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GEOTHERMAL EXPLORATION IN ERITREA STATUS REPORT

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ABSTRACT

Import dependence of refined petroleum products electric power generation, which is wholly based on oil burning plants has an adverse effect to 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 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 geothermal utilization. Alid and Nabro-Dubbi fields are the notable places with ample geothermal manifestations.

The completion of some of the surface studies on Alid prompts here to concentrate on the recent work performed. An assessment of fracture analysis was conducted since geothermal reservoir is stored in some favourable geological structures. Fracture and fault density (FFD) analyses have been performed to know areas of up-flow zone. A 70°N trending high fracture zone is well marked on the FFD contour plot. The resistivity survey which was conducted recently has availed an interesting anomaly at the rift floor and opened a wider perspective in exploration.
The 2011 volcanic eruption in Nabro indicates how the area is tectonically active. The eruption results wide fractures that will play significantly in maximizing permeability. As a result numerous fumaroles are now visible.

1. INTRODUCTION

Generally, 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 and Nabbro-Dubbi fields of geothermal manifestations are prominent (Figure 1).

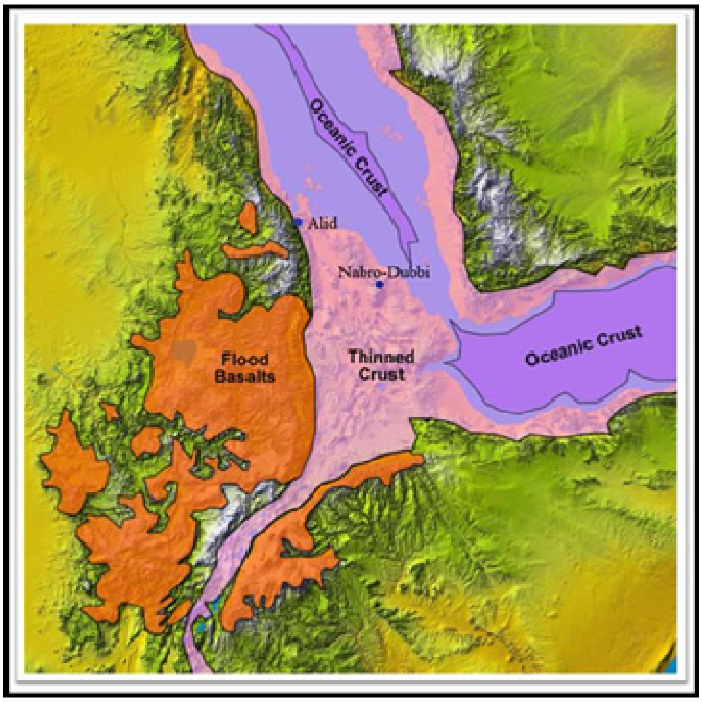

FIGURE 1. Location map of ALid and Nabro-Dubbi in relation to the African Rift Valley

1.1 Previous studies

Previous works are mainly concentrated on 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).

2. REGIONAL 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, 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.

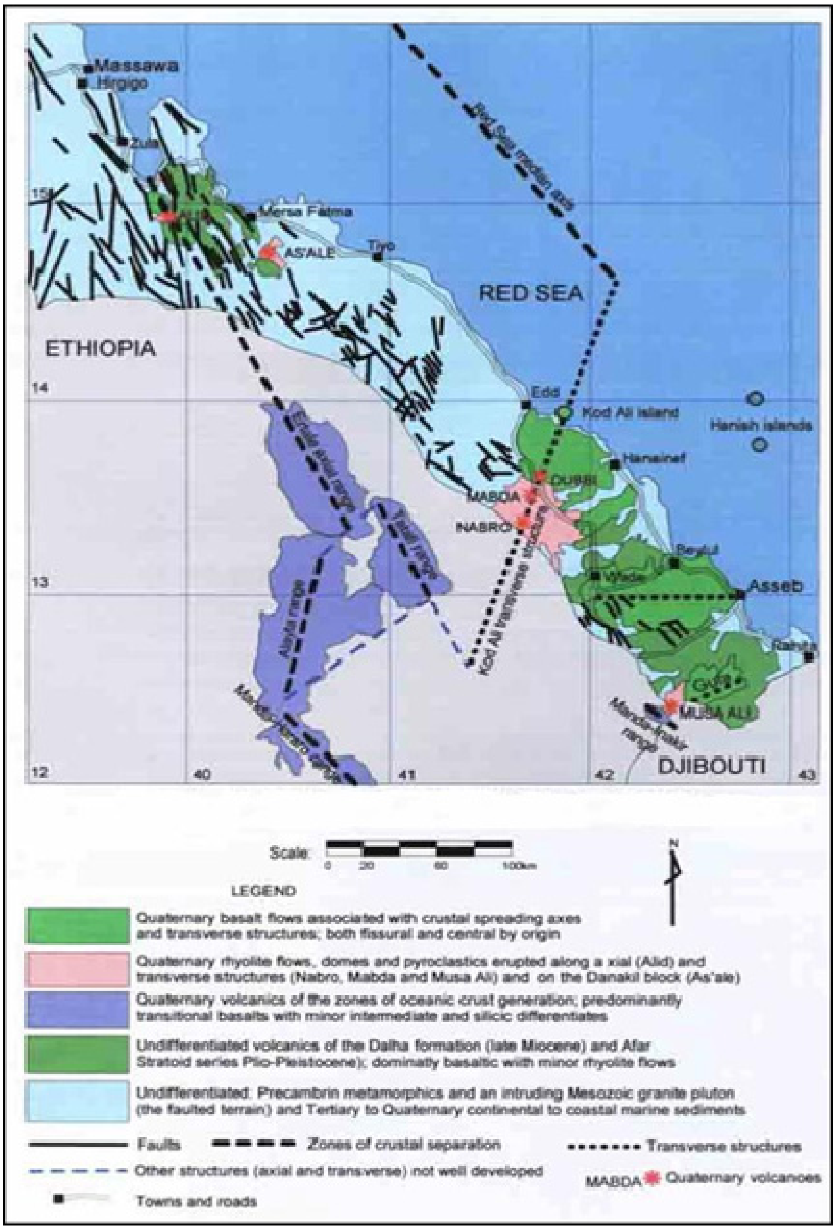

FIGURE 2: Structural features and Tertiary and Quaternary volcanic rocks of the coastal region in southeast Eritrea

3. ALID VOLCANIC CENTRE

3.1 Geological 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, respectively.

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.

Alid is a very late-Pleistocene structural dome formed by shallow intrusion of rhyolitic magma, some of which vented as lavas and pyroclastic flows.
It is characterized by large-scale rhyolitic volcanism associated with E-W extension. The continuous extension, subsidence and volcanic activities influence the geological structure of the area. The

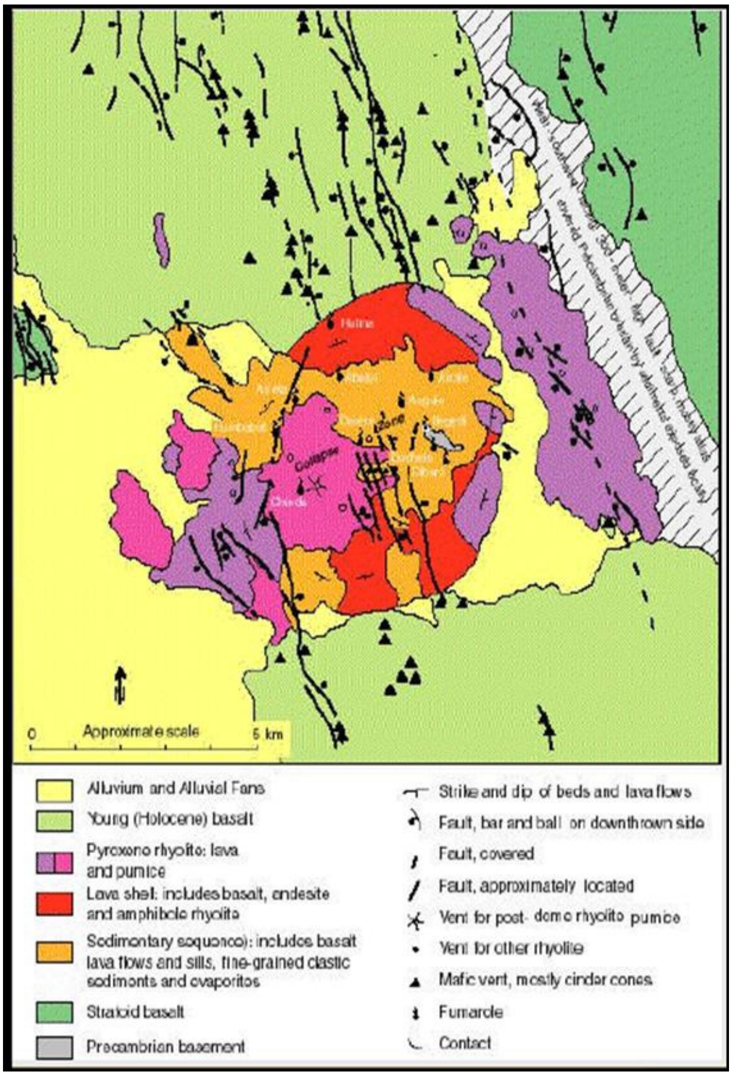

FIGURE 3. Geological map of Alid volcanic center (Clynne etal., 1996)

volcanic succession of rhyolite and basalt are extruded following the NNW fault system of the rift but extended its ellipse towards ENE.

The Alid volcanic centre consists primarily of rhyolite both as massive and as pumice deposits, olivine basalt, and Red Series sediments (See 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.

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.

3.2 Lineament assessment

Based on the previous studies, lineament mapping 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.

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). 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. In young volcanic terrain geological structures mainly faults and fractures have often-recognizable topographic expressions.

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 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.
3. Lineaments striking E-W (270°-280°): These are common as dykes and fractures related to rift tectonics.

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 4).

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.

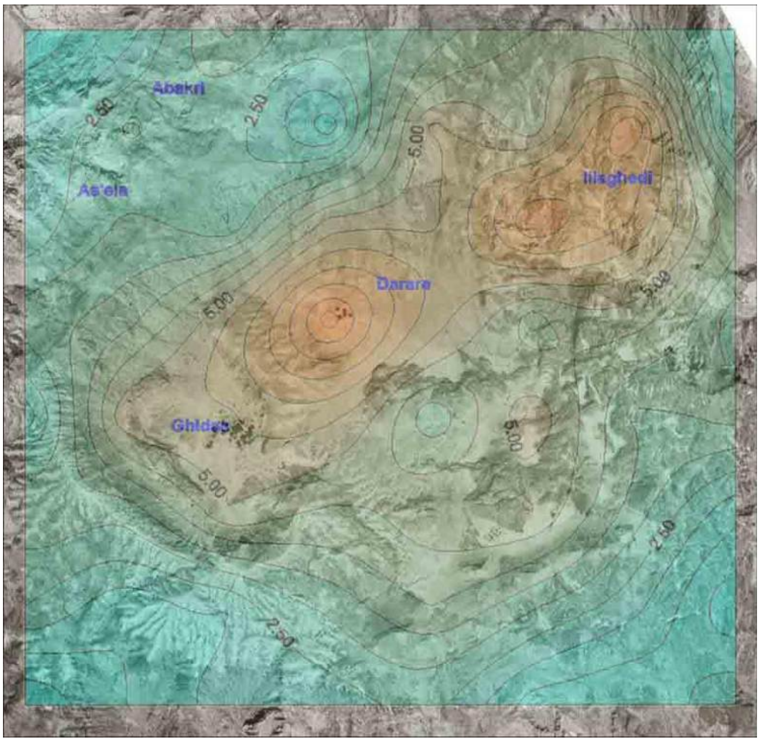

FIGURE 4: Contour plot of Alid area using FFD analysis. Note the high values lie on the Darere-Illeghedi line. It is superimposed on aerial photo

3.3 Geochemical survey

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 collared mainly representing sulphosalts and brown clays, are abundant. Emission of gases through fumaroles is intensive and spatially distributed widely along the stream.

FIGURE 5: Surface manifestation with extensive fumaroles at 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.

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 >225°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 highland waters significantly evaporated 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).

3.4 Resisitivity 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 resisitivity survey has the ability to penetrate deep resistivity structures (some tens or hundreds of kilometers), and is practically the only method for studying deep resisitivity structure it was proposed in Alid. Accordingly with the fund from ICEIDA,

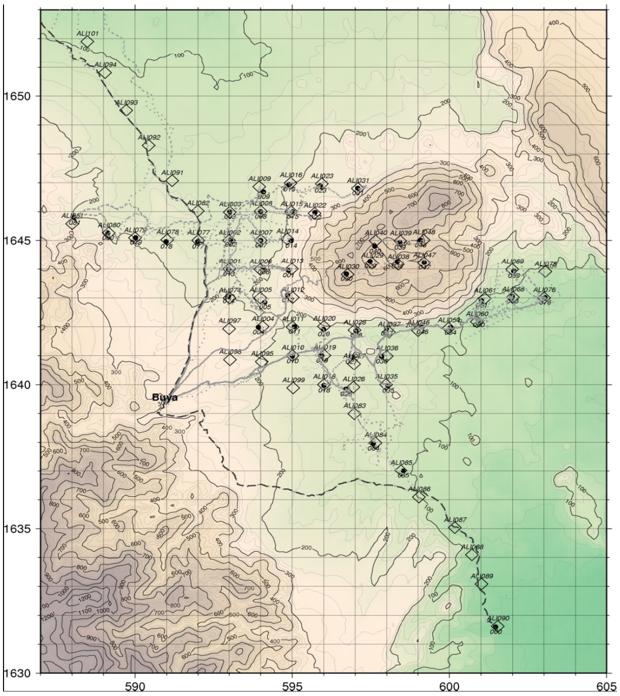

FIGURE 6. Location of TEM (open diamond) and MT soundings (filled circles). Coordinates are in UTM, km units

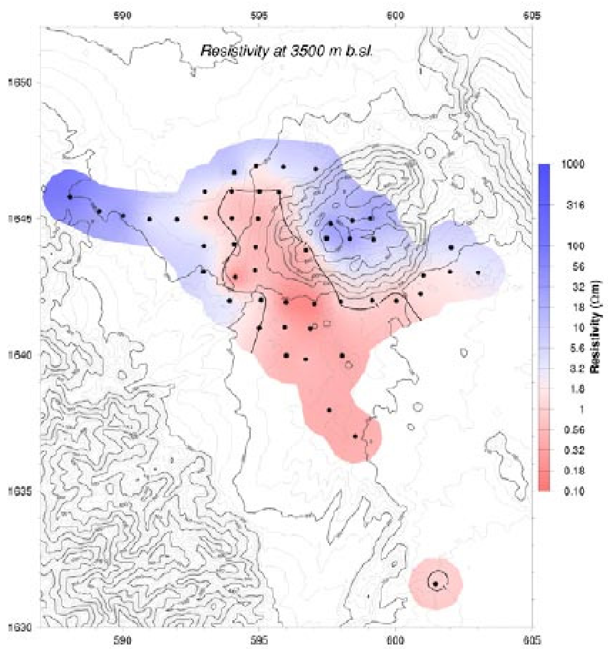

Figure 7. Resistivity map at 3500 metres below sea level. Coordinates are in UTM, km units

ISOR (Icelandic Geosurvey) and the Eritrean Geological Survey carried out MT survey on December, 2009 on Alid dome and adjacent area (see figure 6).

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 7) 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 8.
- 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 8). 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.

4. NABRO-DUBBI VOLCANIC COMPLEX

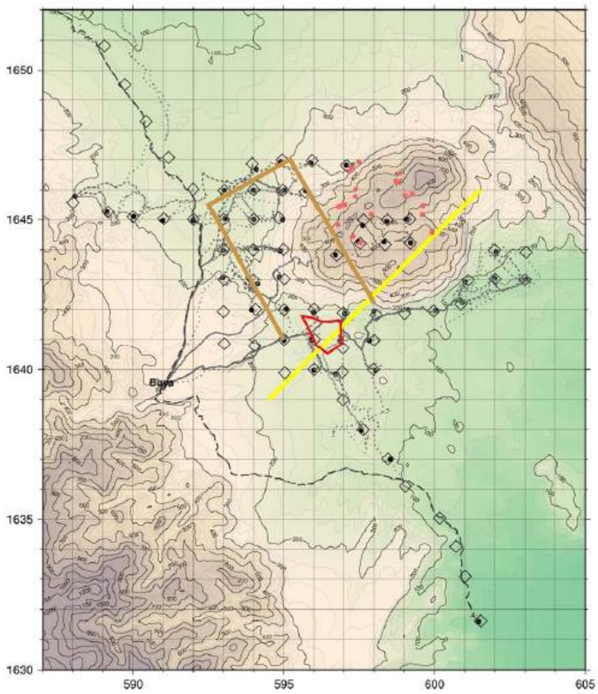

Figure 8. The Yellow line shows the location of the vertical resistivity boundary between ½ and 2 km depth. The brown contour lines outline the low resistivity body west of Mt. Alid at about 2 km depth. Red dots are geothermal vents on Mt. Alid

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 2218m high Nabro stratovolcano is the highest volcano in the Danakil depression and elsewhere in the eastern lowland, which has an 8 Km diameter of the first caldera. Nabro volcano (Figure 9) 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 (Figure 10). 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 km3, 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 is the intersection of the ENE and Kod Ali fault line.

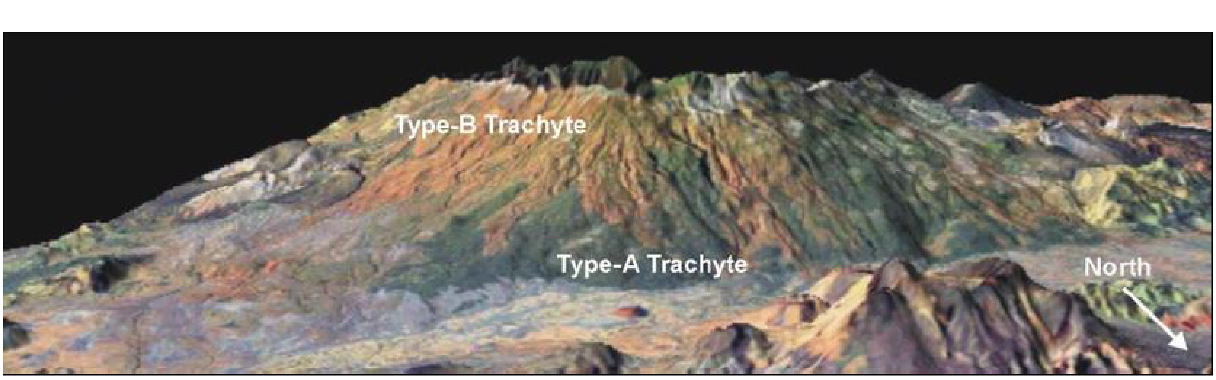

FIGURE 9: View of looking to the south Nabro trachytic volcanic centre

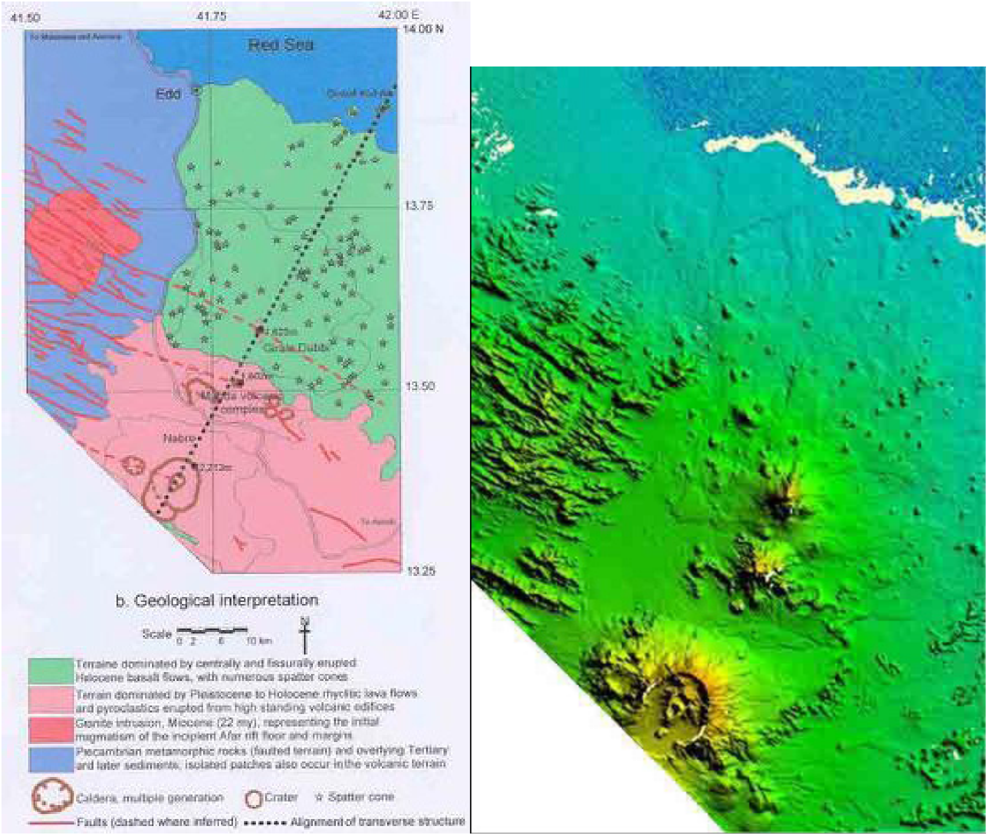

FIGURE 10: Geological interpretation of Nabro-Dubbi area, notice the intersection of structures. The right photo is the DEM of the Nabro-Dubbi (DOM, 2004)

4.1 The 2011 Nabro volcanism

This year a volcanism of basaltic in composition has been erupted since June 12 at Nabro. The increase of magma chamber triggered successive earth quakes which resulted in fracturing the summit and surrounding areas. It started violently with explosive type in the first two days, spewing ash to 14Km high and deposited to south and western direction following the prevailing wind direction at the time of eruption. A lava flow later followed after the pressure released from the vent. The mainly AA type flow continued for days reaching more than 10 Km following a river course south-westerly.

4.2 Geothermal manifestations

Numerous surface manifestations occur at Nabro which all are mainly fumaroles (Figure 11). They essentially arranged at the second caldera rims close to the rim. Clay is the main alteration mineral observed along the older fumaroles. New fumaroles zones are significantly developed with the volcanic eruption. The WNW open fractures produced during volcanic eruption will have a positive role in maximizing permeability for the geothermal fluid

5. 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 220^{0}C) from

FIGURE 11: Fumaroles at Nabro enriched with steam and the new lava flow seen black in the background

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 evaporated highland water or fossil or Red sea water is the source of water for 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. Two high values depicted on the contour map are well accompanies with the thermal manifestation thus worth to commence geophysical investigation and/or drill slim hole to map temperature gradient of the area.

The MT resisitviity 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 newly erupted volcanism at Nabro has significantly increased the permeability, thus will have an important role in the geothermal resource.

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 to know the gas outflow zone and select site of possible target of drill site.
- Gravity and microseismicity is also important in order to clearly define the target.

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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