CONTRIBUTION TO FAVORABLE GEOTHERMAL SITE SELECTION IN THE AFAR TRIANGLE

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ABSTRACT

The Afar triangle has been shown to be the surface expression of the Afro-Arabian plate boundary, having the surface expression of most of the characteristics of a mid-oceanic rift system (Barberi & Varet, 1977). Most of the heat is dissipated at the surface along these major geodynamic features and Afar, like Iceland, therefore represents an exceptional geothermal energy potential. Afar was therefore described as “the future Gulf region for geothermal energy” (Varet, 2006). Many sites have been shown to be of potential geothermal interest on the basis of geological criteria: the presence of a volcanic “axial range” (oceanic-type rift segment) combined with transverse fractures (the surface expression of transform faults) provides both a heat source and a fractured reservoir. In addition, central stratovolcanoes on the Afar Margins also develop favorable conditions similar to those prevailing in the rift valley.

Compared to Iceland, Afar suffers from a major handicap: the composition of the geothermal fluids in geothermal reservoir fed by meteoric water. Since there is much less rainfall in Afar (annual rainfall there being one of the world's lowest), and as a former branch of the Red Sea evaporated in Northern Afar in the Pleistocene, brines predominate over fresh meteoritic water both at and below the surface (Kebede et al. 2008), notably in northern and eastern Afar (where open faults allow the sea to penetrate the depression). The noticeable exception in the Awash valley fed by the river itself and its many tributaries descending from the Ethiopian plateau should be underlined. A new approach is proposed that takes into consideration the hydrological basins feeding the potential geothermal sites, as well as new hydrogeological considerations. This enables us to take a new look at potentially favorable geothermal sites.

The Dallol, Boina, Manda-Hararo and Asal-Ghoubet geothermal sites are particularly discussed.

The technical-economic challenge posed by how geothermal energy might satisfy local needs and aid in the development of this sparsely populated, essentially pastoral region is also addressed.

Key words: geothermal exploration, Afar, ridge, heat source, reservoir, fluid composition, local development

INTRODUCTION: WHY FOCUS ON AFAR?

Our generation will have to pass from a mode of development based essentially on fossil fuels to a “Green New Deal” based on renewable energy. This is imposed on us from “both ends”, by diminishing fossil fuel resources, and by the climate changes induced by CO2 emissions that result from there combustion (Varet, 2005). Geothermal energy will play a role in this new context. Just as the world economy has moved from Europe and North America to Asia due to cheaper labour costs, a similar movement will be observed in the future to meet energy needs. The reason for this is that, in the previous period, the abundance of fossil fuels (notably oil) enabled the cheap transport of energy throughout the world, benefiting regions far away from energy resources, whereas we will soon be constrained by local energy resources with much higher transportation costs.

In such a situation, countries and regions that have accessible, low-emission, renewable energy resources will be of interest for centralized energy-consuming activities. The time has come for regions provided with geothermal resources to develop. As geologists, we know that most of the planet's geothermal energy is dissipated along plate boundaries, with the highest heat flow located along zones of accretion, that is along mid oceanic ridges, and even more in regions affected by mantle plumes. In East Africa, the ARGEO programme organizing this meeting aims at developing the entire East African rift system, and Kenya is already showing the way with significant and steadily increasing geothermal energy production. But in this vast area, we must recognize that geodynamics offer various solutions, ranging from typical continental rift systems to typical emerged oceanic rift zones. Thirty years ago, it was shown (Tazieff et al., 1970; Barberi and Varet, 1977) that Afar is not the northern extension of the Ethiopian rift valley (Wonji Fault Belt, as proposed by Mohr, 1970), but rather the surface expression of the Red Sea – Gulf of Aden oceanic rift system.

The Afar region covering Djibouti, Ethiopia and Eritrea should, therefore, be regarded as being of specific interest for geothermal developers and likewise be of particular interest in the ARGEO programme. Afar and Iceland are the only places on our planet where such an exceptional geothermal energy potential, combining emerged rift zones and mantle plumes, occur. Many Afar sites have been shown to be of potential geothermal interest on the basis of geological and geodynamical criteria in this so called “future Gulf region for geothermal energy” (Varet, 2006). The presence of a volcanic “axial range” (oceanic-type rift segment) combined with transverse fractures (the surface expression of transform faults) should provide both a heat source and a fractured reservoir – the two most favorable conditions for high enthalpy geothermal development (Fig. 1).

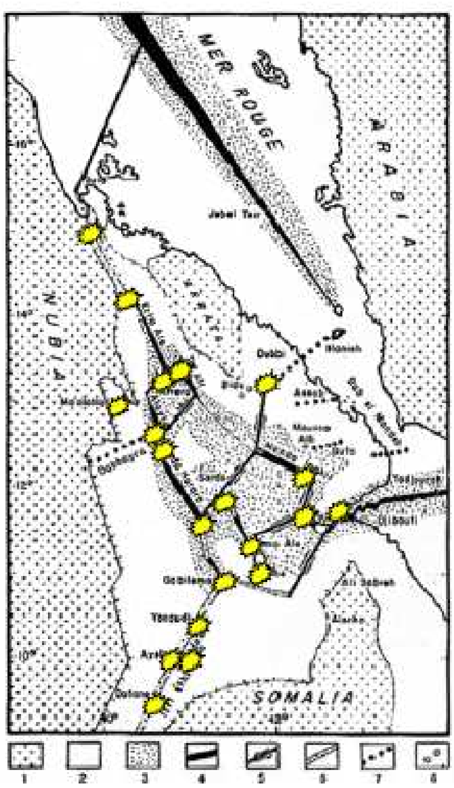


Fig.1: Geothermal sites in Afar, revisited selection by J.Varet (2006) on the basis of new geodynamic considerations, based on Barberi and Varet (1977) map of micro-plate boundaries.

Favourable geothermal sites

While Djibouti relies heavily upon fossil fuels for its energy production, Ethiopia has, to date, relied predominantly on hydropower plants. Although this energy is renewable and environmental friendly, power plant operation has already been affected by seasonal rainfall fluctuations and these are expected to increase in the future due to climate change. Furthermore, the hydropower potential is located in the western part of the Ethiopian plateau, whereas in the eastern part, the huge potential for geothermal energy has not yet been tapped. Northeastern Ethiopia is also an area where the population suffers from very low access to energy. Geothermal power might satisfy these needs as it enables modular development, with the great advantage of progressive investment. Moreover, this technology creates local jobs.

Studies carried out in the 1970s (Tazieff et al. 1970; UNDP, 1973) made it possible to identify several promising sites for geothermal development in the Ethiopian rift valley and Afar. A recent invitation by the Afar and Tigre regional governments, which included a joint field visit (Barberi & Varet, 2010), enabled us to precisely identify targets for providing electricity to rural and peri-urban communities and study the possibility of using these geothermal resources to contribute to the development of mining and agro-industrial activities.

The development of local geothermal projects will provide electricity and benefit rural communities, particularly those near the sites, and improve the socio-economic development of the entire region. Local populations would benefit from enhanced water supply, transportation, health, and other services fostered by the energy produced. In addition, the creation of new energy production sites, and the modular development enabled by geothermal power, would attract investments and induce future developments in various energy-consuming sectors such as mineral extraction and processing. The energy produced from this renewable source will, in the future, be connected to the main grid, thereby benefiting the entire regional energy sector – an important issue in an area that has, up until now, had to rely on seasonal hydroelectricity or costly fossil fuel, and future variable energy resources (wind or solar).

FACING A MAJOR HANDICAP: GEOTHERMAL FLUID COMPOSITION

At the first ARGEO conference in Addis Ababa, a proposal for a guide to geothermal exploration proposed for Afar (Varet, 2006) considered that favourable sites for high enthalpy geothermal development required the simultaneous occurrence of the following parameters:

- a high heat flow, linked with either a very shallow anomalous mantle or a superficial magma chamber
- a highly fractured area, allowing good reservoir permeability
- the recharging of the reservoir by meteoritic water or sea water, or a combination of both
- the development of a mineralised hydrothermal system

In the context of Afar, such sites were shown to offer suitable conditions for development in areas of junction between the axial ranges and the transverse tectonic systems. As described by Barberi et al. (1970), like in Iceland, transform faults are not observed in Afar. Nevertheless, Tapponier and Varet (1974) showed and Barberi and Varet (1977) more precisely confirmed that large oblique fracture systems are in many places the surface expression of a transform fault linking two distant axial ranges. This enables the interpretation of focal mechanisms of earthquakes, such as the Sardo event, in the Tendaho graben to the east of the southern extremity of Manda Harraro, the Afar axial range that is the most similar to mid oceanic ridges. Such a tectonic structure is particularly well developed north of Asal, in the junction area with the Manda Inakir axial range (Fig.2).

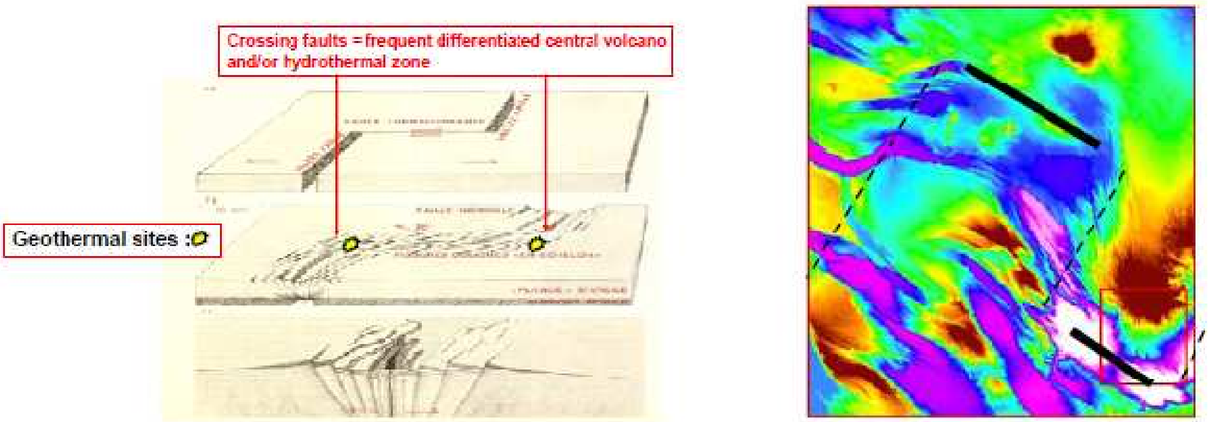


Fig. 2: The surface expression of transform faults in Afar is characterized by fault systems oblique with respect to the direction of the transform movement. Such features, conform to analogical models are particularly well developed on both extremities of Manda-Inakir axial range in Makarassou and Dobi regions (treatment by BRGM from NASA/SRTM).

However, compared to Iceland, Afar suffers from a major handicap – the composition of the geothermal fluids. Whereas in the North Atlantic climate of Iceland, due to high rainfall, geothermal reservoirs are predominantly fed by meteoric water, Afar has a dry tropical climate. Since there is much less rainfall in Afar (annual rainfall there being one of the world's lowest), brines predominate over fresh meteoritic water both at and below the surface (Kebede et al. 2008), notably in northern and eastern Afar.

A new approach is proposed that takes into consideration the hydrological basins feeding the potential geothermal sites and focuses on specific hydrogeological characteristics of the area. This enables us to take a new look at four potentially favorable sites selected among the many potential geothermal areas identified in 2006.

THE ERODED, FAULTED ESCARPMENT: AN EFFICIENT HYDRO-GEOLOGICAL SYSTEM FOR PROVIDING AN ADEQUATE GROUNDWATER SOURCE FOR GEOTHERMAL FLUIDS IN SELECTED SITES

In the escarpment bounding Ethiopia's northern Afar region, there are significant hydrological systems running from the upper part of the plateau down to the Afar floor (Fig.3). Typically endoreic, these basins feed the sedimentary and volcanic aquifers along the slope and under the plain. During the rainy season, the plains frequently turn into temporary lakes. This is the case of the great salt plain (locally called Dagad), where each year the salty crust at the surface is recrystallized after seasonal rains. At other times, the surface flow disappears in the flat-lying plains of the Afar floor. Along the flank of the active volcanic rift axis of Erta Ale, the Alayta and Manda Harraro ranges are notably developed, the largest being Dodom and Teru (Fig. 4).

Fig. 3: Satellite view of the numerous watershed feeding the Afar depression from the Ethiopian plateau and Danakil alps.

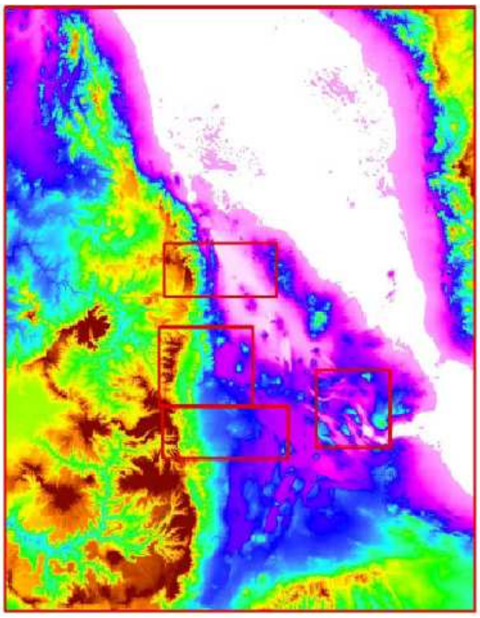


Fig. 4: relief map of Afar from NASA/SRTM, with BRGM processing; the basins feeding the reservoirs of the selected geothermal sites from the Ethiopian plateau are wider from north to south.

Therefore, although the rainfall is very low in the depression itself (a few millimeter to 100 mm/year, 129 mm being the average in Djibouti and 50 mm in Dallol), the western border of the Afar benefits from the much better hydrologic conditions of the Ethiopian plateau (up to 1,300 mm at an altitude of 3,000 m, figure 5 and table 1). As a result, a significant hydrological system developed in a complex array determined by both erosion (E-W direction, perpendicular to the scarp) and tectonics, which determines predominant NNE-SSW normally-faulted blocks and possibly marginal grabens (Fig. 6). The L-shaped (or rectangular drainage) river patterns (Fig. 7), the complex lithology of the faulted material and the intense and active extensional tectonics allow for a more efficient development of groundwater systems in fractures and possibly karst aquifers.

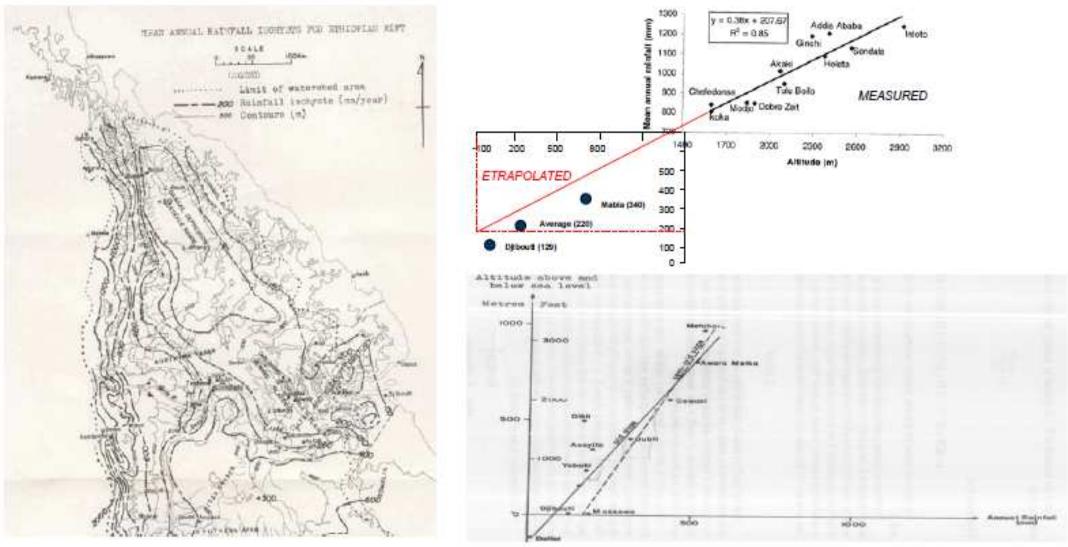


Fig. 5: Pluviometry in the Afar region: map of isohyets and correlation with altitude (UNDP, 1973 and Kebede, 2008)

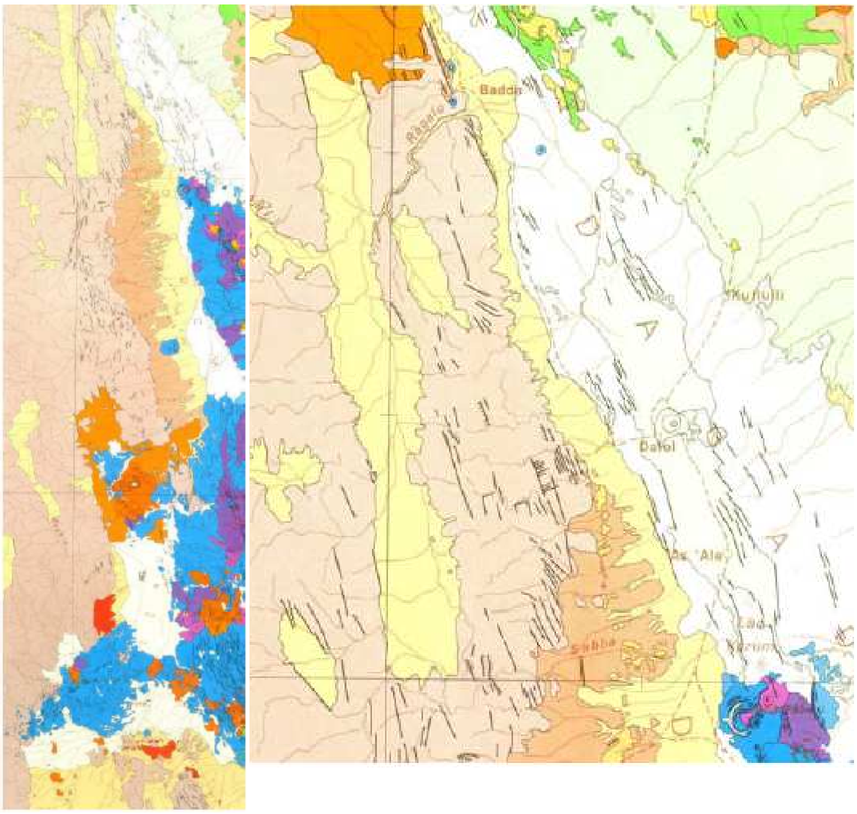


Fig. 6 : The basis of the faulted escarpment of the western Afar margin. Normal faults allow for the development of rectangular drainage and of marginal grabens, with “en echelon” arrangement (from CNR-CNRS map of the Danakil depression, northern sheet, J.Varet, 1978)

As a result, it is possible to select sites that meet the above mentioned criteria in terms of heat sources, transverse faulting, and hydrothermal development, that are also located in areas well fed by suitable hydrological basins crossing through the Ethiopian faulted scarp limiting the Afar depression to the West.

Two of these sites are located in NE Afar, in Ethiopia, i.e. Dallol and Boina. Note that similar contexts can be found in Eritrea (A. Michael, 2005), concerning the Alid volcanic and geothermal site (not studied here).

The third site is in the Djibouti republic, where the highlands of the Dalha plateau – with the well-known Day forest – also act as a meteoritic water source for the North Ghoubet site (Fig. 8).

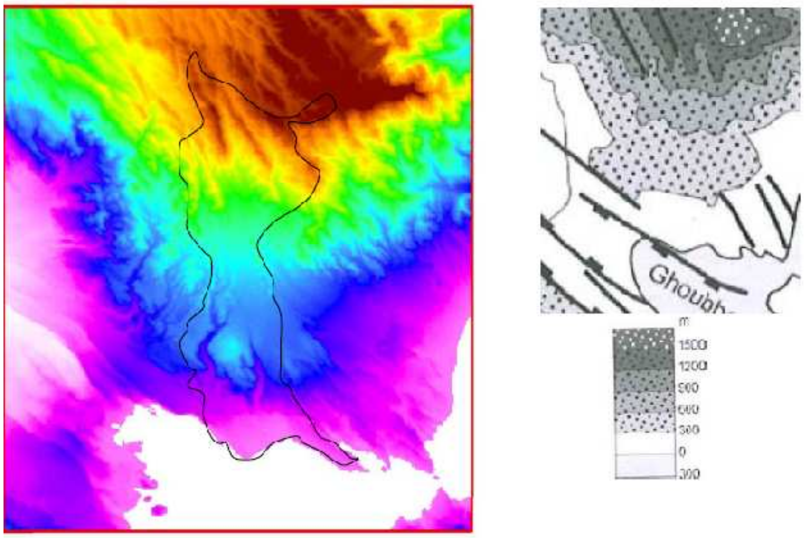


Fig. 7: The North Ghoubet site is fed by an hydrological basin with the head in the Day mountain (Dalha basaltic trapp series), the region in Djibouti Republic with the highest rainfall (processed NASA/SRTM data and current topographic map)

We do not address the geothermal area located near the southern extremity of the Manda Harraro axial range. The tectonic and magmatic crisis observed since 2005 (Ayele, 2006) has confirmed the very active nature of this axial range previously reported by Treuil and Varet (1973). Significant meteoritic water recharge of the entire Tendaho graben is provided by the wide Awash and Mille river basins (Fig. 9). The quality of the geothermal fluids was confirmed by exploration drilling (Aquater, 1996).

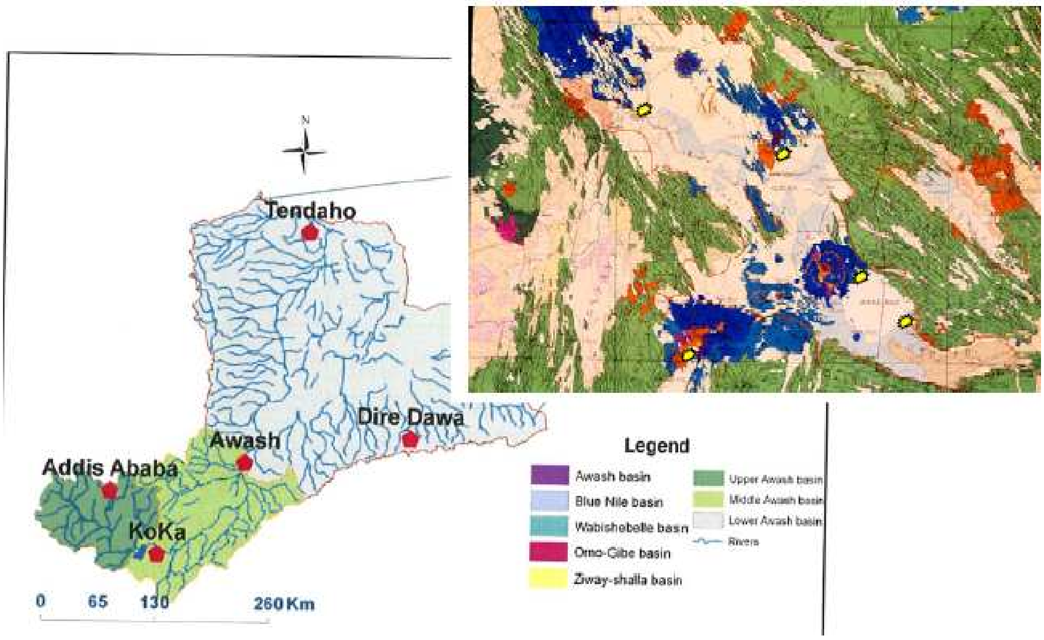


Fig. 8: The Awash river basin in Ethiopia (from Kebede et al. 2008) and the lowest part of the basin in the central Afar (Ethiopia and Djibouti, from CNR-CNRS geological map of central Afar).

DALLOL GEOTHERMAL SITE

The Dallol site is located in the middle of the vast Dagad salt plain. It is a former potash mining site (Holwerda and Hutchinson, 1966; ELMICO, 1984) and also a tourist destination due to the multicolored salt concretions that have developed as a result of spectacular hydrothermal activity. Hot water and fumaroles (the temperature of which may reach 120 °C) deposit sodium, potassium and magnesium chloride as well as metallic sulfurs, creating a wide range of colors at the emission sites, from black and green under reduced conditions, to yellow, red and brown after oxidation (Fig. 9). Springs and fumaroles are clearly aligned along NNE trending fissures, certainly linked with the opening of fissures on the rift axis. Vent locations change with time, as salt deposits plug old vents and new vents appear nearby along a new fissure. This confirms that Dallol is also located on the active Afar rift axis.

Fig. 9: black smoking fumaroles in Dallol, with successive stages of oxidation of the sulfurs offering a large variety of colors from green to yellow and red (Photo J.Varet, 2010).

The Dallol "dome" extends E-W, perpendicular to the rift axis. Rather than a real salt dome, it is a vertical uplift probably resulting from a deep magmatic intrusion. The regularly horizontal strata exposed in Dallol's eroded hills confirm this hypothesis. A similar feature is observed in the northern tip of the Erta Ale range, on the western side of the Kibrit Ale volcano (Barberi and Varet, 1970).

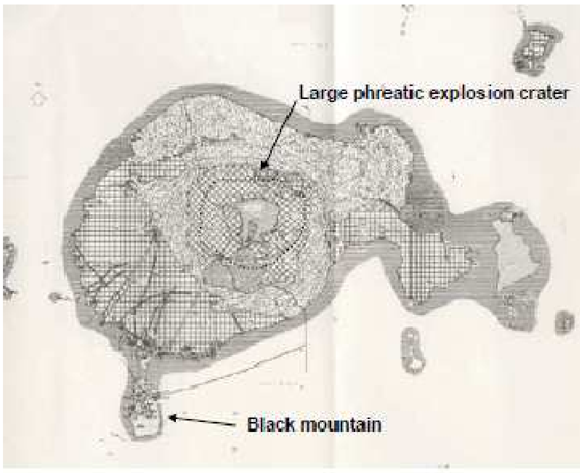


Fig. 10: magnetic field survey of Dallol site, showing a positive anomaly under the Black Mountain, and geologic map (ELMICO, 1984)

Geophysical data (magnetic and gravimetric) show that a magmatic body (most probably basaltic), a few kilometers deep, underlies the sediments, although no volcanic products are found in Dallol. With its location in the middle of the rift, right on the NNE alignment with the Erta Ale range, the presence of an active magmatic heat source is quite plausible. Geophysical data also show E-W anomalies that can be interpreted as being the result of transverse faults. Hence, although the existence of a well-developed and active geothermal system is obvious, we cannot be certain that suitable conditions for true geothermal development are to be found, due to the extremely salty environment, notably the saturation in salt of the geothermal fluids. The UNDP report (1973) concluded that Dallol was unsuitable for geothermal development on the basis of the geochemical content of the hot springs.

After new observations were made of the Dallol site, Barberi and Varet (2010) concluded that this site should be reconsidered as suitable for geothermal development for the following reasons:

1. Phreatic explosions are well-documented in the history of Dallol site and in the surrounding area. On the dome itself, a large crater – in which most of the active vents are located – indicates the presence of a very large phreatic explosion site probably a few hundred years old (Fig. 10) . Another phreatic explosion crater (100 m large) is well-documented in the Black Mountain site located SE of the Dallol dome, as observed in 1926 (Fig. 11). Between the Erta Ale range and Dallol, As Ale is also the expression of a former phreatic explosion, 55 m large. New craters and pools – apparently linked to the 2005 seismic event, according to local tribesmen – were observed during our last visit a few kilometers south from Dallol dome (Fig. 12), and show that phreatic explosions are still occurring. This clearly indicates the presence of a high-pressure, high-temperature (above 180 °C) geothermal reservoir currently active underneath this part of the salt plain.

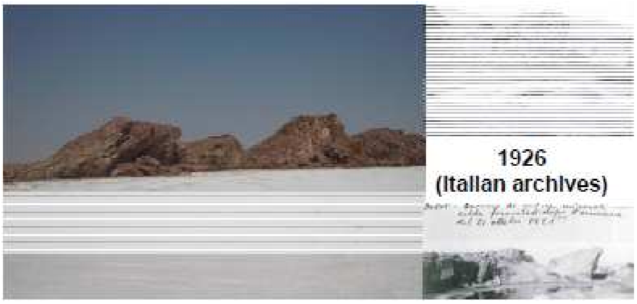


Fig. 11: two phreatic explosion craters near Dallol :
As’Ale skating ring today (J.Varet, 2010), and
Black Mountain in 1926 (Italian archives, in L.Lupi, 2009)

Fig.12 : a new phreatic explosion crater appeared in 2005, producing a lake still affected by hot springs and steam vents.

2. A closer look at the faulted scarp between Makale and Dallol shows that the whole series of the plateau collapsed along the many normal faults delineating the Afar margins. As a result, the Jurassic limestones and the Adigrat sandstones outcropping at 3000 m altitude on the Tigre plateau are observed at sea level and below, in tilted blocks emerging from tertiary detritic terrasses in the vicinity of the salt plain (Fig. 13). As a consequence, it is to be expected that these formations extend eastwards, at deeper depth, underneath the salt. In fact, they reappear on the eastern flank of the depression in the Danakil Alps (Arrata in Afar language).

3. Considering the hydrological and hydrogeological context, the Adigrat sandstones and the Jurasic limestones – the latter heavily karstified – both constitute efficient aquifers that would enable the infiltration of meteoritic water, itself facilitated by the intense normal faulting (and transverse fractures) affecting the escarpment (fig.14).

Fig.13: Tilted blocks of Jurassic limestone, downfaulted from the Ethiopian plateau, observed in the depression, emerging from tertiary detritic deposits, themselves also affected by normal faults.

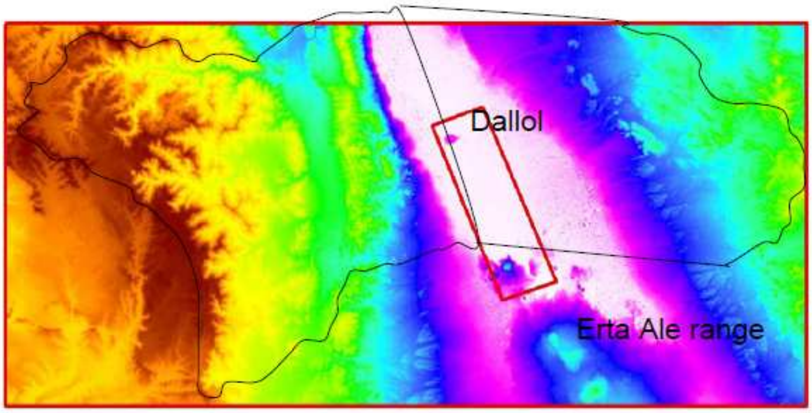


Fig. 14: hydrographic basins feeding the Dallol geothermal site, from Ethiopian plateau to Danakil alps

Under such conditions, a reasonably favorable geothermal model can be developed for the Dallol site where, underlying the salt plain and hyper-saline geothermal system, there might be a deeper aquifer in the Jurassic limestone characterized by both low salinity and regular recharge by meteoritic waters descending from the plateau. The presence of a high-pressure, high-temperature reservoir is evidenced by the numerous past and present phreatic explosions, as well as by the steam vents aligned on NNE trending open fissures frequently reopened though the salt cover (Fig. 15).

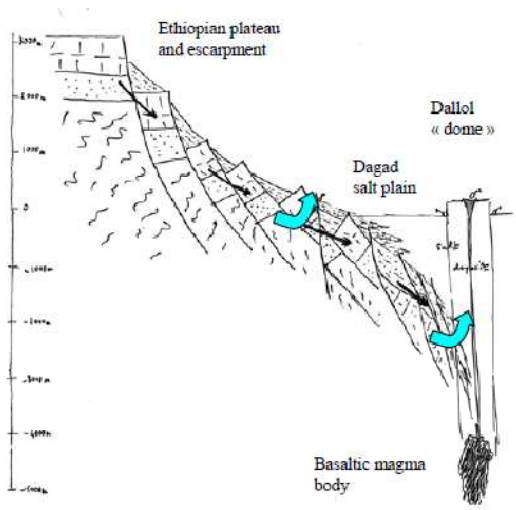


Fig. 15: Geological simplified model for Dallol geothermal system. The target would be to tap a deep aquifer in the Jurassic limestone and fed by the meteoritic water flowing down from the Ethiopian plateau.

Additional geochemical analyses and geophysical surveys should enable us to locate the best drilling sites, the cost of which would be low due to the ease of drilling through simple salt layers (Barberi and Varet, 2010).

In addition to meeting local needs in the surrounding Afar villages, this electrical energy production would also facilitate the re-opening of the Dallol potash mine. Instead of the costly ground mining techniques considered in previous feasibility studies (ELMICO report, PEC engineering, 1984), less expensive solution mining of the potash deposits could be done using the geothermal fluids (either directly or through heat exchangers).

BOINA GEOTHERMAL SITE

South of the Erta Ale range, the two axial ranges of Alayta and Manda Harraro represent the projection of the Red Sea-Gulf of Aden rift system into central Afar. The two active fissural basaltic ranges are not precisely aligned and the central Dabbahu volcano developed on this transition zone, probably a transverse fracture at depth (Fig. 16). This volcano (Fig. 16) is characterized by a complete magmatic series ranging from transitional basalts to hyper-alkaline rhyolites (comendites and pantellerites), described in detail by Barberi et al. (1975). The presence of a shallow magma chamber is evidenced by the series's crystal fractionation conditions. There are numerous fumaroles, locally called Boina (meaning fumaroles or steam vents in the Afar language), many of them exploited by the Afar tribesmen as a source of water with small artisanal steam-condensing units (Fig. 17). Such sites are so well-developed along the western margin of the Dabbahu volcano that Dabbahu may also be called Boina. Silica deposits are frequently observed on these hydrothermal sites, indicating high-temperature at depth.

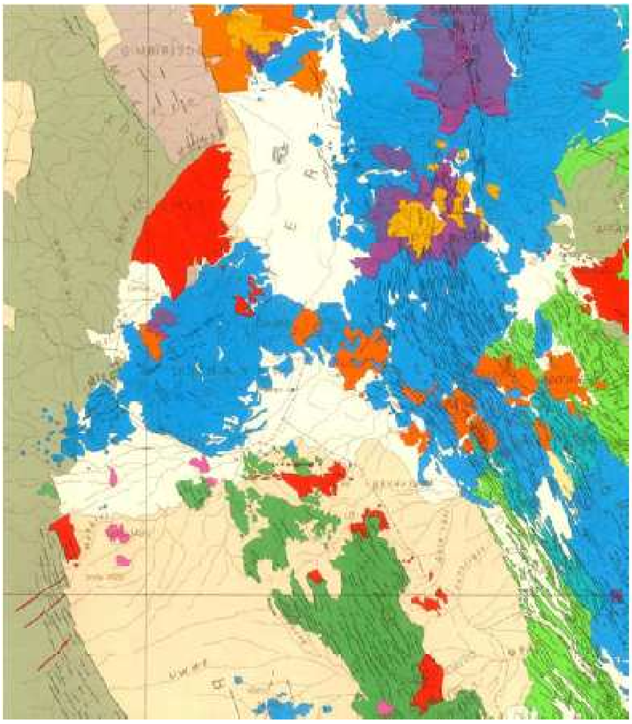


Fig. 16: Geological map of the foot of the Ethiopian escarpment and axial volcanic ranges of central Afar (CNRS-CNR, J.Varet, 1978). Dabbahu (also called Boina), located in area of junction (transverse structure) between Alayta and Manda Harraro axial ranges display a complete magmatic series from basalts to pantellerites. Numerous steam vents (locally called Boina) are observed along faults and open fissures affecting the lower part of the Dabbahu volcanic centre along the Teru plain.

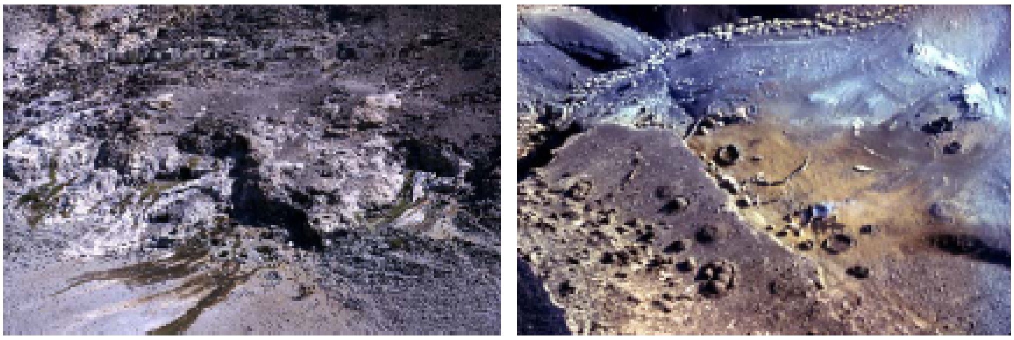
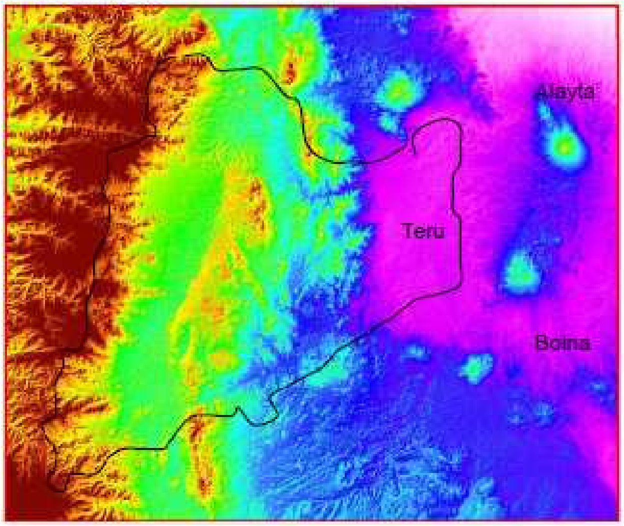


Fig. 17: Steam vents, fumaroles and hotsprings in Boina. Hydrothermal vents develop along faults and fissures affecting the basalts and the sediments of the Teru plain. The sites are frequently exploited by Afar people for steam condensation. Silica white deposits are observed.

The magmatic, geodynamic and hydrothermal characteristics of the site appear to be favorable and the hydrological context also confirms the interest of the area for further geothermal developments. The Teru Plain, one of the most extensive and fertile plains in NW Afar, extends along the foot of the volcano. The plain itself is fed by a large watershed descending from the Ethiopian plateau with several rivers crossing through normal faults and marginal grabens (Fig. 18). There is no outcropping of the Precambrian basement or Mesozoic sedimentary cover in this area, but the thick trap basalt series of the Ethiopian plateau, heavily faulted and tilted along this transition zone between the highest part of the plateau and the Afar depression. The rainfall is higher here than in northern Afar and the surface of the basin is wider, so there is more water available to recharge aquifers. As opposed to the central part of Afar at the same latitude, around Tat'Ali (an axial range parallel to Alayta) where there are saline deposits, no such deposits are observed here.

Fig. 18: Hydrographic basins feeding the Boina geothermal site, from the Ethiopian plateau. Observe the marginal grabens Along the foot of the escarpment.NASA/SRTM source, BRGM processing.



Due to these favorable hydrological conditions, this part of Afar also has a higher population density and the selection of this geothermal site would be of interest for local and regional social and economic development. Furthermore, since the resource is probably of high value in terms of quantity as well as quality, geothermal units of broader interest could be further developed on the Boina site. Additional prefeasibility work should include fluid hydrochemistry and geophysics, making it possible to site exploration boreholes. A small wellhead turbine and a local electricity grid should be installed during the feasibility phase in order to convince the local population of the benefits of developing this geothermal energy resource.

NORTH GHOUBET

In the Republic of Djibouti, following extensive surveys of the whole country, the Asal site was selected for geothermal developments (Farah, 2010). During three successive phases, led by BRGM (France) in the 1970s and by UNDP and Aquater (Italy) in the 1990s, the geothermal resource potential was tested and included deep drilling operations. A new approach has recently been developed by an Icelandic consortium (Reykjavik Energy Invest) and has led to the proposal of industrial development of a 50 MW plant on the Asal site (ISOR, 2008; Hjartarson et al., 2010).

The major problems encountered on the Asal site are not the heat source, which has already been certified by previous drilling campaigns (260 to 360 °C), but the permeability at depth and the fluid composition. Located between the marine gulf of Ghoubet and the halit- saturated Lake Asal, the geothermal fluid prevailing in the reservoir is a salty brine (Battisteili et al., 1990). Currently available technologies make it possible to exploit these geothermal fluids, as shown in the Salton Sea region in California. But finding a geothermal site where a less salty fluid could be tapped would be a real advantage.

The North Ghoubet site would merit more consideration. Located near the Asal-Ghoubet NW-SE trending axial volcanic range, it is also affected by transverse faulting resulting from the transition zone between Asal-Ghoubet range and the submarine rift segments identified along the axis of the Gulf of Tadjura (Fig. 19). This multiple faulting should be favorable to fracturation at depth and hence the development of hydrothermal reservoirs. Indeed, fumaroles have developed along faults in this area, with the development of recent silica deposits indicating the continuous exhaust from an active hydrothermal reservoir (CFG, 1993).

Fig. 19: photographic view of the Dalha basaltic series in the Day region. These trapp basalts are faulted to the south, dipping towards the Gulf of Tajourah and Ghoubet.

An additional consideration is reservoir recharge by meteoritic water. In North Goubhet, as opposed to Asal, a large basin is fed by rivers descending from the Dalha mountains, the highest and most humid part of the Republic of Djibouti. The Day Forest is a well-known tourist destination due to the exceptional climate prevailing in these highlands. Although dryer than the Ethiopian plateau, the conditions on the Dalha basaltic plateau are similar to those described above. Even if the annual rainfall does not exceed 200 to 300 mm, the small basin feeding the North Goubhet site allows not only for occasional flooding, but also for recharging deep aquifers developed in the unconformity between the deeply faulted and tilted basaltic trap series of the Dalha, and circulation within this trap series and in the underlying unconformity with the underlying Mabla rhyolitic unit. Since these successive geological units are characterized by different tectonic regimes (Marinelli and Varet, 1972), we can infer the development of well fractured reservoirs at depth. (Fig. 20, 21).

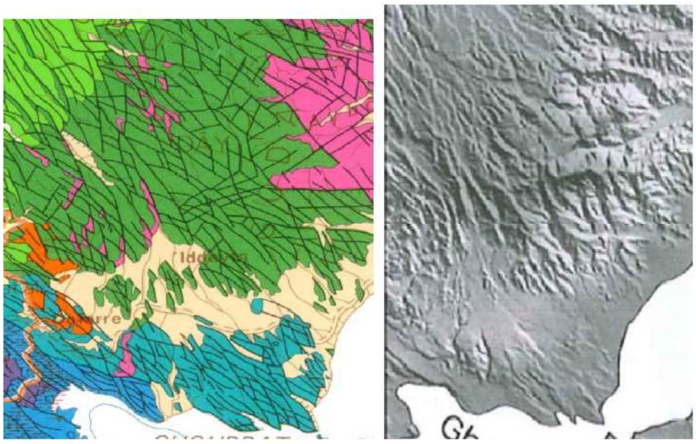


Fig. 20: The North Ghoubet site is fed by an hydrological basin with the head in the Day mountain (Dalha basaltic trapp series). The area is intensively eroded and faulted with normal faults trending NNW-SSE, NW-SE and E-W (from CNR-CNRS map of central Afar and NASA SRTM image).

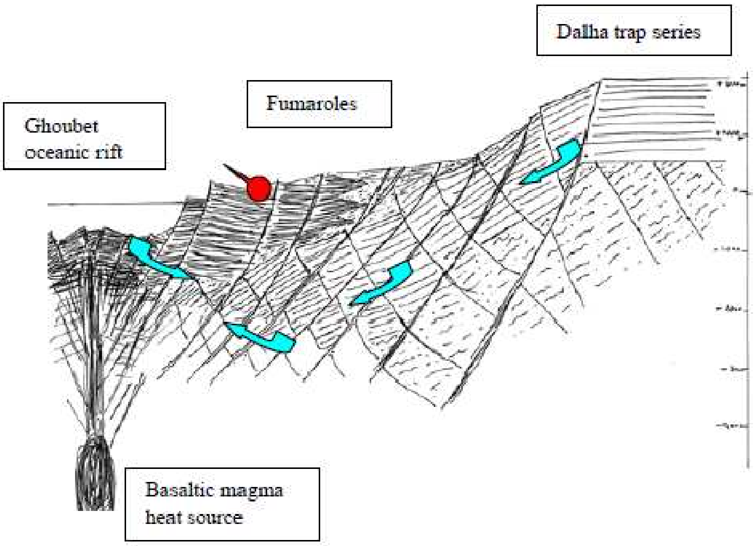


Fig. 21: geological qualitative Model of the North Ghoubet Geothermal site. Meteoritic Water descending from the Dalha plateau penetrates through.The numerous faults in the basaltic Aquifer, heated at depth by the Basaltic magma intrusions along the Ghoubet accreting oceanic ridge

Fig. 22: proposed location for completing geophysical works before drilling exploration wells in the North Ghoubet site. Other geothermal sites in Asal previously drilled and proposed are also indicated.

Considering the active extensional tectonic regime affecting the North Goubhet area in two directions, as well as these hydrogeological considerations, suitable high enthalpy geothermal reservoir conditions should prevail in this area. A geophysical survey should help site exploration wells in order to better delineate this geothermal site (Fig.22).

CONCLUSION

While there are major geothermal sites all along the East African rift valley, several of which having already seen economic industrial developments, notably in Kenya, the Afar region has not yet demonstrated its capability. The purpose of this paper is to show that Afar – in Djibouti, Ethiopia and Eritrea – should possess the largest geothermal resources of the African continent. Due to its exceptional character as an emerged oceanic rift segment and zone of accretion of the Earth's crust, in addition to being affected by an active mantle plume, Afar certainly shares with Iceland the quality of having the world's highest geothermal potential.

As opposed to Iceland, however, climate conditions in Afar are not favorable for the recharging of the geothermal reservoir by meteoritic water. Geothermal brines with corrosive and scaling effects prevail in areas where hyper-saline lakes and salt deposits have developed, as in Assal. Nevertheless, deep aquifers in Afar can be recharged by meteoritic waters due to past wetter climate conditions and to the vicinity of high plateaus. Large water basins enable recharge of the fractured and permeable formations located on the sides of the axial ranges in transverse fracture zones where optimal conditions for geothermal reservoir development prevail.

If there is little doubt that Afar will, in the future, become a region of major renewable energy production, the transition period will be difficult due to the shortage of fossil fuels and the implementation of climate policies. The arid climate has not fostered the social and economic development of the Afar population and, as a first step, it is essential that the geothermal development benefit, first of all, local inhabitants. A well-adapted – probably specific – mode of development that involves the local population as much as possible should be considered. Afar workers presently building the steam condensers should, for instance, be offered employment in the drilling work. This sustainable development issue is a challenge for all, including local authorities, engineering and industrial firms, researchers as well as financing agencies.

To date, most of the prevailing financial schemes in such rural areas have been for smaller energy projects i.e. based on solar or wind energy. As a case in point, the 2010 call for rural energy development projects under the ACP-EU facility did not allow geothermal project to be selected. The capability of development agencies to support geothermal projects adapted to the conditions prevailing in Afar is a real challenge the ARGEO program should allow to master, as soon as possible.

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