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# GEOTHERMAL EXPLORATION IN ERITREA – STATUS REPORT DISCUSSION

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## ABSTRACT

Eritrea is entirely reliant on imported refined petroleum products for its electricity generation. In 2017, 50 MW were added, raising the total installed power capacity to 195 MW. As of the end of this year (2019), 13.5 MW will be generated from solar in the off-grid system. The installed capacity is not sufficient, as development mainly in mining, agriculture and industry sectors is planned to increase. Therefore, harnessing the geothermal potential of Eritrea can have a significant impact on the economic development of the country. The impact can be viewed as greater stability in the electricity price and lesser strain on the environment. Therefore, geothermal energy will have an important input in alleviating expenditure on foreign currency while safeguarding the environment. This year, 24 professionals have undertaken 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 are favourable for harbouring geothermal resources with the potential for being developed, mainly for electricity generation and geothermal utilization. Alid, Nabro-Dubbi and Jalua fields are the notable places with ample geothermal manifestations. The 2011 eruption in Nabro-Dubbi signifies that the area is still an active magmatic zone. The old surface manifestation has covered by basaltic flows and ashes. It is to be noted that other high geothermal manifestation also occur in Jalua volcanic complex but needs exploration study.

There is considerable potential for the utilization of low-temperature thermal springs for recreation spas, health and mineral water bottling etc., 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 concentration on recent work. The hydrogeological assessment performed regionally indicates that the recharge area is mainly from three catchments, with input mainly from 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 reservoir temperature of more than 225°C was estimated in the Alid geothermal prospect using gas geothermometers. The resistivity survey that was conducted recently has availed an interesting anomaly at the rift floor and opened a wider perspective in exploration.

Gravity and microseismic studies, and soil-gas surveys in Alid were planned for completion in 2019, but were postponed until next year.

## 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 (Figure 1). 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 construction of dams in various area recently will mitigate by displacing 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. A major barrier met in the effort to exploit Eritrea's growth potential is the energy problem, as no favourable area for hydroelectric power is present.

On November 2017, 50 MW of electrical generation capacity were commissioned, bringing the total to 208 MW. Out of this, 140 MW is interconnected, but the rest consists of self-contained parts, which serve off-grid villages. But the concern is the fact that most of the power is generated from fossil fuels. As of the end of this year (2019), 13.5 MW will be generated from solar in the off-grid connection.

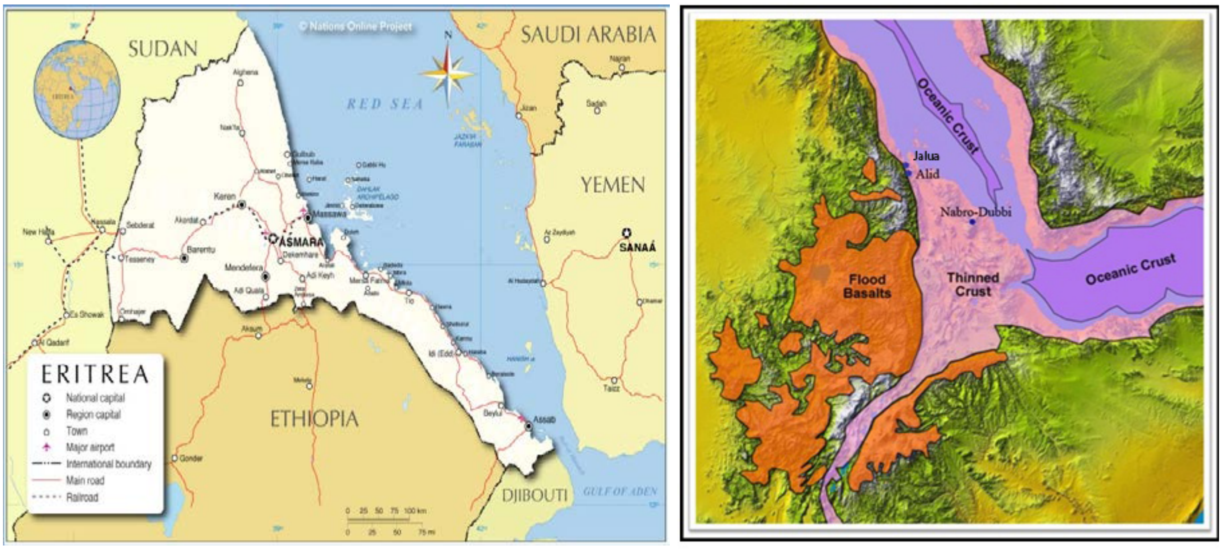


FIGURE 1: a) Location map of Eritrea; b) Locations of geothermal prospects: Alid, Jalua and Nabro-Dubbi in relation to the African Rift Valley

The only indigenous energy option for Eritrea considering the base-load is geothermal. Since Eritrea lies within the African rift system, the potential of using geothermal energy for electricity generation is high. The advantage of the geothermal energy resource for Eritrea is not only based on its environmental impact, but also the replacement of fossil fuels, which the country acquires with hard currency. For this reason, the government has given priority to this sector and investigation is still commencing. The tectonic setting and geological make-up of the southern coastal zone of Eritrea show that it has good potential for the development of geothermal resources. Surface manifestations are abundant in some areas of the Danakil zone, mainly associated with volcanic activities. Of these, the Alid, Jalua and Nabbro-Dubbi fields are the most prominent (Figure 1).

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, showing the good possibility for resource development, the report here concentrates mainly on recent studies carried out there.

### 1.1 Previous works

Previous works have mainly concentrated on the low-temperature hot springs and Alid volcanic center. Angelo Marini of the Italian Institute for Military Geography initiated a preliminary study on the Alid geothermal manifestations during Italian colonial time, in 1902 (Marini, 1938). During subsequent decades, however, no documented studies on geothermal exploration commenced until 1973, when the United Nations Development Programme (UNDP) sponsored a reconnaissance survey by a Geological Survey of Ethiopia team (UNDP, 1973). At first, they located thermal springs along the Asmara-Massawa road and in the Gulf of Zula area south of Massawa. A second survey, launched from the south in the same year, visited some of the fumaroles that manifest 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. 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 for the possibility of epithermal gold deposition (Beyth, 1996).

The only detailed geological and geochemical investigation work that has been carried out at Alid and its surroundings took place during January and February 1996, by a team from 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 inferred below the surface of Alid volcanic centre, from the geothermometry analysis of collected gas samples. A two-phase conceptual model, vapour dominated at the base and steam dominated at the top, was proposed through reinterpretation of the water and gas samples of the 1996 USGS-MEM data (Yohannes, 2004).

A fault and fracture analysis was performed on Alid dome in 2005, which led to the discovery of three structural trends that influence the geothermal fluid path (Yohannes, 2007). Based on the result, a shallow resistivity profiling was conducted in the small locality from Ghinda to Darere. But a comprehensive resistivity survey was conducted recently on the Alid dome and the adjacent rift floor, mainly through MT and TEM methods. Hydrogeological assessment on the catchment basins was also carried out in 2005 to have a better understanding of the ground water flow in the area (Andemariam, 2006). In 2008 an MT/TEM resistivity survey was implemented with the sponsorship of the Icelandic International Development Agency (ICEIDA) 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 within 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 the geothermal resource 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 part of the eastern African continent, Somalia Plate, is pulling away from its parent; 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 plate tectonic triple junction, where the spreading ridges that are 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 of the rifting phase. The crustal separation phase of the Danakil tectonic development commenced at about 4 to 3.5 Ma, which eventually gave 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 Alid volcanic centre is located right on the axis of the Danakil Depression in between the Red Sea and the Afar triple junction, whereas Nabro-Dubbi is situated within the triangle along the line that extends NNE to Kod Ali (Figure 2). Much of the rift consists of down-

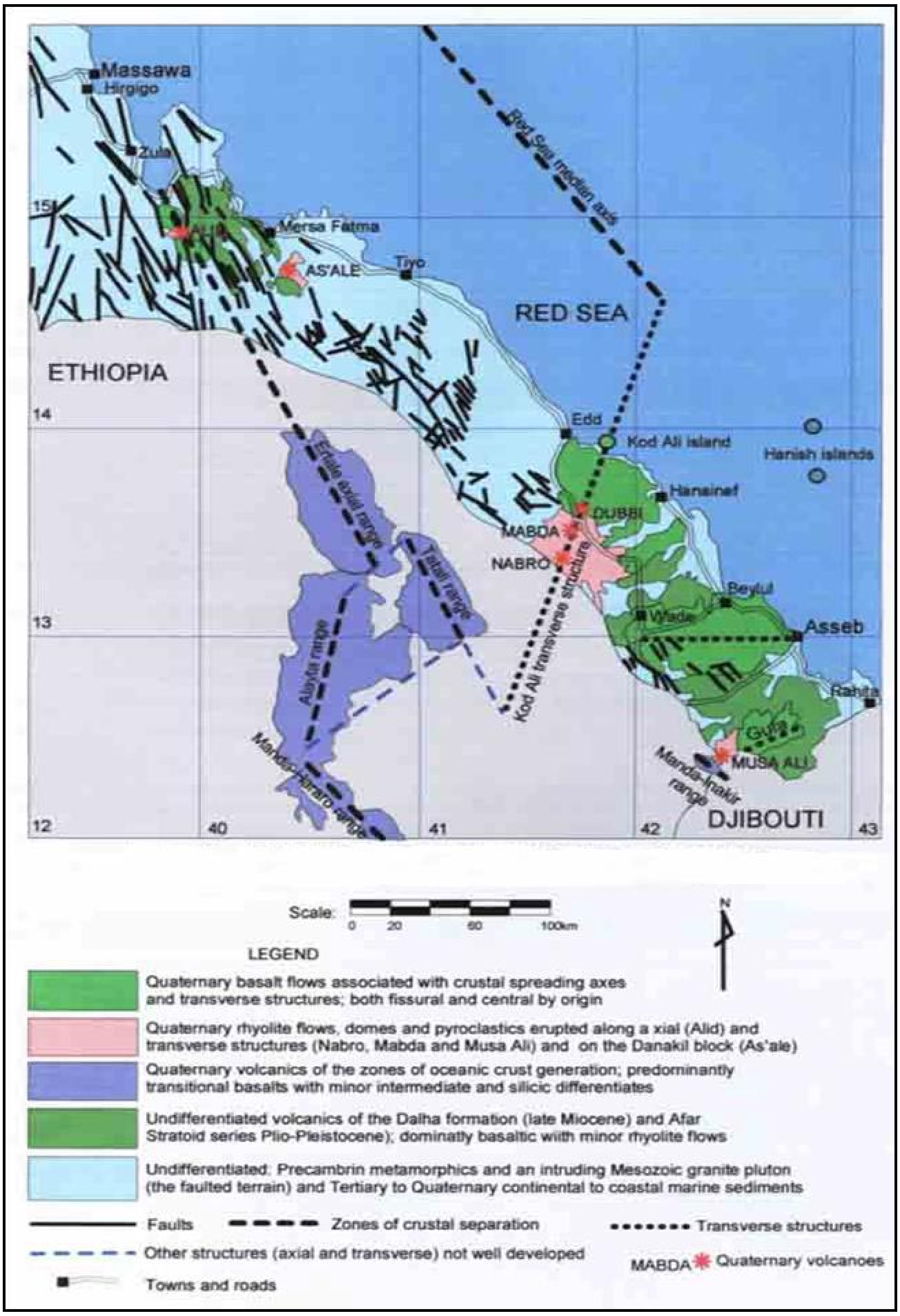


FIGURE 2: Regional geological setting of south-eastern Eritrea

dropped crustal sections, bounded by deep-rooted normal faults (forming grabens) that cut into the resulting extruded basaltic lavas.

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

Recent studies on present day movement of plates close to the Red Sea show that the plates move in segments, i.e. there are more spreading centers or axes. This reinforces the positioning of active zones that are in turn important in delineating the geothermal resource areas. The Danakil Depression and possibly the Nabro – Kod Ali transverse structure could be centers of crustal spreading deciphering from the relative motion of plates.

Tectonic development of the Danakil Depression of the Afar triple junction can be viewed as illustrated with snapshots of representative stages (Figure 3).

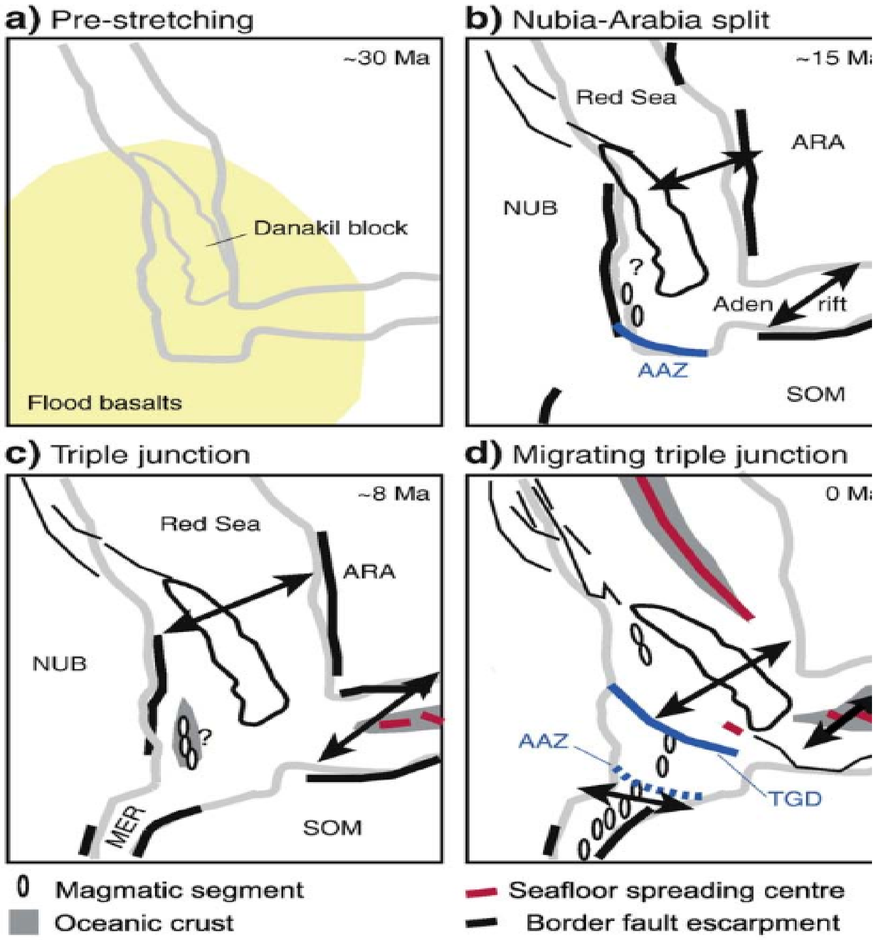


FIGURE 3: Tectonic development of the Afar triple junction based on motion of crustal segments from continuous GPS reading showing different displacement rates

a) Between 35 and 27 Ma, continental rifting commences in Red Sea and Gulf of Aden.
b) Rifting continues in the Red Sea, and seafloor spreading has commenced in the eastern Aden rift. Extension between Nubia and Danakil microplate may have initiated.
c) After 11 Ma, extension in the Main Ethiopian rift initiates to form a triple junction for the first time. Greatest stretching has occurred in southern Afar, where some oceanic crust may have been created by 8 Ma.
d) The triple junction migrates north-eastwards to the present-day Tendaho-Goba'ad Discontinuity due to the counter-clockwise movement of the Danakil Alps.

## 3. GEOLOGICAL AND GEOTHERMAL SETTING

The tectonic environment of the Danakil Depression subordinated by recent magmatic activities favours high heat flow in the upper zone of the crust. Consequently, several places of surface manifestations of high-temperature geothermal fields associated with recent magmatism and low-temperature hot springs related with no recent magmatic activities occur in the Danakil Depression and escarpment of the Red Sea.

### 3.1 Surface manifestation of high-temperature zone - Alid volcanic centre

The Alid volcanic centre is located within the axis of Danakil Depression that extends NNW from the Afar triple junction on the graben trace 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 shoulders 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 activity influence the geological structure of the area. The volcanic succession of rhyolite and basalt are extruded following the NNW fault system of the rift but extended its ellipse towards ENE.

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

Red series sediments are conspicuous at the side and top part of the dome. It contains gypsum layers within the bed. Shouldering effect of the rhyolite emplacement tilts it at the hillside. Olivine basalt occurs mainly at the top of the dome. The olivine concentration varies from place to place but is generally present abundantly. However

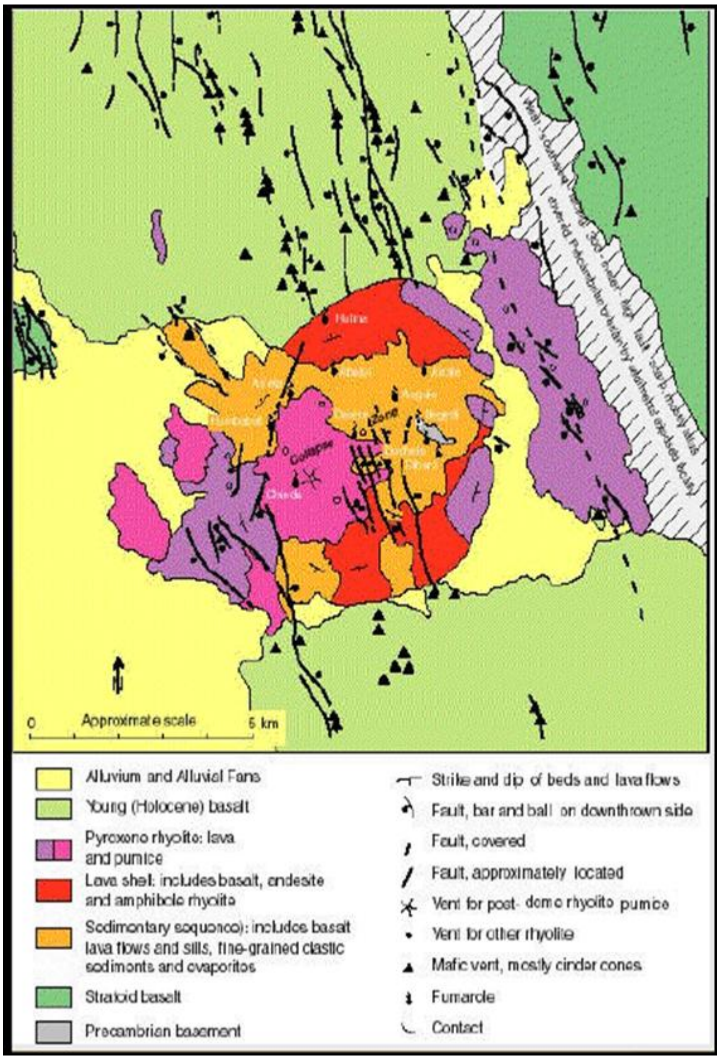


FIGURE 4: Geology of Alid area

weathering is pervasive on olivine. Ignimbritic flows are only confined within the caldera for thin circular pattern surrounding the volcanic centre. Vitrified flows occur in some places within the rhyolite. Thick pumice deposit is the characteristic feature of this dome. It is about 70 m thick. Both white and red colored and various size fractions 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, but distinct sets of directions (Yohannes, 2007). Most of the lineament are aligned along the 70°E direction, related to the major axis of the dome, and it is assumed to play a major role in localizing fluid path.

### 3.1.2 Geothermal setting

Hot mineralized fluids discharge from many locations within the Alid volcanic centre. Most of the manifestations discharge boiling fluids that release free gases. These manifestations, which are either fumaroles or hot springs, are confined to the northern part of the Alid dome. In most cases the free gas issues sulphur, which precipitates in the form of sulphosalts. Sulphosalts and clays are the main constituents of the alteration zone. The intensity of alteration, however, varies from place to place. Hot springs are more likely to occur where the depth to the 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 and abundant in both present and old precipitates. Yellow coloured ones mainly represent sulphosalts and brown ones clays. Emission of gases through fumaroles is intensive and spatially distributed widely along the stream.

Most of the gas geothermometers indicate that the subsurface geothermal system is likely to have temperatures exceeding 225°C.

FIGURE 5: Fumaroles with sulphosolts and clays in Darere

### 3.2 Nabro-Dubbi volcanic centres

Nabro stratovolcano is a prominent volcano located on a line 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. 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$^3$ (Wiart 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 erupted along NNW trending fissures transverse to the trend of the Nabbro-Dubbi volcanic range. Dubbi is a large volcanic massif that rises to 1625 m above sea level and erupted explosively in May 1861. The volume of lava flows alone, 3.5 km$^3$, makes this 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 northeast cover a 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 into 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 volcanic center is the intersection of the ENE structure and Kod Ali fault line.

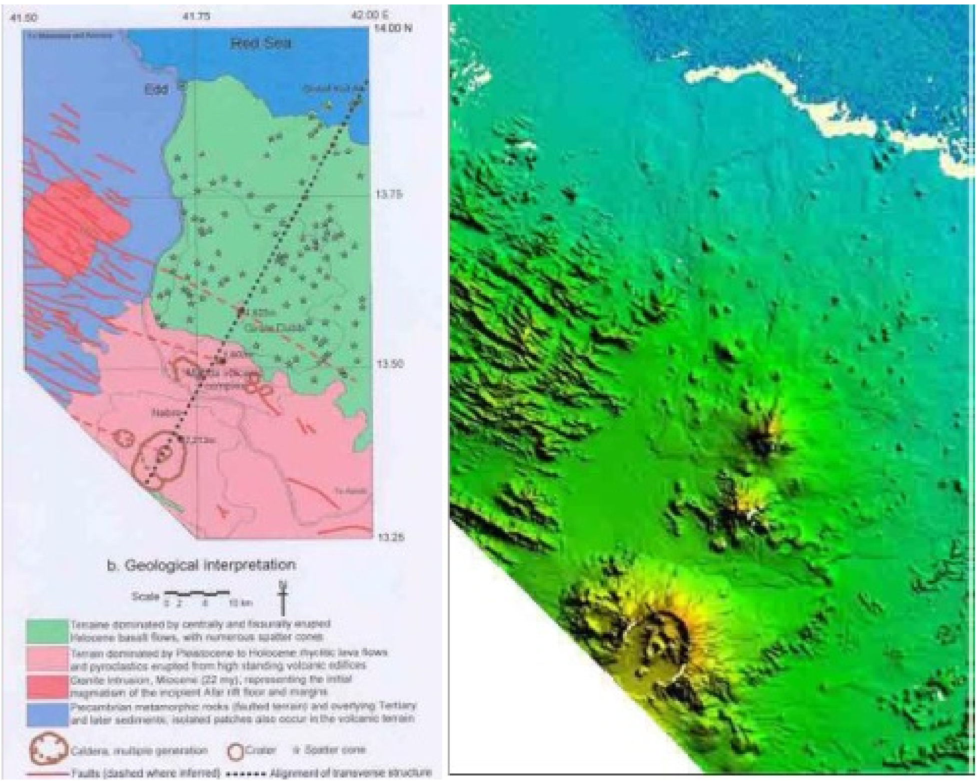


FIGURE 6: Geological interpretation of Nabro-Dubbi area.
The right photo is the DEM of Nabro-Dubbi (DOM, 2004)

A paper published on the 2011 eruption, which involved a number of academia, concluded the following points as deduced from seismic monitoring (Goitom et al., 2015): 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 between neighboring volcanoes; and the origins and significance of the off-axis volcanic ranges in the wider Afar region. 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.

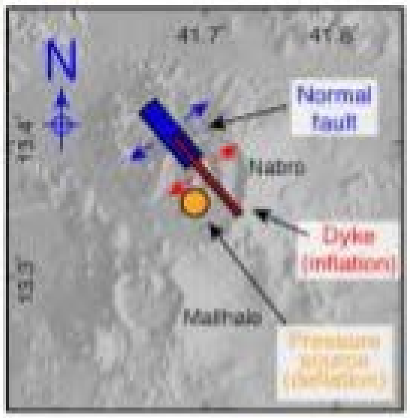


FIGURE 7: Model deduced from elastic inversion of the SAE derived surface displacement field

### 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 which is open to the sea (CNR-CNRS team, 1973). It is mainly built up by a peralkaline silicic nature. The Jalua volcano shows fumarolic activities on its western flank.

Important submarine activities occurred recently west of Jalua (Erafaile surroundings) resulting in "paving stones" basaltic lava flows and hyaloclastite ash rings.

No well-developed surface alteration occur. However abundant fumaroles issue, in particular during rainy season, where people come from afar to take spa. Hot water flows into the sea.

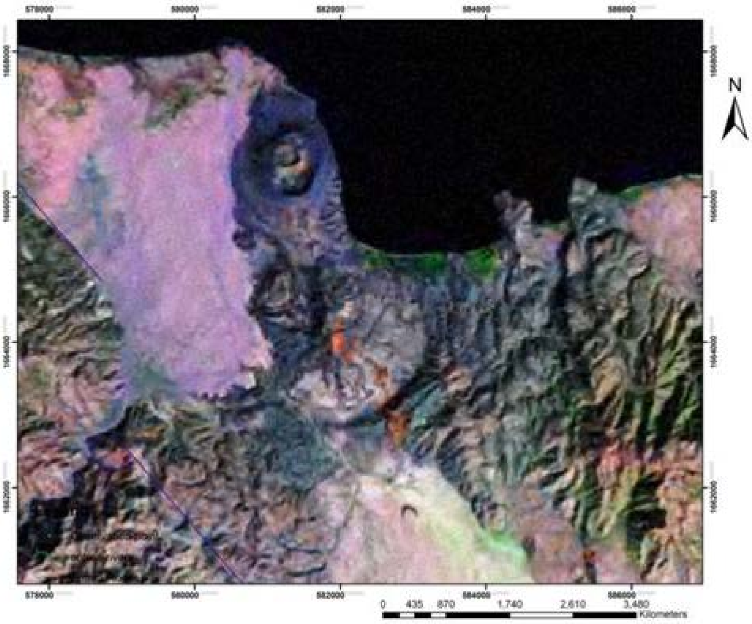


FIGURE 8: Jalua volcano with Erafayle double caldera volcanic centre

The geothermal resource exploration should thus focus on the areas of young silicic volcanism occurring on the above structure due to evidence for the shallow emplacement of magmatic heat source. The shallow magmatic body would install and maintain active geothermal system with high temperature at economically accessible depth.

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

The geological and geochemical exploration carried out on the Alid dome indicate that a geothermal reservoir exists beneath the dome. In order to validate this and estimate the extent and depth of the reservoir, a geophysical survey was anticipated. Since an MT resistivity survey can penetrate deep resistivity structures (tens or hundreds of kilometers), and is practically the only method for doing so, such a survey was proposed in Alid. Accordingly, with the funds from ICEIDA, ÍSOR (Icelandic GeoSurvey) and the Eritrean Geological Survey carried out an MT survey in December 2009 on the Alid dome and adjacent area.

TEM soundings do not suffer telluric shift arising from local inhomogeneity, which distort the electric field. Thus, a TEM survey was conducted along with MT. By interpreting together TEM and MT soundings made at the same (or nearly the same) location, the TEM data can be used to determine the unknown multiplier of the MT apparent resistivity.

Resistivity maps at various depths were drawn ranging from 400 meters above sea level to 10,000 m below sea level (m.b.s.l.). Figure 9 depicts a clear low resistivity NNW-SSE body at 3500 m.b.s.l., below the west of the mountain and connected to the broader WSW-ENE low resistivity to the south.

The following conclusion on the resistivity structures has been drawn from the MT resistivity study on Alid:

- 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 ½–2 km depth shown by a yellow line in Figure 10. This boundary is best seen on the isoresistivity map at 1 km b.s.l.

- 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 there is a low resistivity body, approximately 3 km wide (Figure 10). It reaches the highest elevation at 2–3 km b.s.l., and extends 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.

Attempt has been done to relate the anomaly with the geotectonic set up of the area. The ENE direction low resistive anomaly result marked at 3500 meters b.s.l. is an important structure that extends even westward to the metamorphic basement (Yohannes, 2010). 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 more interesting in dealing with the fluid movement.

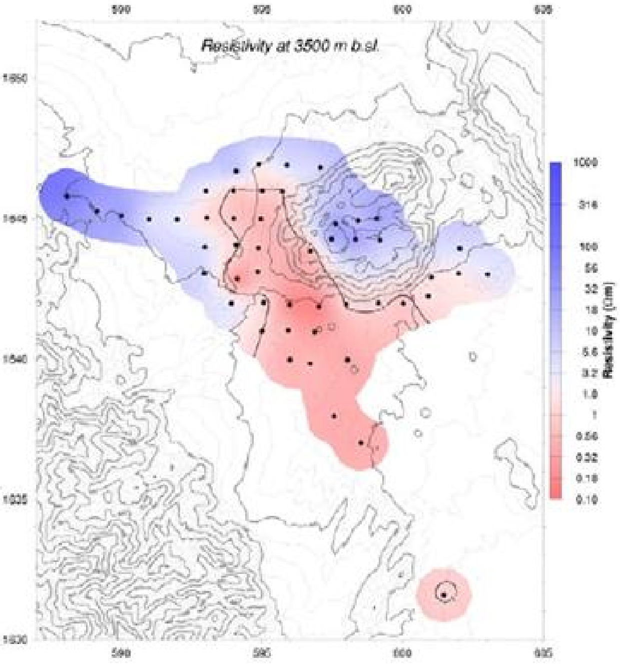


FIGURE 9: Resistivity map at 3500 m below sea level. Coordinates are in UTM, km units

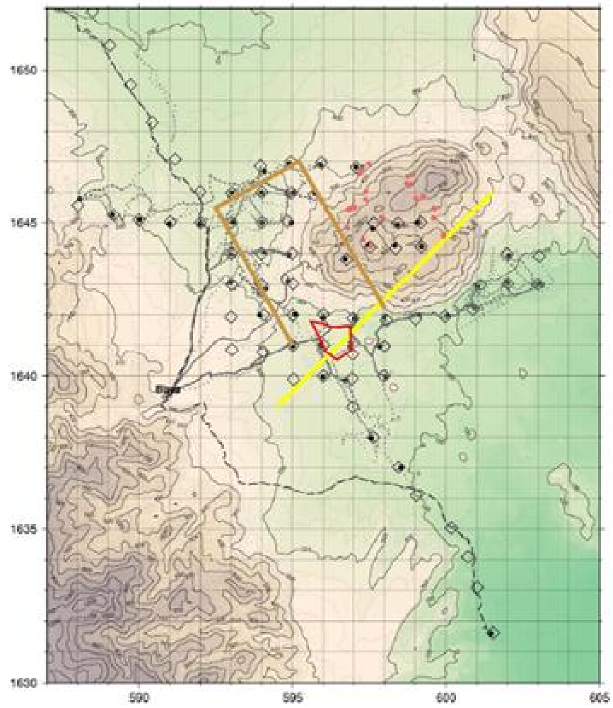


FIGURE 10: Resistivity structures associated with Mt. Alid. Red dots are geothermal vents.

## 5. LOW TEMPERATURE FIELDS

Hot springs in Eritrea occur at the main escarpment along the Asmara-Massawa highway, along the coastal plains and on the Danakil Depressions (Figure 11).

### 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 classified as warm and hot springs (defined based on their temperatures being lower or higher than 50°C). They issue near-neutral bicarbonate waters with low chemical content. All of the springs are of low energy exhibiting quiet flow with no steam separation or gas evolution.

### 5.2 Gulf of Zula area

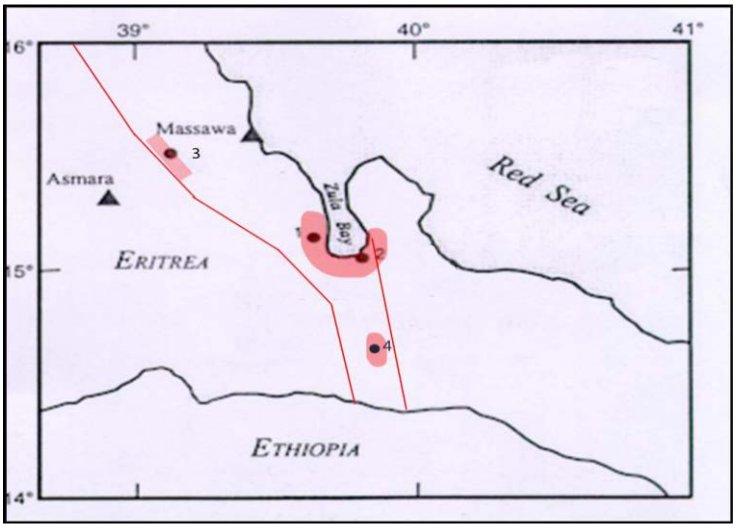


FIGURE 11: Location map of low temperature areas. Symbols 1 and 2 are around gulf of Zula, 3 on the Asmara-Massawa road and 4 on Danakil Depression.

Thermal springs occur at Ua-a and Acfat, 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 thermal 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 dug well located in Erafayle village is 10 m deep. Another well in Zula town is 20 m deep. Both wells have thermal water with a temperature of 36°C and a pH of 7.0. The Gelti group of thermal springs consists of a large number of thermal springs located on the seashore. The water chemistry indicates a large measure of mixing with seawater. Low-pressure steam vents are located within about 200 m of the shore. The steam is thought to be separated at low pressure from underground water bodies flowing toward the seashore.

All the hot springs mentioned above, except for Gelti, the thermal waters along Asmara-Massawa highway, in terrain made up of Precambrian rocks and thermal springs close to Gulf of Zula, do not show any immediate association with magmatism. They are thought to owe their occurrence to ascent, through the rift marginal faults, of waters heated at depth under typically crustal geothermal conditions, with relatively low geothermal gradients. They are judged to have no association with large volume and high temperature fluid circulation at shallow levels. They are thus believed to have no potential for large-scale commercial development for power generation. They otherwise have potential for small-scale, low-temperature, non-power applications, including for 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 area thermal springs occur in terrain made up of Quaternary basalt lava. These springs seem to be associated with heating in underground zones of relatively elevated temperature but it is not certain if 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 indicating the existence of a young shallow magma intrusion. Being in the coastal area, and also having association with high permeability rocks that may allow hot water production in adequate volume, the area holds promise for low temperature geothermal resource application in such uses as fish drying etc.

### 5.3 Thermal springs in the Danakil Depression

The springs are located within the Depression issuing high flow of water along fault planes. The Laele and Bolleli thermal springs are the main localities. The latter is located within the weathered stratoid basalt, which is related to the axial volcanism.

## 6. CONCLUSION AND RECOMMENDATION

The tectonic setting and geological makeup of the Danakil depression provides a suitable environment for the occurrence of geothermal energy.

Alid, Nabro-Dubbi and Jalua are the potential targets for high temperature identified from surface studies so far carried out.

A high reservoir temperature of greater than 225°C is estimated from gas geothermometry conducted on Alid fumaroles.

The MT resistivity survey conducted at Alid depicted a very interesting and new site at the rift floor, rather than beneath the Alid mount. Therefore, it is imperative to study the area in a wider perspective. Accordingly, a comprehensive work supported by ICEIDA and UNEP was initiated in 2015 to complete surface exploration studies in Alid, that is geophysics MT-TEM, microseismic, and gravity and alteration mapping and soil gas survey. These studies will continue in 2019. Subsequently, a proposal for drilling will be initiated coupled with the Geothermal Risk Mitigation Fund (GRMF).

It is recommended to perform the following prospect investigation on Nabro-Dubbi and Asaila:

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

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

## REFERENCES

Andemariam, T., Woldeyohannes, D., and Misghina, M., 2006: *Geology and hydrogeology of Alid and surrounding.* Eritrean Department of Mines, draft report.

Beyth, M., 1996: Preliminary assessment of the Alid geothermal field, Eritrea. *Geological Survey of Israel current research, 10*, 124-128.

Clynne, M.A., Duffield, W.A., Fournier, R.O., Weldegiorgis, L., Janik, C.J., Kahsai, G., Lowenstern, J., Weldemariam, K., and Tesfai, T., 1996: *Geothermal potential of the Alid Volcanic Center, Danakil depression, Eritrea*. U.S. Geological Survey, final report to U.S. Agency for International Development under the terms of PASA No. AOT-0002-P-00-5033-00, 46 pp.

CNR-CNRS team, 1973: Geology of northern Afar (Ethiopia). *Revue de Geographie Pysique et de Geologie Dynamique*, *2*, 343–390.

DOM, 2004: *Eritrea geothermal project pipeline proposed for implementation under ARGeo*. Eritrean Department of Mines, draft report.

Eysteinsson, H., Teklesenbet, A., Rosenkjaer, G.K., and Karlsdóttir, R., 2009: *Resistivity survey in Alid geothermal area, Eritrea*. ÍSOR – Iceland GeoSurvey, Reykjavík, Iceland, report ISOR-2009/016, 42 pp.

Goitom, B., Oppenheimer, C., Hammond, J.O.S., Grandin, R., Barnie, T., Donovan, A., Ogubazghi, G., Yohannes, E., Kibrom, G., Kendall, J.M., Carn, S.A., Fee, D., Sealing, C., Keir, D., Ayele, A., Blundy, J., Hamlyn, J., Wright, T., Berhe, S., 2015: First recorded eruption of Nabro volcano, Eritrea, 2011. *Bulletin of Volcanology, 77*, 21 pp.

Marini, A., 1938: Il volcano Alid nella colonia Eritrea (in Italian). *L'Universo, 19*, 51-65, 131-170.

UNDP, 1973: *Investigations of the geothermal resources for power development*. United Nations Development Programme, report for the Ethiopian Government, 275 pp.

Wiart, P.A.M. and Oppenheimer, C., 2005: Large magnitude silicic volcanism in north Afar: the Nabro Volcanic Range and Ma'alta volcano. *Bulletin of Volcanology, 67*, 99-115.

Wiart, P.A.M., Oppenheimer, C., and Francis, P., 2000**:** Eruptive history of Dubbi volcano, northeast Afar (Eritrea), revealed by optical and SAR image interpretation. *International Journal of Remote Sensing, 21*, 911-936.

Yohannes, E., 2004: Geothermal interpretation of thermal water and gas samples from Krýsuvík, Iceland and Alid, Eritrea. Report 18 in: *Geothermal training in Iceland 2004.* United Nations University Geothermal Training Programme, Reykjavík, Iceland, 403-438.

Yohannes, E., 2007: Assessment of fractures and faults of Alid geothermal area. *GRC Transactions, 31*, 397-400.

Yohannes, E., 2010: Structural significance of the result of resistivity methods in Alid geothermal area. *Proceedings World Geothermal Congress 2010,* Bali, Indonesia, 5 pp.