

Geothermal Development in Eritrea: A Country Update

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ABSTRACT

Dependence of imported refined petroleum products for electric power generation has not only adverse effects on the economic development of Eritrea but also causes environmental pollution. The impact can be viewed both in terms of frequent increment of fuel prices and environment degradation through emission of greenhouse gases. Geothermal energy will therefore have an important input in alleviating expenditure on foreign currency while safeguarding the environment. The tectonic setting and geological setup of the south-eastern coastal zone of Eritrea is conducive for development of a geothermal resource that can be harnessed mainly for electrical generation and direct utilization. Alid and Nabro-Dubbi geothermal areas are notable prospects with ample geothermal manifestations. Surface exploration surveys in Alid geothermal prospect indicated high reservoir temperatures of $>250^{\circ}\text{C}$ as estimated from gas geothermometers. Fracture and fault density (FFD) analyses carried out indicate that structures are permeable and probably the prospect is located at the up-flow zone of the region. A 70°N trending high fracture zone is well marked on the FFD contour plot. The resistivity surveys conducted recently show a positive anomaly at the prospect area and this prompted further exploration surveys to be conducted. The 2011 volcanic eruption in Nabro indicates that the area is tectonically active as evidenced by numerous fumaroles that appeared thereafter.

1. INTRODUCTION

Eritrea is located in the Northeastern sector of Africa between longitudes 36.4 and 43.1°E and latitudes 12.3 and 18.0°N . It has a land area of $124,320\text{ km}^2$ comprising of the central highlands, the western and coastal lowlands and 350 islands in the Red Sea. The highlands have a temperate climate with average annual temperatures ranging between 5°C and 26°C and an annual rainfall of $400\text{-}700\text{ mm}$. The coastal lowlands in the east and the northern part of the western lowlands are hot and arid. The current population of Eritrea is estimated at 5,000,000 people, with an annual growth rate of 3%. The urban population is about 20% of the total with 500,000 people living in Asmara, the capital. The rural population in the highlands practice subsistence agriculture while those in the lowlands are pastoralists.

Eritrea's energy problem may be viewed in terms of the following two features:

- Lack of access to modern commercial energy by three-quarters of the country's population and its consequent reliance on biomass fuel use, which accounts for about three-quarters of all energy consumption; and,
- Import dependence for all modern commercial energy supply, both the refined petroleum products used in the transport, industrial and domestic sectors as well as in electric power generation.

Since Eritrea lies within the African rift system, the potential of having geothermal energy resource for use in electricity generation and direct uses is high. The advantage of geothermal energy resource for Eritrea is not only based on its environmental benign advantages but it also mitigates the use of fossil fuel, which the country has been importing straining foreign currency reserves. For this reason, the government has given priority to this sector and exploration is on-going. The tectonic setting and geological set-up of the southern coastal zone of Eritrea indicates that the area has a good potential for development of geothermal resources. Surface manifestations are abundant in Danakil zone mainly associated with volcanic activities in the area in which the Alid and Nabro-Dubbi prospects are located (Figure 1).

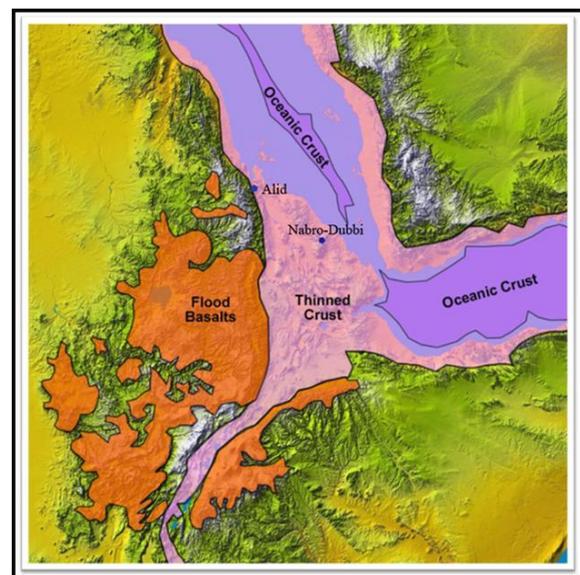


Figure 1: Location map of Alid and Nabro-Dubbi in relation to the African Rift Valley.

1.1 Previous Work

Previous works carried out mainly concentrated on Alid volcanic center. Angelo Marini of the Italian Institute for Military Geography in 1902 during Italian colony initiated a preliminary study on Alid geothermal prospect where he studied the surface manifestations (Marini, 1938). For decades, no documented studies were carried out with bias on geothermal energy exploration until 1973, when the UNDP sponsored reconnaissance survey work was done by the Geological Survey of Ethiopia team (UNDP, 1973). The UNDP team surveyed the thermal springs along the Asmara-Massawa road and in the Gulf of Zula area south of Massawa and later in the year, a second reconnaissance survey studied the fumaroles that occur on Alid volcano. In 1992, the late Prof. Giorgio Marinelli and a staff member from the Department of Energy visited Alid area and prepared a proposal for detailed study of the area. The Ministry of Energy and Mines refined this proposal later and this formed a basis for geological and geochemical surveys to be carried out in the area. In 1994, Mikhail Beyth of the Geological Survey of Israel surveyed the Alid hydrothermal area for the possibility of epithermal gold deposition (Beyth, 1996).

Detailed geological and geochemical investigations were carried out in Alid geothermal prospect and its surroundings by a team of Scientists from the United States Geological Survey (USGS) and the Ministry of Energy and Mines of Eritrea (MEM) in January and February 1996. The work was financed by USAID and the team was led by Robert Fournier of the USGS (Clyne et al., 1996). Results from the survey indicate that a probable high temperature resource occurs below Alid volcanic centre, as estimated from gas geothermometers. A two-phase conceptual model - a vapour dominated at the base and steam dominated at the top - was proposed through re-interpreting the water and gas samples from the 1996 USGS-MEM data (Yohannes, 2004).

2. STATUS OF ELECTRICITY PRODUCTION

Currently, Eritrea is totally dependent on imported oil products to meet its modern energy requirements. This makes the country's energy supply and economy extremely vulnerable to international oil price fluctuations. The 2006

energy balance and statistics indicate that the total national energy consumption was 611 toe out of which 486 toe or 79.7% was consumed by the household sector, 60.5 toe or 9.9% by the public and commercial sectors, 51.1 toe or 8.4% by transport and 13.4 toe or just 2.2% by the manufacturing industry. Electricity generation and charcoal accounted for 51.3 and 66.5 toe respectively and this is not reflected in the tables as it indicates energy used for transformation. The total final energy consumption was 77.3% biomass-based, 19.5 oil products and 3.3% electricity. Fuels used to meet household needs include 73.2% wood, 17.1% agricultural residues and animal waste, kerosene and LPG (4.4%), and charcoal accounted for the balance of 3.6%. About 1/3rd of all households now have access to electricity, yet this energy source contributed only 1.7% of household energy consumption. Currently the total installed capacity stands at 145 MW, all of which are based on diesel generation. The medium term power development plan is to increase the generation capacity by 50 MW. In the long-term plan the input of geothermal energy will unequivocally play an important role in replacing and/or supplementing the existing diesel based power generation.

3. STATUS OF GEOTHERMAL EXPLORATION

3.1 Geothermal Prospects

The two main geothermal prospects, the Alid and Nabro-Dubbi are both located within the Danakil depression; the structural axis that connects the African Rift System with the Red-Sea (Figure 2). The development of the Danakil depression occurred in two phases namely: (i) the continental rifting phase, which marked the change of volcanics from undersaturated trap series basalt to the transitional basalts and associated peralkaline silicic phase and (ii) the crustal separation phase of the Danakil tectonic development, which commenced at about 4 to 3.5 Ma, eventually giving rise to the present day configuration of the Afar Triangle.

Crustal opening was initiated at the end of the continental rifting phase of the tectonic development of the Afar region during the late Miocene (22-15 Ma), however the main volcanic activities took place at Danakil block at about 4-3.5 Ma. The two geothermal prospects are separated by Danakil horst, where a Proterozoic metamorphic rocks and Mesozoic sediments are exposed.

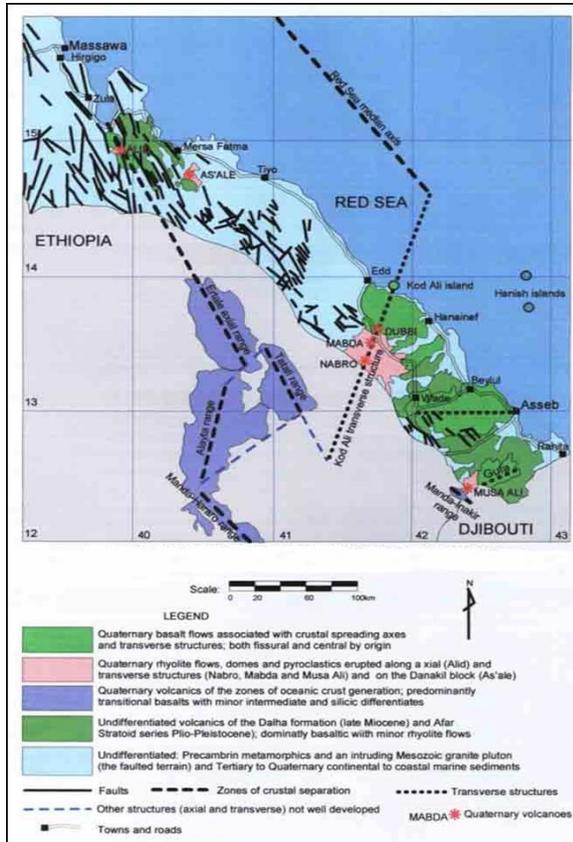


Figure 2: Structural features, Tertiary and Quaternary volcanic rocks in southeast Eritrea.

3.2 Alid Volcanic Center

3.2.1 Geologic Setting

The suitable tectonic environment of the Danakil depression augmented by recent magmatic activities favor a high thermal gradient on the upper zone of the crust. Consequently several areas are dotted with surface manifestation including low temperature hot springs that occur on Danakil depression and escarpments of the Red Sea.

Alid is a late-Pleistocene structural dome formed by shallow intrusion of rhyolitic magma, some of which were erupted as lavas and pyroclastic flows. It is characterized by large-scale rhyolitic volcanism associated with E-W extensions. The continuous extension, subsidence and volcanic activities have influenced the geological structure of the area to some extent. The volcanic succession of rhyolite and basalt are extruded following the NNW fault system of the rift, which extended its ellipse towards ENE.

Alid volcanic centre consists primarily of rhyolite both as massive and as pumice deposits, olivine basalt, and Red Series sediments (Figure 3). In terms of volume, rhyolite and olivine basalt are the most abundant rocks. Although volcanism culminated with fissure flows of basaltic lava on

adjacent areas, the youngest eruption on the dome is the rhyolite, which is dated about 33 ka BP.

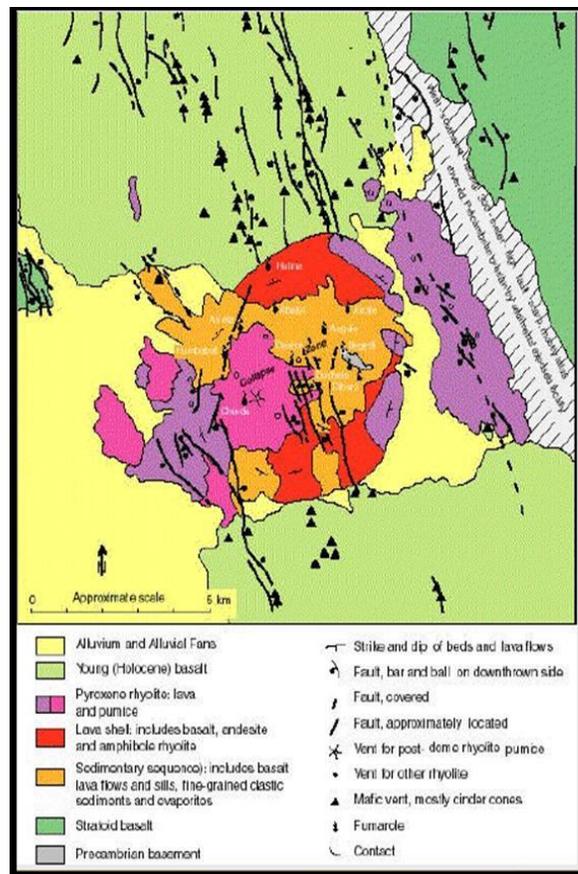
3.2.2 Structures

Faults occurring in Alid area are mainly of normal type with some strike-slip. The opening of the fractures ranges from mm scale to tens of centimeters except for the E-W trending fault which has a relatively wide opening. Fractures are associated with surface manifestation and their relationships are discussed in the subsequent paragraph.

Steaming grounds are mainly associated with the 70°N, trending structure however at Illegهدي the surface manifestations generally trend NNW. Most of the surface manifestations are common along the NNW fractures. Manifestations are common in all the E-W trending fractures.

The lineaments in Alid form a complex pattern but distinct sets of directions. Systematic examination of these faults indicates that they can be classified into three major types depicting different orientations related to different tectonic events (Yohannes 2007).

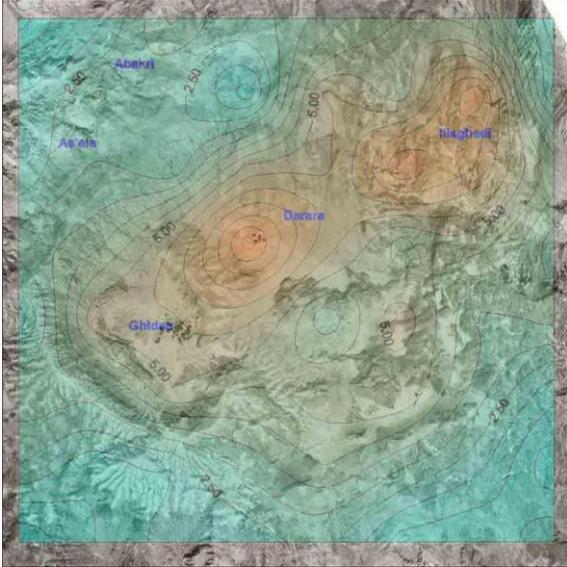
1. Lineaments striking ENE (60-70°): Common lineaments, related to major axis of the dome.
2. Lineaments striking NNW (330-340°): Frequently observed especially at north and south of the dome, related to the trend of the depression.
3. Lineaments striking E-W (270-280°): These are



common as dykes and fractures related to rift tectonics.

Figure 3: Geological map of Alid volcanic center

A contour map of fault and fracture density (FFD), defined as the total length of lineaments per unit area, was



constructed for the study area (Figure 4).

Figure 4: Contour plot of Alid using FFD analysis.

3.2.3 Geochemistry

Hot mineralized fluids discharge from many location within the Alid volcanic centre. Most of these manifestations discharge boiling fluids that release gases. The manifestations, which are either in form of fumaroles or hot springs, are confined to the northern part of the Alid dome. In most cases the gases issues sulfur and as a result it precipitates in the form of sulphosalts. Sulphosalts and clays are the main hydrothermal alteration products in these zones. The intensity of alteration however varies from place to place. Hot springs are more likely to occur where the depth to water table is shallow and subsurface geothermal systems are more likely to be discovered in areas where hot springs are present at the surface. Alteration is wide and intensive at Illegedi and Darere (Figure 5). Sulphosalts and clays of various colours are conspicuous in both present and old precipitates, of which yellowish coloured (mainly representing sulphosalts) and



brown/white clays, are abundant. Emission of gases through fumaroles is intensive and spatially distributed widely along the stream.

Figure 5: Geothermal surface manifestation with fumaroles at Darere.

Geochemical studies indicate that a high-temperature geothermal system underlies the Alid volcanic centre in the northern Danakil depression of Eritrea. Geothermometers indicate that the fumarolic gases are derived from a geothermal system with temperatures $>225^{\circ}\text{C}$. The isotopic composition of condensed fumarolic steam is consistent with these temperatures and implies that the source water is derived primarily from either lowland meteoric waters/fossil Red Sea water or highland waters significantly evaporated or both.

The gases vented from the system include CO_2 , H_2S and He and are largely magmatic in origin. Permeability beneath the volcanic centre may be high, given the amount of intrusion-related deformation and the active normal faulting within the Danakil depression.

3.2.4 Resistivity Survey at Alid and its Surroundings

The geological and geochemical work carried out in the Alid dome indicated that a geothermal reservoir occurs beneath the volcano. To determine the extent and depth of the reservoir, a geophysical survey was proposed. Since MT resistivity survey has the ability to penetrate deep structures and is practically the only method for studying deep resistivity structure it was proposed in Alid. Accordingly with the fund from ICEIDA, ISOR (Icelandic Geosurvey) and the Eritrean Geological Survey carried out TEM/MT survey from December, 2009 on Alid dome and adjacent area (Figure 6). The TEM method was carried out concurrently at same site with the MT resistivity in order to eliminate static or telluric shift problem.

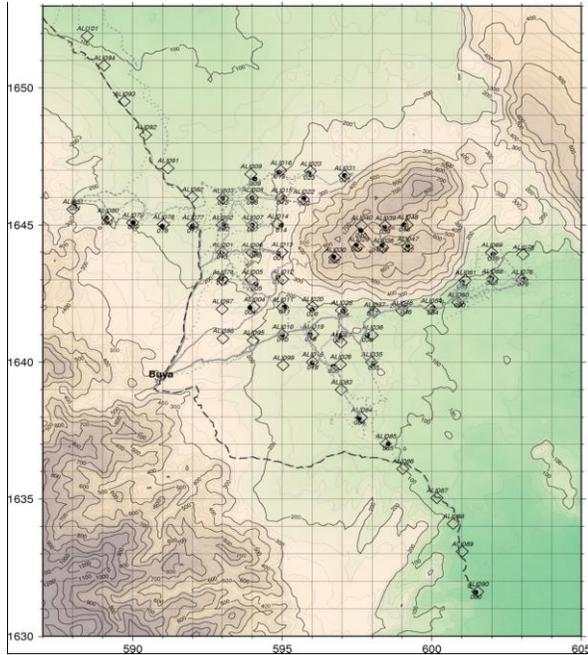


Figure 6: Location map of TEM (diamonds) and MT soundings (circles). Coordinates are in UTM, km.

Resistivity maps at various depths were drawn ranging from 400 meters above sea level (masl) to 10,000 below sea level (mbsl). At 3,500 mbsl (Figure 7) and below a clear low resistivity NNW-SSE body is depicted west of the volcano and connected to the broader WSW-ESE low resistivity to the south.

The low resistive anomaly, depicted at 3500 mbsl as shown in Figure 7, shows a clear NNW-SSE trending body aligned similar to the main fault system that is the main structural trend of the rift system. Similarly the ENE direction low resistive anomaly result also marked at 3500 mbsl is an important structure that extends even westward to the metamorphic basement. It is deep seated as it juxtaposed the low grade and high grade metamorphic complexes at the same topographic level. In addition, the direction is also in line with the emplacement trend of the dome, which makes it more interesting in dealing with the fluid movement.

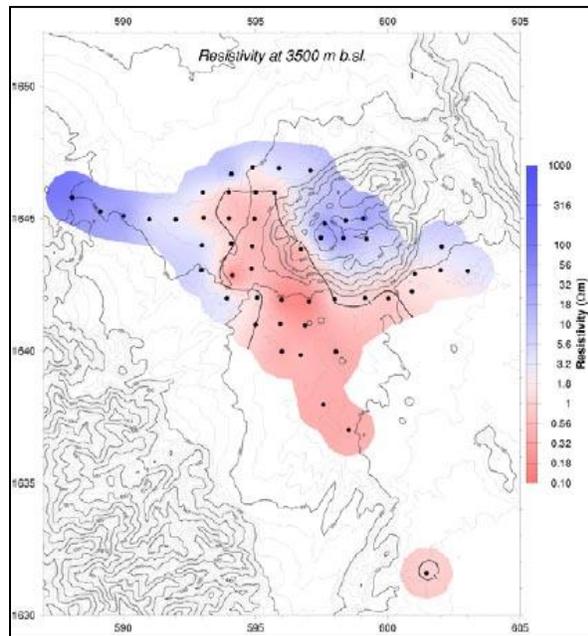


Figure 7: Resistivity map at 3500 mbsl. Coordinates are in UTM, in km units.

Figure 8: The yellow line shows the location of the vertical resistivity boundary between 500-2000 m depth. The brown contour lines outline the low resistivity body west of Mt. Alid at about 2000 m depth. Red dots are geothermal vents on Mt. Alid.

of the MT and TEM pointed out three main features on the Alid dome and surroundings (Eynsteinnsson et al, 2009).

- A SW-NE Lineament. A conductive zone is seen down to about 6–7 km depth (and even more in some places) in the south and southwest of Mt. Alid. This zone has a sharp vertical boundary or a lineament in the depth interval from 500-2000 m depth shown by a yellow line on Figure 8.

The resistivity survey - both the TEM/MT methods - unravel a promising target area at the rift floor. The result

- A low resistivity body defined by the NNW-SSE brown line below the western part of Mt Alid and to the west of the volcano there is a low resistivity body, approximately 3 km wide (Figure 9). It reaches the highest elevation at 2000-3000 mbsl, and extends down to a depth of about 7000 m.
- Beneath most of Mt Alid there is a rather high resistivity, compared to the surroundings, and no deep conductor, except in the westernmost sounding on the mountain.

A conceptual model of two phase vapour-dominated phase below a steam heated zone is developed for Alid (Yohannes, 2004).

4. OTHER PROSPECTS

4.1 Nabro-Dubbi Volcanic Complex

Nabro stratovolcano is the prominent volcano that occurs in a zone of NE-SW direction SW of Dubbi volcano, here collectively named as Biddu or Nabro-Dubbi volcanic complex.

The 2218 m high Nabro stratovolcano is the highest volcano in the Danakil depression and elsewhere in the eastern lowland, which has an 8km diameter caldera. Nabro volcano (Figure 9) itself forms part of an enigmatic double caldera structure with a neighbouring volcano, Mallahle, which has a sub aerial volume of the order of 550 km³ (Wiert and Oppenheimer, 2005). Trachytic lava flows and pyroclastic emplace primarily on the Nabro, followed by post caldera rhyolitic obsidian domes and basaltic lava eruptions inside the caldera and on its flanks. Some very recent lava flows were erupted along NNW trending fissures and transverse to the trend of the Nabro-Dubbi volcanic range (Figure 9).

Dubbi is a large volcanic mass that rises 1625 m above sea level and it erupted explosively in May, 1861. The volume of lava flows alone, 3.5 km³, makes this the largest reported historical eruption in Africa (Wiert et al., 2000). Many cinder cones are located at the summit. Extensive basaltic lava fields to the north and NE cover wide area and reach the Red Sea coast. Almost all the cinder cones belong to the most recent eruptive centres at the summit in 1861. The major transverse structure that extends from the Kod Ali island area of southern coastal Eritrea south-westwards across the north-eastern Afar rift margin on the Ethio-Eritrean border forms the terminus, and south-easternmost transfer mechanism into the Afar, of the Red Sea floor spreading axis which ends in the area to the northwest of Hanish islands (DOM, 2004). This structure separates the Danakil block in two separate units of geological makeup: the Pre-rift basement to the northwest and the Plio-Pleistocene volcanism to the southeast. This structure has

given rise to the most recent and most extensive Nabro, Mabda and Dubbi volcanic activities of the region, where it crosses the numerous northwest-southeast trending faults of the north-eastern Afar rift margin and Danakil block. The Nabro is the intersection of the ENE and Kod Ali fault line.

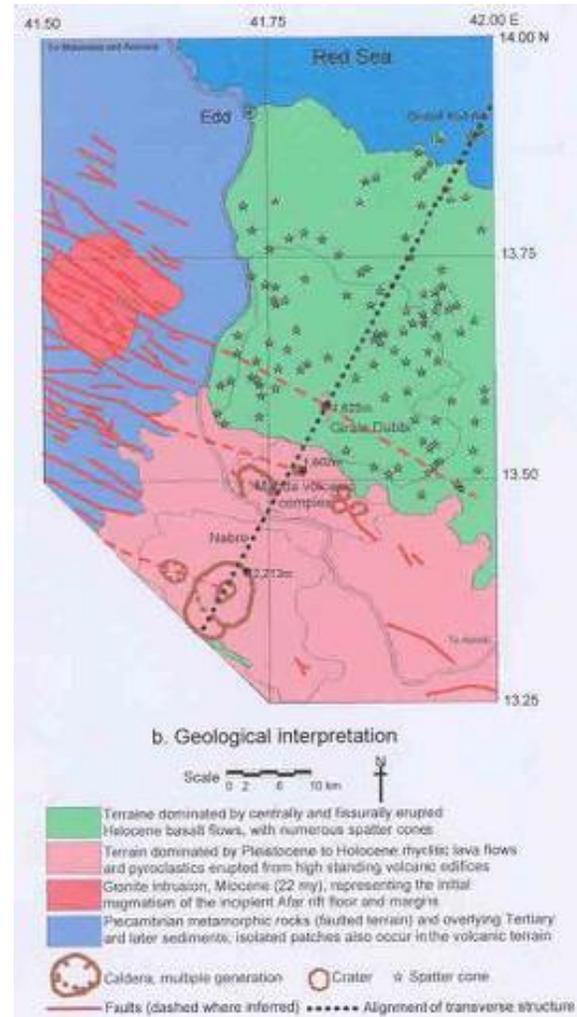


Figure 9: Geological map of Nabro-Dubbi.

4.2 The Volcanic Eruption of 2011

Last year a volcanism of basaltic composition erupted from June 12 at Nabro. The increase of magma chamber triggered successive earth quakes which resulted in fracturing the summit and the surrounding areas.

It started violently with explosive type in the first two days, spewing ash to 14 km high which was deposited to south and western directions following the prevailing wind direction at the time of eruption. A lava flow later followed after the pressure was released from the vent. The mainly AA type flow continued for days reaching more than 10 km following a river course south-westernly.

Sulfur gas in the form SO₂ was released abundantly into the atmosphere and precipitated close to the vent forming a yellowish crust.

Numerous surface manifestations occur at Nabro which are mainly fumaroles. They essentially arranged at the second caldera rims close to the rim. Clay is the main alteration mineral observed along the older fumaroles. New fumaroles zones are significantly developed with the volcanic eruption. The WNW open fractures produced during volcanic eruption will have a positive role in maximizing permeability for the geothermal fluid.



Figure 10: Fumaroles at Nabro, the new basaltic lava flow in a black color at the background.

5. CONCLUSION

- The tectonic setting and geological make up of the Danakil depression provides a suitable environment for the occurrence of geothermal energy.
- Alid and Nabro-Dubbi are the two potential targets for high temperature identified from surface studies so far carried out.
- The estimated high reservoir temperature (greater than 220°C) from previous studies at Alid gave reason to conduct hydrogeology and fracture analysis aimed at selecting up-flow zones.
- Most of the geothermal manifestations are associated with fractures and faults.
- Rosette and field investigation indicate that lineaments in Alid are of three types: lineaments striking ENE (60-70°), NNW (330-340°) and E-W (270-280°).
- Maximum lineament zone defined by ENE strike is well marked on the FFD analysis in line with the major fracture set of the area.
- Two high values depicted on the contour map are well accompanied with the thermal manifestation thus it is worth to commence geophysical investigation and/or drill slim hole to map temperature gradient of the area.
- The MT resistivity conducted at Alid depicted a very interesting new site at the rift floor rather than beneath the Alid mount, therefore it is imperative to study the area in a wider perspective.

- The newly erupted volcanism at Nabro has significantly increased the permeability for geothermal fluid, thus will have an important role in the geothermal resource.

6. RECOMMENDATIONS

6.1 Alid Prospect

The current study recommends that the following detailed work should be commenced on the future on Alid:

- Conduct CO₂ and other gases (radon and mercury) mapping to know the gas outflow zone and select site of possible target of drill site.
- Gravity and microseismicity is also important in order to clearly define the target.

6.2 Nabro-Dubbi

Perform the following prospect investigation on Nabro-Dubbi:

- Conduct geological mapping.
- Collect and analyze water and gas samples and perform geochemical interpretation.

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