

Geothermal Exploration in Eritrea – Country Update Paper Title, Title Case

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ABSTRACT

Harnessing the geothermal potential in Eritrea has a significant impact on the economic development as the country relies its electric power generation from imported refined petroleum products, which is wholly based on oil burning plants. The impact can be viewed both the unreliable cost fluctuation mainly increment of fuel cost coupled with the unfriendly environment. Therefore 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 south-eastern coastal zone of Eritrea is a favorable site for having geothermal resources that are potential for the development of geothermal resources mainly for electrical generation and utilization. Alid and Nabro-Dubbi fields are the notable places with ample geothermal manifestations. The volcanism of the 2011 in Nabro has made impact at present by sealing the surface.

There are considerable low temperature-thermal springs potential for recreation spas, health and mineral water bottling, and etc, 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 that was performed. A more than 250°C reservoir temperature was estimated using gas geothermometers from Alid geothermal prospect. A 70°N trending high fracture zone is well marked on the FFD contour plot. The low resistivity anomaly of the preliminary resistivity survey conducted on the Ghinda-Darere is in line with the contour plot. The hydrogeological assessment performed regionally indicates that the recharge area is mainly from three catchments with mainly inputs from the highland area.. The resistivity survey that was conducted recently has shown an interesting anomaly at the rift floor and opened a wider perspective in exploration.

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 a geothermal energy for the use of electricity is high. The advantage of geothermal energy resource for Eritrea is not only based on its environmental impact but also mitigates the use of fossil fuel, which the country has spending using 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 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 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, which show a good possibility for resource development, the report here concentrates mainly on recent studies carried out on Alid.

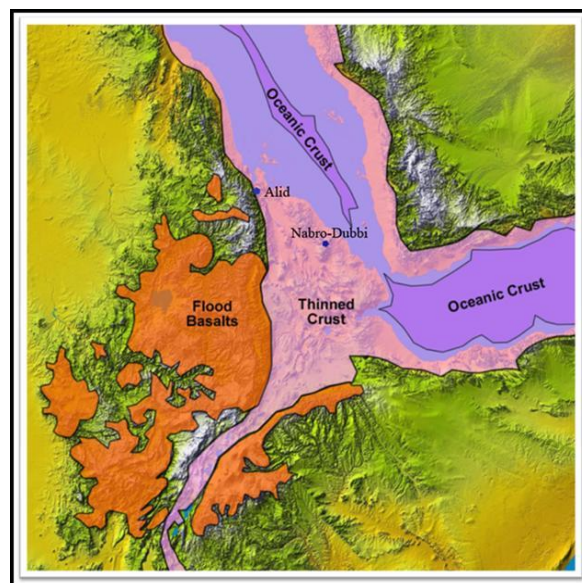


Figure 1. Location map of Alid and Nabro-Dubbi in relation to the African Rift Valley

1.1 Previous studies

Previous works are mainly concentrated on the low temperature hot springs and Alid volcanic center. Angelo Marini from the Italian Institute for Military Geography in 1902 during Italian colony initiated a preliminary study on Alid geothermal manifestations (Marini, 1938). Subsequent decades, however no documented studies on geothermal exploration commenced till 1973, when UNDP sponsored work was done 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 one launched from the south during the same year 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 Alid area and prepared proposal for detail 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 1996, by a team of staff 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 led by Robert Fournier of the USGS (Clyne 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, a 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 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 conducted on the small locality from Ghinda to Darere (Goitom et al, 2005). But a comprehensive resistivity survey was conducted recently on the Alid dome and adjacent rift floor using mainly MT and TEM methods. Hydrogeological assessment on catchment basis was also 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 (Eysteinnsson et al, 2009). However no anomaly zone was depicted on the hill top due to lack of metallic bar penetrating on the hard rock.

2. TECTONIC SETTING

The East African Rift 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 ago, which eventually gave rise to the present day configuration of the Afar Triangle.

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, extruded in the resulting.

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

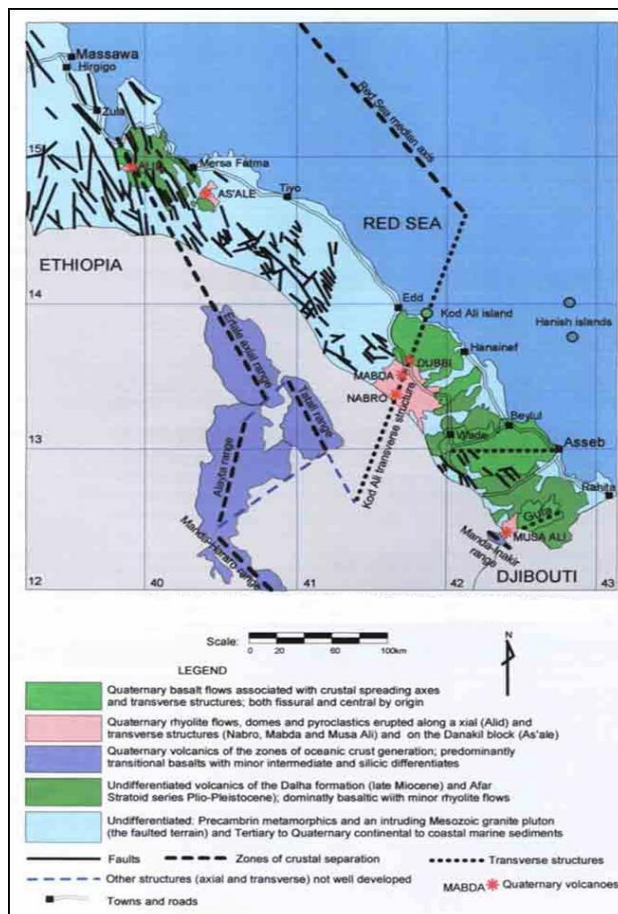


Figure 2. Regional Geological map of the Danakil Depression Much of the rift consists of down-dropped crustal sections, bounded by deep-rooted normal faults (forming grabens) that cut into the basaltic lavas.

Recent studies on present day movement of plates 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 will 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 (Figure 3).

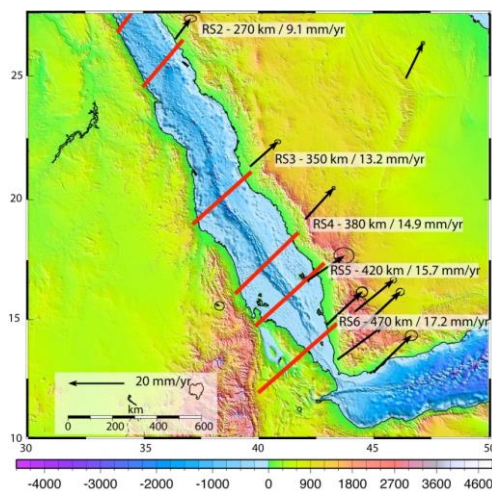


Figure 3. Motion of crustal segments from continuous GPS reading showing different displacement rates (McClusky et al, 2010).

3. GEOLOGICAL AND GEOTHERMAL SETTING

The suitable tectonic environment of the Danakil Depression subordinated by recent magmatic activities favour 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 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

Regionally 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.

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 (See Figure 4). 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 dated for about 33 thousand 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. 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. 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.

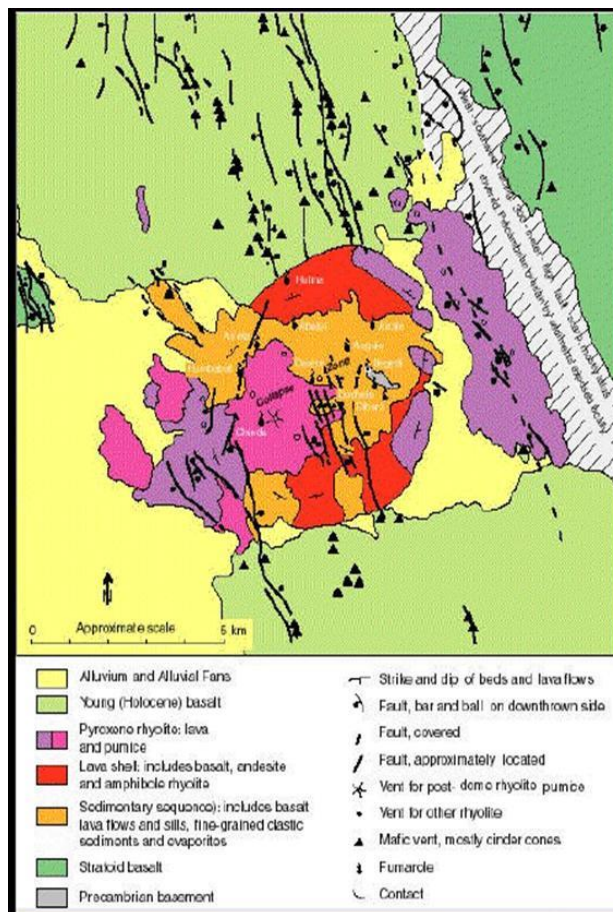


Figure 4. Geological map of Alid geothermal prospect.

Geothermal setting

Hot mineralized fluids discharge from many location 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 sulphur, 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 however varies from place to place. Hot springs are more likely to occur where the depth to water table is shallow and subsurface geothermal systems are more likely to be discovered in areas where hot springs are present at the surface. Alteration is wide and intensive at Illegedi and Darere (Figure 5). Sulphosalts and clays of various colours are conspicuous both of present and old precipitates, of which yellowish colored 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 $>225^{\circ}\text{C}$. The isotopic composition of condensed fumarolic steam is consistent with these temperatures and implies that the source water is derived primarily from either lowland meteoric waters 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 is developed for Alid (Yohannes, 2004).



FIGURE 5: Surface manifestation with extensive fumaroles at Darere

3.2 Surface manifestation of high temperature zone – Nabro-Dubbi volcanic centres

Nabro stratovolcano is the prominent volcano occurs in 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 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 (Wiert 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 Nabro-Dubbi volcanic range (Figure 6). Dubbi is a large volcanic massif rises to 1625m above sea level erupted explosively in May 1861. The volume of lava flows alone, 3.5 km^3 , makes this the largest reported historical eruption in Africa (Wiert et al., 2000). Many cinder cones are located at the summit. Extensive basaltic lava fields to the north and NE cover wide area and reach the Red Sea coast. Almost all the cinder cones belong to the most recent eruptive centres at the summit in 1861. The major transverse structure that extends from the Kod Ali island area of southern coastal Eritrea south-westwards across the north-eastern Afar rift margin on the Ethio-Eritrean border forms the terminus, and south-easternmost transfer mechanism into the Afar, of the Red Sea floor spreading axis which ends in the area to the northwest of Hanish islands (DOM, 2004). This structure separates the Danakil block in two separate units of geological makeup: the Pre-rift basement to the northwest and the Plio-Pleistocene volcanism to the southeast. This structure has given rise to the most recent and most extensive Nabro, Mabda and Dubbi volcanic activities of the region, where it crosses the numerous northwest-southeast trending faults of the north-eastern Afar rift margin and Danakil block. The Nabro 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. In addition the ground at present is also very hot. Sampling of these manifestation is therefore very difficult.

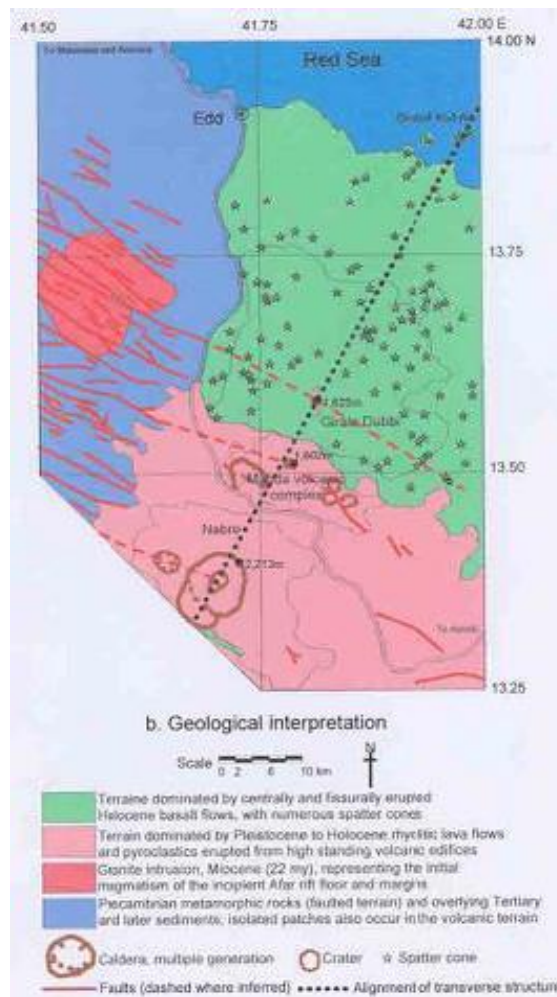


FIGURE 6: Geological interpretation of Nabro-Dubbi area, notice the intersection of structures (DOM, 2004).

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 7).

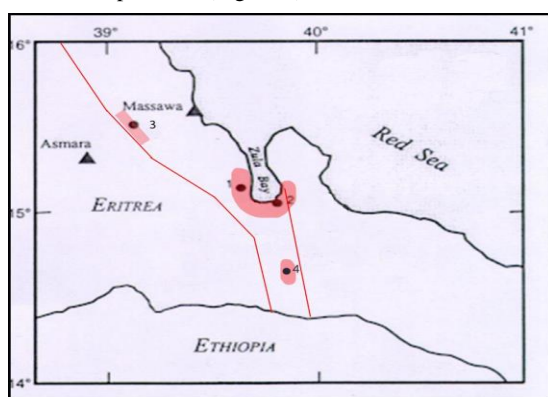


FIGURE 7: Location map of hot springs; locations 1 and 2 are around Gulf of Zula, 3 on the way of Asmara-Massawa and 4 on the Danakil Depression

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 flow with no steam separation or gas evolution. Oxygen isotopes and deuterium has been analysed and the results are in due process.

3.3.2 Gulf of Zula area

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, being steam 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. ALID GEOTHERMAL SYSTEM – ASSESSMENT FROM LINEAMENTS

Geothermal systems are associated with areas of active faulting (Koenig and Mcnitt, 1983), because faults and fracture systems are the principal means by which meteoric fluids penetrate deeply into the crust (Coolbaugh and Bedell, 2004). Recent study (Soengkono, 1999) shows that geothermal reservoir is significantly influenced by faults and fractures that can easily be mapped from surface expressions, as they are often marked by topographic lineaments. Besides statistical studies based on “weights of evidence model” shows that young volcanics and faults have a positive weight in predicting favourable sites of geothermal systems (Coolbaugh and Bedell, 2004).

Faults recorded in Alid area are mainly of normal faults type with some strike-slip faults. The opening of the fractures ranges from mm scale to tenth centimetres; particularly the E-W has a wide opening. Fractures and faults were measured along surface manifestation. The relationship between the local surface manifestation and fracture were assessed clearly and described below briefly. Various structural directions were identified in association with the geothermal manifestation. Steaming grounds are mainly associated with the 70°N, although generally the surface manifestations are aligned at NNW, at Illegedi, the prominent surface manifestation of the area. The NNW fractures are common on most of the surface manifestation. The E-W fractures have wide spacings occur in almost all the manifestation. The lineaments in Alid form a complex pattern but distinct sets of directions. The systematic examination of faults falls into three major directions related to different tectonic origin by looking at the geological exposures:

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

An analysis of detailed aerial photographs of approximately 1:20,000 scale and land sat maps both the image and shaded relief plots was made to identify lineaments mainly caused by faults and fractures in the Alid area.

A dense lineament pattern is mapped out as shown on Figure 9. ENE lineaments are dominant at central part of the area while northerly striking faults and fractures are concentrated on the southern and northern part of the dome.

A contour map of fault and fracture density (FFD), defined as the total length of lineaments per unit area, was constructed for the area (Figure 8).

The zone of high FFD complies well with the central manifestation zone where areas of high surface manifestation occur. It extends for about 5 Km along a linear pattern. Two peaks of anomalous high areas occur in the close to Darere and illegedi area. It has a direction of 70°N beyond the limit of surface manifestation.

The trend is well conformable with the major NNE fracture system. It shows that the major surface manifestations of the area are well in agreement with the FFD contour map. This suggests the significance influence of geological structures on the hydrology of the geothermal system at Alid.

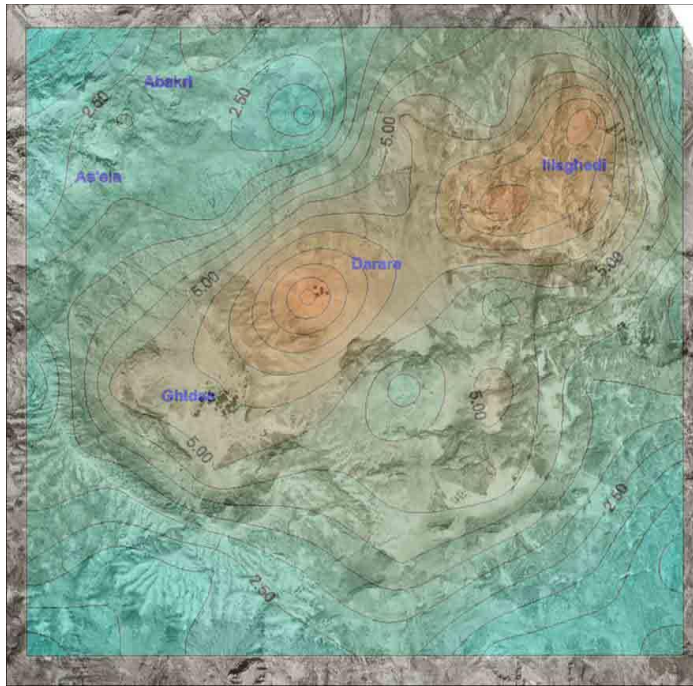


FIGURE 9: Contour plot of Alid area using FFD analysis. Note the high values lie on the Darere-Illegheidi line. It is superimposed on aerial photo.

6. ALID GEOTHERMAL SYSTEM - ASSESSMENT FROM RESISTIVITY SURVEY

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

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

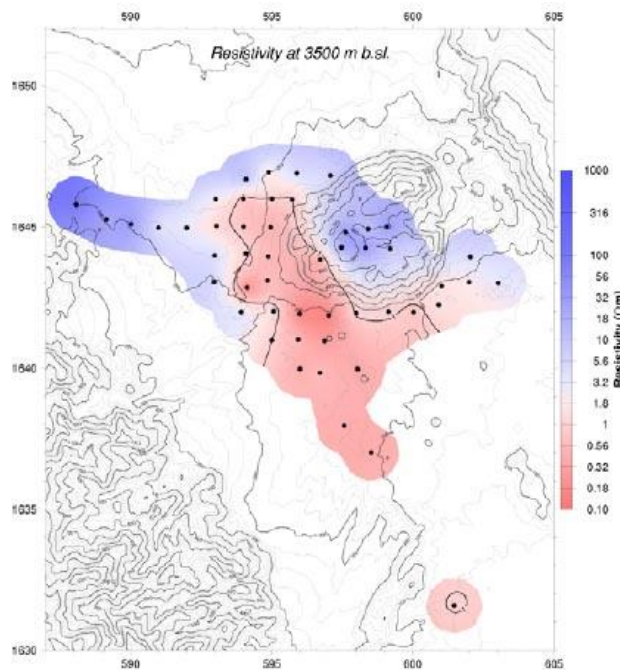


Figure 10. Resistivity map at 3500 metres below sea level. Coordinates are in UTM, km units.

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 on Figure 11. This boundary is best seen on the isoresistivity map at 1 km b.s.l. on Figure 10.
- 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. It reaches the highest elevation at 2–3 km b.s.l., and 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.

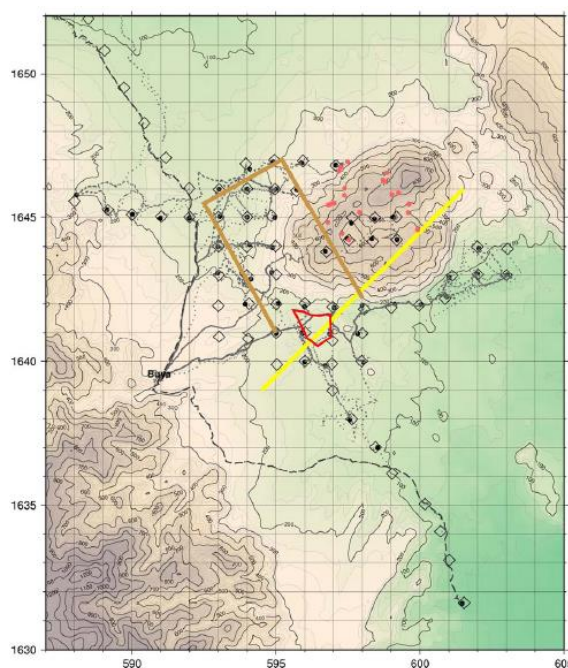


Figure 11. The Yellow line shows the location of the vertical resistivity boundary between ½ and 2 km depth. The brown contour lines outline the low resistivity body west of Mt. Alid at about 2 km depth. Red dots are geothermal vents on Mt. Alid.

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 a 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.

7. SUMMARY AND CONCLUSION

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

Alid and Nabro-Dubbi are the two potential targets for high temperature identified from surface studies so far carried out. The estimated high reservoir temperature (greater than 2200C) from previous studies at Alid gave reason to conduct hydrogeology and fracture analysis aiming at selection up-flow zones.

From the hydrogeological point of view, it is found out that highland water is the source of water for Alid.

Lineaments including measurements of faults and fractures at mesoscopic scale and interpreted from aerial photographs and digital images were analyzed to better define areas of thermal flows at Alid. In order to clearly sort out the relationship between the faults and fractures and thermal flow all the geothermal manifestations were assessed.

Most of the geothermal manifestations are associated with fractures and faults. Rosette and field investigation indicate that lineaments in Alid are of three types: lineaments striking ENE (60°-70°), NNW (330°-340°), and striking E-W (270°-280°).

Maximum lineament zone defined by ENE strike is well marked on the FFD analysis in line with the major fracture set of the area. Two high values depicted on the contour map are well accompanied with the thermal manifestation thus worth to commence geophysical investigation and/or drill slim hole to map temperature gradient of the area.

The MT resistivity conducted at Alid depicted a very interesting 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 detail work to be commenced on the future on Alid:

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

Perform the following prospect investigation on Nabro-Dubbi:

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

Isotope hydrogeology has been conducted in Alid and low temperature fields, the result will be interpreted, and for Nabro-Dubbi prospects the study will be conducted in the near future.

The 2011 volcanism in Nabro-Dubbi prospect has still hot to perform exploration at or close to summit. In addition as discussed the location of surface manifestations are sealed by pyroclastic falls.

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