Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geothermal Exploration in Eritrea – Country Update

Ermias Yohannes

Department of Mines, P. O. Box 272, Asmara, Eritrea

ermias_yohannes@yahoo.com

Keywords: Alid, Nabbro-Dubbi, geothermal exploration, Eritrea

ABSTRACT

Eritrea supplies its electric generation totally from imported refined petroleum products. In 2017, 42 MW have been added to the existing installed power capacity to become a total of 195 MW. The capacity is not enough, as development is expected to increase, mainly in mining, agriculture and industrial sectors. Therefore, harnessing the geothermal potential of Eritrea could have a significant impact on the country's economic development. The impact can be viewed both in stabilizing the currently unreliable cost fluctuation, mainly due to fuel cost, and the unfriendly environmental impact of burning fossil fuels. Geothermal energy will have an important input in alleviating expenditure on foreign currency while safeguarding the environment.

The tectonic setting and geological makeup of the Danakil region of Eritrea is a favorable site for geothermal resources that have the potential for electrical generation and other geothermal end uses. The Alid and Nabro-Dubbi fields are the notable places with ample geothermal manifestations.

The completion of some of the surface studies on Alid prompts concentration in this paper on the recent work performed. More than 225 ^{0}C reservoir temperature was estimated using gas geothermometers from an Alid geothermal prospect. The resistivity survey that was conducted recently has revealed an interesting anomaly at the rift floor and opened a wider perspective in exploration.

The 2011 eruption in Nabro-Dubbi signifies that the area is still an active magmatic zone. The old surface manifestation is covered by basaltic flows and ashes. It is to be noted that other high geothermal manifestations also occur in the Jalua volcanic complex, but this region lacks exploration studies.

There are considerable low-temperature thermal springs that could serve as potential recreational spas, health and mineral water bottling, etc. These are located around the Asmara-Massawa highway, close to Gulf of Zula and within the Danakil Depression. These mostly do not show any immediate association with recent magmatism.

Gravity and microseismic studies and soil-gas surveys are planned to complete surface exploration studies in late 2019 in Alid, so that sites for drilling will be selected.

1. INTRODUCTION

Geothermal energy has become an important energy option both for heating and power generation. This lies mainly on its impact to the environment. Since Eritrea lies within the African rift system, the potential of having geothermal energy for the use of electricity is high. The advantage of the geothermal energy resource for Eritrea is not only based on its environmental impact but also the mitigation of the use of fossil fuels, which the country has been purchasing. For this reason, the government has given priority to this sector, and investigation is underway. 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. These are mainly associated with volcanic activities of which the Alid, Nabbro-Dubbi and Jalua fields of geothermal manifestations are prominent (Figure 1).

The most expeditious progression to power development can be achieved at Alid. At Alid, the completion of some essential surface studies show a good possibility for resource development. Thus, this paper concentrates mainly on these recent studies in Alid.

The country's economic sector is mainly driven by diesel generated electric power. In 2017, a 42 MW thermal power plant was installed to upgrade the 88 MW thermal power plants in Hirghigo. Currently there are two mining companies that mainly operate by diesel fuel generation. Bisha Mining Company is partially displacing to solar power. Two Mining Company is now commissioned and will start mining in a few years time. Thus, the demand for electricity is expected to increase drastically.

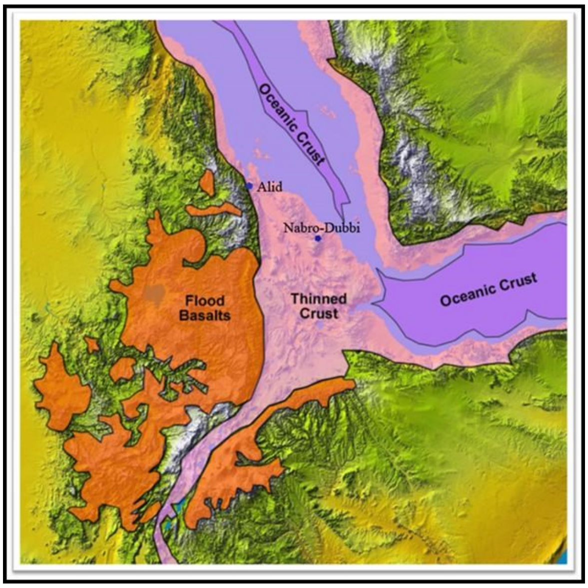

Figure 1: Location map of Alid and Nabro-Dubbi in relation to the African Rift Valley.

1.1 Previous Works

Previous works are mainly concentrated on the low temperature hot springs and the Alid volcanic center. In 1902 during the Italian colonization, Angelo Marini from the Italian Institute for Military Geography initiated a preliminary study on Alid geothermal manifestations (Marini, 1938). In subsequent decades, no documented studies on geothermal exploration existed until 1973, when UNDP sponsored work completed for 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 study launched from the south during the same year and visited some of the fumaroles that occur on Alid volcano. In 1992, the late Prof. Giorgio Marinelli and a staff member from the Department of Energy visited the 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 was carried out at Alid and its surroundings during January and February of 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 estimated below the surface of Alid volcanic centre, as the geothermometry analysis of gas samples was depicted. A two phase conceptual model, vapour dominated at the base and steam dominated at the top, was proposed through reinterpreting the water and gas samples of the 1996 USGS-MEM data (Yohannes, 2004).

A fault and fracture analysis was performed on the Alid dome in 2005 and found three structural trends that influence the geothermal fluid path (Yohannes et al, 2005 or 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 adjacent rift floor using mainly MT and TEM methods. Hydrogeological assessment on a catchment basis was also carried out in 2005 to have a better understanding on the groundwater flow in the area (Andemariam, 2006). In 2008, an MT/TEM resisitivity survey was implemented with the sponsorship of ICEIDA (Icelandic International Agency) in Alid. This study detected an anomaly at the rift floor (Eysteinsson et al, 2009). However, no anomaly zone was detected on the hill top due to lack of a metallic bar penetrating on the hard rock.

1.2 Electricity in Eritrea

The total installed capacity, including the two standalone mining electric generators, is about 195MWe. Of this, 13.5 MWe is generated from solar, while the rest is from fossil fuels (Table 1). The Inter-Connected System (ICS) is supplied by the Hirgigo Power Plant close to Massawa, and the Beleza Power Plant located about 10 km from Asmara. The generation from Hirgigo Power Plant was 88 MWe, and in 2017 an additional 42 MWe was installed. However, the firm capacity of the Hirgigo Power Plant is 81 MWe. With the 5 MWe from Beleza, the total capacity is 86 MWe.

Table 1. Present and planned production of electricity

	Geothermal		Fossil Fuels		Hydro		Nuclear		Solar		Total	
	Capacity MWe	Gross Pro. GWh/yr	Firm Capacity MWe	Gross P. GWh/yr	Capacity MWe	Gross P. GWh/yr	Capacity MWe	Gross Pro. GWh/yr	Capacity MWe	Gross P. GWh/yr	Capacity MWe	Gross P. GWh/yr
In operation in December 2019			86	284					2		88	
Under construction in December 2019									13.25		13	
Funds committed, but not yet under construction in December 2019												
Estimated total projected use by 2020												

1.3 Institutional and Personnel Involved

The geothermal sector in Eritrea is managed by the Ministry of Energy and Mines. It is governed under proclamation No. 68/1995, a proclamation to promote the development of mineral resources. Of the two departments in the Ministry, the geothermal exploration is carried out within the Eritrea Geological Survey under the Department of Mines.

The human resource in the past five years in geothermal has been increased progressively (Table 2). However, we are still lagging in fulfilling specialization on the various fields. The annual short training programme by UNU-GTP and AUC on basic surface exploration has a profound effect in human resource development.

Table 2. Allocation of professional personnel to geothermal activities. Restricted to personnel with university degrees.

(1) Government
(2) Public Utilities
(3) Universities
(4) Paid Foreign Consultants
(5) Contributed Through Foreign Aid Programs
(6) Private Industry

Year	Professional Person-Years of Effort					
	(1)	(2)	(3)	(4)	(5)	(6)
2015	2				7	
2016	3					
2017	3					
2018	2					
2019	2					
Total	26				7	

2. REGIONAL TECTONIC SETTING

The East African Rift is a zone of crustal extension, in which part of the eastern African continent, the 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, also called 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 of 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 ago, 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 the 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 extends 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 into the basaltic lavas, and extrude in the resulting dome (DoM, 2004). The two volcanic centres are separated by a Danakil Horst, where Proterozoic metamorphic rocks and Mesozoic sediments are exposed.

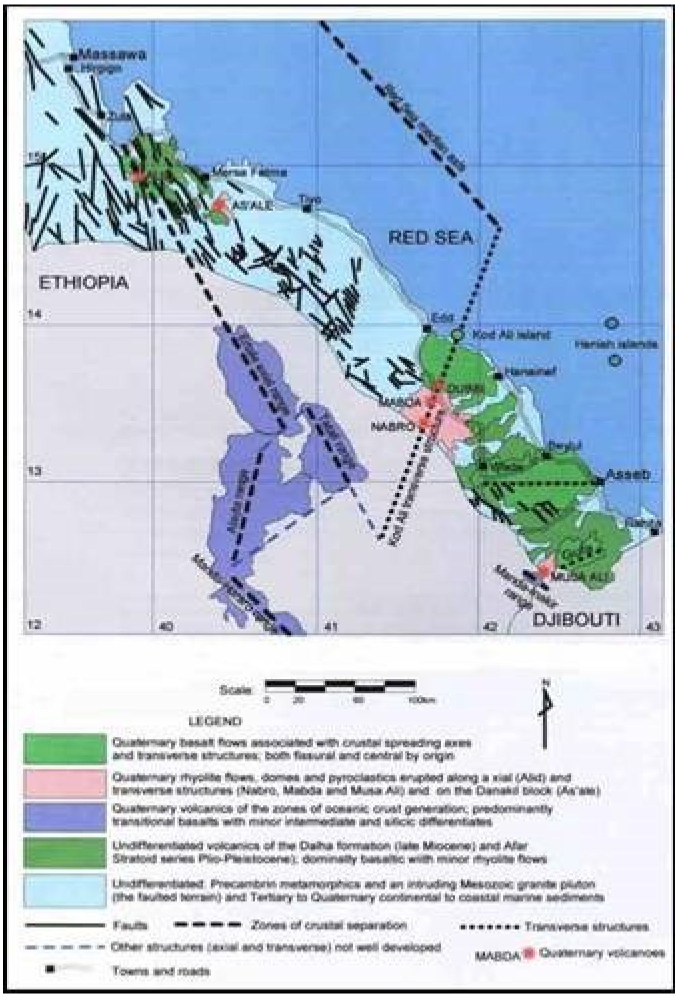

Figure 2: Regional geological map of the Danakil Depression. Much of the rift consists of down-dropped crustal sections bounded by deep-rooted normal faults (forming grabens) that cut into the basaltic lavas.

3. GEOLOGICAL AND GEOTHERMAL SETTING

The suitable tectonic environment of the Danakil Depression, subordinated by recent magmatic activities, favors a high heat flow on the upper zone of the crust. Consequently, several places of surface manifestations of the high temperature fields associated with recent magmatism and low temperature hot springs occur in the Danakil depression and escarpment of the Red Sea. These are not related to recent magmatic activities.

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 trace of the crustal spreading centre. It consists of rifted and faulted young deposits of sediments and basaltic flows. A metamorphic complex to the west and basaltic flows forming a plateau to the east shoulder the plain.

3.1.1 Geological 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 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 was dated to about 33 thousand years old.

Red series sediments are conspicuous at the side and top part of the dome. They contain gypsum layers within the bed. A shouldering effect of the rhyolite emplacement tilts it at the hillside. Olivine basalt occurs mainly at the top of the dome. Ignimbritic flows are only confined within the caldera for thin circular patterns surrounding the volcanic centre.

Vitrified flows occur in some places within the rhyolite. 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.

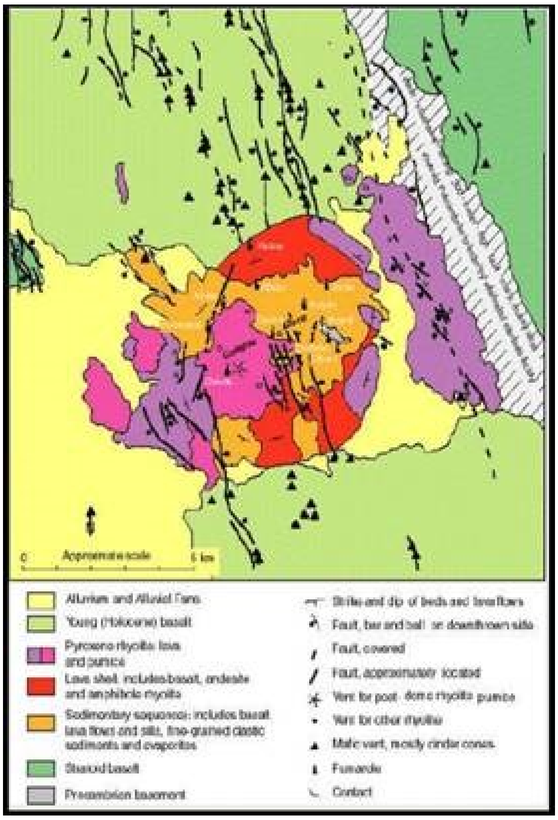

Figure 3: Geological map of the Alid geothermal prospect.

3.1.2 Geothermal Setting

Hot mineralized fluids discharge from many locations within the Alid volcanic centre, of which 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 sulfur. As a result, it precipitates in the form of sulphosalts. Sulphosalts and clays are the main constituents of the alteration zone. The intensity of alteration 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. Sulphosalts and clays of various colors are conspicuous both of present and old precipitates. Yellowish colored precipitates, mainly representing sulphosalts and brown clays, are abundant. Emission of gases through fumaroles is intensive and spatially distributed widely along the stream.

Old silica alterations at places make the rock hardened, as clearly observed on Ghinda hill. At Illegedi silica emanations on the present sites form salty-like features in thin crusts. Apart from sulphosalts, clays, and silica precipitates, considerable malachite stains occur at Humbebet manifestation. The latter alteration could be of potential target for mineral exploration. Geothermal surface manifestations represented by steaming grounds are abundant in Alid. Areas of steaming ground include north of Abakri, parts of Miski Merhada, and Hulma, the northern flank of the dome. These places of steaming grounds are safe havens of grasses, where the areas are always green. Smokes commonly emanate through steam vents; however, steaming in other surfaces are also observed.

Geological and 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 in excess of 225 °C (Lowenstern et al, 1999). 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 or fossil Red Sea water, or both.

Some gases vented from the system (CO_2, H_2S and He) 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. A conceptual model of two phases, a vapour-dominated phase below a steam heated zone, has been proposed for Alid (Yohannes, 2004).

3.2 Surface Manifestation of High Temperature Zone: Alid Volcanic Centre

Nabro stratovolcano is the prominent volcano and occurs in a line of NE-SW direction to the SW of Dubbi volcano. Here, it is collectively named as the 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. The Nabro volcano itself forms part of an enigmatic double caldera structure with a neighboring 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 a 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 (Figure 4).

Dubbi is a large volcanic massif rising to 1625 m above sea level. It 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 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. It is also the south-easternmost transfer mechanism into the Afar from 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 volcanic center is the intersection of the ENE structure and Kod Ali fault line. The 2011 eruption on Nabro has significantly sealed the old surface manifestation occurred close to the summit.

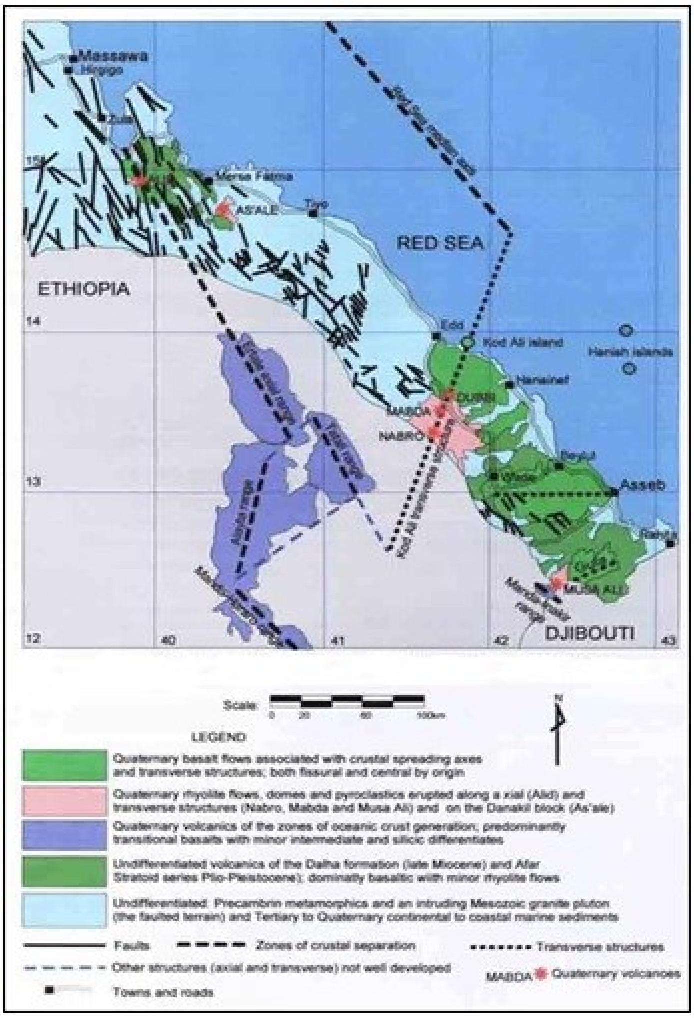

Figure 4: Geological interpretation of Nabro-Dubbi area. Note the intersection of structures (DOM, 2004).

3.3 Low Temperature Thermal Springs

Hot springs in Eritrea occur at the main escarpment along the Asmara-Massawa highway, along the coastal plains, and on the Danakil Depressions (Figure 5).

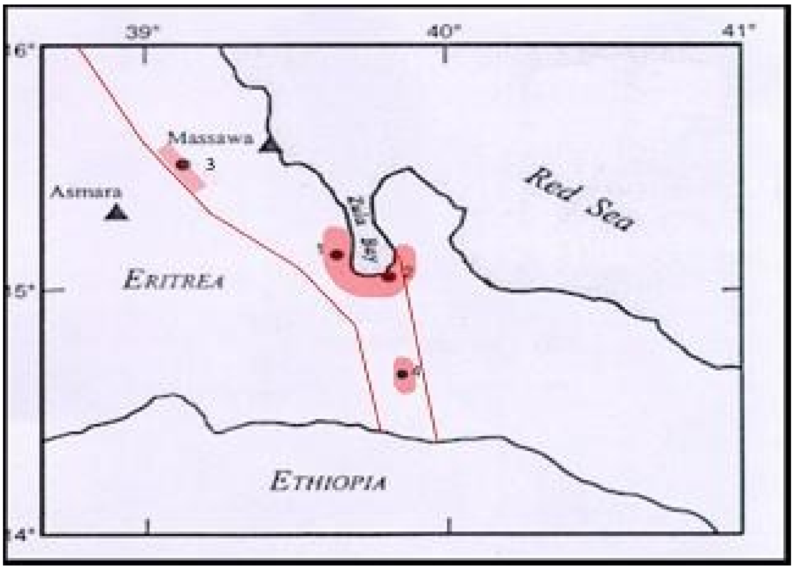

Figure 5. Location map of hot springs. Locations 1 and 2 are around the Gulf of Zula. Location 3 is on the way of Asmara-Massawa, and location 4 is on the Danakil Depression.

3.3.1 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 flows with no steam separation or gas evolution. Oxygen isotopes and deuterium has been analyzed and the results are being processed.

3.3.2 Thermal Springs along Gulf of Zula and Surrounding Areas

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 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 of the hot springs mentioned above do not show any immediate association with magmatism, 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. 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.

4. RECENT ACTIVITY ON ALID GEOTHERMAL PROSPECT

The geological and geochemistry performed on the Alid dome pointed to a geothermal reservoir beneath the Alid dome. To justify this and know the extent and depth of the reservoir, a geophysical survey was employed. Since MT resistivity survey has the ability to penetrate deep structures (some tens or hundreds of kilometers), and is practically the only method for studying deep resistivity structures, it was proposed in Alid. Accordingly, with funding from ICEIDA, ISOR (Icelandic Geosurvey) and the Eritrean Geological Survey, an MT survey was completed on the Alid dome and adjacent area.

According to the MT resistivity survey, the following conclusions were deduced:

- A SW-NE Lineament. A conductive zone is seen down to about 6–7 km depth (and even deeper 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 6.
- A low resistivity body defined by the NNW-SSE brown line below the western part of Mt Alid. To the west of the mountain there is a low resistivity body, approximately 3 km wide. It reaches the highest elevation at 2–3 km b.sl., 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.

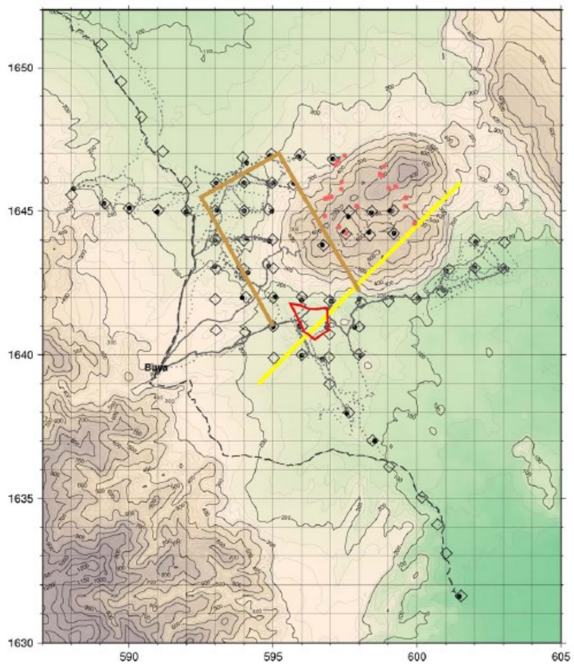

Figure 6. Delineation from MT anomaly. The yellow line shows the location of the vertical resistivity boundary between ½ and 2 km depth. The brown contour lines outline the low resistivity body west of Mt. Alid at about 2 km depth. Red dots are geothermal vents on Mt. Alid.

An attempt has been made to relate the anomaly with the geotectonic setting of the area. The ENE direction low resistive anomaly result marked at 3500 meters b.s.l. is an important structure that extends 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 the discovery more interesting in dealing with the fluid movement.

A comprehensive geological, geochemical and geophysical study was intended to complete surface exploration work in Alid with the help of UNEP and ICEIDA in 2015. At that time, mapping of surface manifestation, and partial gravity measurements were conducted. Unfortunately, due to hot weather conditions, all of the proposed exploration works were not finalized. A proposal is now underway to continue geochemical and geophysical surveys in late 2019. During this time, a radon and CO_2 survey, and an MT/TEM survey will be carried out to fill the remaining gaps. Gravity measurements and six seismic stations will also be set up. The accomplishment of the surface exploration survey will enable us to establish a conceptual model in selecting drill sites.

5. CONCLUSION AND RECOMMENDATION

The tectonic setting and geological make up of the Danakil depression provides a suitable environment for the occurrence of geothermal energy. Alid, Nabro-Dubbi and Jalua are the three potential targets for high temperature, identified from surface studies so far carried out. The estimated high reservoir temperature (greater than 220 ^{0}C) from previous studies at Alid is the reason to go further into detailed exploration to decide on drill sites.

The MT resistivity 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. The current study recommends the following detailed work to be commenced in the future at Alid:

- Conduct CO_2 and other gases (radon and mercury) mapping on the Alid dome to know the gas outflow zone and to select a possible target drill site.
- To complete gravity measurements and set up microseismicity at the mount of Alid and surrounding area.
- Prepare a conceptual model and select possible targets of drill sites.

REFERENCES

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

Beyth, M.: Preliminary assessment of the Alid geothermal field, Eritrea. *Geological Survey of Israel current research,* 10, (1996),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. Geol. Survey, final report to U.S. Agency for International Development under the terms of PASA No. AOT-0002-P-00-5033-00, (1996).

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

Eysteinsson H., Teklesenbet A., Rosenkjaer G.K., and Karlsdottir R.: *Resistivity survey in Alid geothermal area, Eritrea*. ISOR-2009/016 report, Iceland, (2009).

Lowenstern J.B.; Janik C.J.; Fournier R.O.; Tesfai T.; Duffield W.A.; Clynne M.A.; Smith J.G.; Woldegiorgis L.; Weldemariam K.; Kahsai G.: A geochemical reconnaissance of the Alid volcanic centre and geothermal system, Danakil depression, Eritrea. *Geothermics*, 28, (1999), 161-187.

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

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

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

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

Yohannes, E.: Geothermal interpretation of thermal water and gas samples from Krysuvik, Iceland and Alid, Eritrea. Report 18 in: *Geothermal Training in Iceland 2004.* UNU-GTP, Iceland, (2004), 403-438.

Yohannes E.: Assessment of fractures and faults of Alid geothermal area. *GRC Transactions*, 31, (2007).

Yohannes E.: Structural Significance of the Result of Resistivity Methods in Alid Geothermal Area. *Proceedings of the World Geothermal Congress 2010,* Bali, Indonesia, (2010).