Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Geophysical Study of the North Ghoubet Geothermal Prospect

Salahadine Mahamoud, Nasradin Ibrahim and Hassan Magareh

Djiboutian Development Office of Geothermal Energy (ODDEG), Under Presidency, P.O. Box 2025, Djibouti

mahamoudhassansalahadine@gmail.com, kilqijoka2001@yahoo.fr and hassan_med2@yahoo.fr

Keywords: Nord Ghoubet geothermal prospect, magnetotellurics (MT), 1D model structure, Bouguer anomaly.

ABSTRACT

As part of the development of renewable energy, especially geothermal energy, a vast program of multidisciplinary studies carried out on the North Ghoubet prospect. This site is located in the central part of the Republic of Djibouti, north of the Bay of Ghoubet Al Kharab, between Lake Assal and the Gulf of Tadjourah. The CERD (Center for Research and Studies of Djibouti) has just carried out a prefeasibility study for the geothermal site located north of the screen, which presents tectonic effects of the Assal rift, structures of Makarassou and structures from ancient tectonics. This site is close to the sites of Asal-Fiale and Galé-le-Coma. This site presents normal NNW-SSE and WNW-ESE faults and N-S erosion corridors, with Wadi descending in the Goda Mountains (1799 m). The purpose of the geophysical survey was to delineate the boundaries of the geothermal reservoir. This site has hydrothermal features such as hot springs and fumaroles on normal faults. Surface and sub-surface surveys have already been carried out in this area in 1979, 1980 and 1982 as part of a geothermal reconnaissance survey by gravimetric, electrical and audio-magnetotelluric (AMT) surveys. In 2010, the geophysical campaign conducted by the CERD team carried out 30 magnetotelluric (MT) and 26 electromagnetic time domain (TDEM) soundings. Residual anomalies from a Bouguer map established by the BRGM (1993) provide information on three negative anomalies. After these geophysical studies, three areas of geothermal interest from about 1000 m. These areas are at the top of the Moudoueoud horst, southeast of the prospect and at the foot of the south-west.

1. INTRODUCTION

The North Ghoubet site is one of the 23 sites of the Republic of Djibouti which have a geothermal potential. It is located in the central part of the Republic of Djibouti, north of the Bay of Ghoubet Al Kharab, between Lake Assal and the Gulf of Tadjourah. The first geophysical survey was carried out in 1982 by the geophysical department of the Geological and Mining Research Bureau (BGRM), and the Center for Study and Research of Djibouti (CERD) which was known at that time as ISERST. In 2010, a geophysical study was carried out by CERD to prove the geothermal potential of the North Ghoubet prospect. During this geophysical campaign, 30 MT and 26 TDEM surveys were conducted. A recent study was started towards the end of April 2019 on this geothermal prospect. The purpose of this study is to cover the study area well to have a better multidimensional approach when interpreting. This paper presents the results of the geophysical survey (MT/TDEM) from the year 2010.

2. GEOLOGY AND STRUCTURE

2.1 Geological Context

Djibouti is located in the area called the Afar Depression which is interpreted as a crustal extension region. This zone results from the separation of the Arabian and African plates. The areas of accretion arising from this separation are the Gulf of Aden and the Red Sea. The propagation of these two axes of accretion, initiated towards 10 Ma (Gulf of Aden) and 6 Ma (Red Sea) (Cande and Kent, 1992, 1995), is carried out according to two quasi-orthogonal axes, in limits of three lithospheric plates (Arabia, Nubia and Somalia) (Tazieff et al., 1969; Barbéri et al., 1970; Stieljes, 1973). These two axes converge and interfere since 3 Ma at the Afar depression where they connect to the South West, to the Ethiopian East African Rift segment to form a kind of triple junction (McKenzie, 1970) (Figure 1).

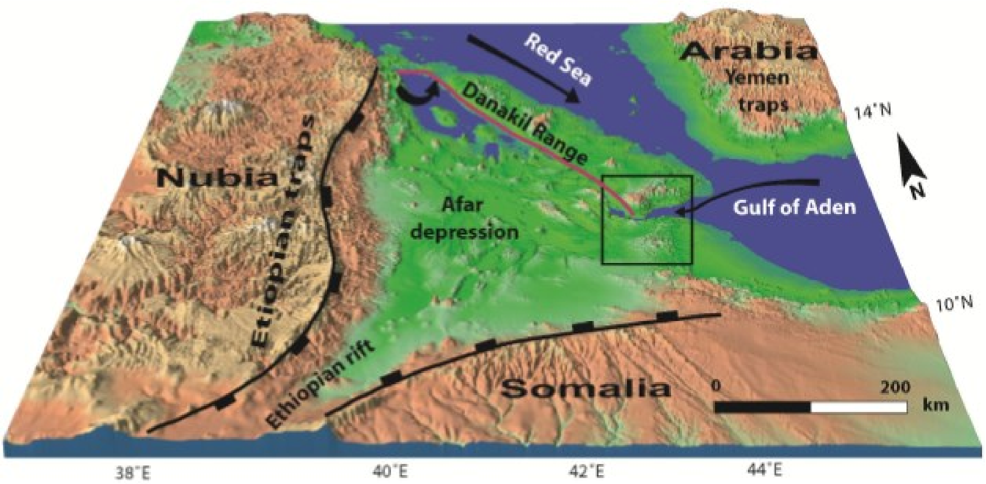

Figure 1: Digital Terrain Model (Gtopo30) of the Afar Triangle. The red line underlines the western boundary of the Danakil "block". The black square indicates the Republic of Djibouti.

The whole of the Afar depression (Barbéri and Varet, 1977) is covered by stratoid basalts, thus partially masking the witnesses of the early stages of rifting whose main manifestations are currently exposed in the basaltic traps of the Ethiopian plateaus (~ 30Ma (Hoffman et al., 1997)) and Yemenites (31-26 Ma (Baker et al., 1996)) (Figure 1), associated with Afar plume recovery.

Located in the SE of the Afar depression, the Republic of Djibouti has been at the center of the important tectono-magmatic activity since the period. We thus find there all the stages of the processes which were accompanied by the formation of the depression for the producing the volcanic series.

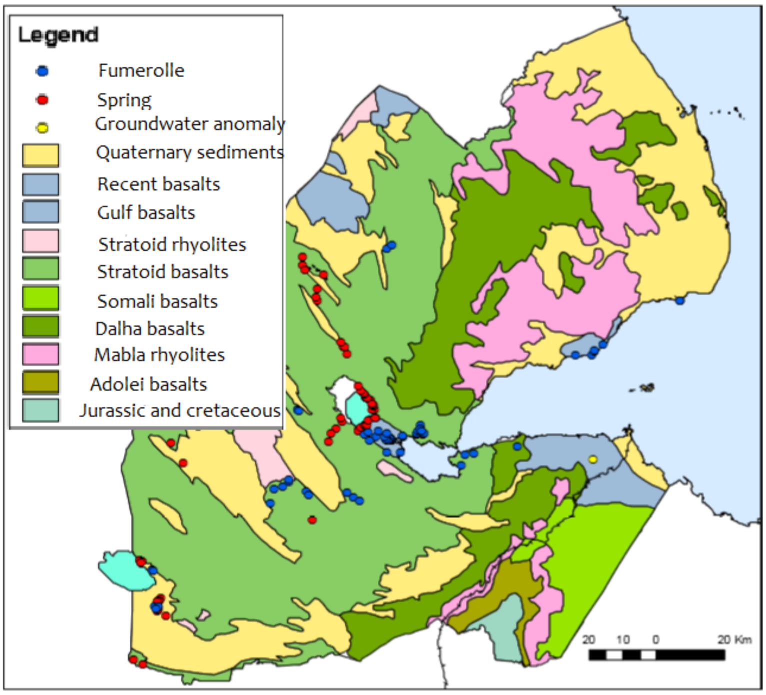

Figure 2: Simplified geological map of the Republic of Djibouti.

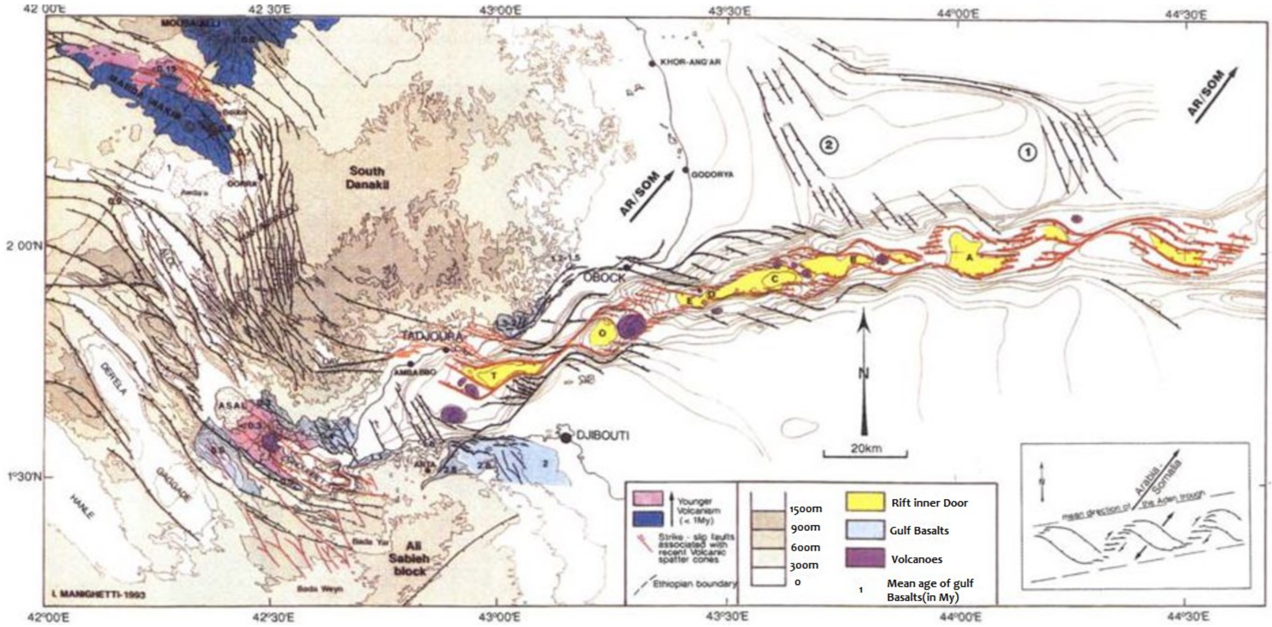

Figure 3: Rift segments of the western part of the Aden Ridge, nearby and within the Afar depression. Tectonic structures are determined from bathymetric and magnetic data at sea, and topographic and morphological data.

2.2 Morphostructure of the Study Area

The overall morphostructural organization of the study area is derived from the analysis and interpretation of Landsat satellite imagery and the ASTER Digital Terrain Model (DEM). The topographic elevation of the region varies from 0 to 560 m on average. The maximum altitude is at the level of the Moudoueoud relief which forms a horst limited by normal N 170° E faults and currently notched Afay wadis in the West and Analé in the East. These wadis provide beautiful geological cuts. The Analé wadi is a reference section where the 2D geometry and the stratigraphy of magmatic complexes associated with sedimentary levels can be observed on verticals more than 100 m high. The whole area is structured by normal faults oblique to the direction of the extension. These faults delineate structural blocks collapsed to the south. A major escarpment N 140° E delineates the volcanic structures of the Asal rift towards the south (Figure 4).

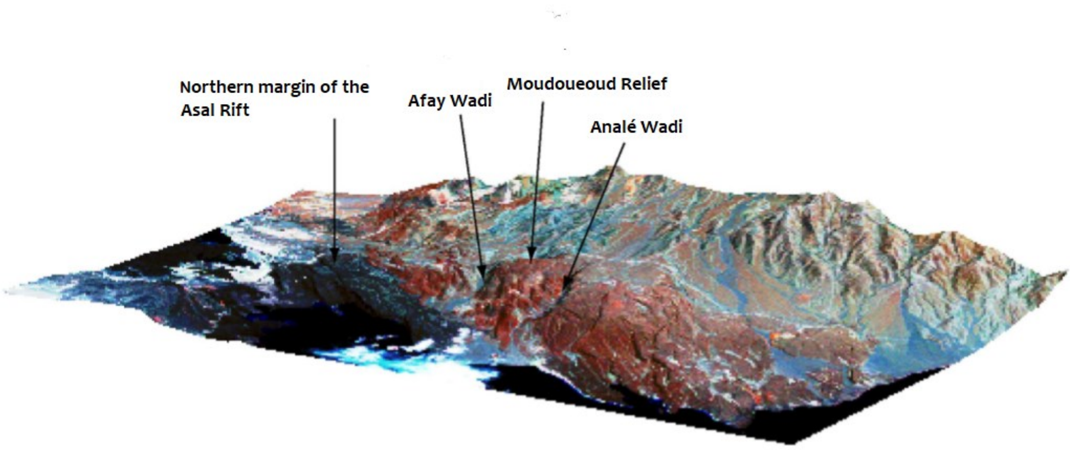

Figure 4: 3D view of the study area obtained by the Landsat image overlaid on MNT Aster.

3. GEOPHYSICAL SURVEY

3.1 Electromagnetic Method

3.1.1 The Magnetotelluric Method (MT)

Magnetotellurics is a passive geophysical method that measures the variation of the natural electromagnetic field along orthogonal directions from the surface of the Earth to obtain an image of the variation of the resistivity under the surface. The MT method is based on the measurement of the currents induced in the ground by the temporal variations of the terrestrial magnetic field. The time-varying magnetic field and the associated electric field generated in the subsurface are measured simultaneously. The components of magnetic (Hx, Hy, Hz) and electrical (Ex, Ey) fields are measured on the Earth's surface along two orthogonal directions. High frequencies give information about the resistivity at shallow depths while low frequencies provide information about deeper structures. The measured time series are transformed into Fourier harmonic components for different periods. The harmonic components of the electric field are related to the magnetic field by what is called the impedance tensor, which depends on the resistivity of the subsoil. For short periods, the tensor depends mainly on the surface resistivity structures, but for long periods it mainly depends on deep resistivity structures. The MT method has the greatest depth of exploration of available for EM methods, a few tens of kilometers (Simpson and Bahr, 2005) up to a hundred kilometers away and is practically the only method available to study deep resistivity structures particularly in volcanic environments.

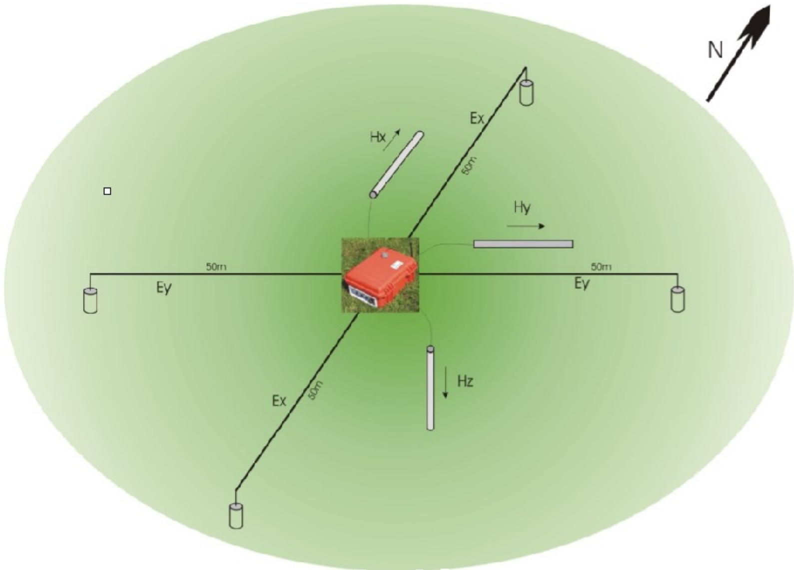

Figure 5: Measuring device for a magnetotelluric sounding.

3.1.2 The Electromagnetic Method in the Time Domain (TDEM)

The TEM method, also called the electromagnetic method in the time domain (TDEM), is a geophysical method that makes it possible to conduct an electrical resistivity probing from a device consisting of one (or more) loop(s) of electric cables. This prospecting technique, which allows a depth of investigation of a few hundred meters, is used to correct the static shift phenomenon caused by the heterogeneities of resistivity near electric dipoles. The static shift only affects the apparent resistivity in the near surface. The TDEM sounding is realized thanks to the electromagnetic induction produced by the abrupt breaking of the electric current in the emitting loop or the static magnetic field. This static field, or "primary", is established on the surface by a loop of cable in which a continuous electric current flows (the transmission loop (Nabighian and Macnae, 1991)). The abrupt breaking of this current induces an electromotive force (emf), which induces a current in the ground (eddy current) whose lines follow a geometry similar to that of the emission loop. The intensity of these currents decreases more rapidly for formations with higher resistance. These electric currents called eddy currents in turn generate a secondary magnetic field. The decay of this secondary field is measured by another loop called the receiving loop. The response of the subsoil is contained in this secondary magnetic field induced by eddy currents.

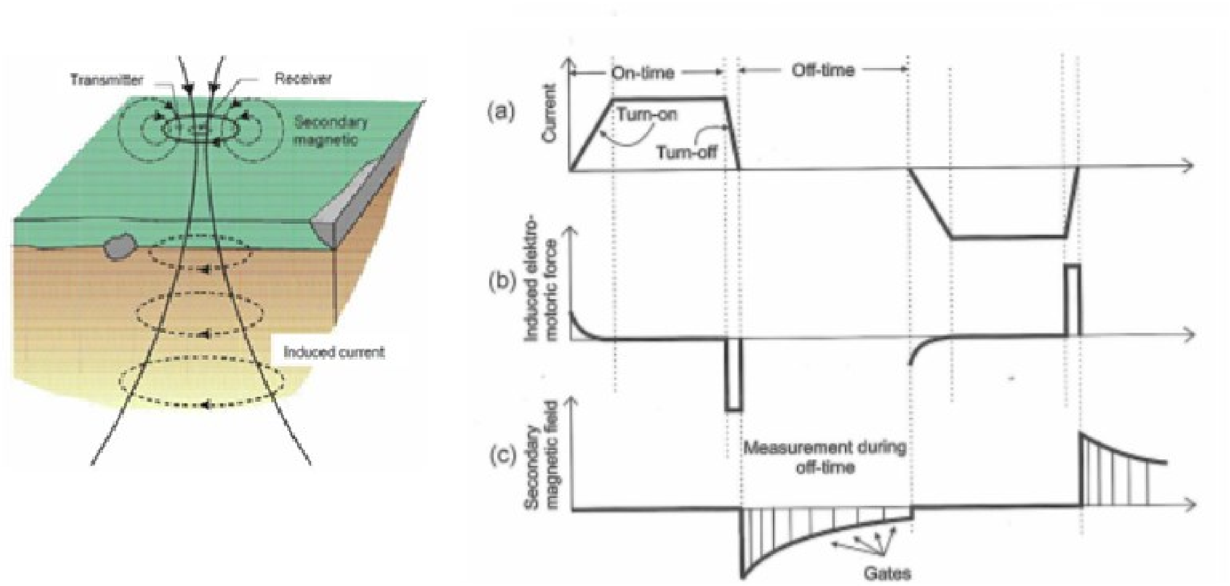

Figure 6: Measurement principles of a TDEM sounding.

<u>3.1.3 Data Acquisition of MT/TEM Soundings</u>

A geophysical campaign for the geothermal prospect of Nord Ghoubet was carried out from March 3 to October 28, 2010 and from February 6 to 16, 2011. The goal of the campaign was to obtain the maximum of surveys to prove the existence of the geothermal reservoir. During this campaign, 30 MT surveys and 26 TDEM surveys were measured. MT data were recorded with 3 types of sampling frequencies (2048, 256 and 128 Hertz). For the TDEM method, we used the so-called "coincident loop" configuration, that is to say that we deployed a transmitting loop and a receiving loop of the same dimensions (100×100 m) but shifted slightly relative to the other.

For the MT method, the equipment used in this study is a Metronix system with an ADU-06 type data logger, MFS-07e type magnetometers to measure magnetic field induction and EFP-06 type electrodes to measure the electrical component of the electromagnetic field. In TDEM, we used the TerraTEM system.

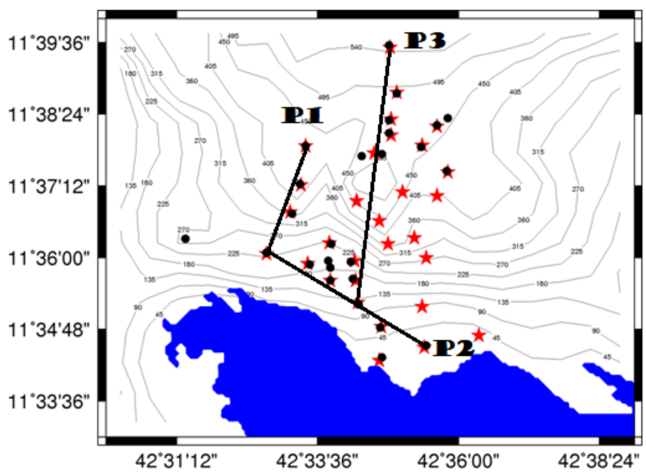

Figure 7: Location map of the MT (red stars) and TDEM (black dots) stations with the three profiles on the North Ghoubet prospect.

<u>3.1.4 Processing and Interpretation of MT Data</u>

To determine the change in apparent resistivity and phase of MT data, we used the ProcMT program. This program first allows the passage of data in the time domain to the frequency domain. Then, it calculates the components of the impedance tensor Z to determine the apparent resistivity and the phase of the data in the diagonal and anti-diagonal directions. This data processing step also called "processing" is important for the inversion or interpretation of geological structures.

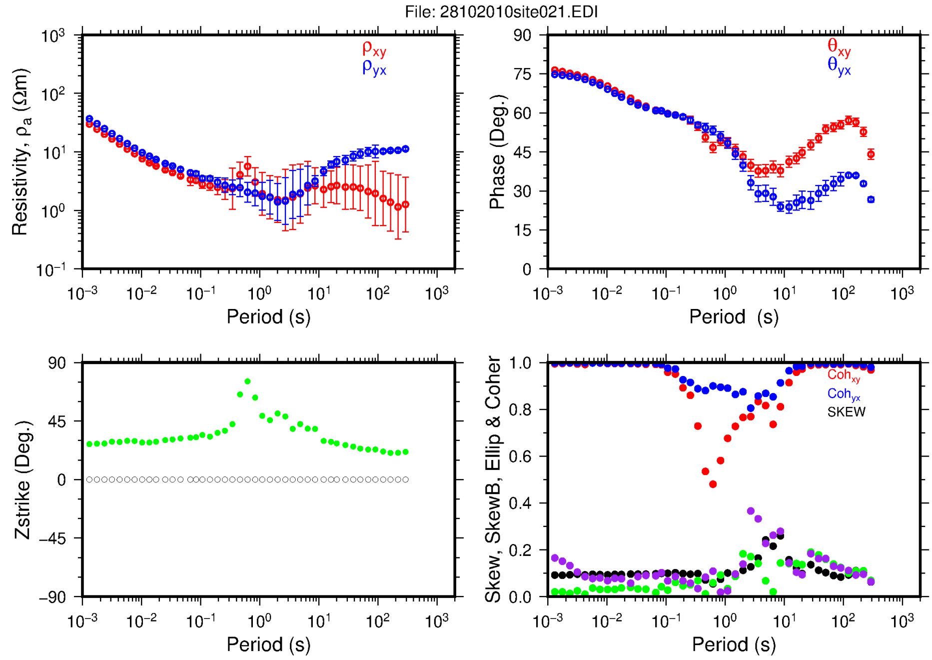

Figure 8: Example results from the MT survey. At the top (left and right) there is, respectively, the MT data transfer function (apparent resistivity and phase). Below (left and right) are the strike and skiew.

After the processing step, the MT data is interpreted to determine the distribution of the true electrical resistivity of the subsoil. The inversion procedure consists of minimizing the difference between the observed data and the simulated data obtained by a theoretical geo-electrical model. Starting from an initial theoretical model, the minimization carried out using an iterative procedure until a threshold set by the experimenter is reached with a good correlation between the observed and the theoretical data.

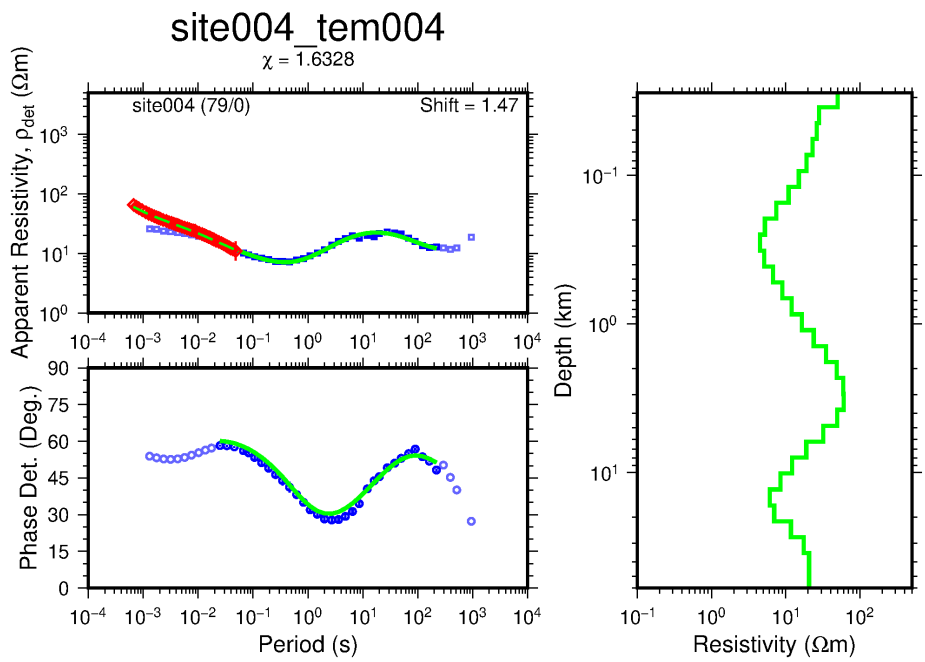

Figure 9: Example of 1D joint inversion of an MT/TEM sounding. The transfer function (on the left) and resistivity model obtained by inverting the MT data (on the right). In the transfer function, red circles are TEM apparent resistivity, the blues circles correspond to the raw data and the solid green line corresponds to the model response.

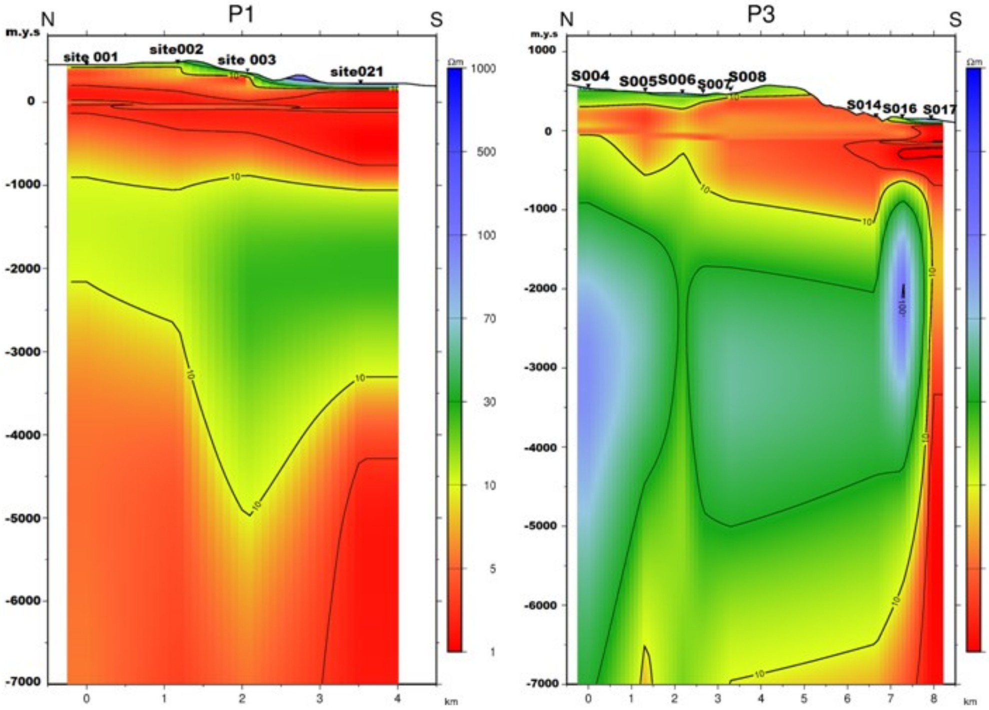

Figure 10: Resistivity cross section NS from P1 and P3 down to a depth of 7000 m.b.s.l.

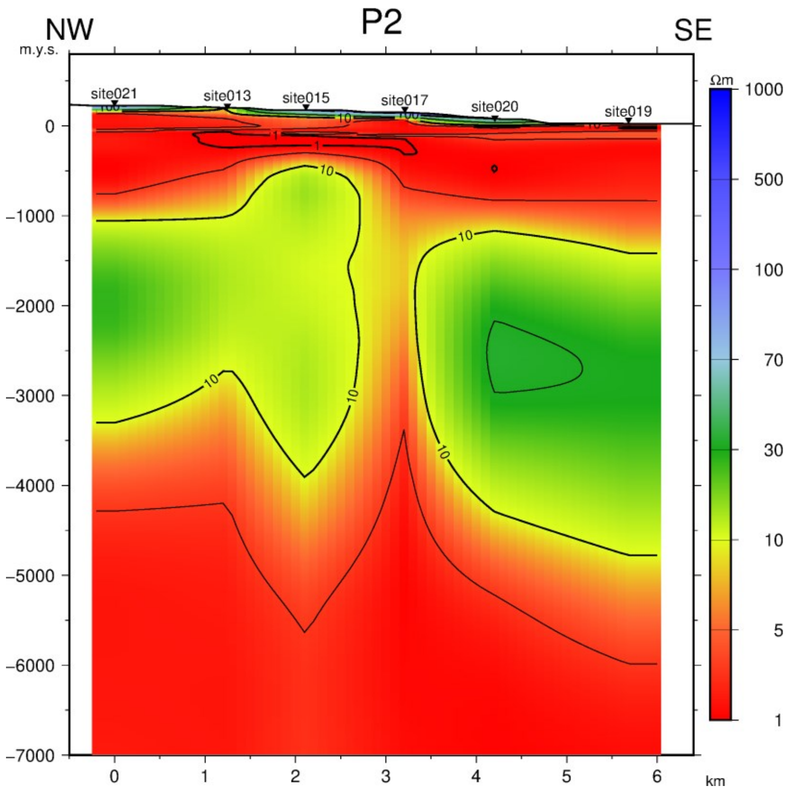

Figure 11: Resistivity cross section NW-SE from P2 down to a depth of 7000 m .b.s.l.

Figure 11 shows the vertical variation along profiles P1 and P3 oriented in the N-S direction. These profiles P1 and P3 respectively comprise 4 stations and 8 stations. Resistivity cross-section P1 shows a very low resistivity at 1000 m.b.s.l. followed by a more resistant layer up to 2000 m.b.s.l. Resistivity cross-section P3 is the longest of the 3 profiles and it crosses the area where the hydrothermal activities are located. This profile P3 highlights two resistant zones (~ 100 Ohm·m) at a depth of 1000 m under the sites 004 and 016. Between these two sites, there is a conductive zone (~ 30 Ohm·m) which may correspond to a geothermal reservoir. This profile shows a slightly resistant medium (~ 30 Ohm·m) close to the surface in its northern part. This resistant medium has a small thickness not exceeding 100 m. Resistivity cross-section P2 shows two zones with a light anomaly (~ 30 Ohm) at a depth of 1000 m and a thickness of 2 km.

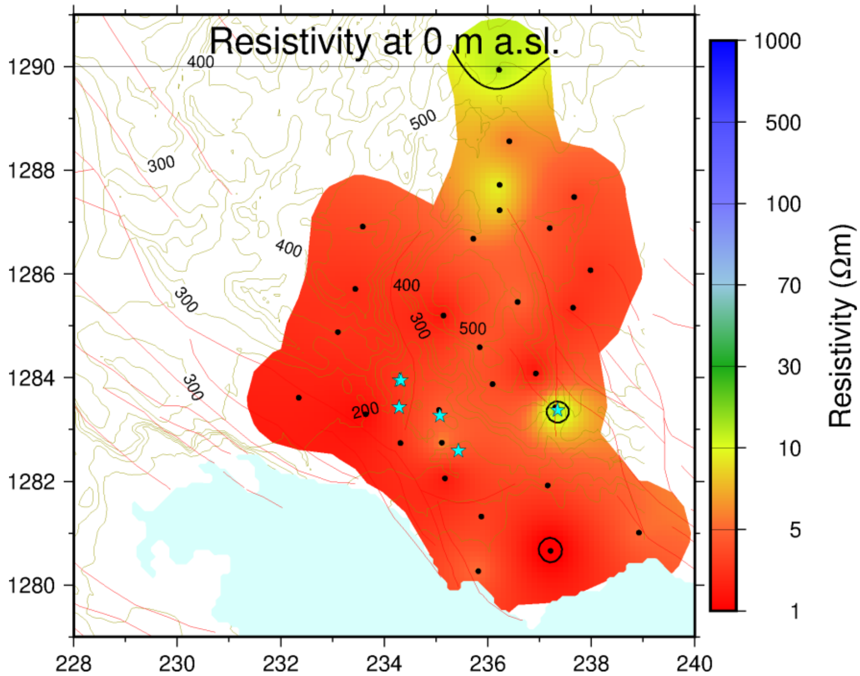

Figure 12: Resistivity depth slice at 0 m a.s.l. Black dots are MT soundings, light blue stars denote geothermal surface manifestations.

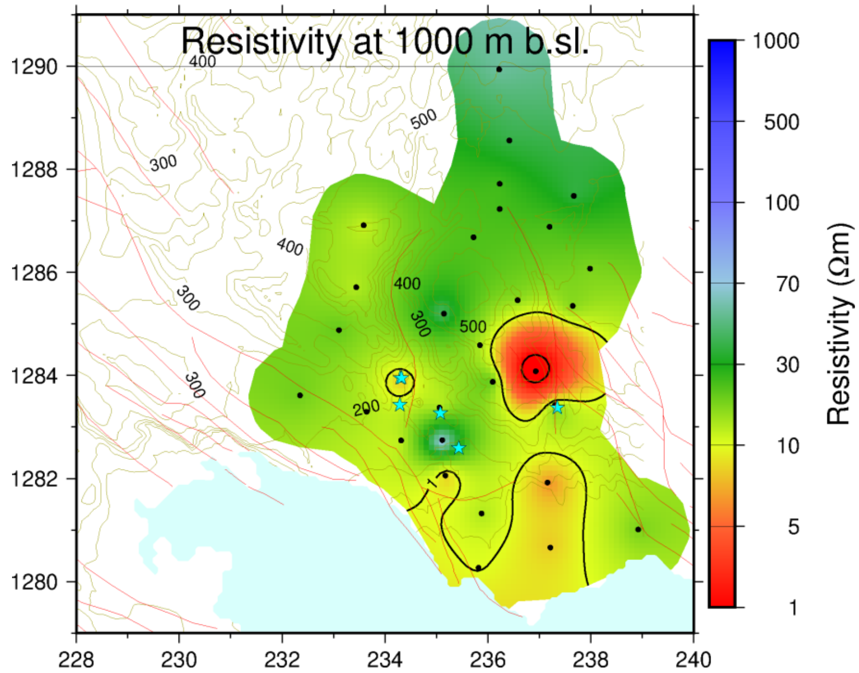

Figure 13: Resistivity depth slice at 1000 m b.s.l. Black dots are MT soundings, light blue stars denote geothermal surface manifestations.

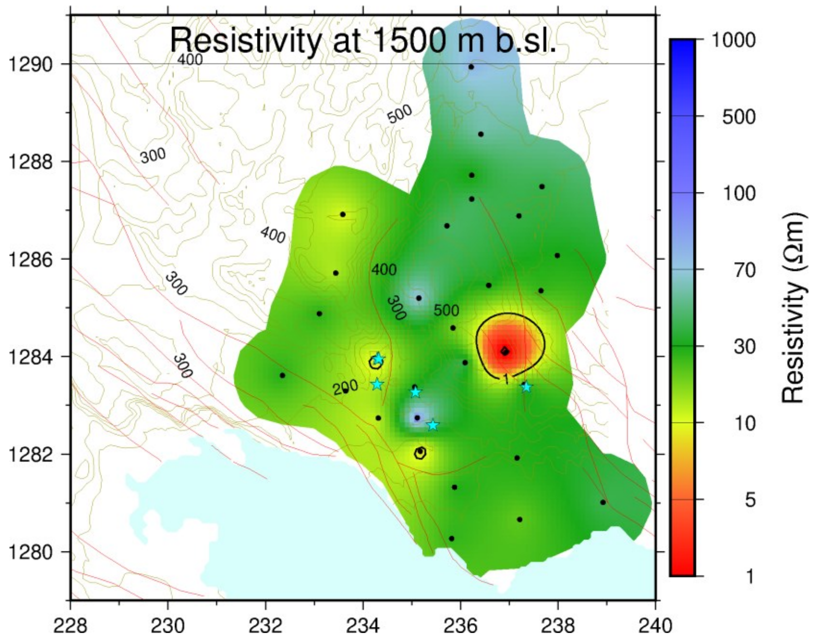

Figure 14: Resistivity depth slice at 1500 m b.s.l. Black dots are MT soundings, light blue stars denote geothermal surface manifestations.

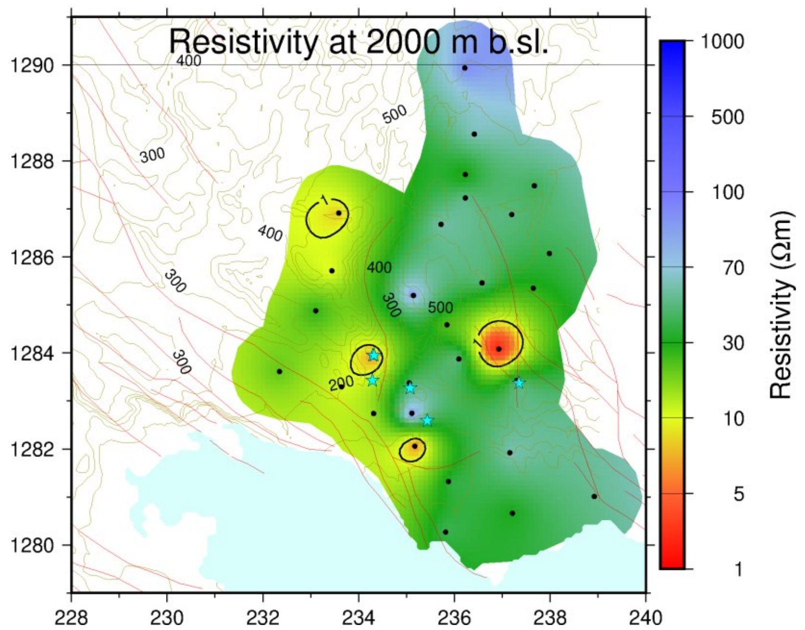

Figure 15: Resistivity depth slice at 2000 m b.s.l. Black dots are MT soundings, light blue stars denote geothermal surface manifestations.

For a resistivity slice at 0 m b.s.l, it can be observed that the imaged subsoil essentially consists of a conductive medium of low electrical resistivity. For resistivity depth slices at 1500 and 2000 m.b.s.l, there is a very large conductive unit on the western part of the prospect. These resistivity slices show conductive units that may correspond to geothermal reservoirs at depths of 1500 and 2000 meters.

3.2 Gravity Survey

The gravity method is a non-destructive geophysical technique that measures the variation of the gravitational attraction of the earth at different locations. This technique is useful and powerful for geothermal energy investigations in order to define the lateral density variation in the subsurface which will be related to basement depth variations, rims of calderas, intrusives, rock alterations, sediments, porosity variations, faults and dykes. The data measured during the old gravity campaigns were used for a Bouguer map made by the BRGM for the entire Assal rifts.

The map of residual anomalies of Bouguer established by the BRGM (1993) provides additional information. Three negative anomalies appear clearly at the horst level, one in the north to the right of the volcanic crater, the second in the south by the fumaroles and the third at the southwestern edge of Horst at the level of the hydrothermal activities. These gravimetric anomalies correspond relatively well with the conductive zones determined by the resistivity maps of the MT survey.

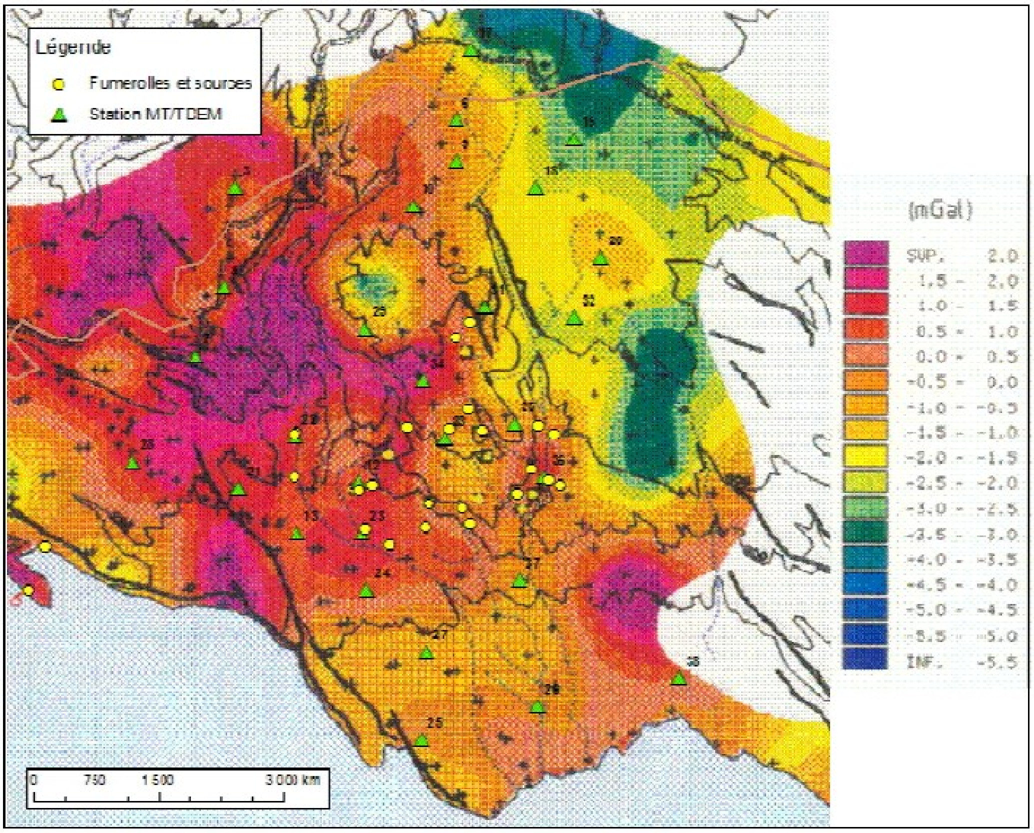

Figure 16: Map of residual anomalies of Bouguer (BRGM 1993).

4. CONCLUSION

Electromagnetic methods (MT/TDEM) were used to image the resistivity of the subsurface at the North Ghoubet Geothermal Prospect. The resulting resistivity slices at different depths as well as the electrical variations along the profiles have highlighted compartmentalized conductive zones that may potentially be geothermal reservoirs that are at depths of 1500 to 2000 meters. The gravimetric method also confirms three light anomaly zones. This joint interpretation between the MT and gravity models allows us to assume that there is a geothermal potential.

A complementary multidisciplinary study (geophysical, geochemical and geological) is planned for this prospect. The objective of this complementary study was to densify the number of MT, TDEM and gravimetric stations in the field in order to cover the entire prospect and second to consider when interpreting these data using a multidimensional approach that better takes into account the geological reality of the mapped subsurface.

REFERENCES

Baker, J., Snee, L. and Menzies, M.: A brief Oligocene Period of Flood Volcanism in Yemen: implications for the duration and rate of continental flood volcanism at the AfroArabian triple junction. Earth. Planet. Sci. (1996), Lett.138 (1-4), 39.

Barberi, F., Ferrara, G., Santacroce, R. and Varet, J.: Structural Evolution of the Afar Triple Junction. In: Pilger, A., Rösler, A. (Eds.) Depression of Ethiopia. Schweizerbart, Stuttgart 1, (1975), 38-54.

Cande, S. C., and Kent, D. V.: A New Geomagnetic Polarity Time Scale for the Late Cretaceous and Cenozoic. Journal of Geophysical Research.-Solid Earth, 97(B10), (1992), 13917-13951.

Hofmann, C., Courtillot, V., Feraud, G., Rochette, P., Yirgu, G., Ketefo, E., and Pik, R.: Timing of the Ethiopian Flood Basalt event and Implications for Plume birth and Global Change. Nature, 389, (1997), 338-341.

Nabighian, M.N. and Macnae, J.C.: Time Domain Electromagnetic Prospecting Methods. Electromagnetic Methods in Applied Geophysics, Vol. 2A, Tulsa, 1991, 427–520.

Simpson, F., and Bahr, K.: Practical Magnetotellurics, Cambridge University Press, Cambridge, (2005), 270 pp.

Stieltjes, L.: The tectono-volcanic axis of Asal.Unpublished thesis, University of ParisSud, Orsay, (1973).

Tazieff, H., Marinelli, G., Barberi, F. and Varet, J.: Geology of Northern Afar. Bull. Volcanol. t.33, fasc. 4, (1969), 1039-1072.