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Resistivity Survey in Alid Geothermal Area, Eritrea

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ABSTRACT

A deep sounding geophysical survey of the Mt. Alid geothermal area in Eritrea was performed in late 2008. The aim of the survey was to delineate if possible the geothermal reservoir by the use of TEM and MT soundings. The original plan was to cover the area of Mt. Alid and its nearest vicinity. Within given timeframe the area to the west and southwest of the mountain was covered as well as the top of Mt. Alid.

The resistivity survey only reveals a part of the geothermal reservoir, due to lack of soundings. A SW-NE lineament is detected at a depth interval 500 meters to 2 km, interpreted as a transform fault intersecting the geothermal reservoir and most likely controls the main up flow into the reservoir.

At the surface at the southwest flanks of Mt. Alid, an area with exceptional vegetation in comparison to the barren dry volcanic landscape around indicates moisture and water in the ground that could be explained by steam up flow from the geothermal reservoir.

1. INTRODUCTION

In this report the geophysical survey consisting resistivities of the electromagnetic type both magnetotellurics (MT) and transient electromagnetic (TEM) conducted at Alid area are well described. The survey was done from November 21 to December 14, 2008 in collaboration with Iceland GeoSurvey.

Mt.Alid is an uplifted volcanic center having a broad caldera on its top. Alid and its surrounding areas are covered with complex and attractive geology. It has many spots of geothermal manifestations and the intensity of the steam coming out of the spots varies from spot to spot, the main ones being Darare and Eleghede.

Alid geothermal area is situated in the arid and semi-arid climatic zone. Even though the area is hot in most of the time, it offers a very friendly climatic condition, except some desert wind and dust during the months of November to February.

The aim of this geophysical study is to delineate the main source for geothermal resources. The survey covered both on top of Mt.Alid where there are strong geothermal manifestations and its nearby volcanic areas (mostly to the south and west of the mountain) with 1 kilo meters station interval. The result obtained form the survey could delineate the possible source and some big structures very well. But some of the lavas and the big boulders were the main constraints to make the survey very complete, especially to the east of the mountain; otherwise, better data could have been collected.

2. GEOLOGICAL AND GEOTHERMAL CONDITION OF ALID AREA

Alid is located about 120 km south east of the port city of Massawa and about 30 km south of Gulf of Zula in the Rift system. (Location map on figure 1b).

Alid mount is an uplifted volcanic center whose summit has collapsed forming big crater rising to an elevation of 600 to 900 meters above sea level. It is about700 meters above the surrounding plains. Terrain on the Alid volcanic center is characterized by small to medium and some times even high hills and ridges with high cliffs almost in all sides of the mountain. The hills and ridges inside the volcanic center made the resistivity survey a bit difficult in most of the area.

Generally, Alid and its surrounding areas are covered with variety and attractive geology. It witnesses rock types of high and low grades of metamorphic, sedimentary and variety types of volcanic rock units (Goitom et. al. 2006).

Young basalt flows cover extensively right north and south from immediate foot of Alid Mountain extending up to approximately 10 Kilometers on both sides (some part of it is on Figure 1). Both scoria and pahoehoe (rope type) lava flows are also available within these young lava flows. Many big caves and fractures are formed in the basalt flows.

West of Alid, Buya area, is covered by the low grade dolomitic rock and graphitic slate that came in contact with high grade kyanite schist. Lithologies in both sides of the contact zone are altered and foliated.

Alid Mountain bounded by Samoti plain in its south to south- east and by Wongobo plain in its north has a complex geology dominantly covered with rhyolites, basalts, pyroclastic units, obsidian and sedimentary rocks (Figure 1).

Geothermometer indicates reservoir temperatures of about 250°C for Ilegedi, the largest and most active of the Alid geothermal manifestations (Clynne et. al. 1996).

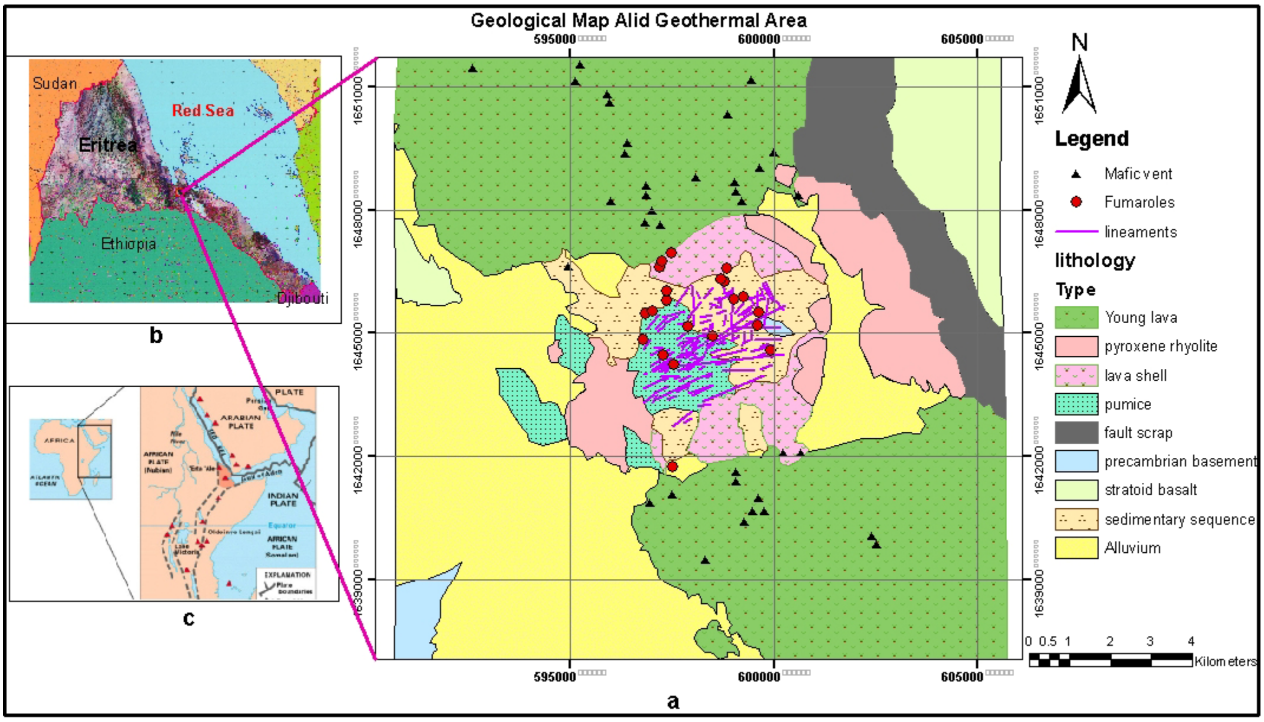

Figure 1: Geological map of Alid geothermal area (a) (modified from Clynne et al. 1996), Map of Eritrea (b), east African rift system (c).

3. DATA ACQUISITION

During the data acquisition two groups worked in the field, one for each method of measurements. During the field work period of 24 days, a total of 52 MT soundings where measured (some of which were repeated due to bad data quality) and 67 TEM soundings (figure 13). This makes 2.2 MT and 2.8 TEM soundings a day on the average. Some days, or part of days, were not productive due to instrument failure.

3.1 The Survey Area

The original plan consisted of 73 MT and TEM soundings. The plan was to carry out the survey on the top of mountain Alid and the area, 2 – 3 km away from the mountain. This was quite an optimistic plan, considering the time available and the difficult terrain. Some of the area is covered with inaccessible lava flows. The bikes came to a good use in the field. It was however only possible to do the TEM and MT measurements on the top of Mount Alid by carrying the equipment on the back of camels.

3.2 TEM Data

In the TEM soundings electrical current is transmitted into a big loop of wire (300 x 300 m) laid on the ground. This current produces a magnetic field. The current is abruptly turned off and the decaying magnetic field causes induction currents in the ground. The strength of the induced currents is dependent on the resistivity structure below the survey site. The ground response is measured by a small coil in the center of the big transmitting loop. The time decaying signal is measured from 88 µs to 70 ms from the time of turning of the current.

The TEM instruments used is from Geonics Ltd. in Canada. The soundings from it can survey the ground resistivity down to about 0.5 – 1 km, depending on the Resistivity of the area. For low subsurface Resistivity, the depth of penetration can be as low as a few hundred meters; but, in higher resistivity surroundings it is possible to explore the resistivity down to about 1 km in favorable conditions. For the conditions in the Alid area and the instrument setup, the depth of penetration of the TEM soundings was generally around 500 meters. One TEM sounding takes a few hours to perform, from the start of setup to the end of the measuring time.

All the TEM data was interpreted in terms of 1-D models (resistivity only varies with depth) using a program developed at ISOR (Iceland Geosurvey).

3.3 MT Data

In the MT method, the natural fluctuations of the earth's magnetic field are used as signal source. Those fluctuations induce currents in the ground and are measured on the surface with two horizontal and orthogonal electrical dipoles (Ex and Ey) and the magnetic field is measured in three orthogonal directions (Hx, Hy and Hz). It is customary to set the x direction to the magnetic north direction. For simple earth (i.e. homogenous or layered) the electrical field is coherent with its orthogonal source magnetic field (i.e. Ex correlates with Hy, and Ey with Hx) and this relation depends on the earth's resistivity structure.

The MT instruments used here are from Phoenix Ltd. in Canada (MTU type), and can measure the MT signals in the frequency range from 320 Hz up to DC. Four MT units where used in this survey. One 5 component (i.e. Ex, Ey, Hx, Hy and Hz) station was kept running continuously at the same location some 10 km south of the survey area and used for remote reference data processing. This is a standard method to get better quality data from the processing. The other three sites were allowed to record continuous for about 20 hours every day. This gives about of time series and MT data in the range from 320 Hz (0.003 sec) to about 1000 seconds. The short-period MT data (high frequency) is mainly dependent on the shallow structures due to their short depth of penetration, whereas the long period data are mainly dependent on the deeper structures. The MT method has the greatest exploration depth of all resistivity methods (some tens or hundreds of kilometers) and is practically the only method for studying deep resistivity structures. In this survey, the exploration depth of the MT soundings was around 10 km, but varied quite much depending on data quality and the resistivity structure.

Three of the MT units are 5 components and one is a two component unit (i.e. measures only Ex and Ey).

The two component unit is always set up close to a nearby 5 component site (usually around 1km), and the magnetic field at that site is used for analyzing the result at the two component site. This is of course only valid if the magnetic field is homogeneous locally, an assumption which is usually valid for short distances.

The quality of the MT data was not always satisfactory and therefore many sites had to be re-measured. The main reason for this was low signal strength. The source for the MT signal are mainly thunderstorms in the equatorial belt of the earth (high frequency) and solar storms interacting with the earth's magnetic field (low frequency). During the survey time the solar activity was at the minimum level in its 11 years activity period, so low signals where expected. In the beginning, the electrode dipole length was kept 50 meters but was increased using all the extra wire at hand up to 125 meters. That usually gave better data quality.

The measured MT time series are Fourier transformed into the frequency domain and the "best" solution is found that describes the relation between the electrical and magnetic fields through the following equation:

$$\begin{bmatrix} Ex \\ Ey \end{bmatrix} = \begin{bmatrix} Zxx & Zxy \\ Zyx & Zyy \end{bmatrix} \begin{bmatrix} Hx \\ Hy \end{bmatrix} \quad (1)$$

Or in matrix notation: $\vec{\boldsymbol{E}} = \boldsymbol{Z}\vec{\boldsymbol{H}}$

Where $\vec{\boldsymbol{E}}$ and $\vec{\boldsymbol{H}}$ are electrical and magnetic vectors (in the frequency domain) and Z is the complex impedance tensor which contains the information on the subsurface resistivity structure. Programs from Phoenix Ltd., SSMT2000, were used to process the time-series signal using a robust processing method technique. The result was edited in MTEDITOR program by Phoenix, and the output was run through a program called edi2edi made by ISOR, which calculates various MT parameters and produces the results in the standard EDI file format. An example of the processed MT data in terms of magnitude and phases of impedance elements are given below.

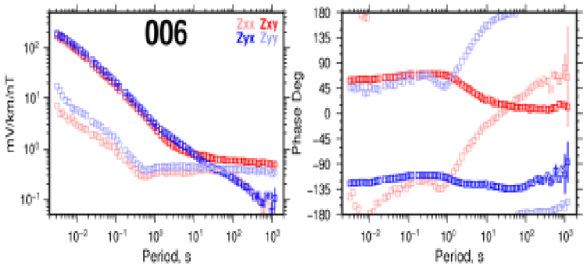

Figure 2: Impedance elements for MT site 006 with the amplitude on the left and the phase on the right. The diagonal elements of the impedance are shown by light red and blue.

The values of the impedance elements are dependent on the resistivity structures below and around the site. For a homogeneous and 1-D earth (resistivity varies only with depth) and Zxx = Zyy = 0. For a 2-D earth, i.e. resistivity varies with depth and in one horizontal direction, it is possible to rotate the coordinate system such that Zxx = Zyy = 0, but Zxy ≠ Zyx. For a 3-D earth all the impedance elements are different. An example of the impedance results for one of the MT sites is shown in Figure 2. As seen there, the diagonal elements of the impedance tensor (Zxx and Zyy) are not zero, but they are more than an order of magnitude lower than the off diagonal elements up to about 1 second, and the main impedance elements (Zxy and Zyx) are about the same indicating 1-D resistivity structure for the shallow part. At greater depths, i.e. for periods greater than 10 seconds, all the impedance elements are in the same order of magnitude showing a high degree of three-dimensionality in the resistivity structures below this site.

From the impedances the apparent resistivities and phases are calculated according to:

$$\rho_{xy} = 0.2T\left|Z_{xy}\right|^2.;\ \theta_{xy}=\arg(Z_{xy})$$
$$\rho_{yx} = 0.2T\left|Z_{yx}\right|^2.;\ \theta_{yx}=\arg(Z_{yx}). \quad (2)$$

Where ρ= apparent Resistivity (Ωm), θ = phase angle (degree), T= period (s) and Z = impedance (Ω).

As mentioned earlier, the MT impedance is dependent on the orientation of the horizontal electrical and magnetic fields. The rotation that minimizes the diagonal elements in the impedance tensor is called the electrical strike direction. The MT parameters in a rotated coordinate system (one fixed rotation angle for all frequencies) are also shown along with the result of the tipper for those sites where vertical magnetic field was measured (the relation between the vertical and the horizontal magnetic fields). A rose-diagram rotation plot for the strike direction is shown in Figure 3 only for periods greater 10 seconds (the data representing the deeper parts). The figure clearly demonstrates that the main geo-electrical strike is parallel to the rift direction.

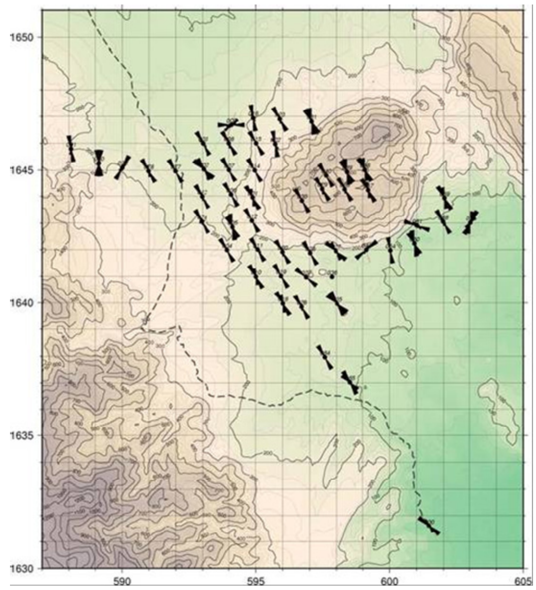

Figure 3: Rose diagrams of strike directions for periods greater than 10 seconds, for all the MT sites. The preferred rotation for each site is shown by a red line through each site.

It is clear from the MT data that the resistivity structures of the Alid area are highly three dimensional. A measure of the three-dimensionality is the so called skew parameter which is the ratio between the magnitude of the sum of the diagonal elements and the magnitude of the difference of the off diagonal elements. This parameter is usually less than 0.1 for periods less than 1 second , but increases dramatically for periods greater than 1–10 seconds, to values even greater than 1. Thus it is clear that for a full understanding of the MT parameters a 3-D interpretation of the data is called for. This is however out of the scope of this work since 3-D modeling is very time consuming. A 1-D modeling (horizontal layered earth) of the MT data is quite straightforward and is the only interpretation of the data used in this report. The question is which parameters should be inverted for? In a 3-D data inversion all the impedance elements are inverted for, where as in a 2-D inversion both the xy and yx pairs are inverted for. But in a 1-D inversion one could invert for either xy or yx parameter or what is becoming more customary nowadays is to invert for some rotational invariant parameter and therefore one has not to deal with the question of rotation. There exist three such invariants, namely:

$$Z_{av} = \frac{Z_{xy} - Z_{yx}}{2} \tag{3}$$

$$Z_{det} = \sqrt{Z_{xx}Z_{yyY} - Z_{xy}Z_{yx}} \tag{4}$$

$$Z_{gm} = \sqrt{-Z_{xy}Z_{yx}} \tag{5}$$

Where Z is impedance, all these parameters give the same values for a 1-D earth response, for 2-D the det (determinant) and the gm (geometric mean) reduce to the same value but the av (arithmetic mean or effective) is different. For 3-D responses, all these parameters are different. A plot of these parameters in terms of apparent resistivity and phase is shown in Figure 4 for two sites. For site 080 there is a little difference between the three invariants, but the average (ave) is slightly different from the others which are in agreement for a 2-D case as discussed above. For site 006 in Figure 4 the det value is quite different than the others, showing a high degree of 3-D.

It is not known which of the three invariants, if any, is best suited for 1D inversion. However several scientists have suggested that the determinant invariant is the one to use based on the comparison of model responses for 2-D and 3-D models (Park and Livelybrook, 1989; Rangabayaki, 1984; Ingham, 1988). Therefore we have chosen to use the determinant invariant impedance for the 1-D inversion.

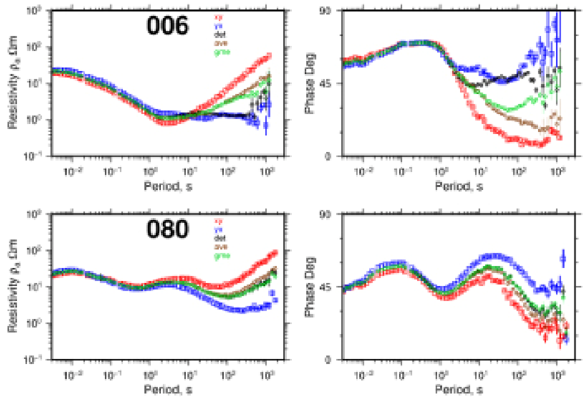

Figure 4: Apparent resistivity and phase for two sites. The different colours refer to different parameters determined form the impedance.

3.4 Telluric Shift in MT Soundings

The MT method, like all resistivity methods where the electric field is measured on the surface, suffers a problem called the *telluric shift* problem. The reason for this is local resistivity inhomogeneity which distorts the electric field, independent of period. The result of this is that the apparent resistivity values have an unknown multiplier (shift of logarithmic values). The TEM soundings do not suffer this problem because they measure magnetic induction in a receiver coil. 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.

Due to this reason the TEM soundings are essential in areas where telluric shifts in MT soundings can be expected, such as in a volcanic area as in the Alid area. This is the reason for setting up the TEM site at the same, or close by the location of the MT sites. The maximum distance between a MT site and a corresponding TEM site is 260 m (site 047).

The shift parameter is found through a joint inversion of the TEM and the MT data where the shift value for the MT apparent resistivity data is one of the inversion parameters. The inversion program used is developed at ISOR and named "temtd". An example of an inversion results is shown in Figure 5. The MT data points are shown by blue dots (apparent resistivity and phase) and the corresponding TEM data is shown by red apparent resistivity points. The 1-D model is shown to the right and its TEM and MT response is shown by red and blue lines respectively. The model response fits the data quite well.

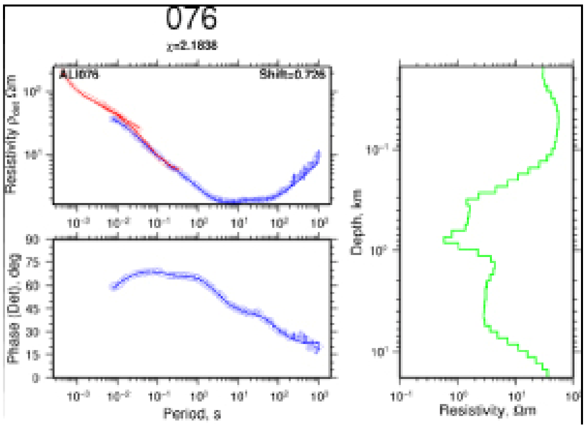

Figure 5: An example of a joint inversion result of TEM (red points) and MT data (blue points). The red and blue solid curves show the TEM and MT responses respectively of the model shown to the right.

The distribution of all the shift parameters in the MT soundings is shown in Figure 6. If the telluric shift in the MT data is random, one would expect a mean value of 1, but as is shown in Figure 6, the mean value is about 0.7, with minimum and maximum values of 0.1 and 1.7 respectively. A shift of 0.1 means that the apparent resistivity data have been shifted down by an order of magnitude due to local resistivity inhomogeneities. Uncorrected interpretation of that sounding would have yielded a model with a resistivity about and order of magnitude lower and depths of layers about 3 times to shallow. A mean shift less than one is quite common in a volcanic environment.

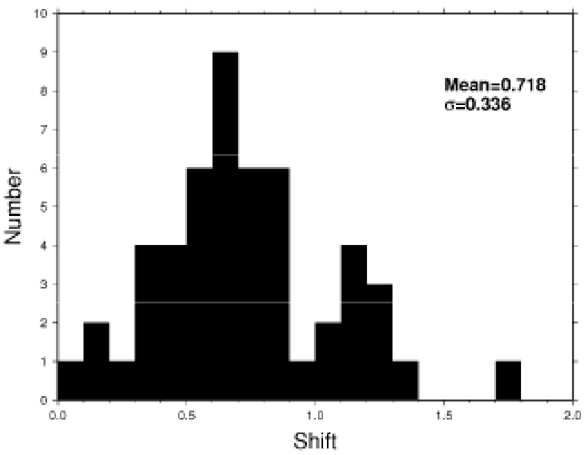

Figure 6: Histogram of shift factors applied to the MT apparent resistivity curves.

4. RESULT OF JOINED INVERSION OF MT AND TEM DATA

The 1-D TEM/MT joint inversion results are compiled into a 3-D resistivity structure and are presented by iso-resistivity maps at different elevations above and below the sea level, and by resistivity cross sections through the survey area.

For each site a depth of exploration is estimated. At sites where only TEM sounding is present, the depth of exploration is much less than the other sites; therefore, those are not used at depths greater than their exploration depth which is usually not more than about 500 meters. For MT sites where data quality is bad at long periods the depth of exploration is as low as 2 km, but generally 6 – 10 km. In some instances where 3-D signal is strong in the long period MT data, a 1-D model could not be generated that fits both the apparent resistivity and phase, therefore the depth of penetration at those soundings is often dramatically reduces in their 1-D modeling.

4.1 Resistivity Maps

In order to explain the resistivity structure of the Mt. Alid area, resistivity maps are presented here for resistivity at 300, 500, 1000, 2500, 3500 and 9000 meters below sea level. The elevation of the survey area is generally 100 – 200 meters above sea level (m a.s.l.) and the soundings on top of Mt. Alid are at around 600 m a.s.l.

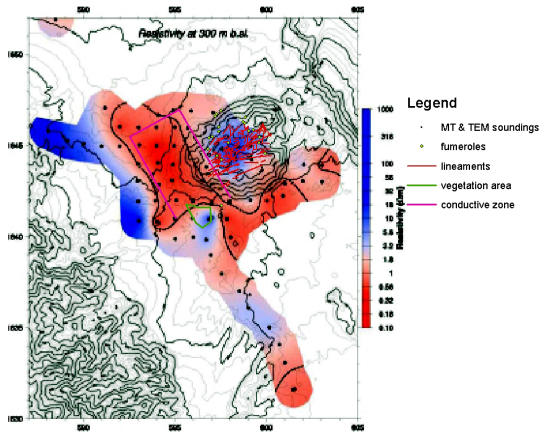

Figure 7: Resistivity map at 300m below sea level.

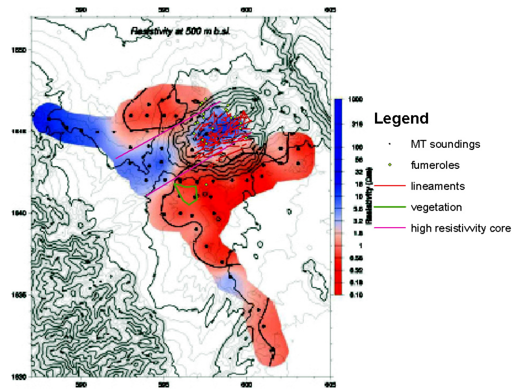

Figure 8: Resistivity map at 500m below sea level.

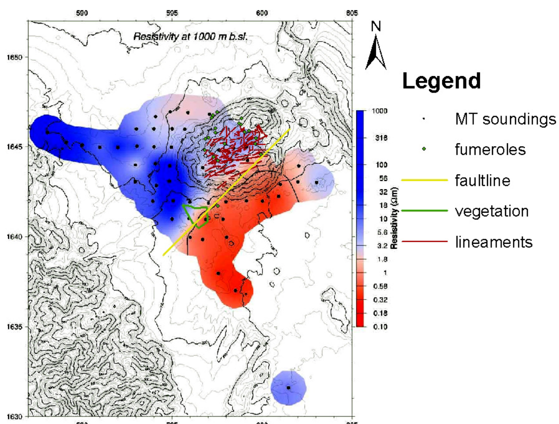

Figure 9: Resistivity map at 1000m below sea level.

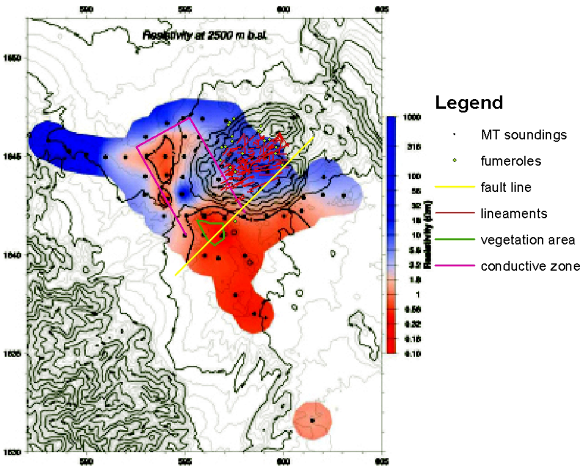

Figure 10: Resistivity map at 2500m below sea level.

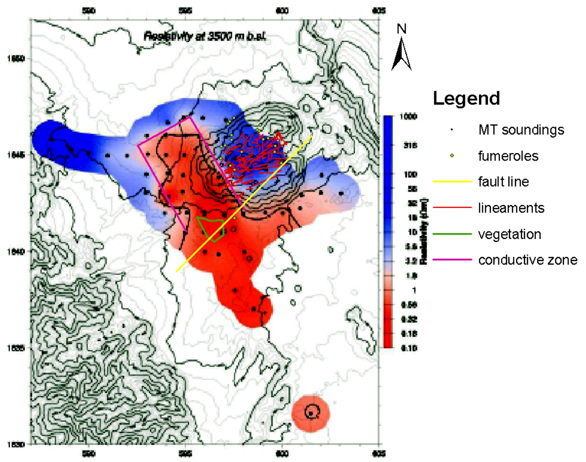

Figure 11: Resistivity map at 3500m below sea level.

At 300 m b.s.l (Figure 7), most of the survey area at this depth shows low resistivity value, and the lowest value is shown to the west of the mountain. This lowest value could be intensified by the formation of the conductive low temperature minerals like zeolites and smectites.

At 500 m b.s.l. (Figure 8), a high resistivity body appears to cut Mt. Alid in a WWS-NEE direction perpendicular to the rift system (bounded by two pink lines). This high resistivity value to the western part of the mountain could probably be interpreted as high resistivity core below the low resistivity cap (as shown in figure 7). It is believed that high temperature minerals like chlorites and epidotes are formed at this relatively high Resistivity depth (Figure 8).

The highest temperature, Ghindae, Darare and Illegede fumaroles are aligned in this high resistivity core. This alignment of the high temperature fumaroles agrees with NE-SW oriented shallow depth low resistivity anomaly of the Shlumberger resistivity survey done in 2006 (Goitom et. al.) and with the major axis of the dome and with the structural lineaments mapped in 2006 (Yohannes et. al).

At 1000 m b.s.l. (Figure 9) the low resistivity west and north of Mt. Alid has disappeared and a clear SW-NE resistivity boundary is observed under the southern part of the mountain. This boundary extends down to about 2000 m b.s.l., below that a low resistivity appears again to the northwest of the mountain (Figure 10), but south and southwest of it, the low resistivity continues to deeper levels. Again no low resistivity is seen below the mountain.

At 3500 m b.s.l. (Figure 11), a clear low resistivity NNW-SSE body is seen west of the mountain and connected to the broader low resistivity to the south. Note that at this depth the resistivity is lowest at the base of the Mt. Alid slopes, SW of it, where the resistivity gets as low as 0.3 Ωm. There appears to be a sharp resistivity boundary in NNW-SSE direction under the western part of the mountain that extends as deep as the resolution of the soundings. This boundary is better seen in the resistivity cross section WE1644 (Figure 15). Below 3500 m b.s.l. the resistivity structure is more or less similar. The low resistivity body west of the mountain widens up to about 7000 m b.s.l., and at 9000 m b.s.l., a clear low resistivity region is observed at the intersection of the main rift system and NE-SW fracture of the mountain plus the fault in yellow line (Figure 12).

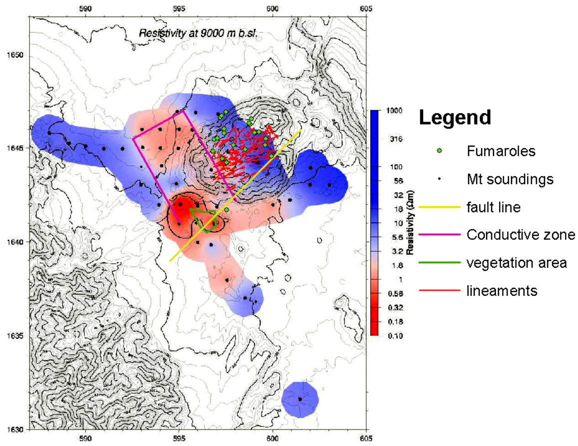

Figure 12: Resistivity map at 9000m below sea level.

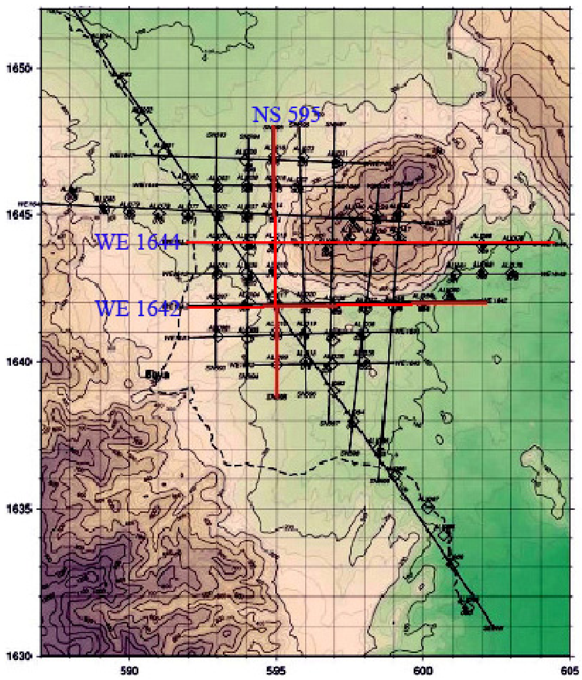

Figure 13: Location of soundings and cross sections (red lines).

Figure 13 shows the location of the cross sections. Here in this manuscript, the red lines represent sections shown on Figures 14 through 16. On all the figures no resistivity is shown below the estimated depth of resolution for each sounding. The name of the WE and SN sections are derived from the north and east UTM coordinates.

Section WE1642, (Figure 14), shows that the lowest resistivity area is bounded to the west under MT soundings of 11 and 20. Section WE1644 (Figure 15) clearly shows the low resistivity body west of Mt. Alid. There appears to be a very sharp vertical boundary running NS under the western part of the mountain.

Sections SN595 (Figures 16), shows that the NS oriented low resistivity body west of the mountain is not seen at the northernmost sites.

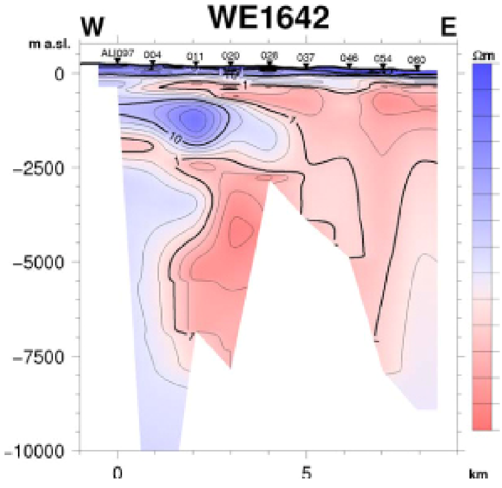

Figure 14: Cross section WE1642.

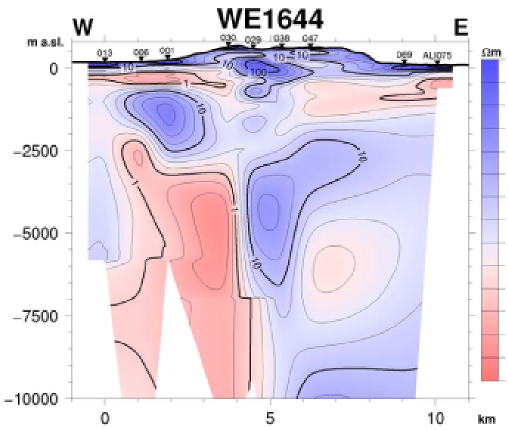

Figure 15: Cross section WE1644.

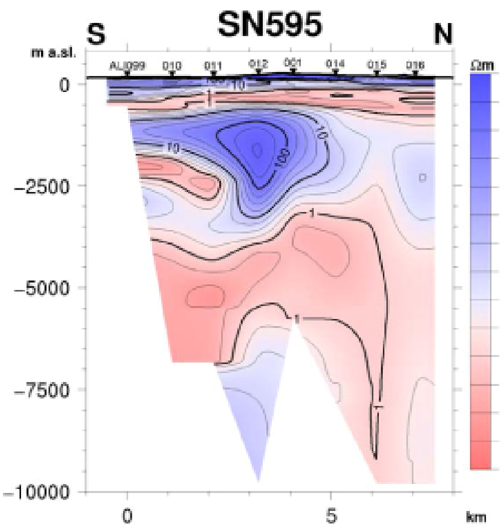

Figure 16: Cross section SN595.

5. CONCLUSION AND RECOMMENDATIONS

Form the results of the survey, a low resistivity layer seen down to 1000 meters depth and is interpreted as the old conductive sea bed and probably from the formation of the highly conductive minerals like zeolites and smictites.

According to Lowenstern et al. (1999), geological and geochemical studies imply that a high temperature geothermal system underlies the Alid volcanic center. The resistivity survey does not cover enough area to compare the resistivity structure beneath Mt. Alid to the structures surrounding it. The high resistivity beneath Mt. Alid does not stand out as an anomaly, as it is not bounded to the east and north-east in lack of soundings. Until we see, if the high resistivity represents a resistive body in low resistivity surroundings we can't conclude that this high resistivity represents the geothermal heat source.

If this, however, were the case, i.e. the high resistivity under Mt. Alid represented the heat source; one would expect it to be imbedded in low resistivity surroundings. From the results of this survey we see that the high resistivity has a very sharp SW-NE boundary with the low resistivity on the southern side. This boundary forms a clear lineament extending from the depth 500 m .b.s.l. down to 2000 m b.s.l. From the depth of 3500 m b.s.l down as far as can be detected, there is a distinctive low resistivity body south-west of Mt. Alid. These low resistivity bodies to the south and west of the mountain could well be the part of a greater area surrounding Mt. Alid, but as of now, we do not have information on the resistivity to the east and northeast.

The lineament mentioned is sure to play a major role in the geothermal system. It most likely represents a SW-NE fault or a fault system that cuts under the southern part of the mountain. According to Clynne et al. (1996), some fumaroles on the top of the mountain, form weak N45°E alignments, the same direction as the lineament. The major axis of the mountain itself has this direction. The geological map (figure 1) shows a shift in the fissure swarm through Mt Alid, where it intersects the NE-SW lineament. This could possibly indicate that the SW-NE lineament represents a transform fault underlying Mt. Alid.

According to the Shlumberger resisitivity survey carried on top of Alid Mountain in 2006 (Goitom et. al.), it is clearly marked that a NE-SW strike low resistivity anomaly. This is also in agreement with the major axis of the dome and with the structural lineaments mapped in 2006 (Yohannes et. al).

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