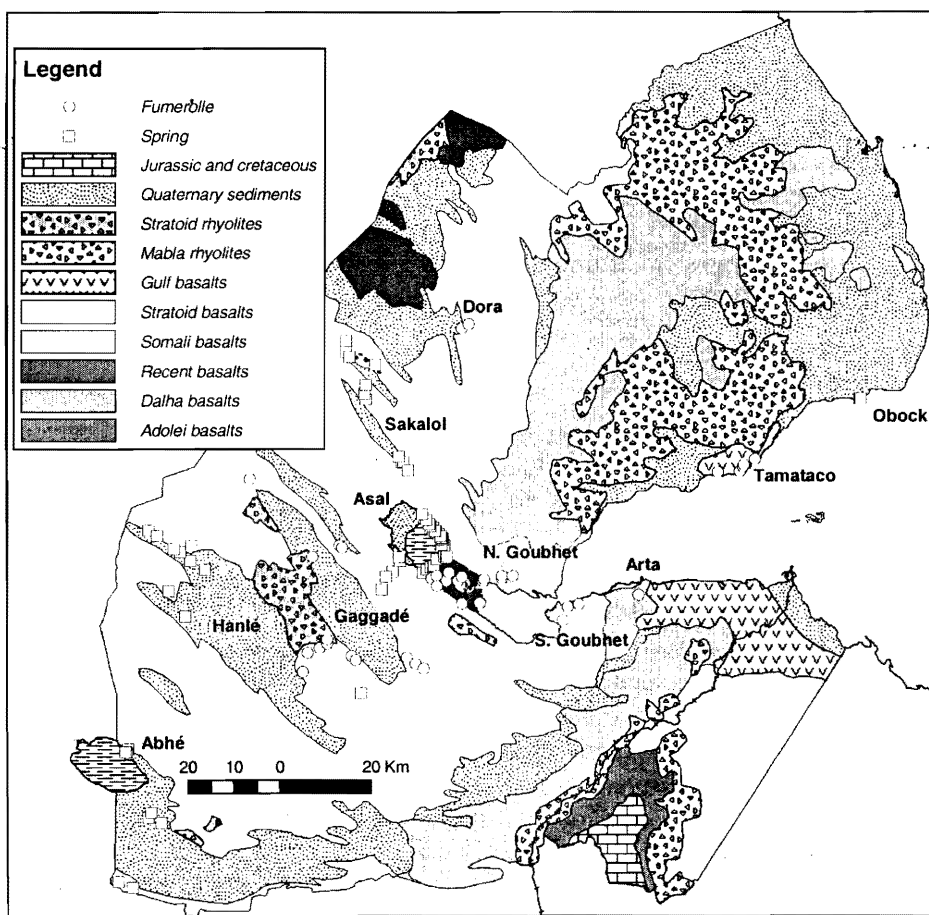


Figure 1: Geology and hydrothermal activity of the Republic of Djibouti

Sedimentary rocks are encountered in coastal areas, in tectonic basins in the south-western part of the country and along the main stream beds. During the Miocene Pliocene, sedimentary rocks (clays and alluviums) are interbedded in Dalha basalts. Alternative humid and arid climates went through the Pliocene period with the outcrop of stratoid basalts. Limestones, clays and diatomites are interbedded in these basalts and fill tectonic basins. In the plains, the thickness of the sedimentary rocks can exceed several hundred of meters and in stream bed it remains between some meters to some tens of meters. During the quaternary period, marine sediments (coral limestones and limestones) were deposited in coastal areas. Since 100 000 years BP five phases of major extension of lakes in the tectonic basins were developed during the humid climates and has formed limestones, diatomites and clays outcrops (Gasse et al., 1980).

3. ASAL RIFT EXPLORATION

3.1 Geochemical origin of the springs and the geothermal reservoirs of Asal

Few geochemical studies were undertaken in Asal rift zone to understand the origin of the numerous springs and the geothermal reservoirs fluids (San Juan, 1990; Fouillac et al. 1983; Fontes et al., 1980; 1989). Several groups of springs are identified in the Asal area: Manda springs are located on the Eastern side of lake Asal where Korili spring is considered separately, wadi Kalou springs in the Southern part of lake Asal, Alifita and Eadkorar springs on the Northern side of the lake.

The analysis of the correlations between major elements associated to the study of trace elements as lithium, strontium, bromine and borum, and to the strontium isotopes allowed to show that the fluid compositions can be explained by the sea water-basalt interaction and by evaporation (San Juan 1990). The absence of any anomaly in the bromine/chloride ratio confirms that evaporites dissolution does not intervene significantly in the fluids composition. A vapour dominated geothermal reservoir can be supported by the low value of the borum/chloride ratio.

All the springs chemical composition analysis show a sea water relationship except one, located in the Kalou waddi in the Southern part of the lake Asal. The latter would have continental water that has reacted with basalts. The geothermometer gives a maximum of 100°C very close to the emergence temperature. Other springs from Kalou and Korili show also a mixing with Lake Asal and sea water. The degree of interaction with basalt is more or less intensive for each group. This is accordingly to the advancement of the reaction or to the mixing of variable proportion between water that has reacted intensively and sea water that has poorly reacted with basalts. It has been shown that the hypersaline water of lake Asal contribute also to the reservoir fluids.

Given the sea water mixing, the geothermometer Na/K could not reveal suitable results. The calculated temperature is lower than 100°C except Eadkorar springs. Equilibrium between water and rocks components has been reached only in the reservoir fluids. Therefore, the superficial water circulations would not be in direct contact with the reservoir fluids, either there is no contact or this contact is limited and followed by equilibrium. Evaporation is the other factor that must be taken into consideration to explain the fluid composition. It has been globally evaluated on the basis of the concentration by evaporation and dilution by the meteoritic waters. Deuterium and ^{18}O relationship shows the effect of evaporation on the fluids. It describes also the mixing of the fluids with sea water and Lake Asal (Fontes et al., 1980).

3.2 Geophysical surveys of the Asal rift

Gravimetric survey points out several heavy body anomalies having different dimensions (CFG, 1993). Those located in the central part of the rift are correlated with the injection of magmatic chamber and the collapse of the ground. Locally small anomalies could be the result of an intensively fractured zone. The comparison with the aeromagnetic data and the gravimetric modelling, with the help of geothermal data, demonstrate the existence of a basement represented by the old Dalha basalt series, splitted in several compartments delimited by intensive fractured zones.

Accordingly to the AMT method, the investigation depth was limited and did not exceed 400-500 meters thus unavailing characterisation of the deep geothermal reservoir and the shallow reservoir BRGM (1979; 1983). However, the different interpretations of AMT data bring out a fairly good correlation with the previous methods in determining the interface, representative of the Dalha and stratoid basalts contact.

The EM survey has also a limited investigation depth in the order of magnitude of few hundred of meters (Orkustofnun, 1988). The survey was mainly focusing on the Eastern-central part of the Asal rift in the continuation of the well Asal 5. Results presented here are from the interpretations of Orkustofnun and BRGM. An "upflow" has been demonstrated in the "lava lake" area based on a supposed hydrostatic level higher than sea level and the absence of high resistivities in depth. The top of the conductor body delineates the groundwater flow gradient toward the lake Asal from the Goubhet, sea water. The latter follows the form of the heavy body identified by gravimetry except in the positive wells area in the Southern part where the geological context is different. The analysis of the difference between the resistant layer and the heavy body altitudes establishes the location of heavy and conductor bodies in the zone of Fiale, which configuration could be of interest for the geothermal exploration.

Previously, another EM method called MELOS was applied by BRGM (1973) to contribute in the first exploration wells location. Although the method has a low investigation depth it has pointed out a superficial elongated conductor anomaly on which the first Asal1 well was located successfully. This anomaly is correlated with a main fracture zone in the Southern part of the Asal rift on which several hyaloclastite complexes are recognized. Two conductor anomalies are identified close to Lake Asal and Goubhet probably in correlation with the sloping of the gravimetric interface. The third conductor anomaly is located in the productive wells area and therefore it could express a possible extension of the geothermal reservoir.

The contribution of the electrical rectangle method (BRGM, 1983) supports mainly the previous interpretations for the superficial structure. It corroborates fairly well the gravimetric interface for the Northern resistant anomalies behaviour. Such correlation is not apparent in the productive well area where the conductor characteristics is more to be related to the geothermal reservoir existence as pointed out by the MELOS method.

Two magneto-telluric methods, MT5EX and low frequency, were applied with a limited number of stations. Only the first one could bring out interesting results in comparison with the electrical method (CFG, 1993).

The seismicity completed by seismic reflexion and PSV methods was also analysed (CERD-IPGP; Hirn et al., 1988). It appears that the geothermal reservoir(s) identified in Asal1 area has a fractured origin and located on the intersection of main faults. Secondly, 2000 to 2300 m below well Asal 4, which has reached a maximum depth of 2013 m, numerous and significant anomalies would correspond to the top of a geothermal reservoir. Finally, the observed seismicity is exclusively concentrated in the "lava lake" area between 2500 and 3000 m depths. This activity would be explained by the interaction between the top of a magmatic chamber area and water circulations.

As a conclusion, although significant results were obtained for some structural and geometrical settings in the Asal rift based on various geophysical methods, questions on

the geothermal reservoirs extensions remain unsolved, either for the deep or the shallow one, respectively at 1000 m and around 700 m depths. This is explained by the limitations of some geophysical method which investigation depth is low. However, their results allow to more adequately programming new geophysical surveys, mainly based upon electro-magnetic methods.

3.3 Deep drilling findings in the Asal rift

Six wells in Asal have various depths between 1137 m and 2105 m (AQUATER 1989; BRGM 1975a, b). Asal 1, Asal 3 and Asal 6 are in the same area, within an explosion crater of hyaloclastites. Asal 4 and Asal 5 are located toward the central part of the rift. They encountered the superficial underground flow toward Asal between 250 m and 280 m. The stratigraphic analysis and the geological cross section are in good accordance with the general geological settings (Figure 2). The geological series are found up to the Dalha basalts and it is assumed that Mabla series appear down the hole of Asal 4 (CFG 1988). The authigenic mineral assemblage is in good agreement with the measured temperatures in five of the six wells (Zan et al., 1990). Asal 4 is almost well correlated for the two first levels of Asal series and stratoid series, meanwhile Asal 5 in the central part of the rift do not allow any easy correlation. Two clayey layers, Pleistocene and Pliocene, mark the separation of the three principal stratigraphic units, Asal series, stratoid series and Dalha basalts, in the area of Asal 3, Asal 6, Asal 2 and Asal 4.

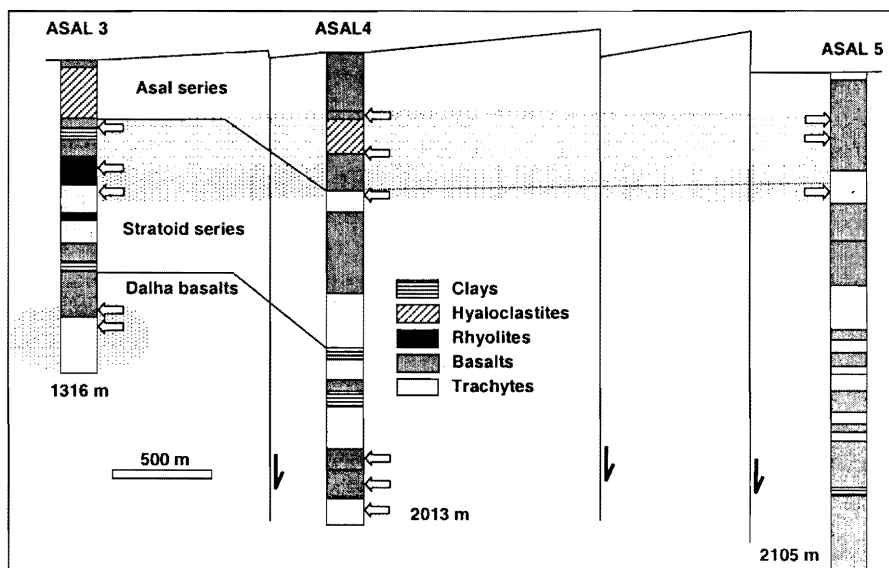


Figure 2. Interpreted cross-section in the Asal Rift Zone

The temperature profiles of Asal 3 and Asal 6 are almost similar and show one intermediate and one deep reservoir, while the latter do not appear on Asal 4 and Asal 5. The significant inversion on the temperature profile of Asal 5 might be explained by the superficial underground flow toward lake Asal which goes deeper on this well. The flow at higher temperature and at intermediate depths is fed most likely by geothermal fluid circulations in major tectonic faults bordering the central part of the rift. The deep reservoir has been tapped by Asal 3 and Asal 6, the first being located 40 m East of Asal 1 and the second 300 m North-West from Asal 3. Its permeable levels on Asal 3 are at 1075 m and between 1225 m and 1250 m, and on Asal 6 they are between 1100 m and 1300 m. The

bottom hole temperatures are respectively 263.5°C and 280°C. At high depths, Asal 4 and Asal 5 exhibited low permeability levels, between 1725 m and 1775 m, and between 1950 and 2000 m for the first and between 2000 m and 2050 m for the second. Their bottom hole temperatures are 345°C and 359°C.

As the objective of the different geothermal drilling explorations was the deep high enthalpy reservoir, the intermediate geothermal reservoir in the Asal rift zone was neglected and only few data are available. Asal rift is between Goubhet and Asal lake (150 m below sea level) thus an important underground flux of sea water occurs in the upper part of the recent volcanic series toward lake Asal mainly through the opened fractures. Below the superficial reservoir and before the deep high enthalpy reservoir all the six drillings in Asal encountered the intermediate reservoir (ENEL, 1990; Jalludin, 1992). According to the stratigraphic analysis of the six well logs, stratoid basalts and rhyolites, and the lower part of the recent volcanic series constitute the intermediate reservoir between 240 m and 600 m depth. In the central part of the rift, zone of Asal 4 and Asal 5, the reservoir is mostly composed of recent basalts of Asal characterized by a high degree of permeability related to the fractures, scoriaceous layers and also holes. In the Southern part of the rift, zone of Asal 3 and Asal 2, the reservoir is represented by the top of the stratoid basalts and rhyolites known for their high permeability too. According to the drilling observations, the rhyolites seem to be the most permeable layers.

The association of the geophysical results to the well log data suggest the presence of the intermediate reservoir with certain continuity in the Asal rift area, which is not the case for the deep reservoir (CFG, 1993; ENEL, 1990; Orkustofnun, 1988; Hirn, 1988; Jalludin, 1992). On the wells Asal 1, 3 and 6 temperature profiles describe two anomalies: one related to the deep reservoir and the second between 300 m and 600 m. The temperatures are about 140°C for the upper anomaly which is correlated with circulation losses during drillings. The highest temperature for the intermediate reservoir is yielded on well Asal 5, 190°C, in the central part of the rift. A thermal study on the superficial underground flow from Ghoubet to Lake Asal and the thermal leaching, and the comparison to the spring's temperatures at the lake of Asal result in a substantial balance between the removed heat and the geothermal flow (ENEL 1990). From this it follows that the lower intermediate reservoir with temperature range of 140°C to 190°C must be thermally protected. Chemical analysis of the reservoir fluid evaluated the total dissolved solids at about 50 g/l which is at least half of the deep reservoir total dissolved solids. These characteristics are particularly interesting from the scaling standpoint.

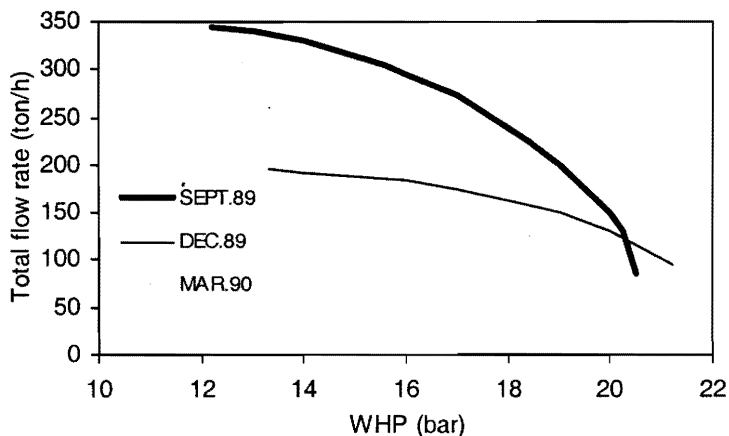


Figure 3: Successive output curves of the well Asal 3

3.4 Production tests and well testing in Asal

The deep liquid-dominated reservoir was produced three times for more than nine months in total. At the initial stage the well Asal 3 evidenced high range of mass flow rates, as have been measured, 360 t/h for 12.5 bars at the well head with a production temperature of 265°C and a vapour fraction of about 35 % (AQUATER, 1989). But most of the time the output rate has remained between 160 t/h and 200 t/h. According to the temperature profiles, the productive zones are between 1000 m and 1300 m. The total dissolved solids content in the reservoir is about 116000 ppm and the non condensable gases yield for 1700 ppm mainly represented by CO₂. The analysis of the production data pointed out several changes in the reservoir and the well bore conditions during and at the end of the production: important decrease of the output (Figure 3), the bottom hole pressure dropped by 3.5 bars and scaling was observed in the well bore and the surface equipments. Scale samples analysis showed sulphides (PbS, ZnS) deposits at high pressure and amorphous silica with Mn and Fe at low pressure (BRGM, 1975; VIRKIR-ORKINT, 1990). Calcite deposits in low proportion have also been detected within the well bore. A caliper was run down and measured a maximum of 10 mm of scaling in the flash zone and around 6 mm to 8 mm up to the wellhead. Reservoir engineering studies (Battistelli et al., 1991) concluded that the Asal 3 output decline was related to a combined effect of the well bore scaling and the decrease in average reservoir pressure. The reservoir might be limited in extension by reservoir boundaries as a decline of the bottom hole pressure is observed. It is also demonstrated that the well bore scaling represents the main factor that constrains the deliverability of the well.

Well test data analysis has been conducted mainly with semilog, Agarwal, multirate drawdown and build-up methods (Figure 4). Transient pressure measurement was undertaken at 1075 m depth. Permeability-thickness product calculated from well test data gives 6.3 dm and 15 dm for Asal 3 (AQUATER 1989; Battistelli 1991; Jalludin 1996). Asal 1 and Asal 6 in the area of Asal 3 are characterized respectively by 2 dm and 5 dm. A low value of Kh has been obtained for Asal 4, 0.6 dm. It is assumed that the reservoir has a relatively high permeability in a limited area close to the well Asal 3 and the boundary effect is confirmed by the low permeabilities of Asal 1 and Asal 6. With a specific well test method Battistelli (1991) interpreted the behaviour of the reservoir as a double

porosity medium but noted that the permeability is in majority controlled by fractures as already pointed out by BRGM (1981). According to VIRKIR-ORKINT (1990) interference test in Asal 3 zone the storativity is low indicating an average porosity of 5% or less. From the available results it seems that the deep reservoir is limited to the Asal 1 area and does not extend in the transverse direction of the Asal rift. Locally the permeability could be high enough to sustain geothermal wells production but the average permeability would be relatively low in the Dalha basalts.

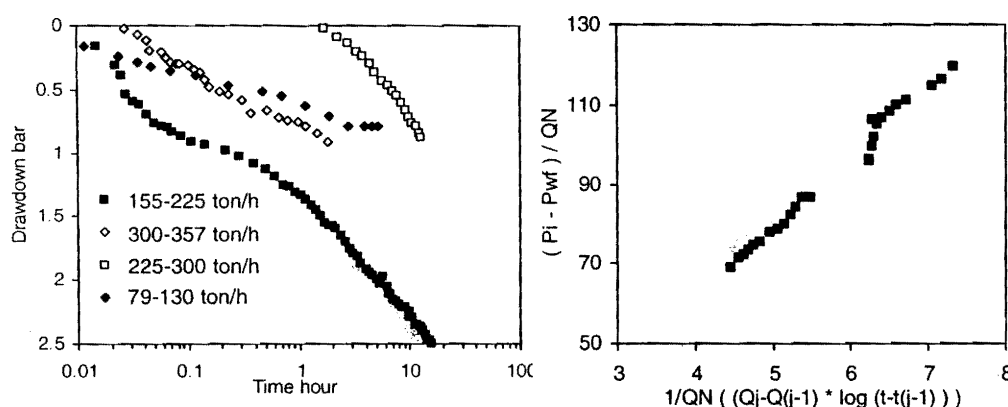


Figure 4: Drawdown and multirate drawdown curves of the well Asal 3

4. HANLE-GAGGADE EXPLORATION

4.1 Surface studies

The prospect site is located in the South-Western region of the country where stratoid basalts circumscribe a succession of high plateaus and sedimentary plains between Lake Abhé and Lake Asal. Within this wide zone several fumaroles and hot springs are identified in Lake Abhé area, Galafi plain, Eastern site of the rhyolitic Baba Alou mountain and along the Northern border of the Gaggadé plain. Temperature of the hot springs can exceed 60°C. The prospection included the plains of Hanlé and Gaggadé.

Geochemical studies undertaken by AQUATER (1981) recognized 5 hydrochemical groups that can be related to the different aquifers or can show mixing between them. The group 1 type is bicarbonated-earth-alkaline and exhibit low mineralization. It corresponds to the low depth waddi bed alluvium aquifers and is characterized by direct recharge from intermittent stream waters. The group 2 type is chlorinated-alkaline and represents all the boreholes catching the regional volcanic aquifer. Several springs located in Hanlé plain at the contact of sedimentary rocks and basalts fault scarps fall also among the same group 2. The springs in Lake Abhe area (Gobaad Plain) are characterized by chlorinated-alkaline-earth-alkaline type of waters and form the group 3. The latter may pertain to the group 2. The group 4 is represented by the sedimentary aquifers which waters type is chlorinated-bicarbonated-sulfated-alkaline. Finally, the group 5 correspond to the mixing of waters between group 1 and group 4, streambed alluvium and sedimentary aquifers. The geochemical anomalies in CO₂, NH₃ and H₃BO₃ allowed defining the ascending fluids mechanisms. On the basis of these hydrochemical analysis an underground water

circulation model is provided by AQUATER (1981). The schematic model suggests that there exist an important underground flow through the stratoid series which is recharged from the downstream valley of Awash river.

Geophysical prospection has been mainly based upon geoelectrical method (AQUATER, 1981) to assess the top of the stratoid basalts and the sedimentary filling thickness. Previous aeromagnetic data has been also considered and a seismic network was implemented to determine the seismic activity. The sedimentary filling, identified by low to very low electrical resistivities due to clays, has important variable thickness probably mainly controlled by the underlying Afar stratoid basalts faults system. This is illustrated by electrical discontinuities in the transverse electrical profiles and the resistivity map. Below this unit the study recognised the group "T" respectively resistant and conductor at its upper and lower part. Its thickness can exceed 200 meters. Deeper, a resistant substratum is represented which upper part can correspond to the top of group "T". Based on geological approach, the group "T" and the resistant substratum are considered as part of the Afar stratoid basalts. Lower resistivity layers within the group "T" could be explained by intercalation of hydrothermal alteration or layers of a different nature as fluvial sediments and paleosols.

4.2 Gradient wells and deep drillings in Hanlé

The first part of the exploration began with three gradient wells of about 450 meters depth in Hanlé plain (Teweol, Garabayyis 1 and Garabayyis 2) in order to confirm the hydrogeological settings and to assess the temperature gradients before carrying on with the deep drillings (GEOTHERMICA 1985; GENZL 1985). They showed heterogeneous sedimentary sequences comprising sandy aquifers overlying stratoid basalts aquifer. Temperature measurements gave a maximum of 87°C on Garabayyis 2 and the estimated temperature gradients are between 1.3°C/100m and 2°C/100m.

Two deep wells (Hanlé 1 and Hanlé 2) realized in Hanlé plain reached respectively 1623 m and 2038 m (AQUATER 1989). Hanlé 1 recorded a maximum of 72°C at 1420m. After the lacustrine deposits the well crosses a rhyolitic complex between 94 m and 307 m overlying a monotonous sequence of basaltic flows. Permeable zones are encountered in the rhyolitic complex, at the contact with the basalts and in the scoriaceous layers. The well is impervious below 800 m. The maximum temperature in Hanlé 2 is 124°C at 2020 m. The lithological sequence is represented mainly by basalts. Highly permeable levels are found down to 450 m (fluid TDS 2 g/l) and the rest of the well remains impervious (AQUATER 1989; Jalludin 2003).

On the basis of these results on permeability and temperature the ongoing programme in Hanlé was revealed not satisfactory for geothermal purposes.

The discussions upon those data pointed out some arguments to explain the geothermal situation in this area. The bottom hole cores give respectively an age of 1.4 Ma and 18.8 Ma for the first and the second well. The late age of the volcanic formation in this part of the Afar Depression denies the hypothesis that the crust under the Hanlé plain is build up with young volcanic series derived from a recent spreading axis. The two gradients measured in the impervious part of the wells give 36°C/km and 24°C/km support that the crust is significantly thick without any shallow thermal anomalies related to intrusions or magma chamber. The fumaroles of Garabayyis would therefore represent an exceptional situation were the major fault system connect to some very deep thermal anomalies.

5. NORD-GOUBHET SURFACE STUDIES

The Nord-Goubhet area is located North-Eastward but close to the Asal rift. Goda mountain and Makarassou region are found in the Northern part and the study zone is limited by the sea in the South. Compared to the Asal rift, the area is elevated up to 500 to 600 meters of altitude. The geology is marked by the Dalha basalts outcrops covered by the more recent Gulf basalts and Pleistocene sediments. The fracture network is well developed. The area is situated between different zones of different tectonic pattern and therefore is affected by several tectonic trends: Asal rift NW-SE faults, Makarassou N-S trends (Tapponnier and Varet, 1974) and old trends identified in the Goda Mountain. As a consequence, the area is tectonically active, confirmed by some faults in the recent sediments and large panels of steep cliffs formed of Dalha basalts.

Along the scarped valleys of the wadis several fumaroles and one boiling spring are found at the bottom of the volcanic cliffs. Different methods applied to the chemical data from the condensate of the fumaroles give estimations for the possible reservoir temperature: 220°C and 170°C (Geothermica, 1987). Stable isotopes analysis of the fumaroles describes an assumption of the origin of the waters. Compared to the fumaroles of the Asal rift zone, Nord-Goubhet fumaroles have significantly lower δD and $\delta^{18}O$. It is suggested that no primary steam from undiluted or diluted deep water exist in this zone. Fumaroles would be more likely the result of a secondary steam from previously condensate steam or boiling groundwater (Geothermica, 1987).

Three geophysical surveys were conducted in the area of Nord-Goubhet: gravimetry, AMT and electric (rectangle method) (BRGM, 1983). The gravimetric results point out several heavy and light anomalies not distributed regularly. Although these anomalies are of low amplitudes they are more or less clearly delimited by the different linear trends, correlated to the tectonic of the area. From their analysis, BRGM retain three main guidelines. First, the Southern Asal rift system delimits light anomalies. Parallel to it and Northward, a large axis comprises a succession of heavy and light anomalies. In the central part, a similar axis is identified along a NNW-SSE trend. It can be noticed that the major part of the hydrothermal activity is located between these two axes. Finally, light anomalies cover the Eastern part of the prospect. The geoelectrical survey shows globally low resistivities and three main zones can be observed. The first one is located on the Eastern part of the prospect. The second low resistivity area is located on the South-Western zone but higher resistivities are found along a NNW-SSE axis. The last and very conductive area is located in the North-Western part. It has been estimated that the bottom of the conductive zone would reach around 1000 meters. The AMT survey identifies in the central zone of the prospect an uplifted conductive body. The results from the three geophysical surveys cannot be completely inter-correlated. However, findings from the gravimetric and the geoelectrical methods bring out interesting approach of the underground structures in relation with the surface hydrothermal activities that can guide a drilling exploration.

6. ARTA SURFACE STUDIES

This geothermal prospect zone is located on the Southern shore of the Gulf of Tadjourah and 45 km west from the town of Djibouti. It has been identified by its particular geological situation, the existence of an active fumaroles and an altered area significant of a near past hydrothermal activity. The geological formations are mainly represented by the Miocene Dalha basalts and the other units comprise Mabla rhyolites, stratoid basalts and

Gulf basalts. The plain is filled with coarse quaternary sediments. The zone shows a particularly intensive fracture network controlled by strike slip faulting and recently by normal faults (Arthaud et al., 1980). This geological situation implies the existence of a volcanic and tectonic activity in the area with the presence of a close magmatic chamber, however this activity would have stopped over the last 2 Ma ago (Geothermica, 1982). This past activity has probably been at the origin of the past hydrothermal activity recognized on the field by the altered areas. The interest for the geothermal development remains as the fractured Arta zone is located close to the Gulf of Tadjourah ridge and there exist surface hydrothermal manifestations.

Geochemical studies of shallow wells and springs determine two main chemical types. One is alkaline-bicarbonate characterizing superficial groundwater with typical recharge from wadi beds during run off. The geochemical temperature is slightly under 75°C (Geothermica, 1982). The second type is alkaline-chlorine in relation with sea water intrusion and probably in relation with underlying high TDS waters as it has been demonstrated in the country (Bouh, 2006; Jalludin et al., 2006). The geochemical temperatures range from 75 to 95°C. Likely, these waters do not exhibit any anomaly corresponding to a possible geothermal reservoir. This fact might be explained by the insulation of the geothermal reservoir by the existence of a cap rock zone. However, the ammonia content in the fumaroles could be the results of the boiling at 100°C of a reservoir of pure alkaline-chloride type (Geothermica, 1982).

Two geophysical methods explored the Arta area with gravimetry and electric. The gravimetric survey delineates an upwelling zone with positive anomaly that would be represented by a rhyolitic dome. The underground structures showed by the mapping of the anomalies seem to corroborate one of the main fracture trends, NE-SW. The main findings from the geoelectrical soundings are constituted by the presence of a several hundreds meters thick conductive layer. Within the scope of the geological situation of the area, this might be related to highly altered volcanic rocks, most likely Dalha basalts, as it is observed also in the field elsewhere. Consequently, from the geothermal reservoir standpoint, this analysis sustains the existence of a cap rock of relatively elevated thickness.

In order to fulfil the geothermal reservoir exploration in the Arta region, Geothermica (1982) suggest that the objective would not be at shallow depth and drilling exploration might cover two thousands of meters to possibly tap a deep geothermal reservoir.

7. OTHER POTENTIAL GEOTHERMAL ZONES

Besides the previous geothermal zones explored by advanced surface studies and by drillings for some of them, there are several other potential sites concerned by the geothermal development in the Republic of Djibouti. These geothermal sites are identified by the surface hydrothermal activities, hot springs and fumaroles, and also groundwater abnormally elevated temperatures: Obock, lake Abhé, Sakkalol, Tamataco, Wead (Djibouti plain), North of lake Asal, South-Goubhet and Dora. The first two are briefly described in the following.

The Obock prospect zone is close to the town of Obock located on the Northern shore of the Gulf of Tadjourah on its Eastern limit. This geothermal site is based on the resurgence of several hot springs and one fumarole on the beach. Some hot springs can be identified only during low tides. The outcrops close to the hydrothermal manifestations are formed of

quaternary madrepores covered by the alluviums all over the wide Obock plain. In the upstream part, are found the volcanic rocks dominated by the intensively fractured Mabila rhyolites in forms of mountains and scarped reliefs. The fractures on the quaternary plain area are observed exclusively close to the shore as E-W open fissures in the madrepores. Based upon marine geophysical and tectonic studies, the surface hydrothermal activity appear to be related to the near Gulf of Tadjourah ridge which fault system reaches the Obock site (Manighetti, 1993). Some geophysical prospections were undertaken for the purpose of groundwater development and also for the geothermal development, but their outcomes are not significant as they are limited in investigation depth or not complete. These are electrical soundings with short AB lengths (CGG, 1965) and magnetic survey with insufficient points (Essrich and Brunel, 1990). Geochemical analysis give an alkaline-chloride dominated waters in relation with sea water. Geothermometers found a possible reservoir temperature of 210°C (Houssein, 1993).

Lake Abhé zone is located in the South-Western region of the country, on the border with Ethiopia. This hypersaline lake is the Western end of the Gobaad plain and the Eastern end of the downstream valley of Awash river coming from the Ethiopian plateau. The geology is characterized by the stratoid basalts plateaus limited by E-W faults configuring the Gobaad plain, filled by quaternary and probably late Pliocene sediments. The lake area is particularly rich of surface hydrothermal manifestations with fumaroles and hot springs but also travertine constructions, some of them being elevated at more than 60 m above ground level. The travertines are aligned on the main fracture trends. Fumaroles are located on those travertines and the hot springs occur at the bottom of these travertine chimneys. The temperature of resurgence of the hot springs is generally higher than 90°C. Only geochemical preliminary studies cover this prospect and give mainly two types of waters. Most of the hot springs are alkaline-chloride-sulphated and few of them present also a bicarbonated type as a result of surface water mixing. The surface hydrothermal manifestations are spread over an area of about one hundred square kilometres. This observation suggests that in Lake Abhé zone there exist an important thermal anomaly representing potential geothermal reservoir.

8. CONCLUSION

The detailed glance at the geothermal studies in the Republic of Djibouti, based upon a consistent bibliographical research, results and data analysis, brings out several interesting conclusions as far as methodology-techniques and geothermal resources in Djibouti are concerned.

Asal rift zone is the most advanced in exploration with the demonstration of a deep and an intermediate reservoir. The applied geophysical methods can be compared in some way to the drillings data but reveal how much the Asal rift is a complex structural system and correlations are not systematically evident. More generally, some geophysical methods applied in the past show their limits in investigating geothermal reservoirs at medium and high depths and their interpretation remains sometimes questionable. New geophysical campaigns applying new techniques are therefore necessary to better appreciate the structural features for the explorations and for the reservoirs geometry to give directions for the next drillings.

Numerous surface hydrothermal manifestations clearly located on the Western part of the country where recent stratoid basalts outcrop and along the Gulf of Tadjourah ridge

support an important thermal anomaly in these regions. At least, twelve sites of surface hydrothermal manifestations are therefore identified including the Asal rift. The preliminary or advanced geochemical studies describe fairly well the underground thermal water circulations and their relationships with permanent water bodies and meteoritic waters. This is mainly the case of Asal and the South-Western regions. Estimated possible reservoir temperatures from geothermometers range between 170°C and 220°C. These knowledges completed with the surface structural features and geology, give a strong support for the existence of geothermal reservoirs in the Republic of Djibouti and for the programmes for their explorations.

REFERENCES

AQUATER, 1981. Projet pour l'évaluation des ressources géothermiques. CERD. 137pp

AQUATER, 1989. Geothermal exploration project. Republic of Djibouti. Final Report. CERD. 159pp.

Arthaud F., Choukroune P. and Robineau B., 1980. Evolution structurale de la zone transformante d'Arta (République de Djibouti). Bulletin de la Société Géologique de France, t.XXII, n° 6, pp. 909-915.

Barberi F., Ferrara G., Santacroce R. and Varet J., 1975. Structural evolution of the Afar triple junction. Afar Depression of Ethiopia, Bad Bergzarben, Germany, April 1-6 1974. A. Pilger and A. Rösler, vol. 1. pp38-54.

Battistelli A., Rivera J. and Ferragina C., 1991. Reservoir engineering studies at the Asal field: Republic of Djibouti. Geothermal Resources Council Bulletin. Nov. 1991. pp280-289.

Ballestracci R. et Benderitter Y., 1979. Mesures magnétotelluriques (8 Hz-1 700 Hz) dans le rift d'Asal. CRNS report. CRG Garchy. pp 46.

Black M., Morton W.H. and Rex D.C., 1974. Block tilting and volcanisme within the Afar in the light of recent K/Ar age data. Afar Depression of Ethiopia, Bad Bergzarben, F.R. Germany, April 1-6 1974. Edition A. Pilger and A. Rösler, pp296-299.

Bosch B., Deschamps J., Lopokhine M., Marce A. et Vilbert C., 1974. La zone géothermique du lac Asal (TFAI). Résultats de terrain et études expérimentales. Bull. BRGM. Section II, n°:4. pp367-383.

Bouh H., 2006. Etude de l'aquifère des basaltes du Golfe et des aquifères adjacents (République de Djibouti). Approche hydrochimique et isotopique. Thèse de Doctorat, Université de Paris Sud, pp; 117.

BRGM, 1970. Reconnaissance géothermique du TFAI. 70SGNGTM. pp59.

BRGM, 1973a. Territoire Français des Afars et des Issas: étude géochimique de la région du lac Asal. 73SGN140GTH. pp 32.

BRGM, 1973b. Etude géophysique par sondages Melos et sondages électriques de la région du lac Asal (TFAI). 73SGN010GTH. pp 18.

- BRGM, 1975a. Territoire Français des Afars et des Issas: rapport de fin de sondage: résultats des premiers essais de production. 75SGN442.GTH. pp 18.
- BRGM, 1975b. Territoire Français des Afars et des Issas: rapport de fin de sondage, interprétation des données géologiques de Asal 1 et Asal 2. 75SGN443GTH. pp 19.
- BRGM, 1973. Etude géothermique de la région du lac Asal, campagne 1972-1973. 73SGN144GTH, pp 22.
- BRGM, 1980a. République de Djibouti, champ géothermique d'Asal: synthèse des données disponibles au 1^{er} juin 1980. 80SGN525GTH. pp 42.
- BRGM, 1980b. Report on project DJI78/005. Testing on geothermal fluids. Lac Asal (République de Djibouti): Phase 1. 80SGN400GTH. 27pp.
- BRGM, 1983. Reconnaissance géothermique par prospections gravimétrique-électrique, audio-magnétotellurique dans la région du Nord-Goubhet (République de Djibouti). 83GPH014. 27pp.
- CFG, 1993. Champ géothermique d'Asal. Djibouti. Synthèse des données. 93CFG06. pp 87.
- CFG, 1988. Assistance à l'ISERST dans la définition du projet géothermie d'Asal. Djibouti. 88CFG27.CGG 1965. obock
- CNRS-CNR, 1973. Geology of Northern Afar (Ethiopia). Rev.Géog.Phys. Géol.Dyn., (2),XV,4, pp443-490.
- ENEL, 1990. Djibouti geothermal project. Report on the state of mining knowledge on the Asal zone. Proposals and recommendations. pp 28.
- Fontes J.-C., Pouchan P., Saliège J.-F et Zuppi G.M. 1980. Environmental isotopic study of groundwater systems in the Republic of Djibouti. En:"Arid zone hydrology", IAEA, Vienna, pp.237-262.
- Fontes J.-C.,Sichère M.-C, Pouchan P et Zuppi G.M. 1989. Teneurs en brome et en chlore du lac Asal (Djibouti) et bilan en eau et en sels d'un système évaporitique complexe. C.R. Acad. Sci. Paris. (309, sér. II): pp701-706
- Fouillac C., Fabriol R. et Lundt F., 1983. Champ géothermique d'Asal. Synthèse des données disponibles au 1^{er} janvier 1983. Rapport 83SGN022GTH, pp. 71
- Essrich F. and Brunel P., 1990. Geophysical study of Obock. CERD, Report, pp. 19
- Gasse F., Richard O., Robe D. Et Williams M.A.J., 1989. Evolution tectonique et climatique de l'Afar Central d'après les sédiments plio-pléistocènes. Bull. Soc. Géol. Fr., 7, XXII, 6, pp. 987-1001.
- GENZL, 1985. Results of temperature gradient drilling in the Hanlé area. Djibouti. pp 31.

Geothermica, 1985. Interprétation of gradient wells data. Hanlé plain. Republic of Djibouti. pp 29.

Geothermica, 1987. Geochemistry of North Goubhet and Asal regions. Report, pp 28.

Geothermica, 1982. Evaluation of the geothermal resources of the Arta region. Prefeasibility study. Final report, pp 14.

Gaulier J.M. and Huchon P., 1991. Tectonic evolution of Afar triple junction. Bull. Soc. Géol. France, t. 162, n°3, pp. 451-464.

Hirn A., 1988. Etude sismique sur Asal. In: Champ géothermique d'Asal. Djibouti. Synthèse des données. 93CFG06. pp56-60.

Houssein I., 1993. Interactions eau-roche au voisinage de l'équilibre: mécanisme réactionnel et géothermométrie. Thèse de Doctorat, Université de Paris 7, pp. 203.

Jalludin M., Travi Y. et Bouh H., 2006. Caractérisation hydrochimique des eaux souterraines en République de Djibouti, Corne de l'Afrique. *In preparation*

Jalludin M., 2003. An overview of the geothermal prospections in the Republic of Djibouti. Results and perspectives. Kengen Geothermal Conference, Nairobi 2003.

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

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

Manighetti I., 1993. Dynamique des systèmes extensifs en Afar. Thèse de Doctorat, Université de Paris VI, pp. 242.

Orkustofnun, 1988. Geothermal resistivity survey in the Asal rift in Djibouti. Vol. I and Vol. II.

San Juan B., Michard G. et Michard A., 1990. Origine des substances dissoutes dans les eaux des sources thermales et des forages de la région Asal-Goubhet (République de Djibouti). Journal of Volcanology and Geothermal Research, 43 (1990) pp.333-352.

Tapponnier P. et Varet J., 1974. La zone de Makarassou en Afar: un équivalent émergé des "failles transformantes" océaniques. C.R. Acad. Sc. Paris, t. 278, Série D, pp. 209-212.

VIRKIR-ORKINT., 1990. Djibouti. Geothermal scaling and corrosion study. Final report. pp 109.

Zan L., Gianelli G., Passerini P., Troisi C. and Haga A.O., 1990. Geothermal exploration in the Republic of Djibouti: Thermal and geological data of the Hanlé and Asal areas. Geothermics, vol. 19, n°: 6. pp. 561-582.