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GEOTHERMAL EXPLORATION IN ERITREA STATUS REPORT DISCUSSION

Ermias Yohannes,
Ministry of Energy and Mines, Department of Mines
P.O. Box 272, Asmara
ERITREA
ermias_yohannes@yahoo.com

ABSTRACT

Manuscript Eritrea relies its electric generation totally from imported refined petroleum products, which is based on oil burning products. Therefore harnessing the geothermal potential has a significant impact on the economic development of Eritrea. 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 Danakil region of Eritrea is a favourable site for having geothermal resources that are potential for the development of geothermal resources mainly for electrical generation and geothermal utilization. Alid and Nabro-Dubbi 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 also that other high geothermal manifestations occur in Jalua volcanic complex.

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 performed. The hydrogeological assessment performed regionally indicates that the recharge area is mainly from three catchments mainly the input is from highland area. Thorough assessments of Rose diagram and fault and fracture (FFD) analyses have been performed to know areas of up-flow zone. A more than 225^0C reservoir temperature was estimated using gas geothermometers from Alid geothermal prospect. 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 survey will be conducted in 2015 to complete surface exploration studies so that sites for drilling of exploratory wells 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 a geothermal energy for the use of electric 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 on 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, Jalua and Nabbro-Dubbi fields (Figure 1) of geothermal manifestations are prominent.

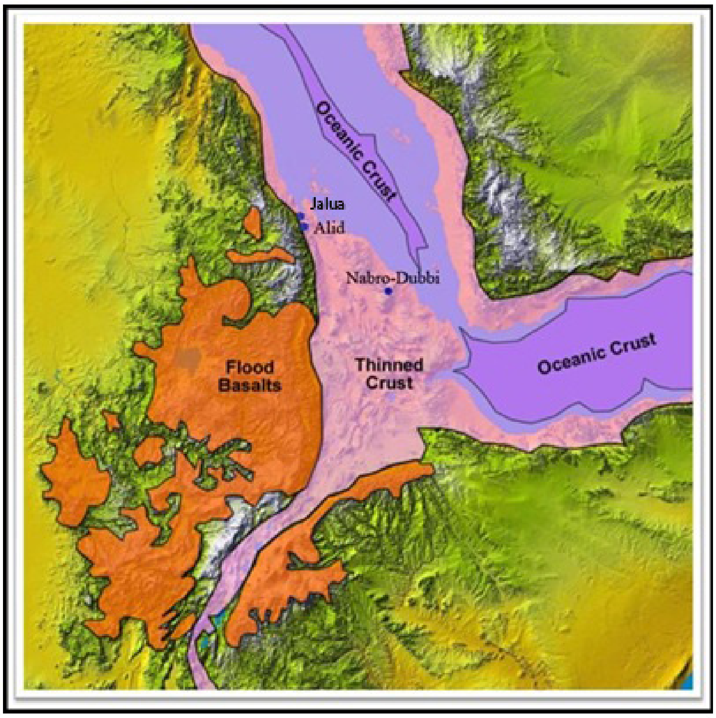

FIGURE 1: Location map of Alid, Jalua and Nabro-Dubbi in relation to the African Rift Valley

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 on Alid.

1.1 Previous studies

Previous works are mainly concentrated on the law 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 that 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 (Clynne et al., 1996). A high temperature reservoir is estimated below the surface of Alid volcanic centre, as the geothermometry analysis of gas samples depicted. A two phase conceptual model, 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 out three structural trends that influence the geothermal fluid path (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, 2006). But a comprehensive resisitivity survey was conducted recently on the Alid dome and adjacent rift floor mainly MT and TEM methods. Hydrogeological assessment on catchment basis also carried out in 2005 to have a better understanding on the ground water flow in the area (Andemariam et al., 2006). In 2008 an MT/TEM resisitivity survey was implemented with the sponsorship of ICEIDA (Icelandic International Agency) in Alid depicting an anomaly at the rift floor (Eysteinsson et al, 2009). However no anomaly zone was depicted on the hill top due to lack of rod penetrating on the hard rock.

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 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.

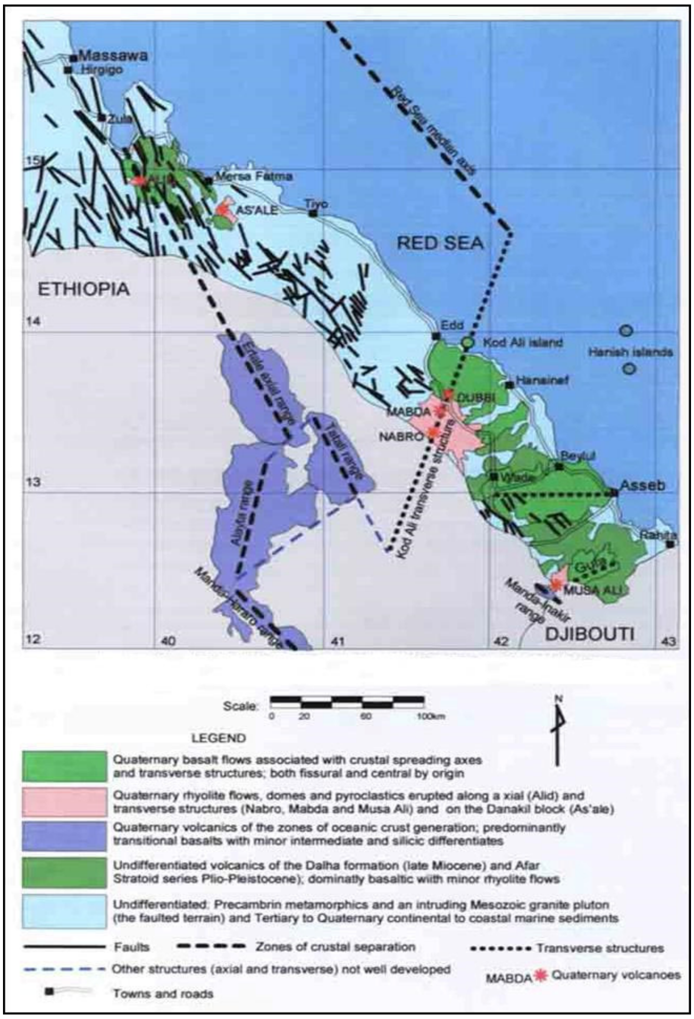

FIGURE 2: Regional geologic setting of the area

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-KodAli transverse structure could be centres of crustal spreading deciphering from the relative motion of plates (Figure 3).

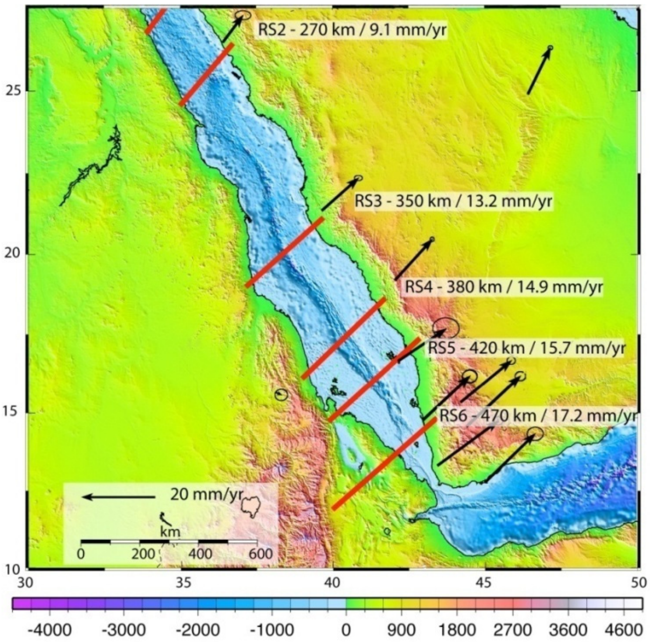

FIGURE 3: Motion of crustal segments from continuous GPS reading showing different displacement rating

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 high temperature fields associated with recent magmatism and low temperature hot springs related with no recent magmatic activities occur on Danakil depression and escarpment of the Red Sea.

3.1 Surface manifestation of high temperature zone - Alid volcanic centre

Regionally the Alid volcanic centre is located within the axis of 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 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 (Figure 4).

It is characterized by large-scale rhyolitic volcanism associated with E-W extension. The continuous extension, subsidence and volcanic activities influence the geological structure of the area. The volcanic succession of rhyolite and basalt are extruded following the NNW fault system of the rift but extended its ellipse towards ENE.

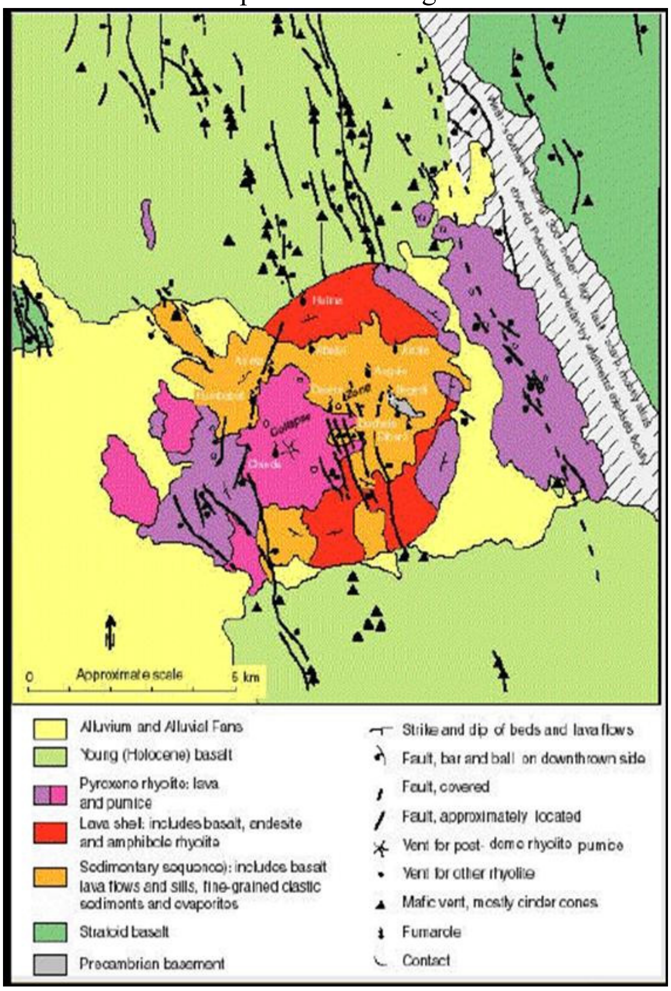

FIGURE 4: Geology of the Alid area

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 dated for 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 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 extends for about 70 m thick. Both white and red collared, 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.

3.1.2 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 intense 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.

FIGURE 5: Fumaroles with sulphosalts and clays in Darere

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 evergreen. Smokes commonly emanate through steam vents, however steaming in other surfaces are also observed.

3.2 Surface manifestation of other high temperature zone

3.2.1 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 (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 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. 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 (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, 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.

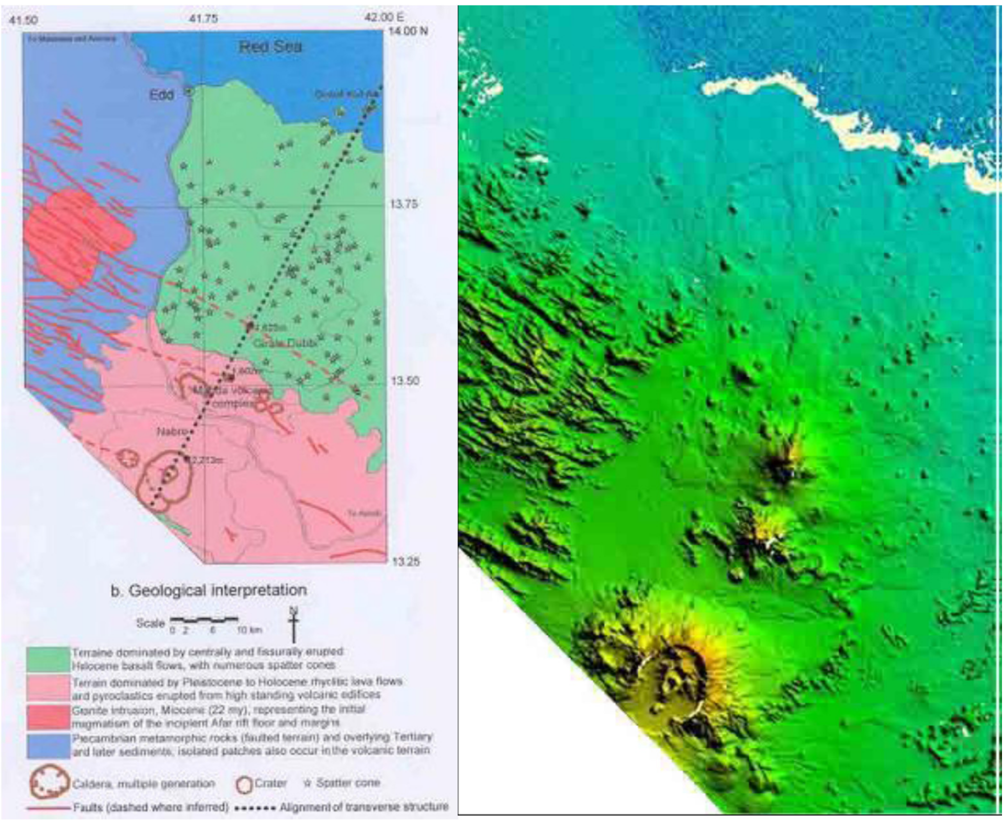

FIGURE 6: Geological interpretation of Nabro-Dubbi area.
The right photo is the DEM of Nabro-Dubbi (DOM, 2004)

3.2.2 Jalua volcanic complex

The Jalua volcano is located close to the Gulf of Zula (Figure 7). It is a big silicic stratovolcano affected by a large central volcanotectonic 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 a fumarolic activities on its western flank.

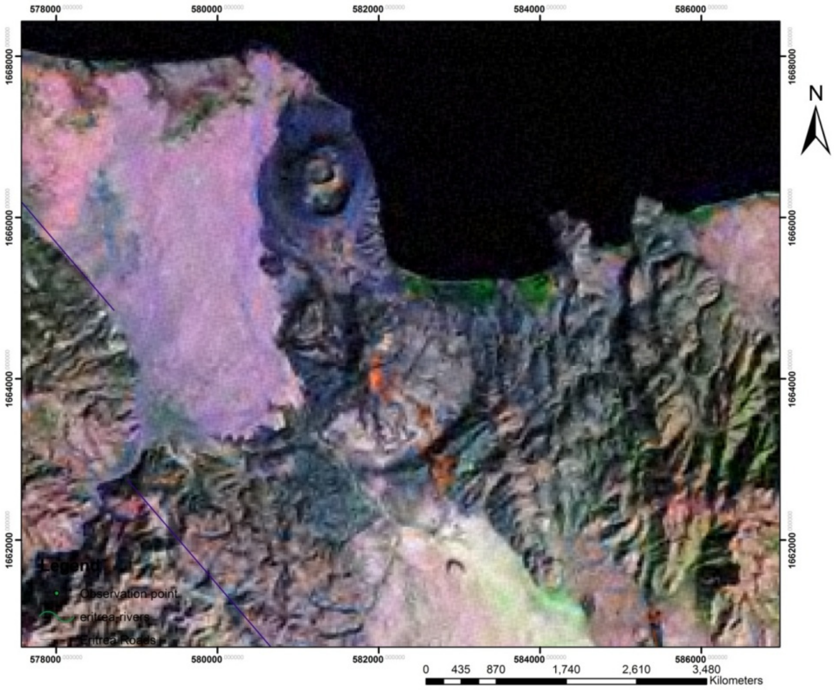

FIGURE 7: Jalua volcano with Erafayle double caldera volcanic centre

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

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

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.

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 8).

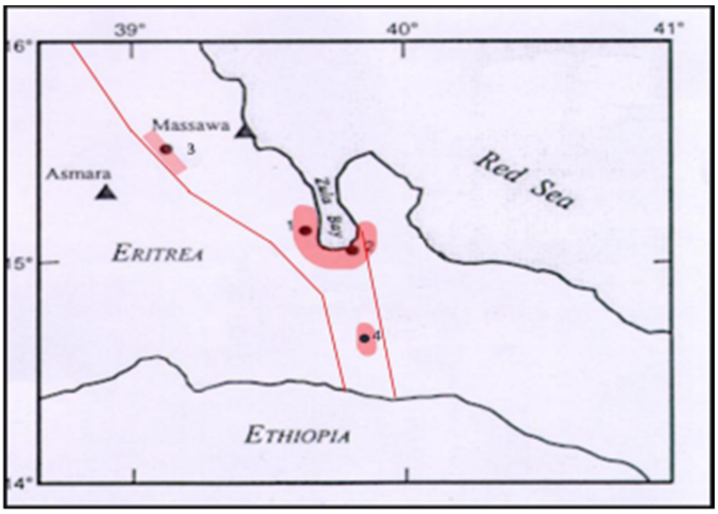

FIGURE 8: Location map of low temperature geothermal areas; symbols 1 and 2 are arou Gulf of Zula, 3 on the Asmara-Massawa road and 4 on Danaki Depression

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.

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.

Figure 9: Bolleli thermal spring, discharging hot water along fractures

3.3.3 Thermal springs on the Danakil Depression

The springs are located within the Depression issuing high flow of water along fault planes. The Laele and Bolleli thermal springs (Figure 9) are the main localities. The latter is located within the weathered stratoid basalt whereas the earlier is related to the axial volcanism.

4. HYDROGEOLOGY OF ALID AND SURROUNDINGS

In general, the study area is divided into two major sources of surface water. These are the eastern and the western surface waters relative to the location of Alid dome that drains from the Danakil horst and the highland plateau, respectively (Andemariam et al., 2006). The western surface water flow has relatively gentle topography leading to slow to moderate run off. Recharge occurs in the valleys of the Alluvium cover and other permeable rocks.

Water that reaches the Samoti plain partly infiltrates and partly evaporates. Evaporation exceeds percolation because temperature is very high. The amount of water that infiltrates appears to come out, through a fault, in the form of hot spring in Lake Bada. Rainfall is very little. Some highly jointed and fractured stratoid basalts occur east of Alid, and provide opportunities for direct and indirect infiltration to the plains both north and south of Alid. Regional structure east of Alid, which is reported by Clynne et al. (1996) as "Alid Graben master fault", has a great contribution to the Wengebo and Samoti ground water recharge and to the Alid geothermal potential indirectly.

In the highlands however, the amount of infiltration is relatively high through the permeable formations at times of intense rainfall and this water moves to the lowlands indirectly as part of ground water. From the hydrogeological point of view the study area is mainly divided in to three catchments based on the drainage flow patterns (Figure 10):

1. Wengebo catchment;
2. Alid or central catchment area; and
3. Samoti catchment.

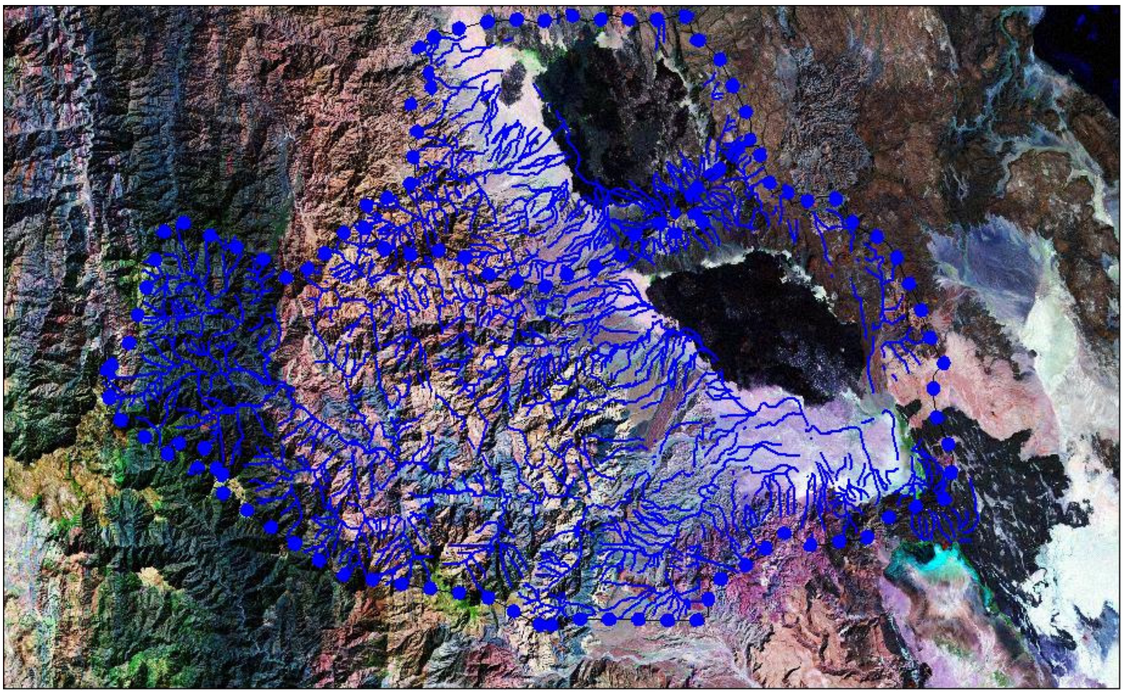

FIGURE 1: Catchments flowing to Alid; 1. Wengebo (northern part) 2. Alid (the Alid dome) and 3, Samoti (southern catchment)

Most of the run off from the escarpment percolates into the Pleistocene sediments and boulder beds, where it travels as shallow ground water and replenishes the evaporating Alat oasis which is located at the north-western margin of Samoti plain, south of Alid.

The hydrogeology of Alid and surrounding is mainly governed by:

1. Topographic level;
2. Presence of cemented sand and clay deposits, which act as barriers; and
3. The ground water level is higher than the surface water. Therefore it feeds the surface water.

From Geological and hydrogeological observations the Wengebo catchment drains directly to Alid and it can be assumed that the catchment is feeder of surface and subsurface water to the Alid geothermal reservoir. In addition to that ground water from Drawler River can possibly feed the Alid Geothermal field because the river follows an East-West Fault. However the Samoti catchment is a discharge area with very little contribution, if any, in recharging the ground water to the Alid geothermal potential.

5. ALID GEOTHERMAL SYSTEM – ASSESSMENT FROM LINEAMENTS

The axial tectonic zone extending from the Gulf of Zula in the northwest to the Erta Ale volcanic range located in the southeast in Ethiopia marks one of the zones of oceanization of the Afar crust. Alid is the Pleistocene to recent eruption occurs along this zone is a product volcanism fed from a shallow magma body (DOM, 2004).

The studies so far carried out show that a high temperature reservoir is estimated beneath Alid volcanic centre (Clynne et al. 1996, Yohannes 2004). Based on the previous studies, lineament mapping and geophysical exploration is conducted to define target-drilling sites in Alid area. And since geothermal energy is the anomalously high heat energy stored in some favourable geological structures within the top kilometres of the earths' crust (Shalivan et al., 2004), it is viable to conduct faults and fracture assessment.

The aim of this of preparing a lineament map of the area of both field and remote-sensing data is to acquire an understanding of the relationship of the lineament with the mapped geothermal manifestation. Therefore structural data pertinent to fractures and faults was measured and geothermal manifestation was recorded. A better understanding of the fractures and faults allows us to identify and locate potential geothermal sites.

Geologic lineament mapping is considered an important tool in geothermal exploration. 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). 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. 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 Illeghedi, 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; and

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 11a. 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 11b).

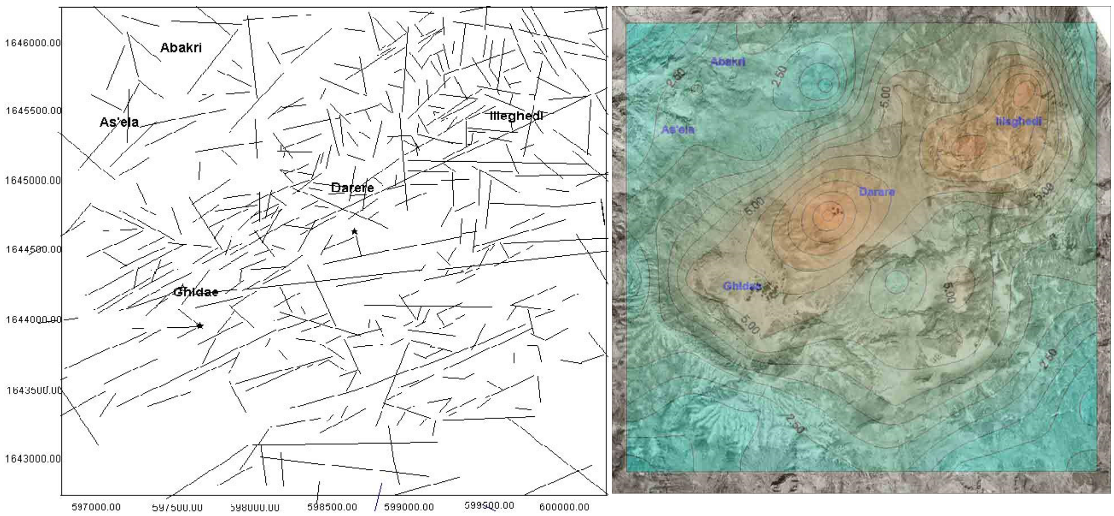

Figure 11: a) Lineaments interpreted mainly from aerial-photo and digital images of Alid and b) Contour plot using FFD analysis

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.

6. ALID GEOTHERMAL SYSTEM - ASSESSMENT FROM GEOCHEMICAL SURVEY

All of the samples contained over 95% steam, with the exception of the boiling pool of Ilegedi, where most of the steam condensed in the pool and consequently could not be collected. Because the fumarole samples were not superheated with respect to their atmospheric venting temperatures (all about 95°C or less) some steam may have condensed as the vapors rose through the mountain (Clynne, 1996).

The N_2:Ar ratio for the fumarole gases generally ranges from 41 to 48 similar to a value of 38 for air!saturated water (Figure 12) . Within geothermal systems, the oxygen in air-saturated groundwater is removed by reaction with rocks at high temperature, whereas N_2/Ar and He remain relatively unchanged. All data fall on a trend from air-saturated water toward He-rich and CO_2 rich components (Lowenstern, 1999).

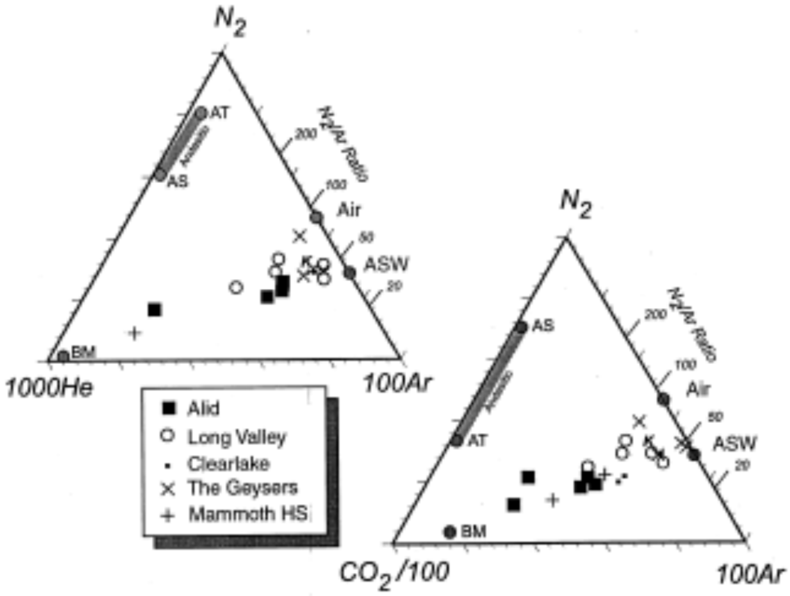

FIGURE 2: Triangular diagrams of N_2 vs 1000He vs 100Ar and N_2 vs CO_2/100 vs 100Ar for fumarolic samples of Alid volcanic center. Fumaroles from non arc hosted geothermal systems are plotted for comparison (Lomenstern, 1999). The samples trend from an end-member of air saturated groundwater (ASW) contaminated with air towards a mantle end-member composition. BM, AS, AT and k, denote end member basaltic mantle, andesitic subducted, andesitic thermogenic and Olkaria sample, respectively. Samples are from Giggenbach (1992)

Most of the gas geothermometers have been applied to the gas samples of Alid fumaroles (Clynne, 1996, Yohannes, 2004). The result indicates that the subsurface geothermal system is likely to be greater than 225°C (Lowenstern, 1999).

7. 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 survey was anticipated. Since MT resistivity survey has the ability to penetrate deep resistivity structures (some tens or hundreds of kilometres), 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 December, 2009 on Alid dome and adjacent area.

The TEM soundings do not suffer telluric shift arising from local inhomogeneity which distorted electric field thus TEM survey was conducted along with TEM. 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.

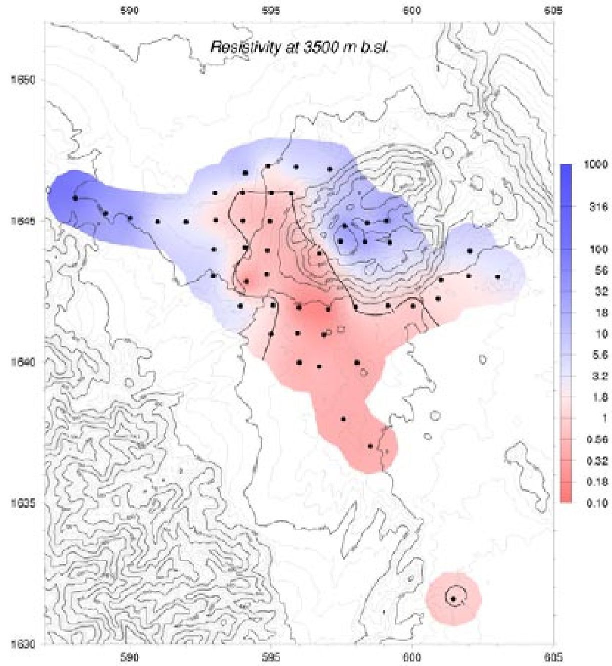

Figure 13: Resistivity map at 3500 m below sea level. Coordinates are in UTM, km units

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.sl. (Figure 13) 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.

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 13. 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 14). 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.

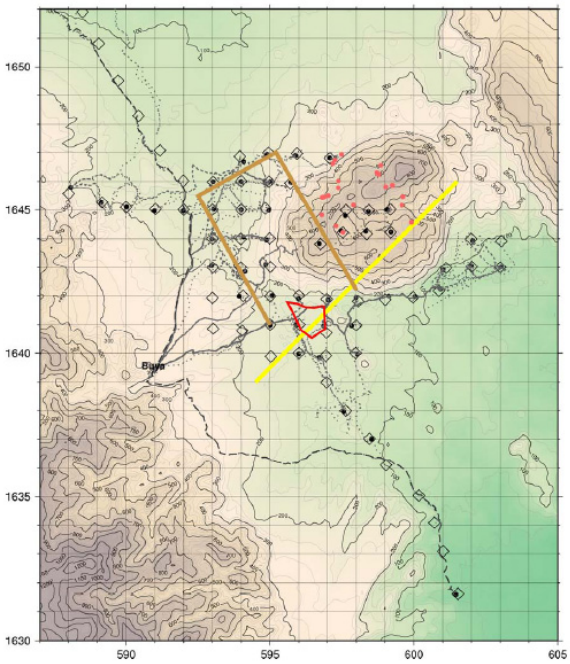

FIGURE 14: The yellow line shows the location of vertical resistivity boundary 5 and 2 km depth. The brown contour lines outline the low resistivity body west of Mt. Alid at about 2 km depth. Red dots are geothermal vents on Mt. Alid

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.

8. SUMMARY AND CONCLUSION

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.

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. 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.

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

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 CO_2 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 are also important to conduct at mount Alid and surrounding in order to clearly define the source and structures that are important to bear geothermal fluid.

For this reason, the Department of Mines is in a position to conduct the above studies in 2015, so that will pave a way to commence drilling.
Perform the following prospect investigation on Nabro-Dubbi:

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

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