1D Inversion Resistivity Structure of the High-Temperature Geothermal System in Arta Prospect, Republic of Djibouti

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ABSTRACT

The region of Arta (Figure 1) is considered as one of the most promising geothermal site in the Republic of Djibouti. A combined Magnetotelluric (MT) and Time Domain Electromagnetic (TDEM) surveys were carried out in February 2018 at the Arta geothermal prospect. On this field, 63 pairs of co-located MT/TDEM soundings were performed. The MT time series were acquired by using two sets of Metronix system. The TDEM data were collected by using a terraTEM system with a coincident loop configuration (100m x 100m). Each MT station was kept running overnight (about 12 to 18 hours each). The MT data from Metronix system were processed using the ProcMT program from Metronix. The TDEM data obtained from the field were processed by Geotools software from General Company of Geophysics (CGG). After processing the data, 1-D resistivity model was estimated from inversion MT data after we have applied a static shift correction to the MT data using TDEM data as reference. The resistivity models from the 1D inversion have been interpolated into vertical resistivity cross-sections (4WE, 3 NS, 2 NW-SE and 2 SW-NE cross sections) and into resistivity maps as function of the depth. All the cross-sections in EW and NS from 1D inversion show a shallow low resistivity (5-10 Ωm) from a depth of 0 to 800m deep and a resistive body below the shallow low resistivity. It suggests that there is a possibility of the existence of a geothermal system. The low resistivity of the rocks has often been considered as a good indicator of the presence of a geothermal reservoir or its clay cap. The underlying resistant bodies at a depth of 2500 m may be more directly associated with the base of the reservoir. An intermediate resistivity zone (20-40 Ωm) is observed between the deep resistive body and the shallow conductive body. This intermediate resistivity is interpreted as the geothermal reservoir. The general increase in resistivity as a function of depth is interpreted as an indication of a typical high temperature geothermal system. This will mean that the resistivity values are controlled by the types of alteration, fluid content, and temperature. In this case the shallow low resistivity is due to alteration into smectite, highly conductive clay that forms at more than 50 degrees Celsius. The low resistivity layer forms the cap-rock for the geothermal system. The resistivity values below the fumaroles vary significantly laterally irrespective of depth. This suggests the existence of flow paths of the geothermal fluids close of fracture zones or a high permeability fault zones that extend from deep to below the fumaroles.

1. INTRODUCTION

The Arta prospect study (Figure 1) was financed by GRMF and supervised by the Japanese consulting company; Nippon Koei, JMC (Japan Metals and Chemicals) Geothermal Engineering, and Sumiko Resources Exploration and Development. The study was conducted to estimate the potential of geothermal resources and prepare further development plans. The evaluation of the geothermal potential was carried after the interpretation of geology, geochemistry and geophysical data. Based on the geological and geochemical results, basaltic volcanic rocks are mainly distributed in the area and rhyolitic rocks are intercalated. Some of rhyolitic rocks are observed as lava domes and hyaloclastite, which indicates in-situ volcanism at submarine environment. N-S and NNW-SSE faults and fractures are dominant in this area. Alteration zone was identified; mordenite was mainly observed with clinoptilolite, heulandite and analcime. Smectite is common and, mixed-layer and chlorite were also identified. It was considered that the area is classified as mordenite-clinoptilolite alteration zone. In few areas, chlorite was partly observed at greenish-altered rhyolitic rock. It indicates the trace of hydrothermal alteration zone and maximum temperature is assumed as 200-250C. There are few fumaroles in a limited area. There are no obvious clues of contribution of geothermal fluid to the chemistry of spring waters in the area. An upflow zone or a permeable flow path of geothermal fluid is postulated to occur around the active fumaroles. It might be said that a well-developed cap rock layer prevents upflow of geothermal fluid from an assumed geothermal reservoir to the surface. The fumarolic gas effused from the surface consists mainly of the atmospheric components and the geothermal steam is small. But the chemical composition of the fumarolic gas included mantle origin components. It suggests that the magmatic heat source exists in the deep area and the magmatic fluid is rising up to the surface.

The main for this paper is to delineate with MT/TEM survey the lateral and depth extensions of such potential reservoirs and show the correlation between resistivity structure and the geological and geochemical results.

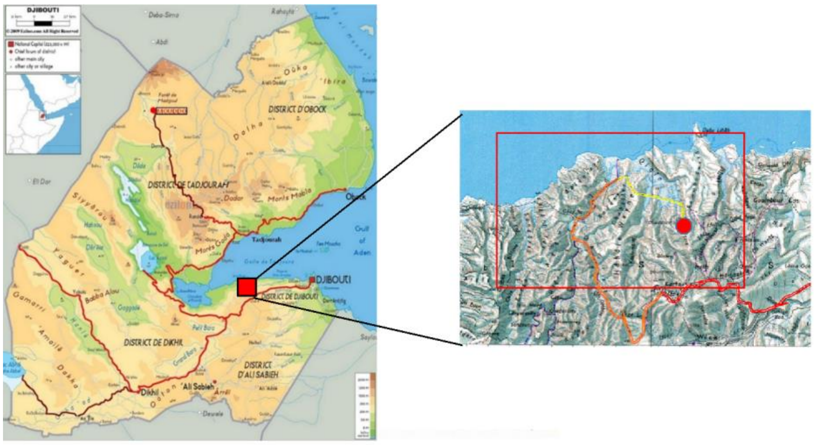

Figure 1: Location of Arta survey

2. DATA ACQUISITION

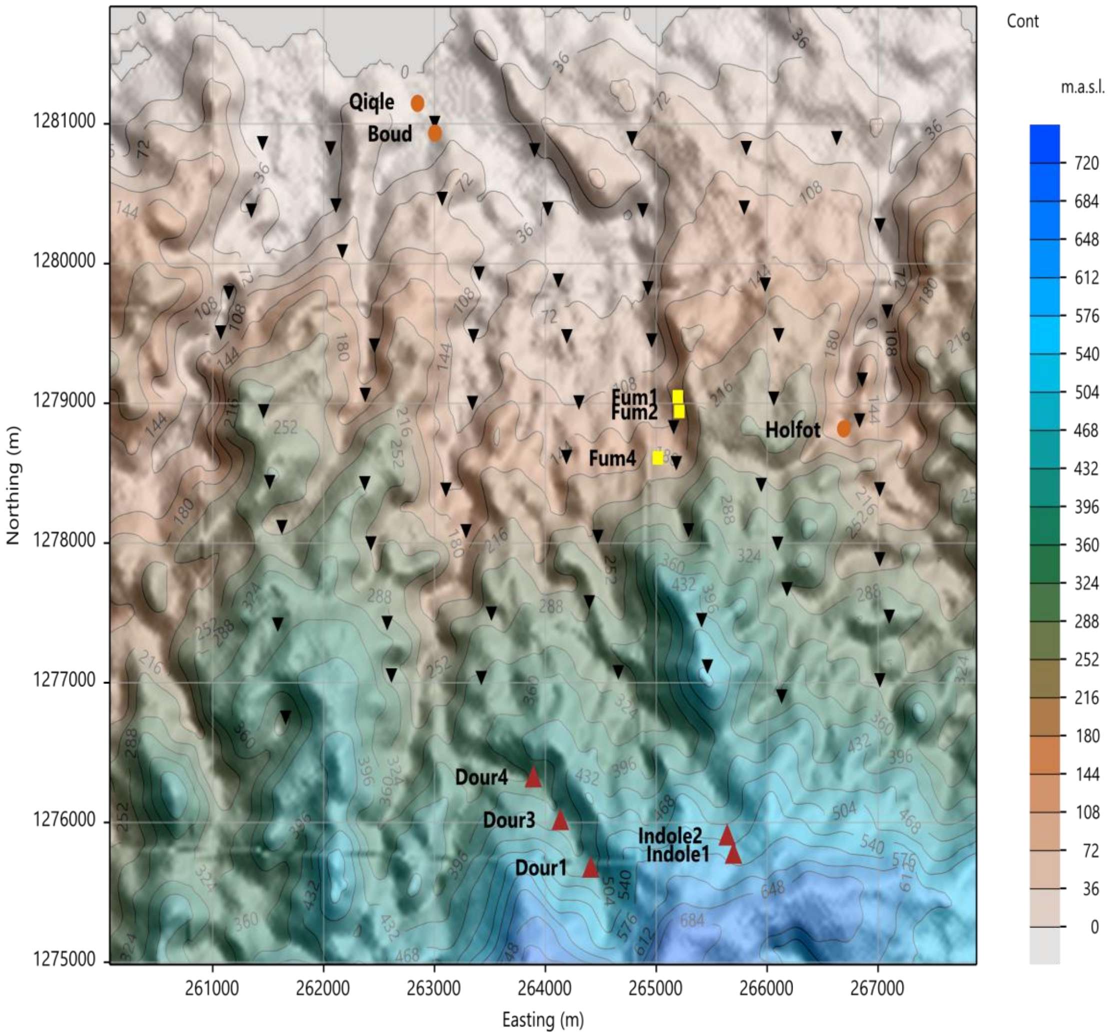

Figure 2: Location of the MT and TDEM soundings black triangle, Yellow Square for fumaroles, Brown triangle for spring and circle for water well

A combined MT and TDEM (Figure 2) surveys was conducted from February to October 2018 by ODDEG. On this field, 63 pairs of MT/TDEM soundings were performed. The procedures applied for the acquired MT and TDEM data are described below.

2.1 Magnotellurics Data (MT)

The working principle of MT is based on electromagnetic induction and in our case we measure simultaneously on the surface of the subsoil the two components of the natural or telluric electric field (Ex and Ey) and natural magnetic field (Hx, Hy and Hz) (Figure 2). By using Maxwell's equation, the two characteristic parameters of MT sounding (the apparent resistivity and the associated phase (Figure 4)) are obtained by the determination of the impedance tensor.

For the acquisition of MT data, two ADU-07e type acquisition systems (Metronix) were used for the collection of MT data. The sensors used to collect MT data are three magnetometers to measure the three components of the magnetic field and two dipoles (each consisting of two non-polarizable electrodes) to measure the electric field. The data collected in the field are in the form of time series sampled according to four frequencies 4096, 2048, 256, 32 Hertz respectively of 2 min, 5 min, 30 min and from 8 h to 24 h of measurement time. Figure 2 and 3 shows the measurement configuration of an MT survey and the data acquisition in the field, respectively.

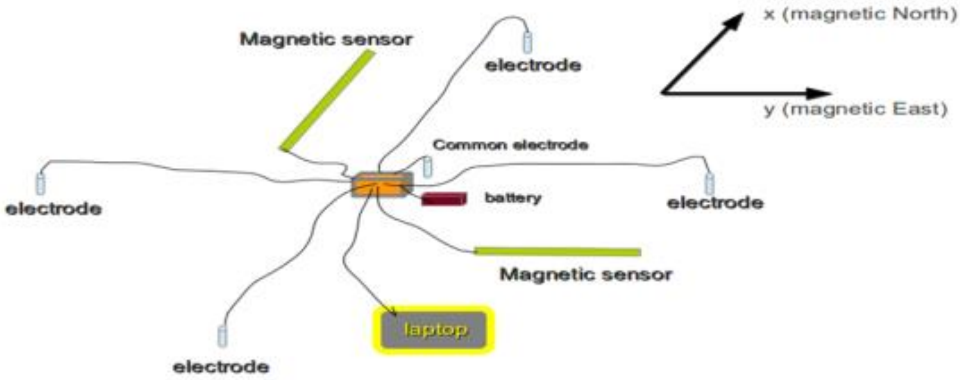

Figure 3: Measurements configuration

Each MT station was kept running overnight (about 12 to 18 hours each). The obtained MT data were processed using the ProcMT. The quality of the MT data is good and the range of apparent resistivity is between 10^3Hz and 10^{-3}Hz (Figure 4).

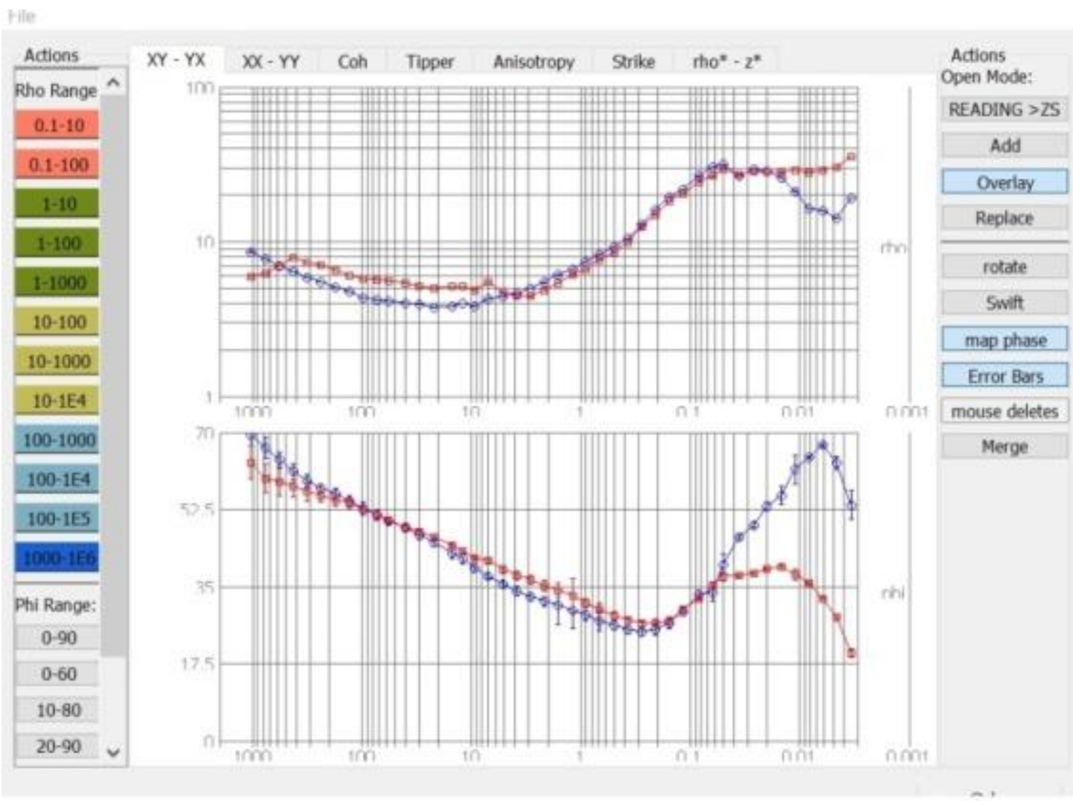

Figure 4: Result of ProcMT processing, apparent resistivity up and phase down

2.2 Time Domain Electromagnetic Data (TEM)

TDEM surveys were conducted with the Terra TEM acquisition system. The configuration used for this data collection is the "coincident loop" type, which consists of choosing a transmission loop and a reception loop of the same dimensions (100mx100m square) coincident but slightly offset one in relation to the other. For each survey and each configuration, we recorded two types of time series (High resolution and medium resolution) and for each resolution we made 6 measurements (2 measurements with gain 64, 2 measurements with gain 16 and 2 measurements with gain 2). The acquisition of TDEM data realized by electromagnetic induction (Fig. 5) produced by the sudden interruption of the electric current in the transmitter loop or the static magnetic field (Goldman, 1994; Spies and Frischknecht, 1991). This static field, or "primary", is established on the surface by the emission loop in which a direct electric current flows (the emission loop). The sudden cut of this current induces an electromotive force (fem), which generates in the ground a circulation of electric current (Foucault current) whose lines follow a geometry similar to that of the emission loop (Nabighian and Macnae, 1991 ; McNeill, 1994).The obtained TDEM data were processed by Geotools software from General Company of Geophysics (CGG). The program calculates averages and standard deviations of repeated transient voltage measurements and calculates apparent resistivity as a function of time.

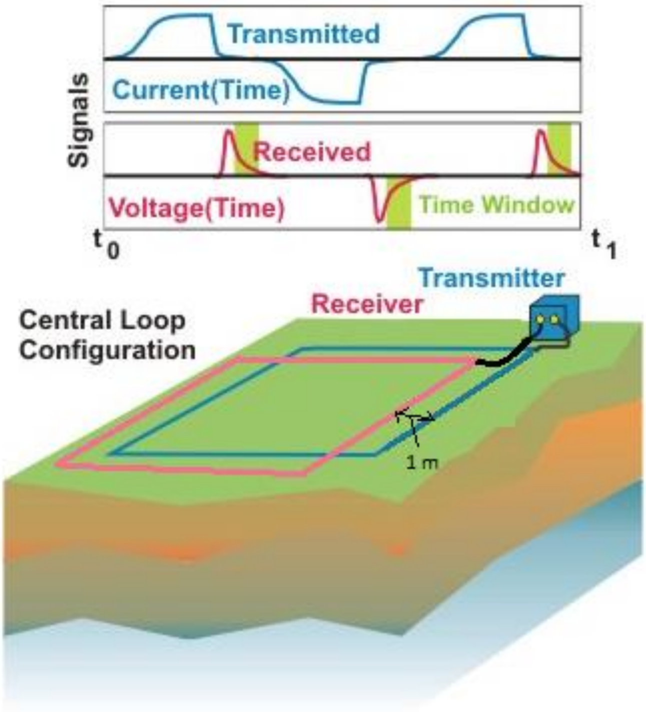

Figure 5: Principle of measurement of TDEM surveys

3. DATA INTERPRETATION

3.1 1D Inversion

After processing the data, 1-D resistivity model was estimated from inversion for MT data after we have applied a static shift correction to the MT data using TDEM data as reference. It is in order to correct the static shift phenomena that affect MT apparent resistivity in the high frequency (Arnason 2015). The 1-D inversion method adopted in this report is with Geotools from General Company of Geophysics (CGG). It consists to fit apparent resistivity and phase from each sounding by the response of models with many layers with constant thicknesses, increasing exponentially with depth. The unknown parameter that is determined in this procedure is the true resistivity in the subsurface.

The resistivity models from the 1D inversion have been interpolated into vertical resistivity (Figure 8,9,10 and 11) cross-sections (4 WE , 3 NS ,2 NW-SE and 2 SW-NE cross sections figure 6) and into resistivity maps as function of the depth (Figure 7). A few resistivity cross sections and maps will be shown and discussed specifically in this report to emphasize the main results of the 1D inversion.

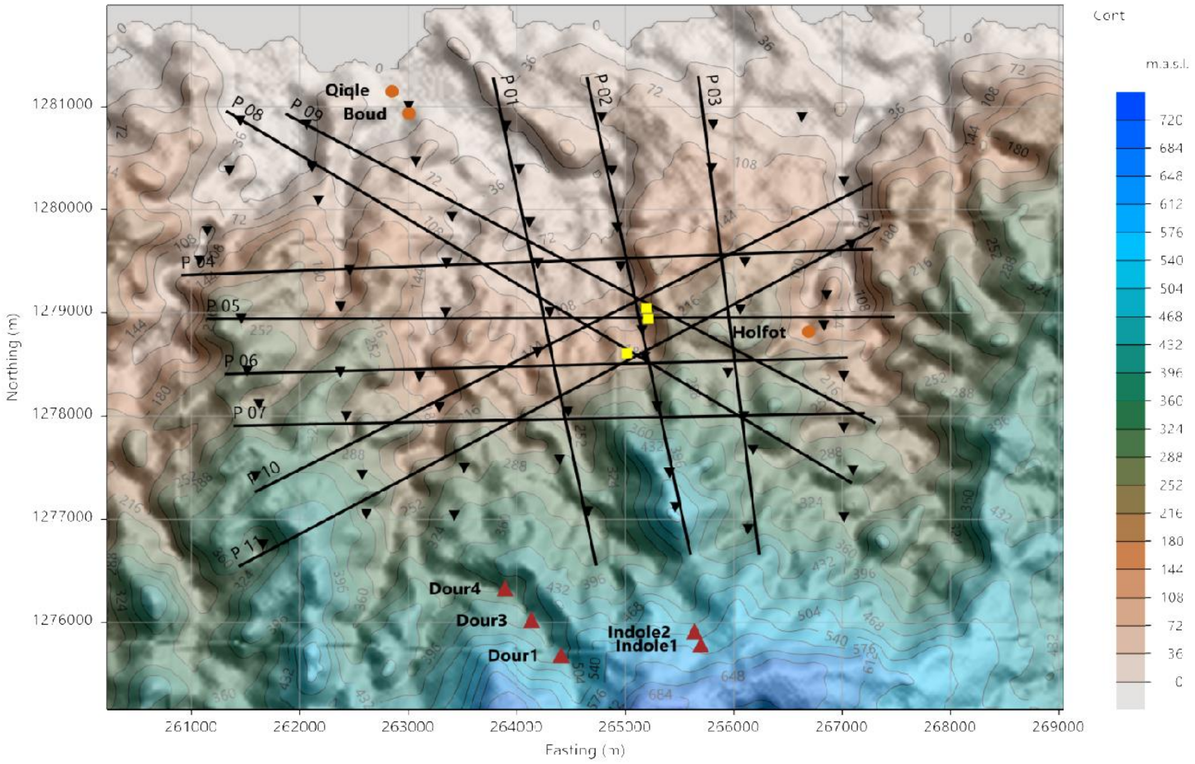

Figure 6: Profile of cross-section: P01, P02, P03 for NS; P04, P05, P06, P07 for WE; P08, P09 for NW-SE and P10, P11 for SE-NW.

3.2 Resistivity slices

The resistivity structures estimated from the 1D inversion ware compiled and interpolated into resistivity depth slices. Six depth slices (Figure 7) are shown and discussed specifically in the report to emphasize the results from 1D inversion. The 100 m and 500 m b.s.l maps show the low resistivity in the West, East, and North and below existing fumaroles. The 1000 m and 2500 m maps also show the intermediate resistivity. All the maps show the large resistivity gaps below the vicinity of the fumaroles. This resistivity gap also looks continuously ranged in N-S direction. It suggests that there is a possibility of the existence of a geothermal structure, such as a fault.

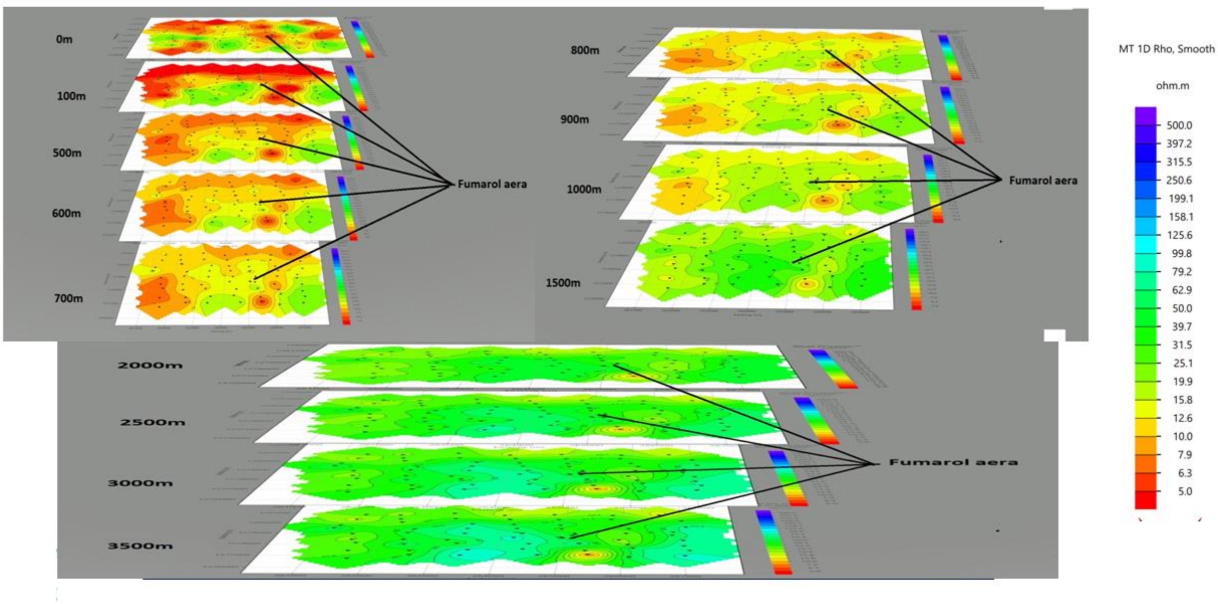

Figure 7: Resistivity by MT / TDEM 1D inversion depth slice at 0 m b.s.l to 3500 m b.s.l.

3.3 WE resistivity Cross-sections

Figure 6 and 8shows the location map of the WE resistivity cross sections. In this study, the following WE resistivity cross sections from 1D inversion are considered: P04, P05, P06 and P07. All WE Profiles from 1D inversion shows a heterogeneous medium in the first 800 meters with resistivity varying between 5 and 70 Ωm. Above sea level, the resistivity model shows resistive units (40-80 Ωm) that probably correspond to unsaturated volcanic rocks. However, at these depths (> 0 m), there are also conductive anomalies underlying the shallow resistive formations. These conductive units may be associated with sedimentary intercalations that are sometimes observed in outcrop in the study area along the Wadi. We also observe two conductive bodies below sea level with resistivity less than 10 Ωm and a thickness between 400 and 800 m. One is lying at the west of the profiles (P5 and P6) and the other at the east of the profile (P05 and P06) below the fumaroles. These conductive anomalies can be associated with permeable and saturated volcanic formations. Given the presence of fumaroles below of the conductive unit to the east, this aquifer may be thought to be warmed by the presence of an underlying reservoir. In Deep (> 1000 m), all WE profiles show a resistive homogeneous medium (~ 30 Ωm) which is being up to 2500 m. From 3000 m, it appears a very resistive anomaly (90 Ohm.m) that appears to be discontinuous in 1D resistivity model. All WE profiles show a resistivity ranging from 20 Ωm to 40 Ωm at 1000 m to 2500 m deep. It might be supposed that there is a possibility of the existence of a geothermal reservoir in these depths. In the profile P05 and P 06, a conductive body like a dyke could be observed below the resistive zones to 6000 m of depth. This conductive body is continuously observed on the other profiles P 04 and P 07 up to 3000 m deep. This dyke shaped body could be interpreted as a heat ascending through a fault and feeds to the fumaroles or a high permeable zone which path the geothermal fluid in NS elongated fault.

3.4 NS resistivity cross-sections

Figure 6 and 9 shows the location map of the NS resistivity cross sections. In this report, the following NS resistivity cross sections from 1D are considered: P01, P02 and P03.All NS profiles show us the same observations with WE profiles. Except that for the NS profiles the low resistivity has a large thickness reaching the 1000 m depth to the North and thinner towards the South. The NS profiles are parallel to the main faults, it is also the paths by which the water infiltrates, to the North we have the infiltration of the seawater which dominates and to the South the infiltration of the meteoric water which has low precipitation due to low of rain, it is for this reason that the resistivity get lower towards the South. Regarding the resistivity change in the depth direction, the 1D inversion result shows the same tendency in all NS and WE cross sections. At the northern area of all cross-sections, the low resistivity body (less than 10 ohm-m) appears in the shallow area, and it can be considered to the intrusion of seawater.

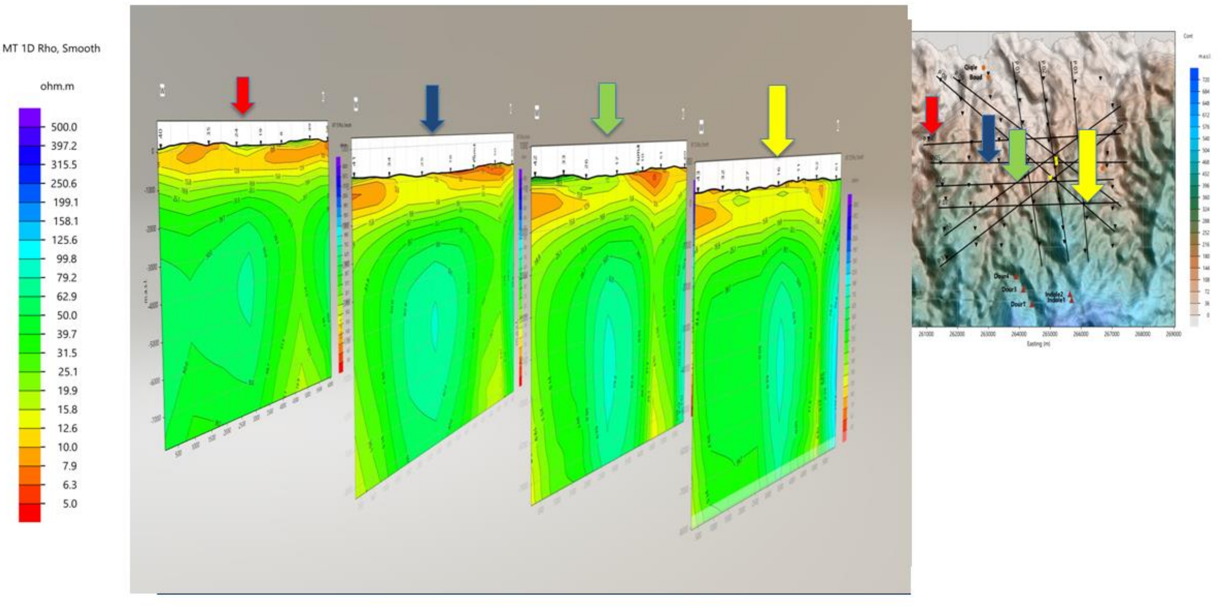

Figure 8: Resistivity by MT / TDEM 1D inversion cross section WE from P04, P05, P06 and P07 profile down to a depth of 8000 m b.s.l.

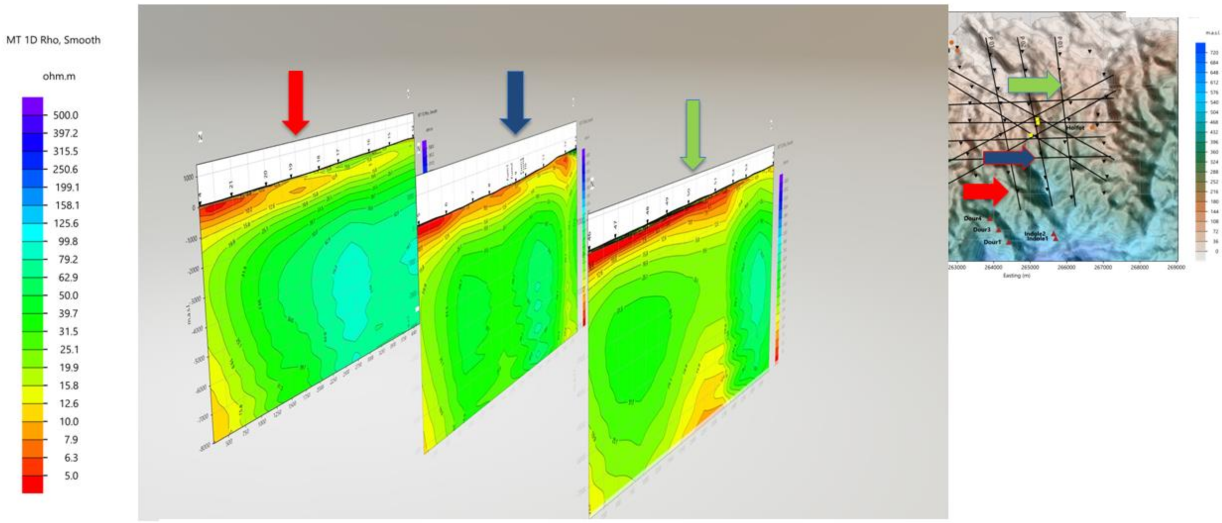

Figure 9: Resistivity by MT / TDEM 1D inversion cross section NS from P 01, P02 and P03 profile down to a depth of 8000 m b.s.l.

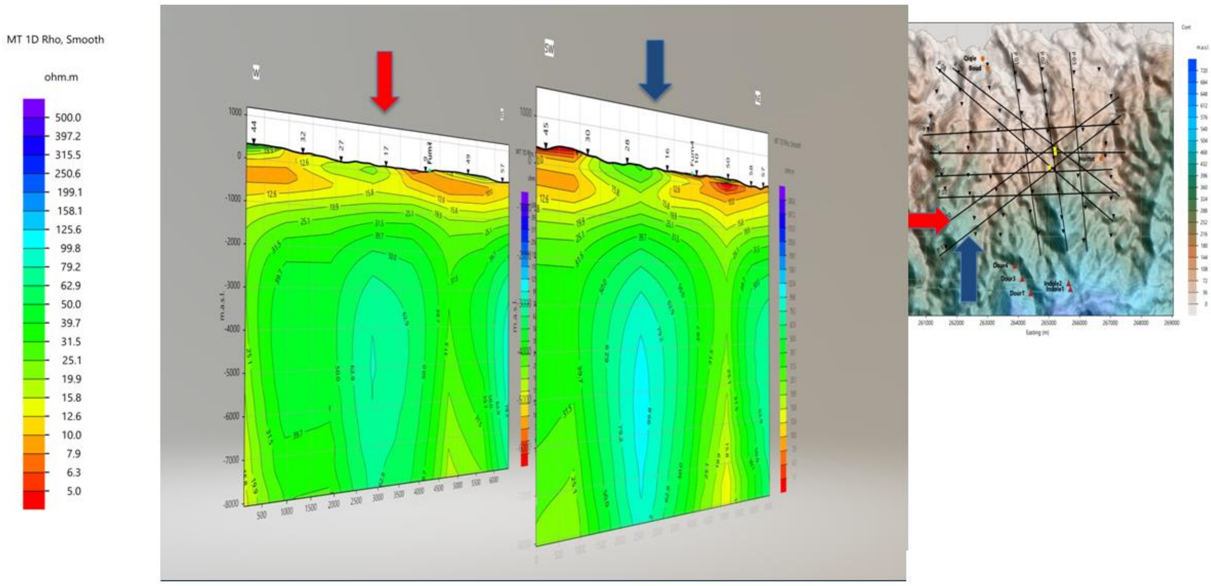

Figure 10: Resistivity by MT / TDEM 1D inversion cross section SW-NE from P10 and P11 profile down to a depth of 8000 m b.s.l.

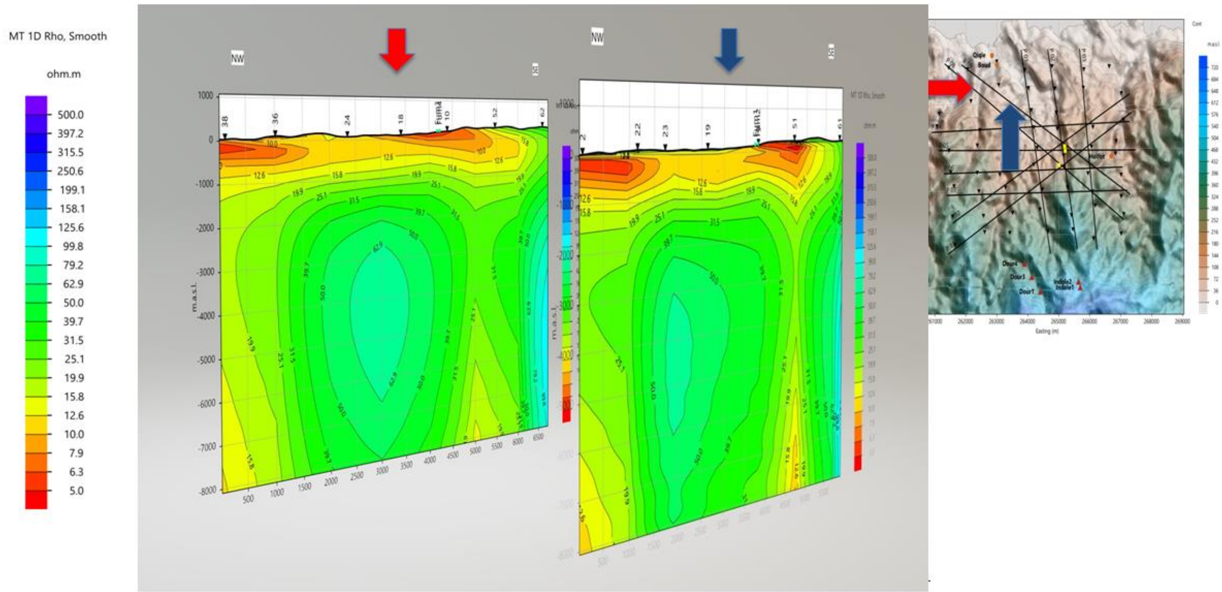

Figure 11: Resistivity by MT / TDEM 1D inversion cross section NW-SE from P09 and P09 profile down to a depth of 8000 m b.s.l.

4. DISCUSSION

All the cross-sections from 1D inversion show a low resistivity (0- 800m deep) zone near the surface and a resistive body in the deep area. It might be suggested that the presence of a geothermal system. The low resistivity of the rocks has often been considered a good indicator of the presence of a geothermal reservoir or its clay cap. The underlying resistant bodies below2500 m deep may be more directly associated with the basement of reservoir. An intermediate resistivity zone (20-40 Ωm) can be observed between the resistive body in a deep area and the conductive body in shallow area. This intermediate resistivity may be associated with the reservoir; the length and width are estimated approximately 3.0 km and 1.3 km. Next, based on the gap of resistivity by the MT/TEM survey, we assumed that reservoir thickness is 1.0km. Under these assumptions, reservoir volume is estimated 3.9 km3 .We generally observe an increase in resistivity as a function of depth, which may mean that we are probably in the presence of a typical geothermal system. This will mean that the resistivity value is controlled by the types of alteration, fluid content, and temperature. In this case the low resistivity in the most superficial zones could be matched by an alteration in smectite, highly conductive clay that forms at more than 50 degrees Celsius and which gives a cap-rock. Intermediate resistivity result in the process of appearance of minerals becoming more and more resistive (Anderson and al 2000). Also, the resistivity values below the vicinity of the fumaroles (figure 10 and 11) are varying significantly in horizontal direction irrespective of depth. It suggests that the existence of the flow path of the geothermal fluid (a fracture zone or a high permeability zone in the fault) continuing from the deep area to below the fumaroles.

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