# Geothermal Exploration in Eritrea - Country Update

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**Keywords:** Alid, Nabro-Dubbi, Geothermal, Eritrea.

## ABSTRACT

Eritrea relies its electric generation totally from imported refined petroleum products, and is based on oil burning products. In 2017, 50 MW have been added to a total installed power capacity to become 195 MW. As of the end of 2019 13.5MW will be generated from solar in the off-grid system. The capacity is not enough as development mainly in mining, agriculture and industry sectors are planned to increase. Therefore, harnessing the geothermal potential has a significant impact on the economic development of Eritrea. Therefore, geothermal energy will have an important impact in alleviating expenditure on foreign currency and not affecting the environment. This year 24 professionals have took a basic training in surface exploration studies in Asmara with the sponsorship of UNEP/ICEIDA.

The tectonic setting and geological makeup of the Danakil region of Eritrea is a favourable site for having geothermal resources mainly for electrical generation and geothermal utilization. Alid, Nabro-Dubbi and Jalua fields are the notable places with extended geothermal manifestations. The 2011 eruption in Nabro-Dubbi signifies that the area is still an active magmatic zone. The old surface manifestation has been covered by basaltic flows and ashes. It is to be noted that other high geothermal manifestation also occurs in Jalua volcanic complex, but needs exploration studies. There are considerable low temperature-thermal springs potential for recreation spas, health, and mineral water bottling, etc. They occur at around the Asmara-Massawa highway, close to Gulf of Zula and within the Danakil Depression, which mostly do not show any immediate association with recent magmatism.

The completion of some of the surface studies on Alid prompts here to concentrate on the recent work performed. The hydrogeological assessment performed regionally indicates that the recharge area is mainly from three catchments fed by the highland area. Thorough assessments of Rose diagram and fault and fracture (FFD), analyses have been performed to know areas of up-flow zone. A more than 225$^0$C reservoir temperature was estimated using gas geothermometers from Alid geothermal prospect. The resistivity survey that was conducted recently resulted in an interesting anomaly at the rift floor and opened a wider perspective in exploration. Gravity and micro-seismic studies and soil-gas surveys were planned to complete surface exploration studies, but they were not developed yet.

## 1. INTRODUCTION

Eritrea is located in Northeast 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 km$^2$ comprising the central highlands, the western and coastal lowlands and 350 islands in the Red Sea. The growth potential in Eritrea is in agriculture and fishing, in mining, in small to medium scale manufacturing and in tourism. Only about 22% of the 2 million hectares of potentially arable land is presently cultivated. Though water shortage is still a problem, the recent construction of dams in various areas will transform farming from traditional rain-fed to irrigation. The potential for fish production from the Eritrean part of the Red Sea is about 70,000 tons per year, but only 7% of that is exploited. The growth potential in Eritrea is in agriculture and fishing, in mining, in small to medium scale manufacturing and in tourism. Mining is now progressing with two projects in operation and two, Colluli and Asmara for potash and precious and base metal, respectively, are on their way to be mined. A major barrier met in the effort to exploit Eritrea's growth potential is the energy deficit.

The total installed electric capacity in the country is 208MW. Only 140MW are interconnected, but the rest is isolated and supplies off-grid villages. Most of power is generated from fossil fuel, but the government is interested to shift to renewables and 20MW is now generated from solar plants off the grid.

The only indigenous, base-load energy option for Eritrea is geothermal. Since Eritrea lies within the African rift system, the potential of having geothermal high temperature resources for electric generation is high. The advantage of geothermal energy resources for Eritrea is not only its low environmental impact, but also can reduce import of fossil fuels, on which the country spends hard currency. For this reason, the government has given priority to this sector and investigation is still starting.

The tectonic setting and geological make-up of the southern coastal zone of Eritrea shows that it has good potential for the development of geothermal resources. Surface manifestations are abundant on some of the Danakil zone, mainly associated with volcanic activities of which the Alid, Jalua and Nabbro-Dubbi fields of geothermal manifestations are prominent.

Since the most expeditious progression to power development can be achieved at Alid, due to the completion of some of the essential surface studies there and showing good possibilities, this report is focused mainly on recent studies carried out on that zone.

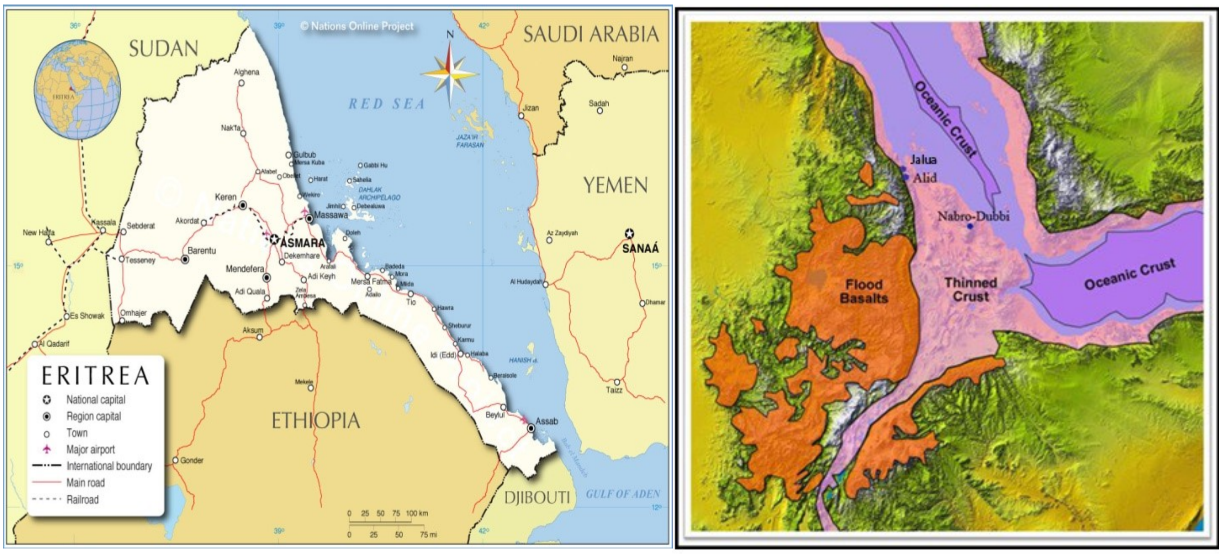


**Figure 1. a: Location map of Eritrea b: Locations of geothermal prospects: Alid, Jalua and Nabro-Dubbi in relation to the African Rift Valley.**

### 1.1 Previous works

Previous works are mainly concentrated on low temperature hot springs and Alid Volcanic center. Angelo Marini from the Italian Institute for Military Geography initiated a preliminary study on Alid geothermal manifestations in 1902 during the Italian colony (Marini, 1938). Documented studies on geothermal exploration continued till 1973, when UNDP sponsored a reconnaissance survey by a Geological Survey of Ethiopia team (UNDP, 1973). They identified thermal springs along the Asmara-Massawa road and in the Gulf of Zula area, south of Massawa. In 1992, the late Prof. Giorgio Marinelli and a staff from the Department of Energy visited Alid area and prepared proposal for detailed study. The Ministry of Energy and Mines refined this proposal later. This laid the basis for the geological and geochemical studies carried out in the area. In 1994, Mikhail Beyth of the Geological Survey of Israel surveyed the Alid hydrothermal area looking for epithermal gold deposition (Beyth, 1996).

The only detailed geological and geochemical investigation work was carried out at Alid and its surroundings during early 1996, by a team of the United States Geological Survey (USGS) and the Ministry of Energy and Mines of Eritrea (MEM). The work was financed by USAID and the team was led by Robert Fournier of the USGS (Clynne et al., 1996). A high temperature reservoir is estimated below the surface of Alid volcanic centre, as the geothermometry analysis of gas samples depicted. A two-phase conceptual model, with vapour dominated at the base and steam at the top was proposed by reinterpreting the water and gas samples of the 1996 USGS-MEM data (Yohannes, 2004).

A fault and fracture analyses were performed on Alid dome in 2005 and found out three structural trends that influence the geothermal fluid path (Yohannes et al, 2005; Yohannes, 2007). Based on the result of the structure, a shallow resistivity profiling was conducted on the small locality from Ghinda to Darere (Goitom et al, 2005). A comprehensive resistivity survey was conducted recently on the Alid dome and the adjacent rift floor, mainly MT and TEM sounds. Hydrogeological assessment on the catchment was carried out in 2005, to have a better understanding on the ground water flow in the area (Andemariam, 2006). In 2008 an MT/TEM resistivity survey was implemented with the sponsorship of ICEIDA (Icelandic International Agency) in Alid, depicting an anomaly at the rift floor (Eysteinsson et al., 2009). However, no anomaly zone was depicted on the hill top due to lack of rod penetrating on the hard rock.

### 1.2 Institutional set up and training

The geothermal sector of the country is governed by the Eritrea Geological Survey, under the Department of Mines, Ministry of Energy and Mines. The recent training of 24 professionals in April 2019 in basic surface exploration by UNEP/ICEIDA has a positive role in exploring geothermal resources in the country.

## 2. REGIONAL TECTONIC SETTING

The south-eastern part of Eritrea lies in the East African Rift system. It is a zone of crustal extension, in which the Somalia Plate is pulling away from the African plate along one arm, separating the divergent blocks that stem from the Afar triple junction. The Afar Depression, or the Danakil Depression, is a triple tectonic junction, where the spreading ridges forming the Red Sea and the Gulf of Aden emerge on land and meet the East African Rift. The western margin of the triangle extends to the Red Sea, while the south-eastern part extends to the Gulf of Aden off the Arabian Peninsula. The growth of the Danakil depression can be viewed in two phases of development. The continental rifting phase marks the change of volcanics from undersaturated trap series basalt to the transitional basalts and associated peralkaline silicic series of the rifting phase. The crustal separation phase of the Danakil depression commenced at about 4 to 3.5 Ma, which eventually gave rise to the present day configuration of the Afar Triangle.

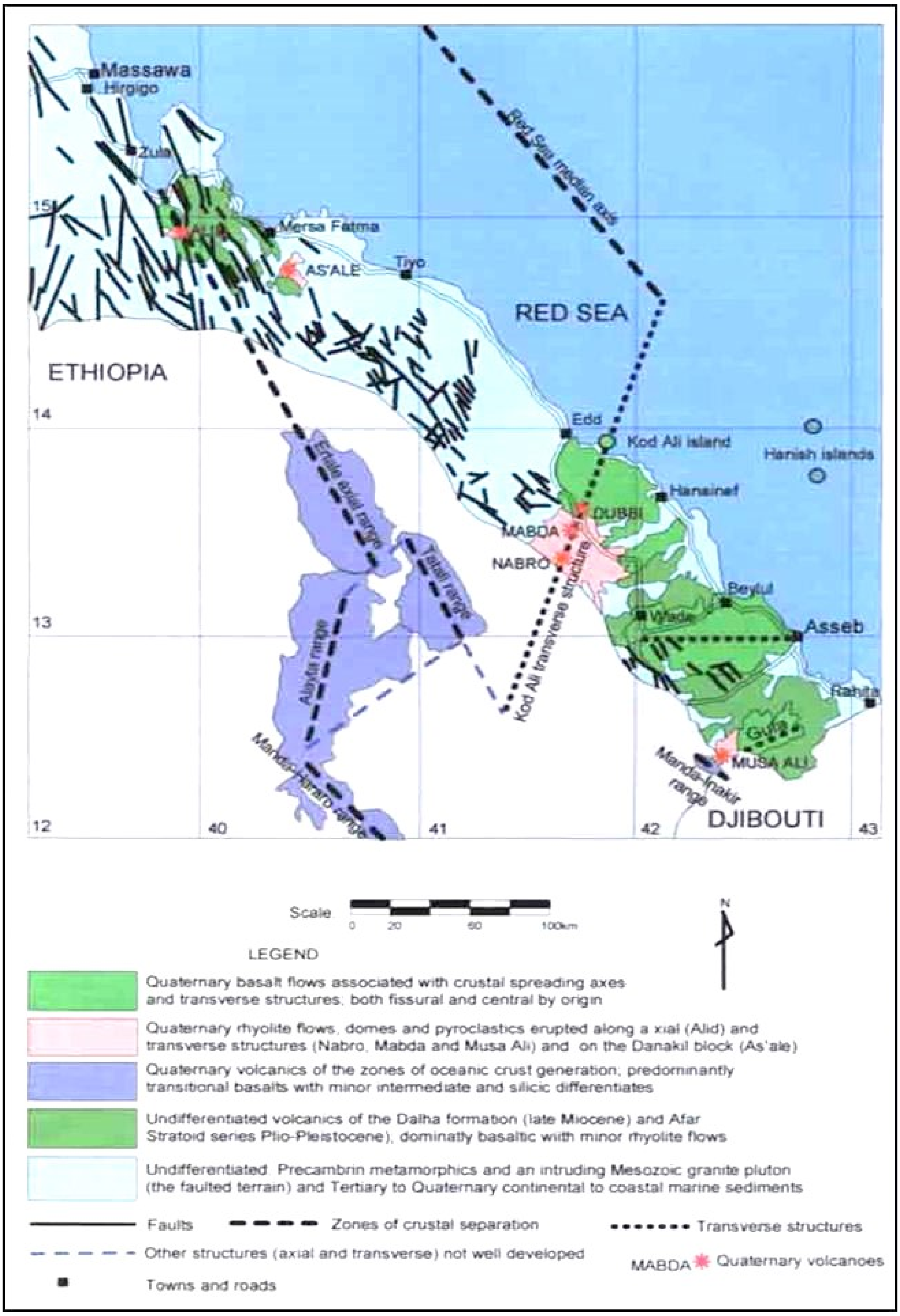


**Figure 2: Regional geological setting of south-eastern Eritrea**

Crustal opening started at the end of the continental rifting phase 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 Alid volcanic centre is located right on the axis of the Danakil Depression in between the Red Sea and the Afar triple junction, whereas the Nabro-Dubbi is situated within the triangle along the line that extending NNE to Kod Ali (Figure 2). Much of the rift consists of down-dropped crustal sections, bounded by deep-rooted normal faults (forming grabens) that cut the basaltic lavas extruded as result.

The two volcanic centres are separated by the Danakil Horst, where Proterozoic metamorphic rocks and Mesozoic sediments are exposed.

Recent studies on the current plate movement close to the Red Sea shows that the plates move in segments i.e., there are more spreading centers or axes. This will reinforce the positioning of active zones that are important in delineating geothermal resource areas. The Danakil depression and possibly the Nabro-Kod Ali transverse structure could be centers of crustal spreading.

Tectonic development of the Danakil Depression of the Afar triple junction, can be separated in the following representative stages (Figure 3).

a) 35 - 27 Ma: Continental rifting starts in Red Sea and Gulf of Aden.

b) 27 – 11 Ma: Rifting continues in the Red Sea, and begins seafloor spreading in the eastern Aden rift. The extension between Nubia and Danakil microplate may have started.

c) After 11 Ma: Extension in the Main Ethiopian rift begins to form a triple junction for the first time. Greatest stretching has occurred in southern Afar, where some oceanic crust may have been created at 8 Ma.

d) Then the triple junction migrated north-eastwards to the present-day. Tendaho-Goba'ad Discontinuity due to the counter-clockwise movement of the Danakil Alps.

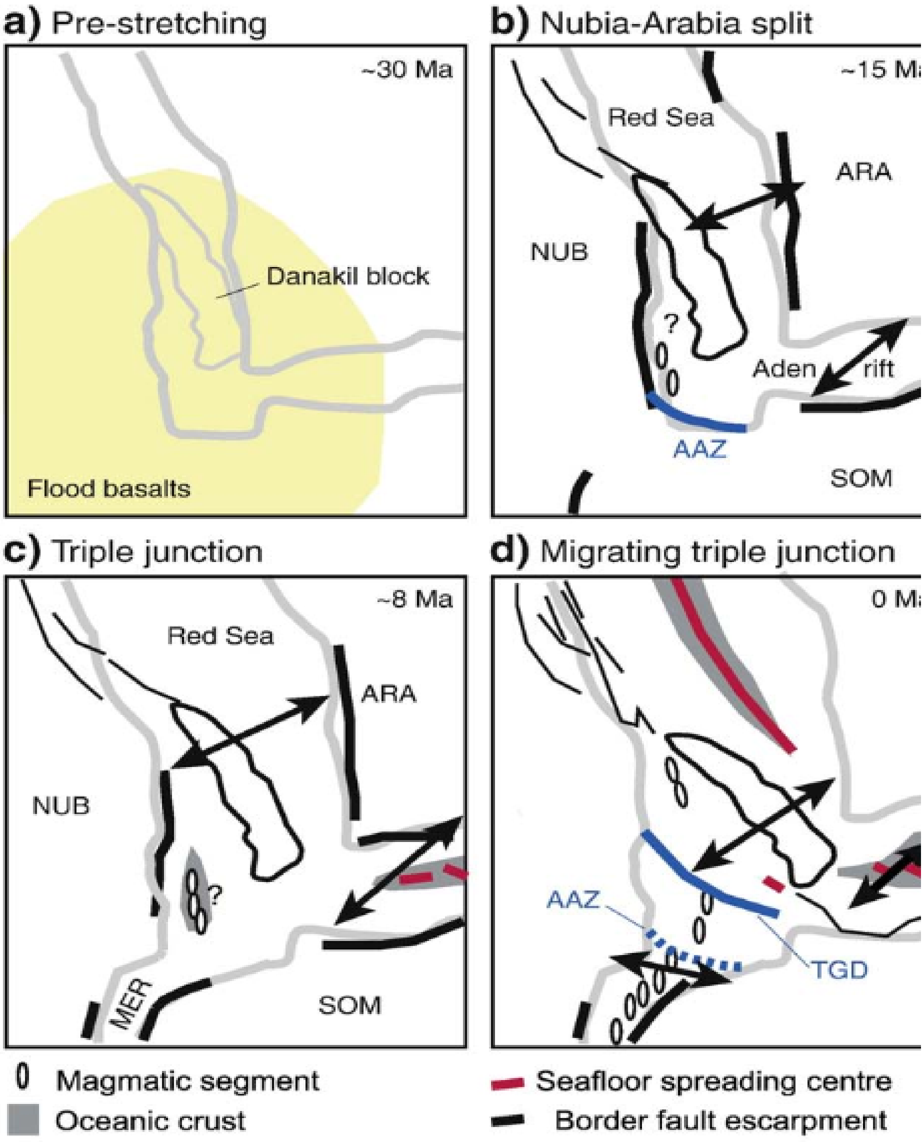


**Figure 3: Tectonic development of the Afar triple junction based on motion of crustal segments (after Eagles et al., 2002).**

## 3. GEOLOGICAL AND GEOTHERMAL SETTING

The suitable tectonic environment of the Danakil Depression and recent magmatic activities favour a high heat flow on the upper zone of the crust. Consequently, there are several places of surface manifestations of high temperature associated with recent magmatism and low temperature hot springs related with no recent magmatic activities on Danakil depression and escarpment of the Red Sea.

**3.1 Surface Manifestation of High Temperature Zone – Alid Volcanic Centre**

Regionally the Alid volcanic centre is located within the axis of the Danakil depression that extends NNW from the Afar triple junction on the graben. Traces of crustal spreading centre consists of rifted and faulted young deposits of sediments and basaltic flows. Metamorphic complex to the west and basaltic flows forming plateau to the east borders the plain.

3.1.1 Geologic setting

Alid is a very late-Pleistocene structural dome formed by shallow intrusion of rhyolitic magma, some of which vented as lavas and pyroclastic flows.

It is characterized by large-scale rhyolitic volcanism associated with E-W extension. The continuous extension, subsidence and volcanic activities influence the geological structure of the area. The volcanic succession of rhyolites and basalts is extruded following the NNW fault system of the rift, but it extends towards ENE.

The Alid volcanic centre consists primarily of rhyolite, both as massive and as pumice deposits, olivine basalt, and Red Series sediments (See Figure 3). Volumetrically, rhyolite and olivine basalt are the most abundant. Although volcanism culminated with fissure flows of basaltic lava on adjacent areas, the youngest eruption on the dome is rhyolitic, dated at about 33,000 years, However the rhyolitic eruption occurred in phases that lasted 10,000 years.

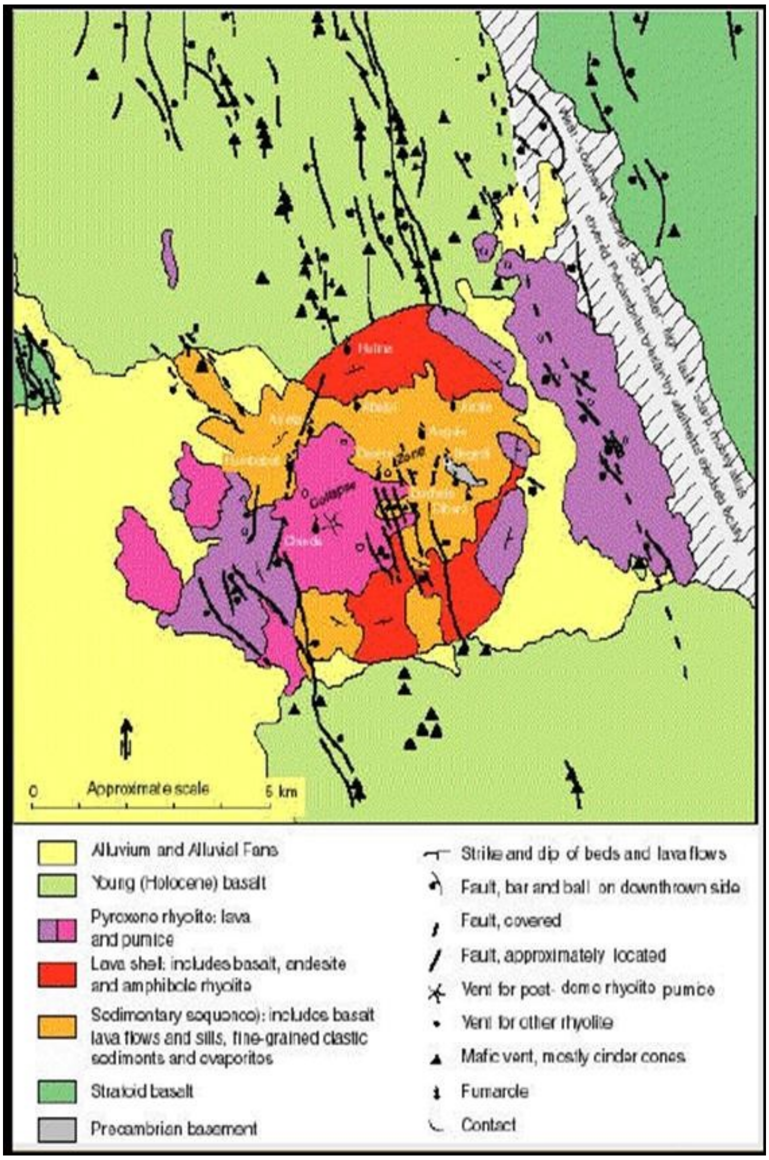


**Figure 4 Geology of Alid area**

Red series sediments are conspicuous at the side and top parts of the dome. It contains gypsum layers within the bed. Olivine basalt occurs mainly at the top of the dome. The olivine concentration varies from place to place but is abundant in general and presents weathering. Ignimbritic flows are only confined within the caldera for thin circular pattern surrounding the volcanic center. Vitrified flows occur in some places within the rhyolite. Thick pumice deposit (around 70 m thick) is the characteristic feature of this dome. Both white and red colors and various size fragments occur within the strata. Isolated granite boulders are also found elsewhere within this unit. Pumice covers the plateau portion of the mountain. Roof pendants of kyanite schists expose close to Illegedi. Some of the Illegedi geothermal manifestation occurs in this rock type.

The lineaments in Alid form a complex pattern with distinct sets of directions (Yohannes, 2007). Most of the lineaments are aligned at $70^0$ NE, related to the major axis of the dome, and it assumed to play a major role in the fluids path.

3.1.2 Geothermal setting

Hot mineralized fluids discharge in many locations within the Alid volcanic centre, most of which discharging as boiling fluids that releases gases. These manifestations, which are fumaroles and hot springs, are confined to the northern part of the Alid dome. In most cases the gas discharges sublimate as native sulphur or sulfosalts. Sulfosalts and clays are the main constituents of the alteration zone, which 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 occur in areas where hot springs are present at the surface. Alteration is wide and intensive at Illegedi and Darere (Figure 5). Sulfosalts and clays of various colours are conspicuous in recent or old precipitates. Emission of gases through fumaroles is intensive and spatially distributed along the stream.

Most of the gas geothermometers indicate that the subsurface geothermal system is likely at more than $225^0$C.

**Figure 5. Fumaroles with sulfosalts and clays in Darere**

### 3.2 Nabro-Dubbi volcanic centres

The Nabro stratovolcano is aligned with Dubbi volcano in a NE-SW diection, for which they are named as Biddu or Nabro-Dubbi volcanic complex. At 2218 masl, Nabro is the highest volcano in the Danakil depression and elsewhere in the eastern lowland. Nabro volcano (Figure 6) 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 $km^2$ (Wiart and Oppenheimer, 2005). Trachytic lava flows and pyroclastics are the primary constituents of 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 transverse to the trend of the Nabbro-Dubbi volcanic range.

Dubbi is a large volcanic massif rising up to 1625 masl, erupted explosively in May 1861. The volume of lava flows alone is 3.5 $km^3$, making the largest reported historical eruption in Africa (Wiart 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. A regional structure separates the Danakil block in two distinct parts: the Pre-rift basement to the northwest, and the Plio-Pleistocene volcanism to the southeast. That structure is related to the most recent and extensive Nabro, Mabda and Dubbi volcanic activities in the region, where it crosses numerous northwest-southeast trending faults of the north-eastern Afar rift margin and Danakil block. The Nabro volcanic center sites at the intersection of the ENE structure and the Kod Ali fault line.

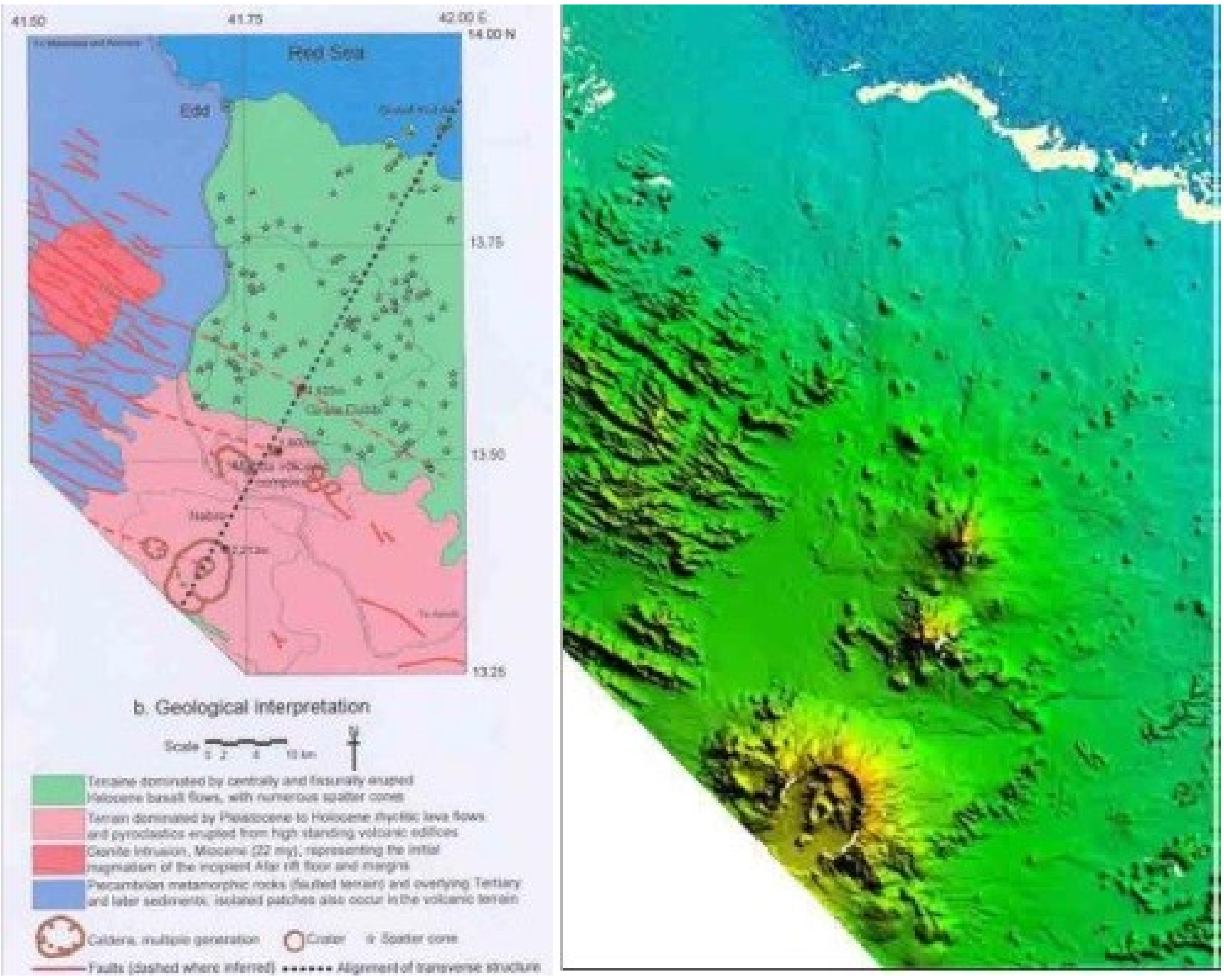


**Figure 6. Geological interpretation of Nabro-Dubbi area. The right photo is the DEM of Nabro-Dubbi (DOM, 2004)**

The 2011 Nabro eruption offers a valuable opportunity to develop our understanding of unrest and eruptive activity of caldera systems, the local interactions between tectonics and volcanism and neighboring volcanoes, and the origins and significance of the off-axis volcanic ranges in the wider Afar region. (Goitom et al., 2016). Analysis of ground deformation suggests the eruption was fed by a shallow dike oriented in a NW-SE direction (Figure 7). This result is consistent with the alignment of old structure rather than the transverse axis.

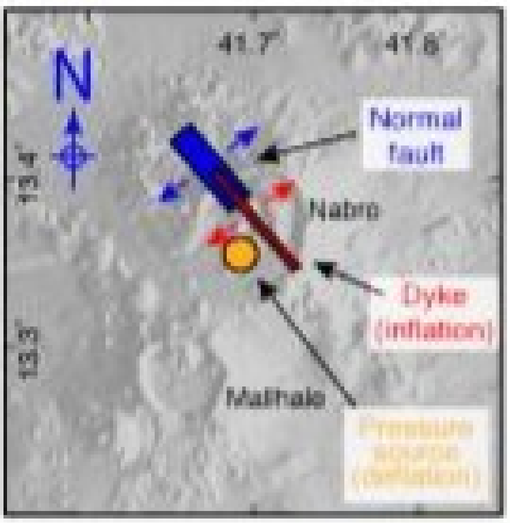


**Figure 7. model deduced from elastic inversion of the SAE derived surface displacement field**

### 3.3 Jalua volcanic complex

The Jalua volcano is located close to the Gulf of Zula (Figure 8). It is a big silicic stratovolcano affected by a large central volcano-tectonic depression open to the sea (CNR-CNRS team, 1973). Lavas are rhyolites of peralkaline composition. The Jalua volcano shows fumarolic activities on its western flank. Important submarine activities occurred recently west of Jalua (Erafaile surroundings) producing basaltic lava flows and hyaloclastite ash rings.

No well-developed surface alteration occurs, but there are abundant fumaroles particularly during the rainy season. Hot water flows into the sea.

Geothermal exploration should focus on the areas of young silicic volcanism occurring on the above structure. The shallow magmatic chamber of the volcano is the heat source of the probable geothermal system.

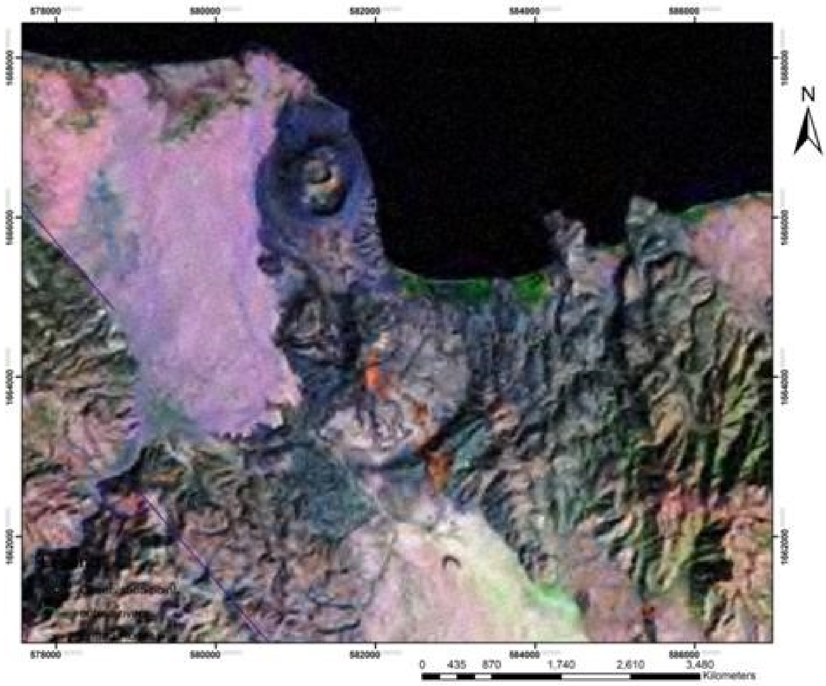


**Figure 8: Jalua volcano with Erafayle double caldera volcanic center.**

## 4. ALID GEOTHERMAL SYSTEM – ASSESSMENT FROM RESISTIVITY SURVEY

Geological and geochemical studies performed on the Alid dome pointed out that a geothermal reservoir is possible to occur beneath the Alid dome. To confirm this possibility and know the extent and depth of the probable reservoir, a geophysical survey was carried out. This was a MT and TEM survey made by ISOR (Icelandic Geosurvey) and the Eritrean Geological Survey in December 2009 on the Alid dome and adjacent area.

Resistivity maps at various depths were drawn, ranging from 400 masl to 10,000 mbsl. At 3500 mbsl and below, a clear low-resistivity NNW-SSE body is depicted west of the mountain and connected to the broader WSW-ENE low resistivity anomaly to the south.

The following conclusions were obtained from the survey:

- 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 0.5–2 km depth shown by a yellow line in Figure 10. This boundary is best defined in the iso-resistivity map at 1000 mbsl.
- There is a low resistivity body defined by the NNW-SSE brown line below the western part of Mt Alid and to the west of the mountain. It is approximately 3 km wide (Figure 9) and reaches its highest elevation at 2000–3000 mbsl extending down to a depth of about 7 km.
- 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.

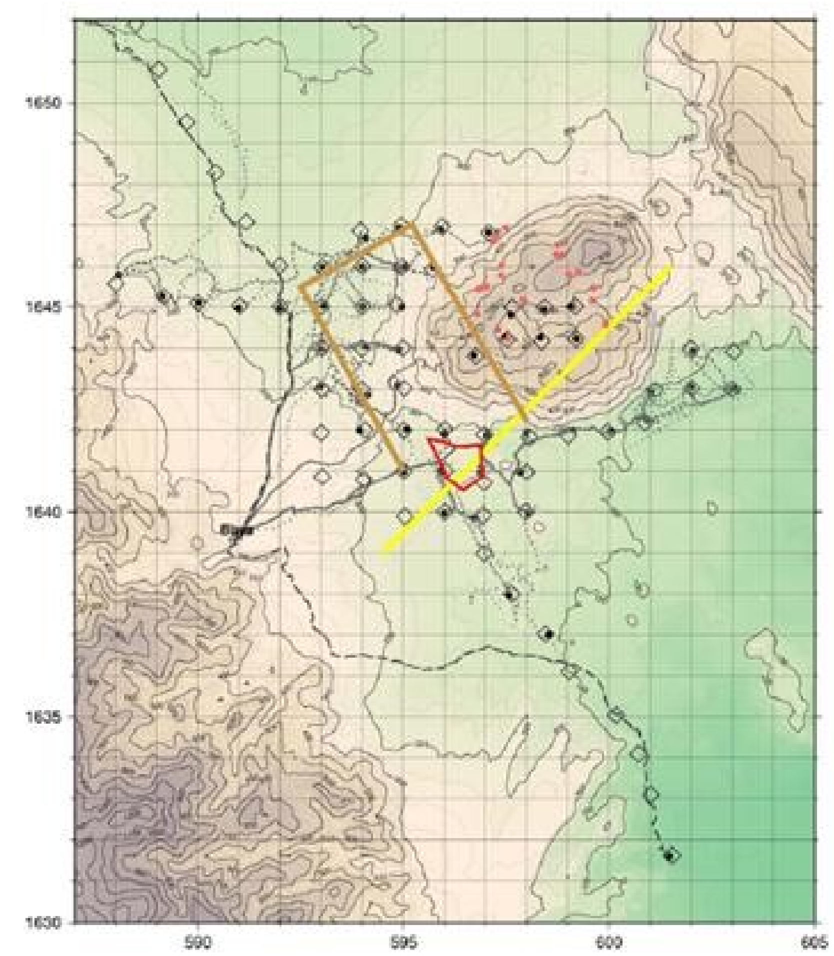


**Figure 9. The yellow line shows the location of vertical resistivity anomaly boundary. It outlines the low resistivity body west of Mt. Alid at about 2 km depth. Red dots are geothermal vents on Alid dome.**

The ENE low resistive anomaly 3500 mbsl is an important structure that extends westward to the metamorphic basement (Yohannes, 2010). It is deep seated and is 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 more interesting in dealing with the fluid movement.

## 5. LOW TEMPERATURE MANIFESTATIONS

Hot springs in Eritrea occur at the main escarpment along the Asmara-Massawa highway, along the coastal plains and on the Danakil Depression (Figure 10).

### 5.1 Thermal Springs Along the Asmara-Massawa Highway

The thermal springs along the Asmara-Massawa highway are on a section of the middle to lower levels of the western part of the escarpment of the Red Sea graben. Surface temperature measurements, flow estimation and chemical analyses were carried out for the Ali Hasa, Dongolo, Sabarguma and Ailet spring areas. The hydrothermal features in these areas are warm and hot springs, with temperatures being lower or higher than 50°C, respectively. They are near-neutral bicarbonate waters with low chemical content. All the springs are of low energy presenting quiet flow with no steam separation or gas.

### 5.2 Gulf of Zula Area

Hot springs occur at Ua-a and Acfat, and thermal water wells in Arafali and Zula villages, all to the west of the Gulf of Zula, and in Gelti area on the south side of the gulf. Ua-a hot spring is located about 20 km northwest of Foro village, situated to the north of Zula town. It occurs in an area covered by fluvial deposits, has a large discharge, a water temperature of 36°C and pH of 7.5. The Acfat group of thermal springs is located about 4 km north of Zula village and about 1.5 km from the sea. The main spring has a temperature of 43°C, a large discharge and a pH of 7.0. The springs occur on the edge of a swamp. A large diameter well located in Erafayle village is 10 m deep. Another in Zula town is 20 m deep. Both wells have thermal water with temperature of 36°C and pH of 7.0.

The Gelti group of thermal springs consists of large number of hot springs located on the seashore. The water chemistry indicates high mixing with seawater. Low-pressure steam vents are located within about 200 m of the shore, being steam thought to be separated at low pressure from underground water bodies flowing toward the seashore.

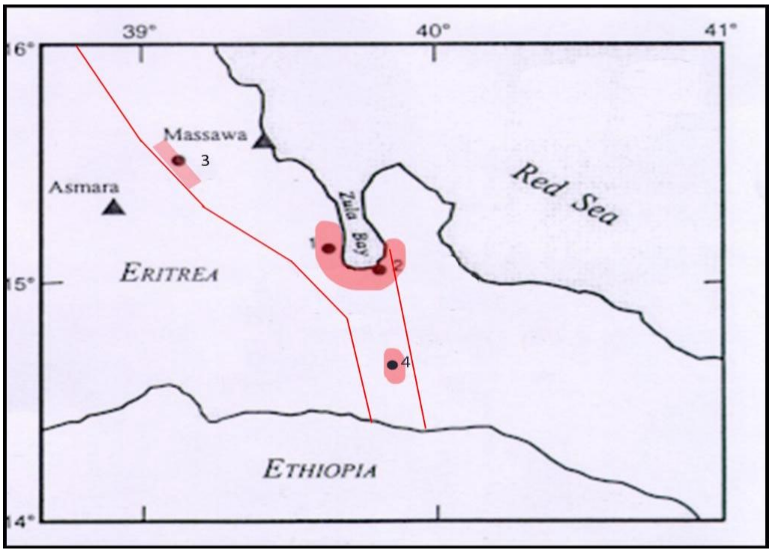


**Figure 10. Location map of low temperature areas; symbols 1 and 2 are around gulf of Zula, 3 on the Asmara-Massawa road and 4 on Danakil Depression.**

Excepting Gelti hot springs, all the remaining manifestations do not show any immediate association with magmatism. They are thought to be ascending deep waters through the rift marginal faults, of waters heated at depth under typically crustal geothermal conditions, with relatively low geothermal gradients. They are thus believed to not having potential for large-scale commercial development for power generation, but for small-scale, low-temperature, non-power applications, including mineral water bottling, health and recreation spas, etc., as already demonstrated at the Dongolo, Sabarguma and Ailet springs which have histories of bottling popular brands of mineral water.

The Gelti hot springs occur in Quaternary basalt lavas. These springs seem to be associated with heating in underground zones of relatively elevated temperature, but it is not certain they are associated with high temperature and volume of hot water circulation at shallow depth, due to the absence of signs of recent silicic volcanism. Being in the coastal area, and having association with high permeability rocks that may allow hot water production in adequate volume, the area has potential for low temperature geothermal resource applications.

### 5.3 Thermal springs on the Danakil Depression

The springs are located within the Danakil Depression and present high flow along fault planes. The Laele and Bolleli hot springs are the main localities. The latter is located within a weathered basalt related to axial volcanism.

## 6. CONCLUSIONS AND RECOMMENDATIONS

The tectonic setting and geological setting of the Danakil Depression provides a suitable environment for the occurrence of high temperature geothermal systems at depth.

Alid, Nabro-Dubbi and Jalua are the potential targets for high temperature resources, according to the geoscientific studies carried out so far.

A high temperature reservoir (>225$^0$C) is estimated from gas geothermometry conducted on Alid fumaroles.

The MT resistivity survey conducted at Alid defined a very interesting and new site at the rift floor rather than beneath the Alid mount. Therefore, it is recommendable to study the area in a wider perspective. Accordingly, a comprehensive survey supported by ICEIDA and UNEP was started in 2015 to complete surface exploration studies in Alid, They include geophysics MT-TEM soundings, microseismic, and gravity, as well as superficial alteration mapping and soil gas survey. These studies will be accomplished in the coming years. Subsequently, a proposal for drilling will be outlined, to be made with the Geothermal Risk Mitigation Fund (GRMF) founding.

- It is recommendable also to develop geological mapping and geochemical sampling and interpretation in the areas of Nabro-Dubbi and Asaila.

In addition, it is necessary continue to build up the capacity of the Eritrea Geological Survey and introduce institutional framework.

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