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Magnetotelluric (MT) Survey in Noth-Ghoubbet geothermal field, Djibouti

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ABSRACT

The magnetotelluric (MT) method is one of the effective geophysical techniques for geothermal exploration. As part of this study, the data of two electrical methods (MT and TDEM) have already been conducted. A total, of 30 sounding MT and TDEM were collected. The objective of this research is to identify the possible reservoir to produce geothermal energy using the magneto-telluric (MT) method. In this research, I used 1D inversion and the inversion algorithm is the Island code called run1D. According to the result in this inversion, the resistivity profiles show a structure of High, Low, and High resistivity. On these profiles, we observed a resistant ground in the surface, this resistant structure extends up to 100m to 0m above sea level. The profiles almost show the high resistivity structure on the surface and this resistant ground has a small thickness not exceeding the 100m. On the other hand, this resistant unit is absent from certain stations, especially with the PP5_NS profile, where we tap directly on the conductor (< 10 Ωm) from the first meters. This can be explained by the fact a sedimentary basin consists mainly of alluvium. The conductive structure occupies the central part of the profile with depths ranging from 0m to 1.5km below sea level. In terms of the geological structure, this central unit could correspond to the Dalla basalts, possibly altered by hydrothermalism. Below this low resistivity layer, the resistant structure is increasing with depth, up to (70 Ωm to 100 Ωm). This resistant structure could correspond to a possible geothermal reservoir.

1. INTRODUCTION

Geothermal energy is not only clean and pollution-free energy, but also renewable. It is considered one of the most valuable new and green energies to operate in the 21st century. Comparing with other renewable energy, it has a very special advantage because it is not seasonally dependent, and it is reliable. The Republic of Djibouti is in the Horn of Africa where three major extensional structures, the Gulf of Aden, the East African Rift, and the Red Sea, meet to form the Afar Depression (Fig.1). Most of Djibouti is covered by volcanic rocks, mainly basalt. North-Ghoubbet is one of the most important sites for geothermal development, selected by the Djiboutian Office for Geothermal Energy Development (ODDEG). North-Ghoubbet geothermal prospect is in the eastern part of the capital city about 140 km. Asal has been the main target area for geothermal research programs in the country, but in the Assal region, we have a problem with high salinity. Thus, the study area is the second promising site which is not far from Assal area. This zone compared to Assal, has less salinity because in this zone there is a recharge of the meteoric water which comes from infiltration at Goda-mountain massif. The regional topographic difference varies from 0 to 560 m on average. A hot spring at 80 ° C is identified on the coast, and several fumaroles have been found on the normal faults. Three volcanic series (Dalha Basalt, Gulf, and Asal) are present in this study area which is the results from a polyphase tectonic-magmatic evolution of the rift zone. The main fault systems in the region tend to be NNW-SSE and NW-SE, comprising several faults. Most of the surface geothermal activity is located along these faults, and a hot spring has been found where it is intersected by an E-W trending fault.

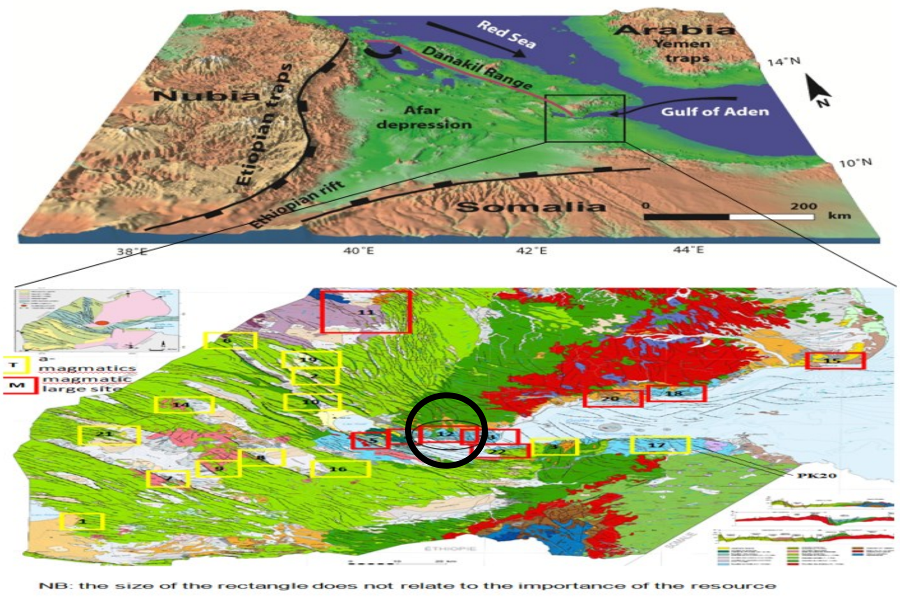

Figure 1:Map chawing geothermal sites in Djibouti and black cercle show the study area.

2. GEOLOGICAL SETTING

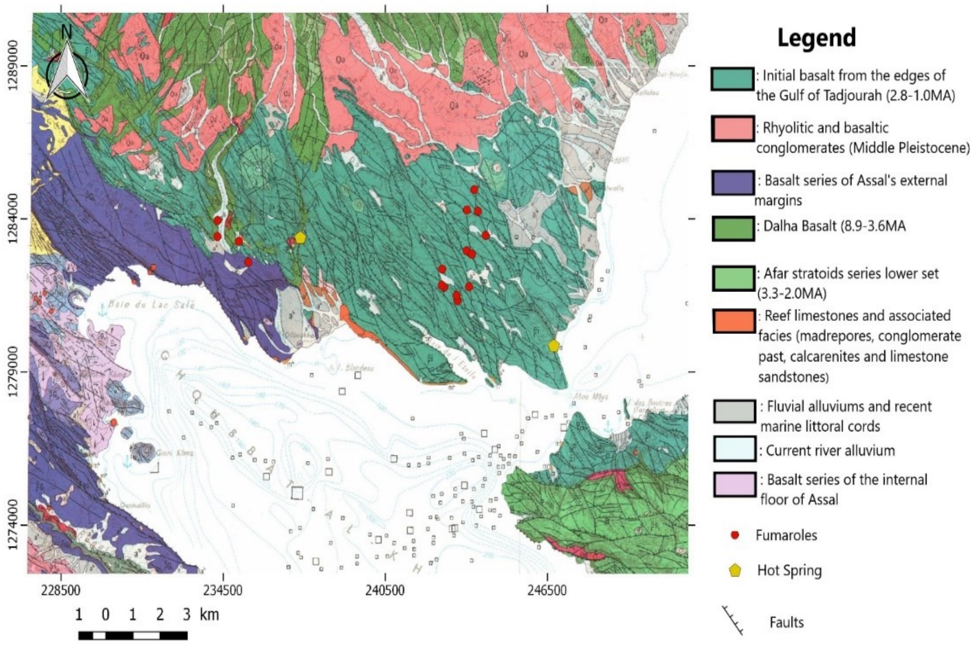

Figure 2:Geological map of the Noth-Ghoubbet geothermal field (Djibouti, Modified from M. FOURNIER, F. GASSE, O. RICHARD, and J-C. RUEG).

From the volcano-stratigraphic point, geological sections were used to specify the vertical organization of the effusive and intrusive sequences, as well as, the involved sedimentary deposits encountered in the northern Ghoubbet area. The volcanic series present in the study area (Dalha Basalts, Gulf and Asal) fill paleo-depressions which result from polyphase tectono-magmatic evolution of the rift zone. Between each major volcanic episode occurs a phase of uplift-erosion. The relatively thin Gulf basalt flows (several tens of meters), and sub-horizontal position occupy the top of the reliefs made up of basaltic flows of the lower Dalha series, the age of which is between 3.6 and 5.9 Ma. In the Wadi Analé sector, acid flows of the rhyolite type are found interspersed in the basalts of the lower Dalha. In the same area the intercalation of volcanic flows with lake levels. These levels are described by Gasse et al. 1985 as being fluvio-lacustrine sediments, a few meters thick made up of finely bedded limestones, and diatomic silts with Malanoid shells alternating with detrital beds (sandy and conglomeratic silts). Towards the south, approaching the northern edge of the Asal rift, basalts of the outer margin of Asal form the bulk of the piles. These are fine basaltic flows with a total thickness of 150 to 200 meters (Gasse et al. 1985) which lean in onlap against the N130 escarpments of the faults affecting the Dalha basalts and the Gulf basalts. Often scoriaceous on the surface and bullous on the inside, these basalts are distinguished by the presence of plagioclase (bytownite) megacritals, always associated with olivine and clinopyroxene megacrystals. The geothermal events in the northern Ghoubbet area are mainly located on the edges of the small horst of Moudoueoud. Some fumaroles are exposed on the sides of this relief. Cartographically, these manifestations are localized along tectonic structures. The most important manifestations associated with numerous hydrothermal alterations are observed in the Analé wadi. These are fumaroles and a hot water source with a surface temperature of 98 and 99 ° C, respectively. According to The XRD analysis performed by the Jica team in 2014, the analysis identified an alteration mineral combination of smectite and quartz/calcite that suggests mineral formation temperature would be 100 ºC–150 ºC. From these geological observations, the JICA Survey Team considered that there may be prospective geothermal resources for development in North-Ghoubbet.

3. MT METHOD

The magnetotelluric (MT) method is an electromagnetic geophysical exploration technique that images the electrical properties (distribution) of the earth at subsurface depths. The energy for the magnetotelluric technique is from a natural source of external origin. The MT signals are generated from two sources: 1. At the lower frequencies, generally less than 1 Hz, or more than 1 cycle per second, the source of the signal is originated from the interaction of the solar wind with the earth's magnetic field. As solar wind emits streams of ions, it travels into space and disturbs the earth's ambient magnetic field and produces low-frequency electromagnetic energy that penetrates the earth. 2. The high frequency signal, greater than 1 Hz or less than 1 cycle per second, is created by world-wide thunderstorm activity, usually near the equator. The energy created by these storms travels around the earth in a wave guide between the earth's surface and the ionosphere, with part of the energy penetrating the earth.

$$\begin{pmatrix} E_X \\ E_y \end{pmatrix} = \frac{1}{\mu_0} \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix} \quad (1)$$

With Ei is the electric fied, and Bj (i, j = x, y) is the magnetic field variation observed along the north(x) and east (y) direction, respectively. The μ_0 is the magnetic permeability of free space. Z, is known as the impedance tensor, its frequency dependent and contains the information about the subsurface conductivity structure. The elements Zijare usually displayed in terms of apparent resistivity, ρ_a

$$\rho_{aij} = \frac{1}{\mu_0 \omega} |z_{ij}(\omega)|^2 \quad (2)$$

With ω is the angular frequency

Being a tensor, Z also contains information about dimensionality and direction. For a 1-D Earth, wherein conductivity varies only with depth, the diagonal elements of the impedance tensor, Z_{yy} and Z_{yy} (which couple parallel electric and magnetic field components) are zero, while the off-diagonal components (which couple orthogonal electric and magnetic field components) are equal in magnitude, but have opposite signs, i.e., in 1-D situation

$$\left.\begin{matrix} Z_{xx} = Z_{yy} = 0 \\ Z_{xy} = -Z_{xy} \end{matrix}\right\} \text{1-D} \qquad (3)$$

3.1 Principle of the EM (MT/TDEM) methods

Subsurface electrical resistivity can be classified into two methods: Galvanic method (DC) and Electro-Magnetic (EM) method. DC methods, mainly the Vertical Electrical Sounding (VES) are widely used for probing subsurface. These methods have some difficulties in the field, for example, in the permafrost area where it is not easy to inject the current in the ground and a depth capable of being estimated by the method is the first few hundred meters from the ground. Nowadays, principally in geothermal exploration, which is required to determine the deep subsurface structure, the EM methods are largely used to image the areas presented low resistivity. To estimate the deep subsurface electrical resistivity structure and create a geothermal conceptual model, Magneto-Telluric (MT) method and Time Domain Electro-Magnetic (TDEM) method, which are the kind of EM method, are adopted on this study. There are several methods for measuring the principle of the MT method, one is the measurement of currents induced in the ground by time variations of the Earth's magnetic field. The fundamental theory was first developed by Cagniard (1953) and Tikhonov (1986). The time-varying magnetic field and the electric field generated in the surface are measured simultaneously. The electric field is measured in two perpendicular horizontal directions and the magnetic field in the same horizontal and the vertical direction. The measured time series signals are Fourier transformed into the frequency domains. The frequency components of the electric field are related to the magnetic field by the so-called impedance tensor, which depends on the subsurface resistivity. The short period component is mainly dependent on shallow resistivity structure, and the long period component is mainly dependent on deep resistivity structure. The MT method has the greatest depth of exploration (some tens or hundreds of kilometers) and is practically the only method for studying deep resistivity structures. TDEM Method admits a depth of investigation from 200 to 500 m depending on the size of the electric wire loop (transmitting loop) and provides a resistivity structure with a good resolution. The fundamental principles of the TDEM method were developed by Kaufman (1983) and Decloîtres (1998). TDEM method also makes it possible to correct the static shift, which affects the apparent resistivity obtained from the MT method in the near surface. The principle of this method consists to generate an electric current at the ground by a transmitting loop. This electric current will induce a magnetic field in the ground. Then, by abruptly turning off the current, there is a creation of an electromotive force (fem.) which will generate electric currents, called eddy currents, in the ground. These currents generate in the ground a second magnetic field, which will be to measured by a receiver loop posed on the ground.

3.2 Electromagnetic (MT/TDEM) data acquisition and processing

A combined MT and TDEM surveys were carried out in the North-Ghoubbet geothermal prospect. On this field, 30 pairs of MT/TDEM soundings were performed (Figure 4). The MT time series were acquired by using two sets of Metronix system. The TEM data was collected by using a terraTEM system with a coincident loop configuration (100m x 100m).

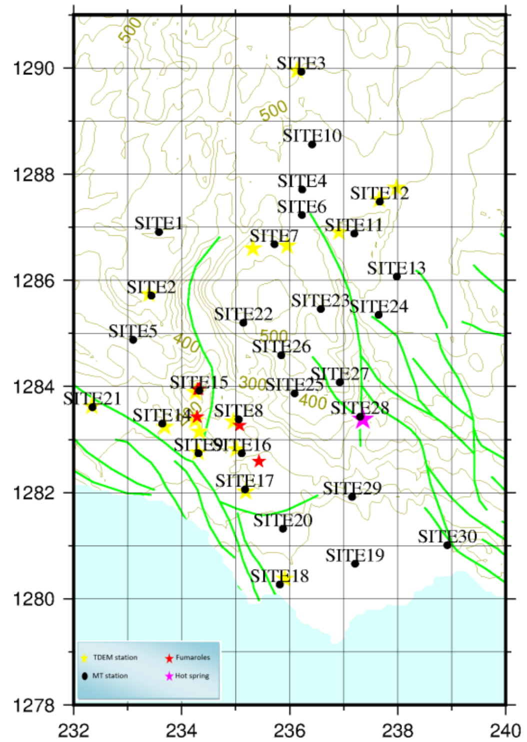

Figure 3:Location map of MT, TDEM Soundings, and surface manifestation.

Each MT station was kept running overnight (about 12 to 18 hours each). The MT data from Metronix systems were processed using the ProcMT program from Metronix. The quality of the MT data is good in the range of 0.001 s to about 800 s. Unfortunately, a big error bar on the MT impedance tensor is observed for the soundings. However, the MT data seem to be smooth in the range between 1000 Hz (0.001 s) and about 900 s, and this big error bar might be due to the processing phase with ProcMT. The TDEM data obtained from the field were processed by using TemxUSF program (Árnason, 2006b). The program calculates averages and standard deviations of repeated transient voltage measurements, and calculates apparent resistivity as a function of time after turning off the current.

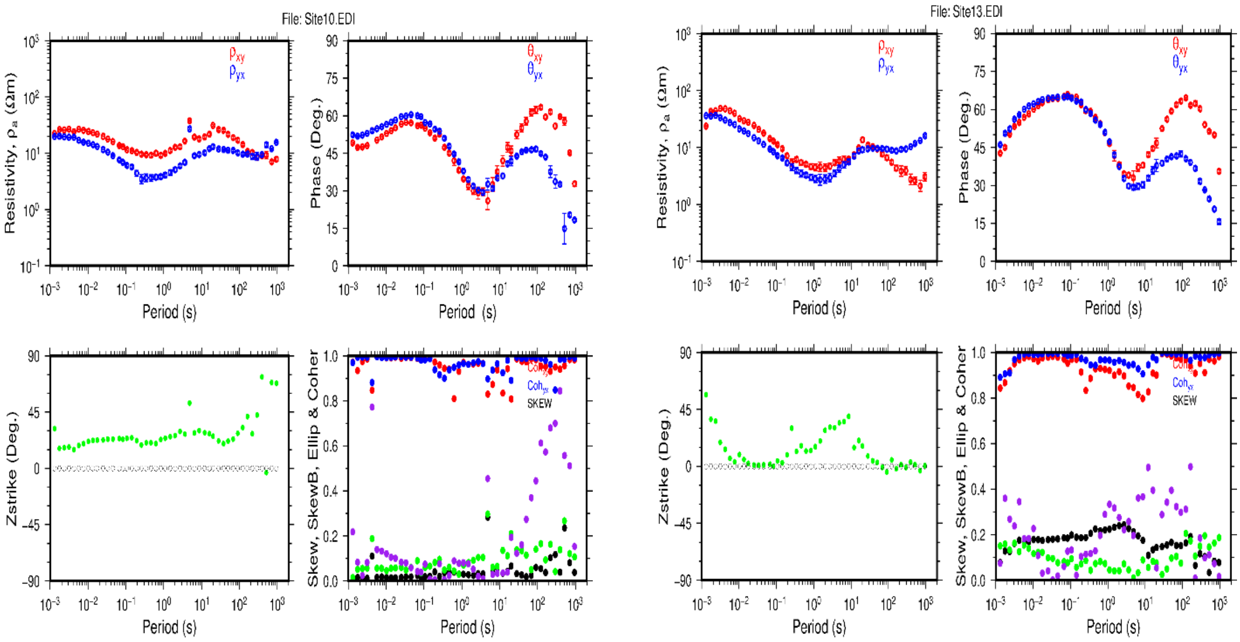

Figure 4: Example of the result from MT data processing phase. Upper panel: the apparent resistivity and phase derived from the determinant of the impedance tensor. Lower panel: strike and skew.

3.3 EM data Inversion

After processing the data, 1-D resistivity model was estimated from joint inversion for MT/TDEM data of the same location. It is to correct the static shift phenomena that affects MT apparent resistivity in the high frequency (Arnason 2015). The 1-D joint inversion method adopted in this report is so-called “minimum structure” or Occam's inversion (Arnason 2016). It consists to fit apparent resistivity and phase from each sounding by the response of models with many layers (30 layers in this report). with constant thicknesses increasing exponentially with depth. The unknown parameter that is determined in this procedure is the true resistivity in the subsurface. The following figure shows the typical result of a joint inversion of MT/TDEM data carried out on North-Ghoubbet geothermal site. Here, the TDEM data was used to correct the static shift affected by the MT apparent resistivity, but not added in the MT apparent resistivity like the 1D joint inversion.

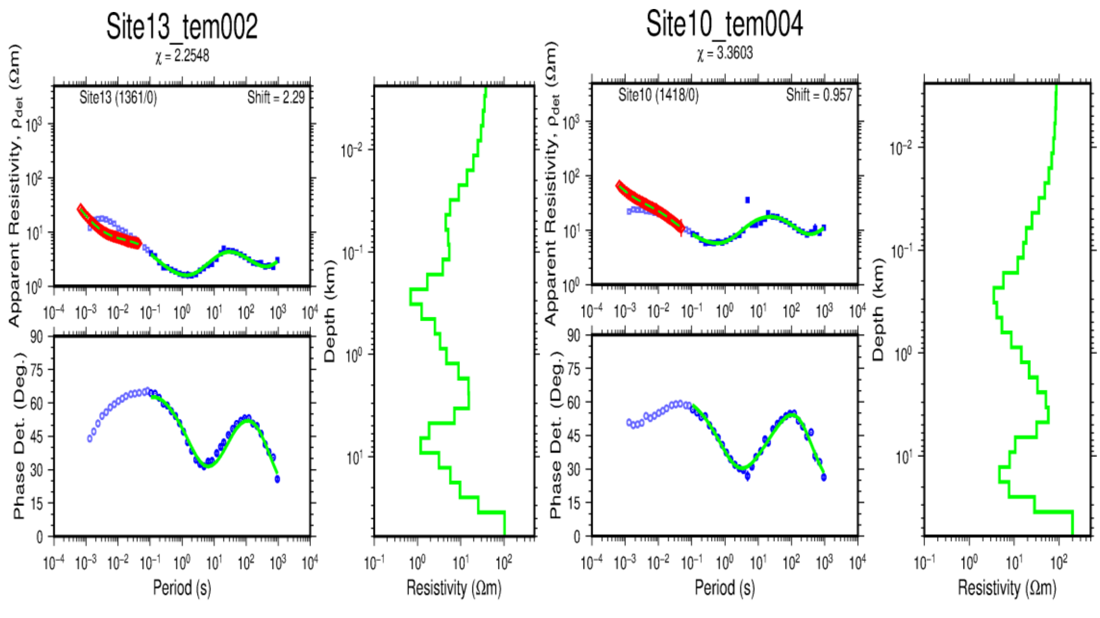

Figure 5:: Example of a 1-D joint inversion of MT and TDEM data. Red circles are TEM apparent resistivity and blue circles are apparent resistivity and phase derived from the determinant of MT impedance tensor. The green solid lines to the right show the geoelectrical model of the subsurface.

3.4 EM data interpretation

The resistivity models from the 1D joint inversion have been interpolated into vertical resistivity cross-sections (4 NS cross sections) and into resistivity maps as function of the depth. A few resistivity cross sections and maps will be shown and discussed specifically in this report to emphasize the main results of the 1D joint inversion.

3.4.1 Resistivity depth slices

The resistivity structure estimated from the 1-D joint inversion was compiled and interpolated into resistivity depth slices. Seven depth slices (0 m a.sl. 500 b.sl. 1000 m b.sl. 1500 m b.sl. 2000 m b.sl. 3000 m b.sl. and, 4000 m b.sl.) are shown and discussed in this research to emphasize the results from 1-D joint inversion. At 0 m a.sl. the low resistivity (10 Ωm) covers the entire map. Then, from 500 m b.sl to 1000 m b.sl, the apparition of intermediate resistivity (30 Ωm) structure is shown on the north part of the map. From 1500 m b.sl to 4000 m b.sl we observe a high resistivity structure (100 Ωm) along the center from north to south, and the low appears on the East and the West of the study area. All the maps show the large resistivity gaps below the vicinity of the fumaroles. This resistivity gap also looks continuously ranged in the N-S direction. It suggests that there is a possibility of the existence of a geothermal structure, such as a fault. So, from that observation, we could estimate that our reservoir can be locate in the North at station 3, or in the center on the stations (7 and 23), or again, the last option is south of the stations (30 and 19) that are close to the sea.

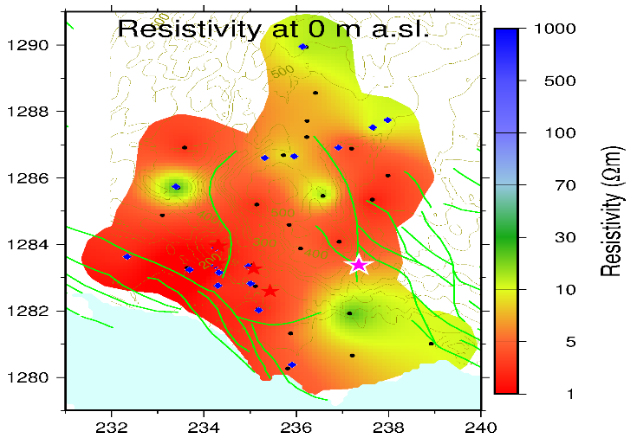

Figure 6 : Resistivity by MT / TDEM 1D joint inversion depth slice at 0 m a.s.l. Black dots and blue square are EM (MT/TDEM) soundings, red and purple star are, fumaroles and hot spring, green line represent the faults.

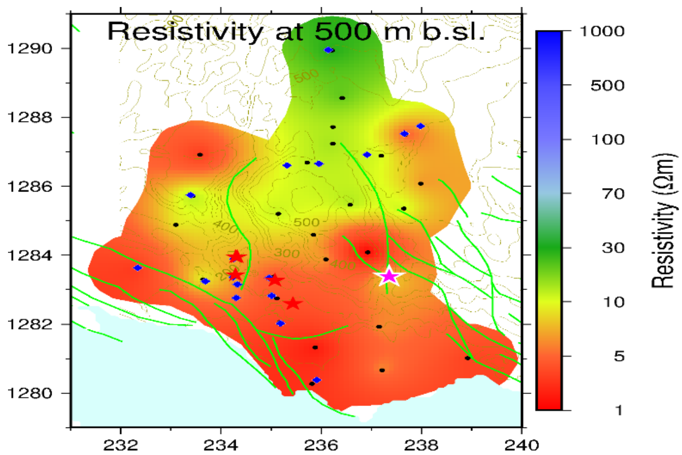

Figure 7 :Resistivity by MT / TDEM 1D joint inversion depth slice at 500 m b.s.l. Black dots and blue square are EM (MT/TDEM) soundings, red and purple star are, fumaroles and hot spring, green line represent the faults.

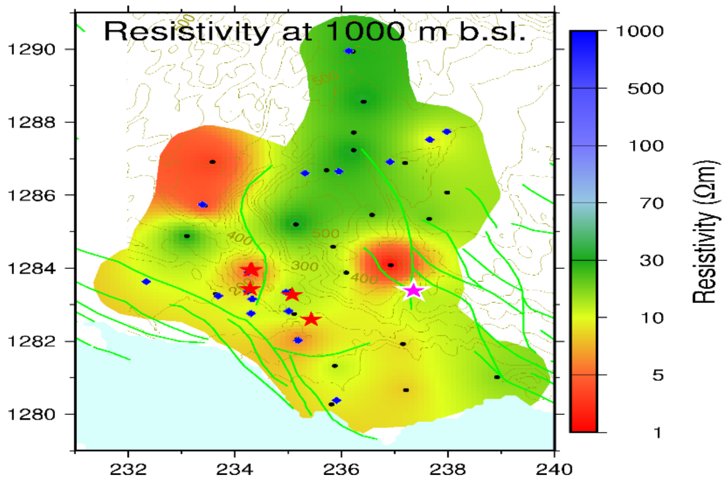

Figure 8:Resistivity by MT / TDEM 1D joint inversion depth slice at 1000 m b.s.l. Black dots and blue square are EM (MT/TDEM) soundings, red and purple star are, fumaroles and hot spring, green line represent the faults.

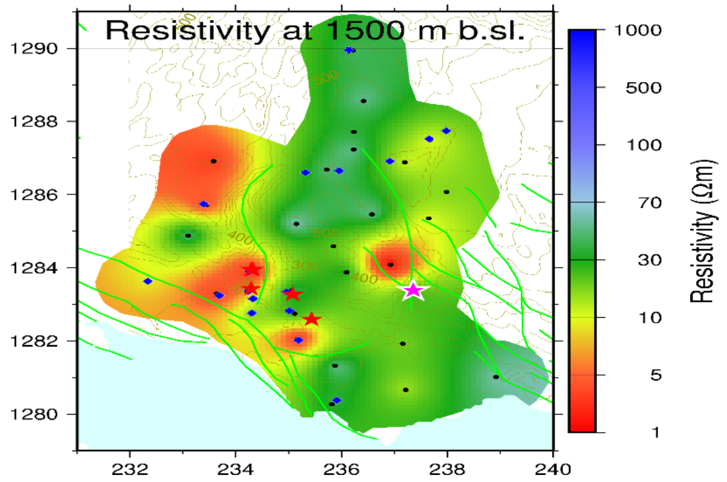

Figure 9:. Resistivity by MT / TDEM 1D joint inversion depth slice at 1500 m b.s.l. Black dots and blue square are EM (MT/TDEM) soundings, red and purple star are, fumaroles and hot spring, green line represent the faults.

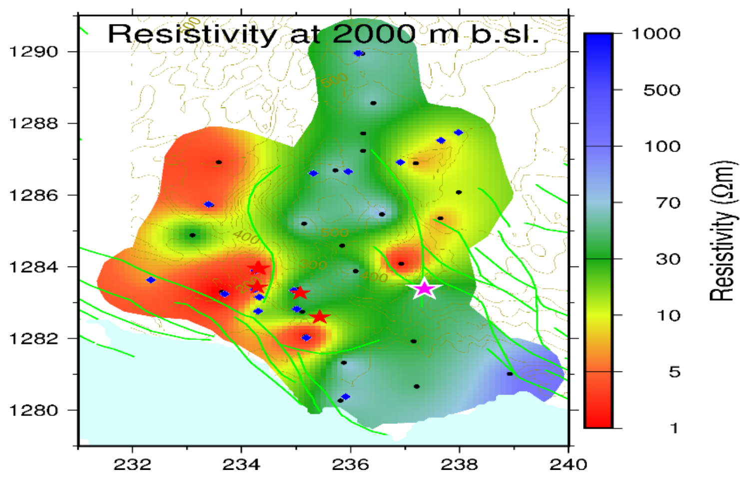

Figure 10:Resistivity by MT / TDEM 1D joint inversion depth slice at 2000 m b.s.l. Black dots and blue square are EM (MT/TDEM) soundings, red and purple star are, fumaroles and hot spring, green line represent the faults.

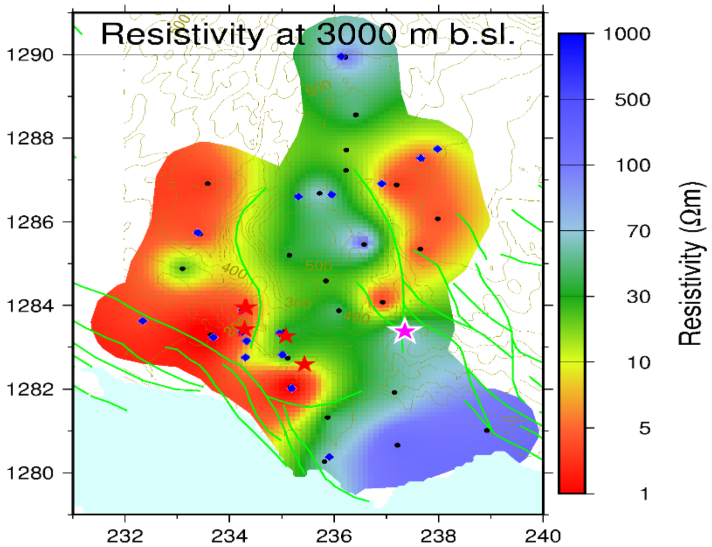

Figure 11:Resistivity by MT / TDEM 1D joint inversion depth slice at 3000 m b.s.l. Black dots and blue square are EM (MT/TDEM) soundings, red and purple star are, fumaroles and hot spring, green line represent the faults.

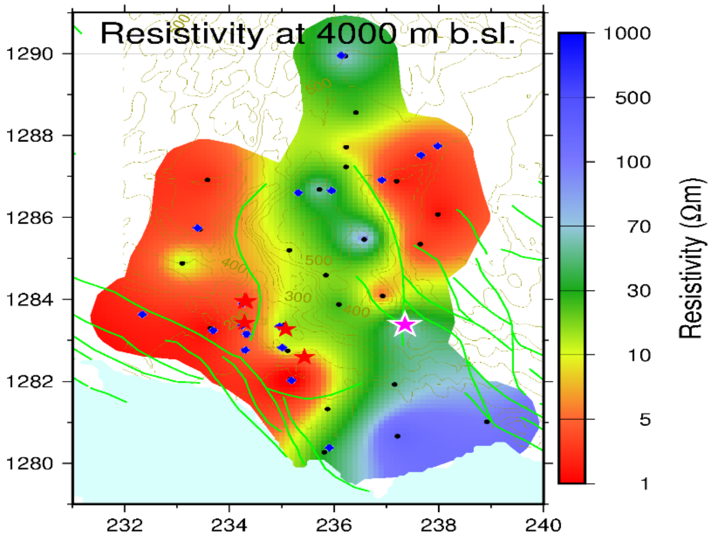

Figure 12:Resistivity by MT / TDEM 1D joint inversion depth slice at 4000 m b.s.l. Black dots and blue square are EM (MT/TDEM) soundings, red and purple star are, fumaroles and hot spring, green line represent the faults.

3.4.2 NS resistivity cross-sections

All the NS resistivity cross-sections from 1 D inversion show high and low, and high resistivity structures especially on the profile PP3, PP4, and PP5 (Figure15). The surface part, where a high resistivity structure is observed, can be explained by the fact that a sedimentary basin is mainly made up of alluvium. The conductive structure occupies the central part of the profile, this central unit could correspond to Dalla basalts, probably altered by hydrothermalism. Below this layer of low resistivity, the resistant structure increases with depth, this structure can be interpreted as a deep reservoir.

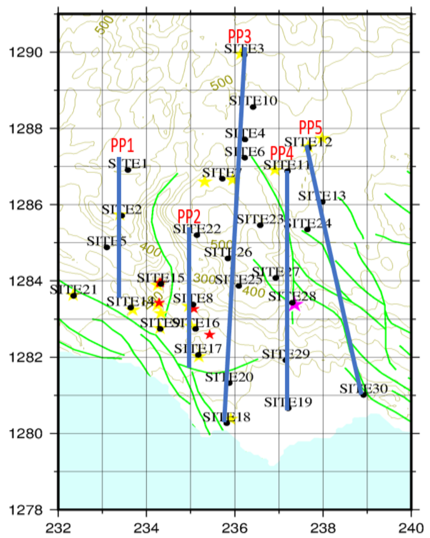

Figure 13:Location map of MT, TDEM soundings, and Gravity station, and surface manifestation. And Layout of NS Resistivity cross sections (PP1 to PP5).

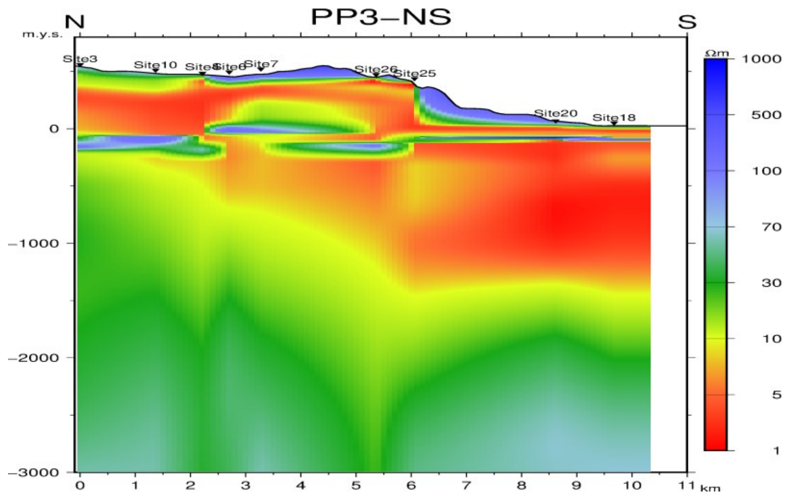

Figure 14:Resistivity by MT / TDEM 1D joint inversion cross section NS from PP3 profile down to a depth of 3000m b.s.l.

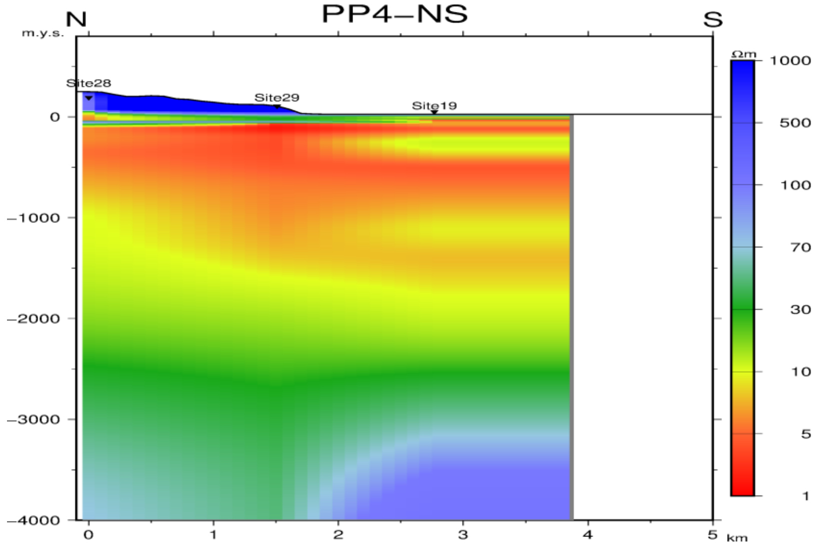

Figure 15:Resistivity by MT / TDEM 1D joint inversion cross section NS from PP4 profile down to a depth of 4000m b.s.l.

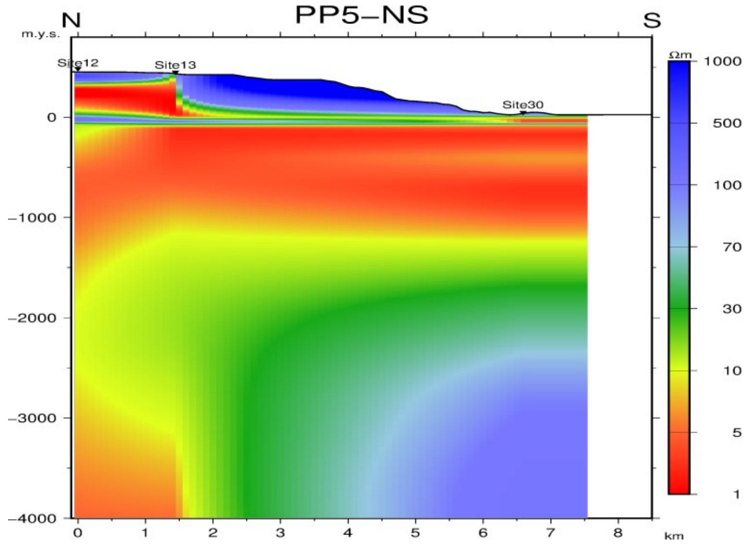

Figure 16:. Resistivity by MT / TDEM 1D joint inversion cross section NS from PP5 profile down to a depth of 3000m b.s.l.

CONCLUSION

The high resistivity layer at the surface can be explained by the fact that a sedimentary basin is mainly made up of alluvium. The conductive structure occupies the part of the near-surface (0-1500m). This conductive unit could correspond to Dalla basalts probably altered by hydrothermalism. Below this low resistivity layer, the resistant structure increases with depth, up to (70 Ωm to 100 Ωm), this resistive structure can be interpreted as a deeper reservoir.

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