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Geophysical Study on Arta Geothermal Prospect, Djibouti

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ABSTRACT

As part of the geothermal research program in the Republic of Djibouti, the Djiboutian Office for Geothermal Energy Development (ODDEG) conducted a surface study on the geothermal field Arta. Arta geothermal prospect is on of nearest active geothermal system to Djibouti town (Situated about 40 km away).The purpose of this study is to identify and delineate geothermal resources in the Arta geothermal field. Several geoscientific studies have been carried out (geology, geophysics and geochemistry). In this study, my discussion is limited to geophysical surveys. Several integrated geophysical surveys have been carried out, namely: Gravity and Magnetic, over Arta geothermal field. The Arta geothermal prospect is one of the several geothermal prospects in Djibouti, situated on the southern shore of Tadjourah gulf. The Tadjourah gulf is a young oceanic rift whose geology and tectonic activities have been investigated by several researches. Some of the units observed in the field include the 'Dalha' basalt and the 'Ribta' rhyolite both have been strongly altered by geothermal fluids and could constitute a sealing impervious formation, a possible explanation for the scarcity of surface thermal manifestation in the area. The most active faults' direction which is in the NW-SE and fumaroles manifestations is related to it on- shore, but more thermal output could be presented in the off-shore portion of the field. A total of 451 gravity stations were measured in two phases using a Scintrex CG-5 gravimeter and a differential global positioning system (DGPS) for an accurate elevation of each station. The first phase consists of a total 233 points spaced by 500 m covering the whole area of the prospect and a second phase consists of a total 218 points spaced by 250 m covering specifically the central part of the region including the alteration zone and fumaroles of Qiqleh zone. Ground magnetic survey (Magnetometer) was carried out in the Arta geothermal prospect. The objective of the survey was to take measurements of magnetic fields on 250 station using two GSM19 proton magnetometers with integrated GPS (Global position system) and a high sensitivity Overhauser effect measuring the Earth's magnetic field with 0.01 nT resolutions and 0.1 nT absolute accuracy. The gravity survey has an important role in geothermal energy investigation. Gravity data were done to give a better imagery of the underground and also to locate a possible geothermal reservoir for geothermal energy production. Several corrections were done to the measured gravity values to obtain the final gravity anomaly called Bouguer anomaly including regional and local anomaly and also same filtering method. The analyzed results of the magnetic survey revealed many distinct magnetic lineament which can suspect the presence of fracture or/and fault with the NW-SE, NE-SW, E-W and N-S directions.These anomalies resulting from both gravity and magnetic surveys were expected to have a strong relationship to the thermal sources of the Arta geothermal system. This expectation was supported by geological observation of the field, and it was revealed that the basement Rocks areas are intensively altered and intruded by Dome and /or Dyke. From both horizontal derivative X and Y direction, it was revealed that these structural configurations can be associated to the different tectonic activity realized in the Arta zone.

1. INTRODUCTION

The object of our relative gravity study in Arta is to directly map the structure of the subsurface. Gravity is the force of attraction between two or more bodies. Gravimetry, a technique for detecting variations in density (according to the composition of the terrain) from the measurement of the intensity of the gravity field g compared to a reference value, is therefore based on the Laws of Universal Attraction (Newton's Laws). In order to obtain the variations of the gravitational field due to geological causes, it is necessary to correct our readings of all the other external causes which can influence them (drift of the apparatus, tide, ellipticity of the Earth ...).The method can infer location of faults, permeable areas for hydrothermal movement. It is however, more commonly used in determining the location and geometry of heat sources. For reliable interpretation of gravity anomaly it is advisable to consult other geophysics data such as magnetic and seismic. In our case, it is coupled with a magnetic study, which will be explained below. The Earth has a magnetic field that can be likened to a right magnet (dipole).There are variations in the value of the magnetic field due, for example, to the composition of the subsurface. These variations are called magnetic anomalies. Unlike the force of gravitation, which is always attractive; the magnetic force can be attractive or repulsive. Deep structures such as faults and fractures needed clarification; therefore, gravity and magnetic data was evaluated using gradient analysis techniques in order to estimate the relationships between structure and geothermal manifestations on the surface area. The purpose of this study is to identify and delineate geothermal resources in the Arta geothermal field. In a first step we will approach the geological context followed by the gravimetric then the magnetic method and we will conclude with the conclusion.

2. GEOLOGICAL CONTEXT

This zone of Arta which has a complex history understanding (including) several tectonic events during 4 last ones MY, asked for a complete structural work. The region of Arta presents a big geologic interest for rocks and particular structures which it possesses, but also geodynamics because it was interpreted as a rare example of transformative weakness(fault) "outdoors" moving a well defined oceanic ridge which would emerge to succeed in the rift valley of Asal-Ghoubbet. The region of Arta is considered as one of geothermal site the most estimated by the Republic of Djibouti. The flush volcanic trainings (formations) are: Rhyolites de Ribta, Rhyolites de Mabla, Basalt of Dalha, series stratoid of the Afar and Basalts of the gulf. The major part of Arta is established (constituted) by acids (rock rhyolitique) very comparable to those who appear in Ribta and of basalts of Dalha who is the most important unity (unit) in the zone of Arta. The basalt of Dalha consists essentially of piles of the various lava flows with one thickness variant going to maximum 20-30 meters (Geothermica, on 1982), and is characterized fissurals castings of basalts and

Hawaiites with some lakeside and detrital insertion of sediments; or of ignimbrite rhyolitiques in the top. The basalt puts itself by being discordant in the rhyolites formations of Mabla. The basalt of Dalha is recut by numerous injections (dykes and domes) rhyolitiques, these injections are aligned on fractures (splits) N0 to N40. These series rhyolitiques emitted(uttered) after the terminal phase of the volcanic cycle of Dalha, covered by put into series him(it) stratoide of the tray(plateau) of Arta; and also follow on fracture(split) N20 to N40; This new series is said Rhyolit of ribta (O. Richard, 1979).

The emplacement of acid rocks on each end of volcanic events is a peculiarity of Afar volcanism (Treuil M, Varet, 1973). The acids of the Arta region are distinguished according to their emissions, The rhyolite of Ribta are generally in the form of intrusion which follow in a direction N20-40 and the rhyolites of Mabla in the form of generally very altered flows strongly colored in red but his presence at Arta raises the debate, according to (Robineau, 1979, Olivier, 1979) this training does not flop in the area of Arta. According to the geological excursion of the mission of Arta, the rhyolite of Mabla is observed below the basalt of Dalha; on the stratigraphic principle it is impossible that these formations is the Ribta so necessarily it is rhyolite of Mabla or the Basalt of Dalha very altered.

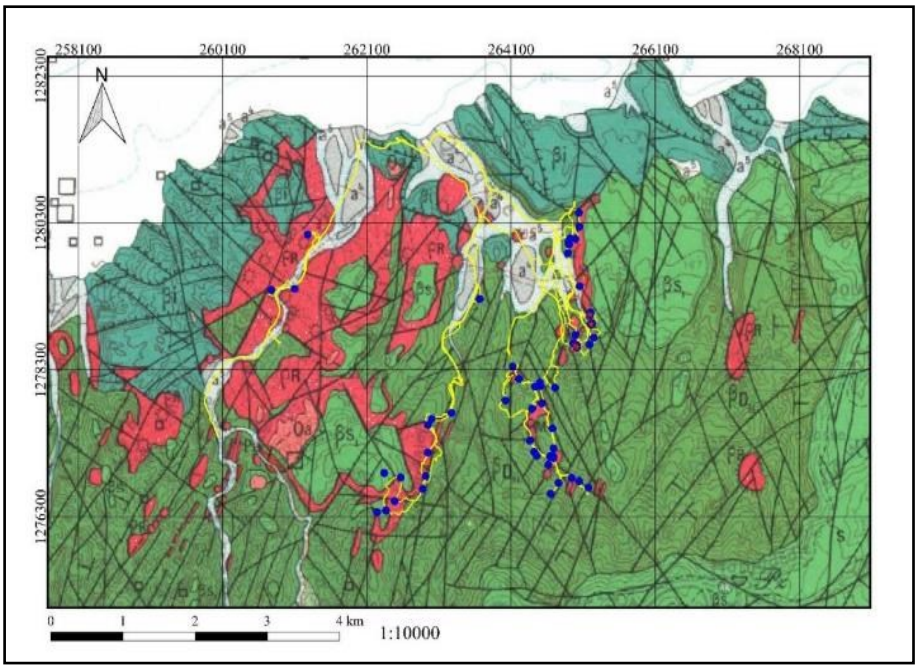

Figure 1: Geologic (map) simplified, the blue square indicates the zone of study (extracted of geologic card (map of the republic of Djibouti, on 2015).

From geologic point of view, the transformative weaknesses (faults) of direction (management) NNE-SSW affect (allocate) intensely basalts of Dalha (8 in 4Ma) and the rhyolites of Ribta (3Ma. Basalts of the gulf are affected (allocated) by the normal weaknesses (faults) of direction (management) NW-SE and the basalt of stratoides. Fumaroles are situated to the crusaders of weaknesses (faults) NNE-NNW. An intense vertical fracturing of direction (management) N0 to N40, affects (allocates) the whole ground " anterior-stratoid ". These fractures (splits) are completely original for a region known in distension. The directions (managements) of the dominating weaknesses (faults) are N0-N40 who is the major direction (management) of the injection rhyolitiques of Ribta. These acid injections are bound (connected) to a deep accident. All the dykes, the acid domes follow this direction(management). The weaknesses (faults) N140-160 which (who) sometimes shares the basalt stratoides and the rhyolite of Ribta as well as the basalt of Dalha and series of acids of Ribta. The intersection of these two directions (managements) of weaknesses (faults) was set up the demonstrations (appearances) of surface to know the fumarole 3 and the fumarole 4.

Various hypotheses on the emanations of the site of Arta:

Fumeroles is set up on basalts of Dalha what implies (involves) the opening of the weaknesses (faults) responsible for fluids hydrothermal are recent that the implementation of puts into series acids Ribta.These weaknesses (faults) are previous to the implementation of the rhyolitiques intrusions what suggests that these weaknesses (faults) are reactivated by the acid intrusions. After the rhyolite of Ribta, it will had phenomena tectonic which (who) replayed the structures of the weaknesses (faults) .

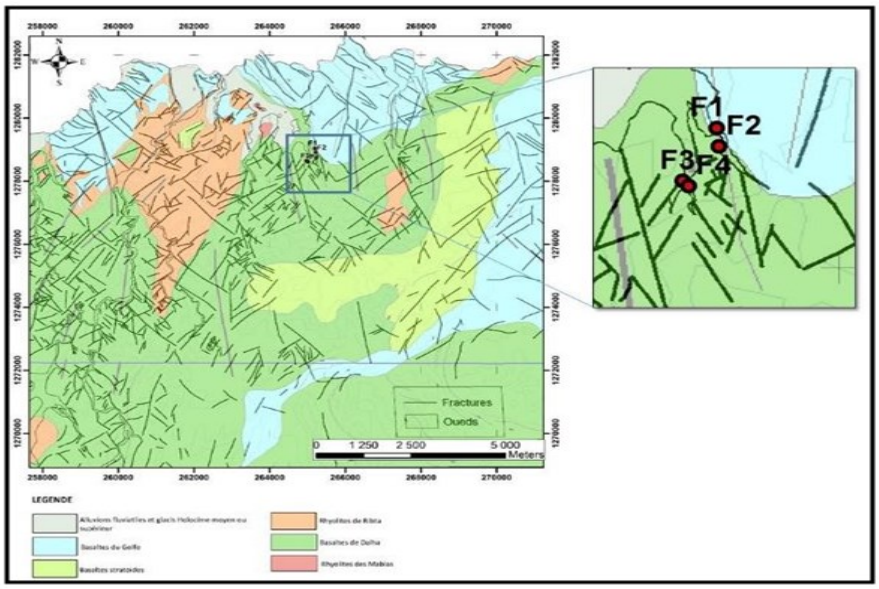

Figure 2: Fracture map with Arta geological formation

There are several fracture directions, which can be grouped into 3 groups:

3. GRAVITY SURVEY

The gravity survey has an important role in geothermal energy investigation. La gravimétrie est une méthode géophysique qui permet d'étudier les variations spatiales du champ de gravité. Elle est appliquée aux études de subsurface pour calculer les variations de densité des terrains in the subsurface that may be related to basement depth variations, rim of caldera, intrusive, rock alteration, porosity variations, faults, or dykes et permet d'imager à différentes échelles la structure interne de la Terre. An extensive gravity survey was carried out from February 2018 to May 2018 covering the Arta region by the geophysical team of ODDEG. The purpose of this survey is to provide the detailed information concerning the subsurface structures and specifically to detect and delineate possible acidic intrusions which caused the tipping of the volcanic formations and which could represent indirectly the heat source of the Arta geothermal system. A total of 451 gravity stations were measured in two phases using a Scintrex CG-5 gravimeter and a differential global positioning system (DGPS) for an accurate elevation of each station. The first phase consists of a total 233 points spaced by 500 m covering the whole area of the prospect and a second phase consists of a total 218 points spaced by 250 m covering specifically the central part of the region including the alteration zone and fumaroles of Qiqleh zone (Figure 1). The local gravity base station in Arta prospect was tied to the reference station located in the geophysical observatory of Arta.

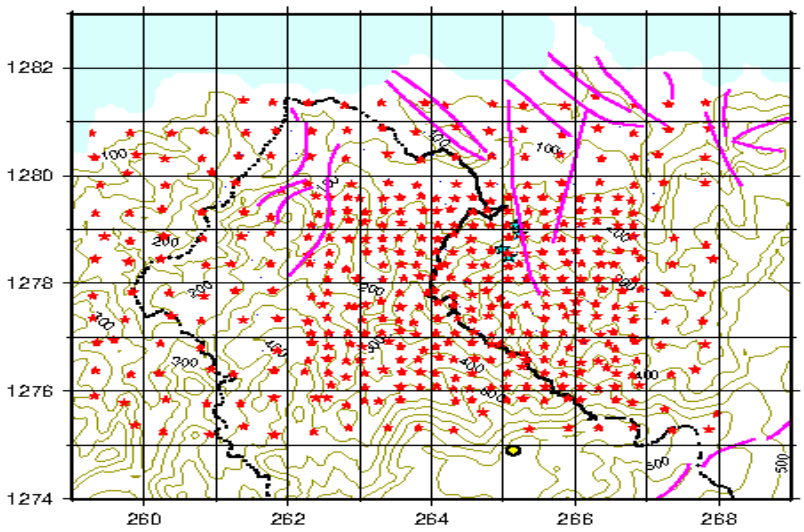

Figure 3: Location of gravity stations and topography with faults

3.1 Gravity Data Processing

The observed gravity reading obtained from the gravity survey reflects the gravitational field due to all masses in the earth and the effect of the earth's rotation. *In* order to remove all these effects, following corrections are applied to the field gravity readings:

By this correction, one tries to eliminate the influence brought on the measures by the tides and the fatigue of the instrument. The shape of the drift correction gravity anomaly is given by:

$$OG3= ((OG4-OG1)*(T3-T1) / (T4-T1)) + OG1, \quad (1)$$

Where OG is the observed gravity and T is the time.

In the graph below, we try to calculate the coefficient of the straight line that passes through the middle point (barycenter) of this cloud of points. The line that passes through this average point has for equation:

$$y = ax + b \quad (2)$$

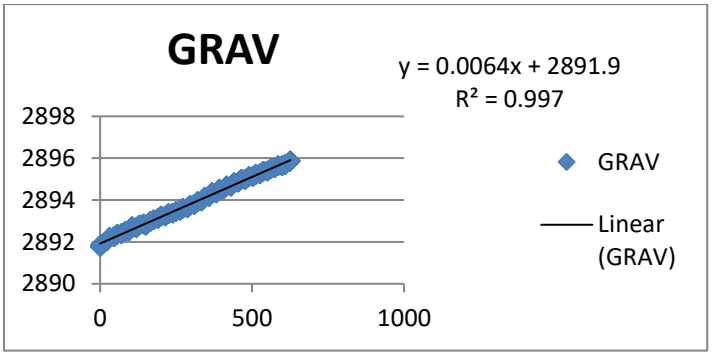

Figure 4: Instrument drift

Latitude Correction (g_n): Correction subtracted from *gobs* that accounts for Earth's elliptical shape and rotation. The gravity value that would be observed if Earth were a perfect (no geologic or topographic complexities), rotating ellipsoid is referred to as the *normal gravity*. The form of the Latitude Correction gravity anomaly in mgal, g_n, is given by:

$$g_n= 978032.7*(1+0053024*\sin^2(lat)-0.0000058*\sin^2(2lat)), \quad (3)$$

Where lat is Latitude in degree. Calculation formula is as follows:

Free air correction: The free-air correction accounts for gravity variations caused by elevation differences in the observation locations. The form of the free air correction gravity anomaly, g_{fa}, is given by:

$$g_{fa}=0.308596*h. \quad (4)$$

Where h is the elevation (in meters) at which the gravity station is above the datum (typically sea level).

Bouguer correction: The Bouguer correction is a first-order correction to account for the excess mass underlying observation points located at elevations higher than the elevation datum (sea level or the geoid). Conversely, it accounts for a mass deficiency at observation points located below the elevation datum. The formula of the Bouguer gravity anomaly, g_{ba}, is given by:

$$g_{ba}= -0.419*rho*h, \quad (5)$$

Where rho is the average density of the rocks underlying the survey area.

Correlation analysis between gravity and elevation method is applied to determine optimal density of terrain and Bouguer correction making map of assumed density 2.2, 2, 3, 2.4, 2.5, 2.6 and 2.67 g/cm^3.

In this study the optimal density is determined as 2.4 g/cm^3, and then it was used for further analysis of gravity data.

3.2 Results

3.2.1 Bouguer anomaly

Bouguer anomaly map created by corrected density 2.4 g/cm3 is shown in Figure 3. In the view of large scale, high gravity anomaly values trending from northeast to southwest is observed in the Bouguer anomaly map and coincide with the main fault of NE-SW direction resulting from the tectonic activities of the region.

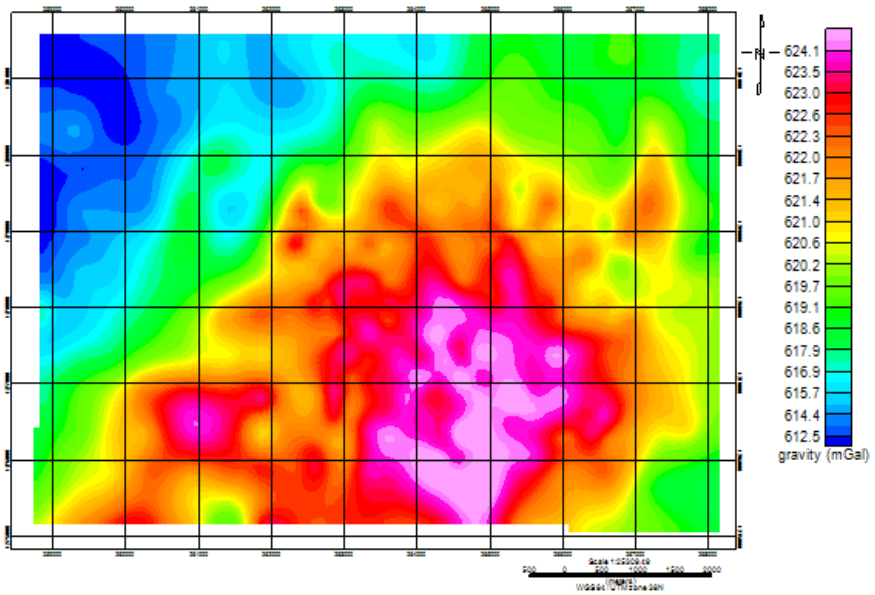

Figure 5: Bouguer anomaly map (correction density 2.4g/cm3)

3.2.2 Residual Bouguer anomaly

To remove regional gravity, 2nd order polynomial fitting had applied and a residual gravity map was created is shown in Figure 4. This kind map shows a local distribution of distinct residues of high density in the central part of high anomaly and it trend to the southwest of the study area.

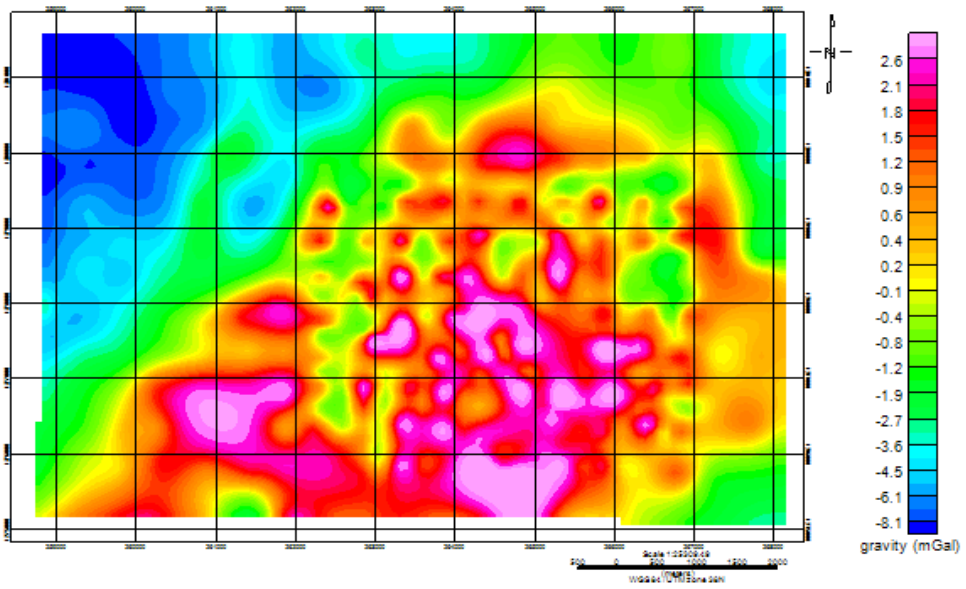

Figure 6: Residual Bouguer anomaly Map

3.2.3 First vertical derivative filter

The vertical derivative filters give high resolution by raising the signal of superficial objects and removing the regional component. The First vertical derivative map obtained from bouguer anomaly is shown in Figure 5.This map shows a significant increase in contrast specifically within the central part of high gravity anomaly of Bouguer gravity map.These contrast reflect the lateral variations of density in the subsurface of this high anomaly . It is also possible to identify several distinct lineaments that are very difficult to detect in the maps of Bouguer and/or residual anomaly. However these lineaments could be related to the existing structure features in the Arta zone such as fault, fracture or dyke.

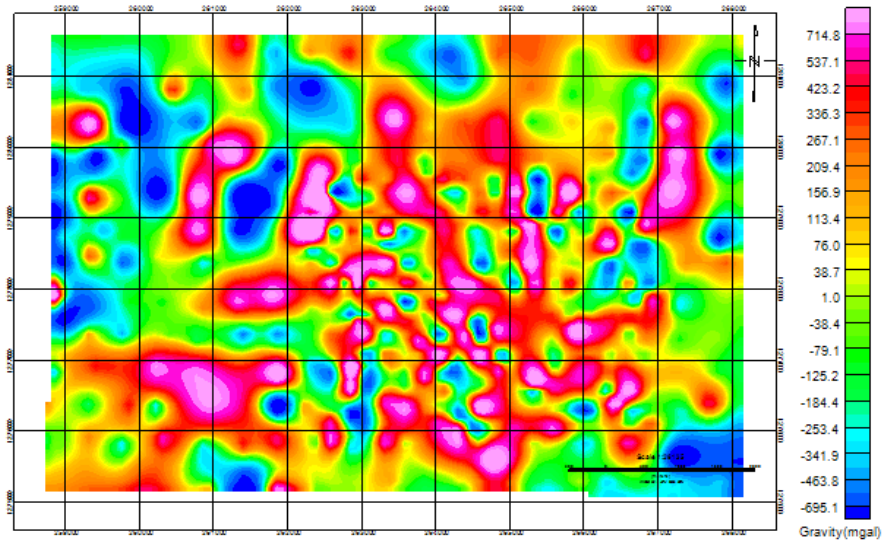

Figure 7: First vertical derivative Map of Gravity

3.2.4 Horizontal derivative filter

Horizontal Derivative filtering techniques are often used in potential field data processing for gravity and magnetic especially to define better the borders of the lineaments. The Horizontal derivative in X direction obtained from Bouguer anomaly is shown in the figure 6. This map shows clearly a boundary of the high gravity anomaly toward East direction by a dominance of low gravity anomaly of North-South trending lineaments. In the central part, there are some of Northwest-Southeast oriented lineament seem to cross-cut the Northeast-Southwest structural pattern.

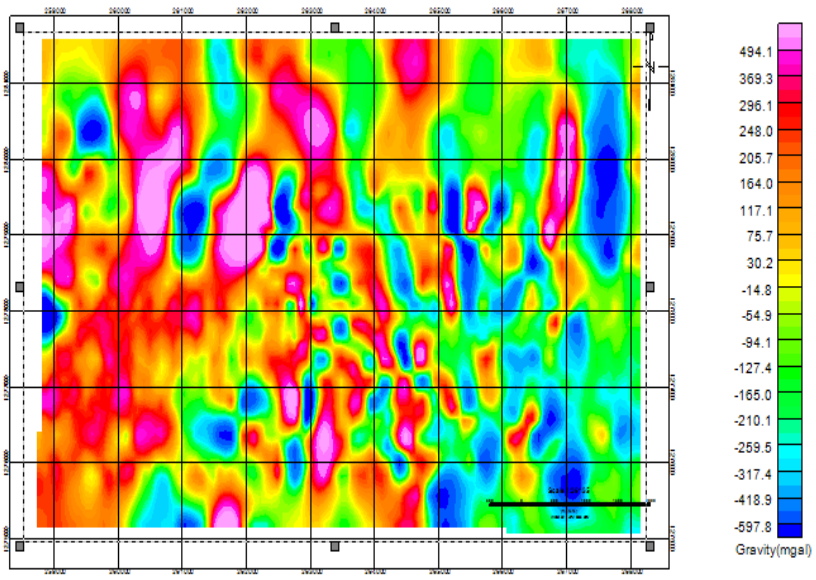

Figure 8: Horizontal derivative HX

The horizontal derivative in Y direction shows clearly lineaments or edges of the high gravity anomaly in NW-SE trending resulting from Bouguer anomaly. The boundaries toward the north, west and southwest direction are identified respectively by West-East, NE-SW and W-E trending lineaments associated with low gravity anomaly.

3.2.5 Analytical Signal filter

The analyzed results from Analytical signal revealed that the high gravity anomaly is bordered by a circular shap which could be associated to an intrusion body.

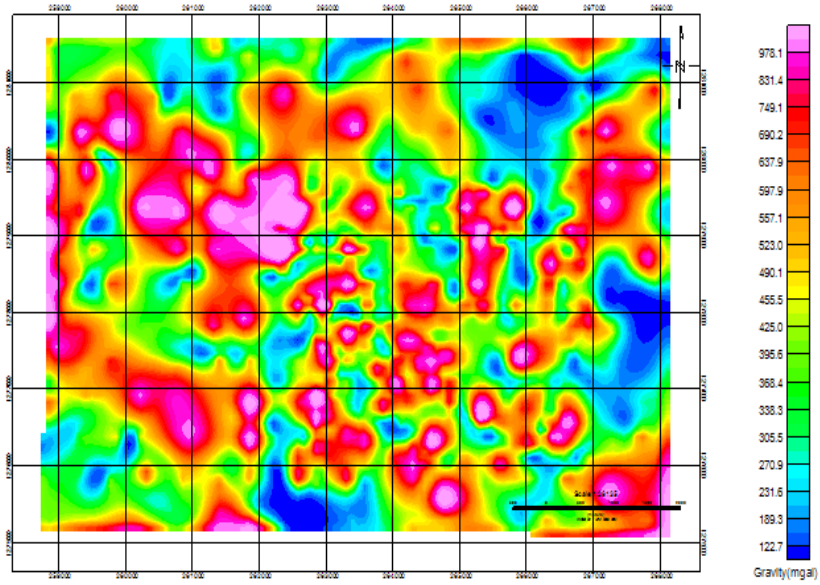

Figure 9: Analytical signal map

3.3 Interpretation

The Bouguer anomaly map shows gravity high, toward the NE-SW direction. The residual Bouguer revealed a concentration of this high gravity anomaly specifically in the central part presumably reflecting an intrusive body covering the basement of the Arta zone. The vertical derivative applied to the Bouguer anomaly revealed a significant increase in contrast of high gravity which can reflected the acidic magma intrusion consolidated in the subsurface and become slightly dense than the surrounding structure . It was revealed distinct gravity lineaments toward NW-SE which seem to cross cut the NE-SW structural pattern which could be suggested that these structural configurations represent deformation zones dominated by brittle deformation, possibly overprinting original ductile structures.

4. MAGNETIC SURVEY

The aim of a magnetic survey is to investigate subsurface geology on the basis of the anomalies in the earth's magnetic field resulting from the magnetic properties of the underlying rocks. Sometimes aeromagnetic surveys are used as a reconnaissance tool in selecting prospect areas for more detailed exploratory work. Ground magnetic surveys are often done as a complement to other geophysical methods and geological mapping, particularly in order to detect vertical structures. In geothermal application the main objective of the magnetic study is to contribute with information about the relationship among the geothermal activity, the tectonic and stratigraphy of the area by means of the anomalies interpretation of the underground rocks' magnetic properties (Escobar, 2005). In some high temperature geothermal areas, a good correlation is found between altered ground and the reduced intensity of magnetization caused by the alteration of magnetic minerals (Palmasson, 1975). But the greatest potential of the method, in the highest temperature geothermal area, lies in its ability in the determination of heat source by mapping the Curie point isothermal temperature. Ferromagnetic materials exhibit a phenomenon characterized by a loss of nearly all magnetic susceptibility at a critical temperature called the "Curie temperature". Various ferromagnetic minerals have differing Curie temperatures, but the Curie temperature of titano-magnetite, the most common magnetic mineral in igneous rocks, is in the range of a few hundred to 570°C. In the low temperature geothermal fields ground magnetic are extensively used for tracing the faults that often control the flow of thermal water to the surface.

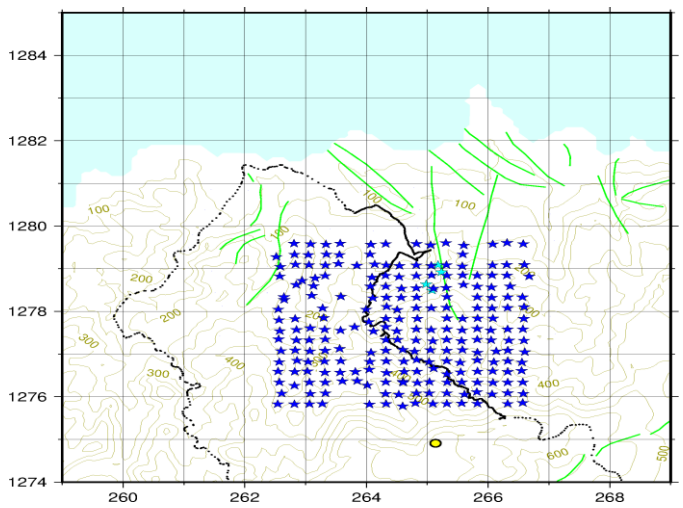

Figure 10: Magnetic soundings and topography with faults and the green star represent the fumaroles of study area

4.1 Results

The figure 2.41 shows the map of total intensity magnetic field of Arta survey. In the view of large scale, this map shows a distribution of contrast susceptibility, mostly in the central part of the survey. Since many near surface magnetite sources such as dykes and other intrusion can be found in the area, it is so difficult to understand the magnetic anomaly field sources.

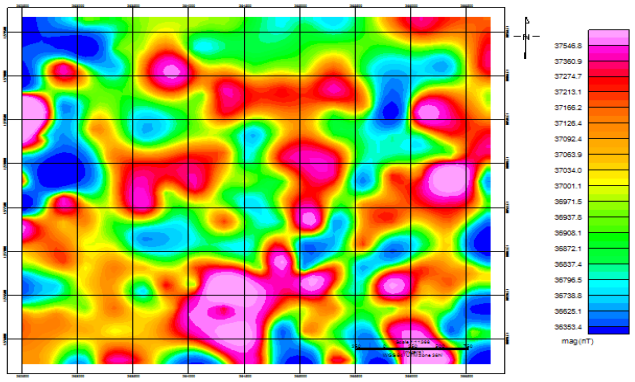

Figure 11: Total magnetic field

In order to enhance the analysis of the total anomaly magnetic fields, different methods of analysis were applied using original Total magnetic intensity data such as upward continuation, directional derivative and analytical signal.

4.1.2 First vertical derivative

The First vertical derivative map obtained from the total magnetic field is shown in the Figure 2.44. This map reflects a high contrast of the magnetic anomaly in the superficial of the whole area study, which could be reflecting the different existing of composition minerals containing in the rocks. In addition, some of them were reflected as the lineaments with different direction NW-SE and NE-SW which can suspect the presence of fault and/or fracture.

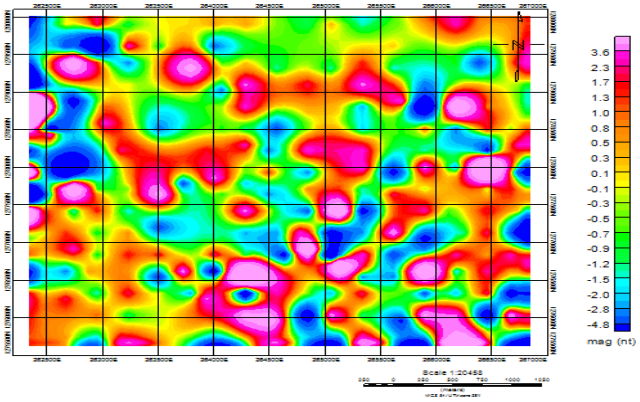

Figure 12: Vertical derivative map

4.1.3 Horizontal Derivatives

The horizontal derivative in X and Y directions created from total magnetic field are shown in the Figure 2.45 and Figure 2.46:

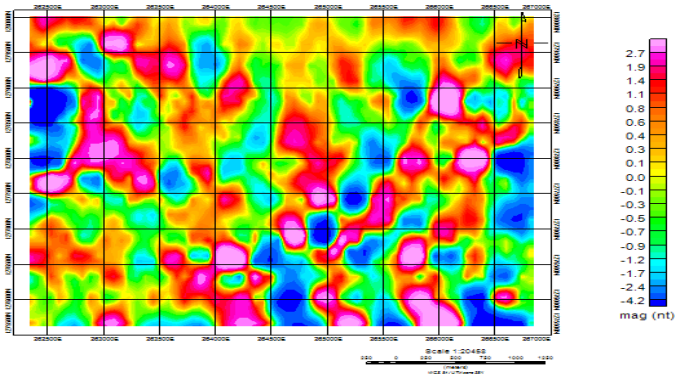

Figure 13: Horizontal derivative in X direction

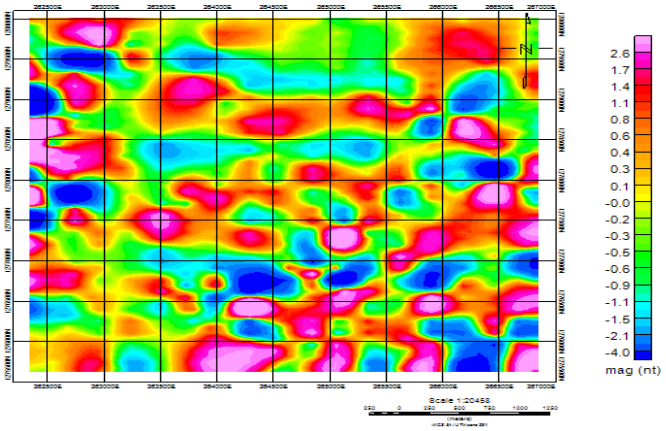

Figure 14: Horizontal derivative in Y direction

The result from the horizontal derivative in the Y direction (Figure 2.46) shows clearly in the northern part parallel magnetic lineaments with an elongation West-East direction. In the other part of the area it is also possible to identify several of NW-SE lineaments seem to cross up the NE-SW trending lineaments. This phenomenon of crossing is highlighted better in the horizontal derivative in X direction (Figure 2.47).

From both horizontal derivative X and Y direction, it was revealed that these structural configurations can be associated to the different tectonic activity realized in the Arta zone.

4.1.4 Analytical signal

Analytical signal created from the total magnetic field is shown in the Figure 2.47. This map shows a magnetic anomaly well delineated in the cercular sharp toward NE-SW direction.

This map revealed a delineation of high magnetic value which is concentrated mostly in the central part of the area study. Because of the cercle sharp, this anomaly could be related to the dome intrusive rock.

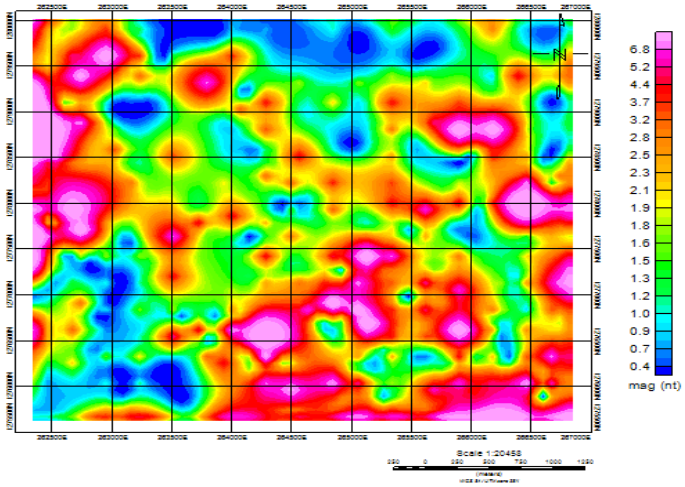

Figure 15: Analytical signal map

4.2 Interpretation

The results of the magnetic survey revealed many distinct magnetic lineament which can suspect the presence of fracture or/and fault with the NW-SE, NE-SW, E-W and N-S directions. In addition, the analyzed results of the upward continuation show a clear dominance of wide high magnetic lineament toward North-Sud direction which could be inferred to reflect the regional basement. Because the location is close to the magnetic equator (within +-10°) this high magnetic become dominantly low magnetic anomaly which could be caused by a hydrothermal demagnetization that may also due to a hot intrusive magmatic. The existence of fumaroles and the high thermal anomaly resulting from temperature survey around the area of this magnetic anomaly are consistent with our hypothesis.

5. CONCLUSION

We present an interpretation of the gravity and magnetic anomalies at Arta Volcano caused by the distribution of subsurface geological formations and their structure. Consequently, it can be concluded that these anomalies resulting from both gravity and magnetic surveys, were expected to have a strong relationship to the thermal sources of the Arta geothermal system. This expectation was supported by geological observation of the field, and it was revealed that the basement Rocks area are intensively altered and intruded by Dome and /or Dyke. The application of horizontal gradient methods to gravity and magnetic data clarified

the subsurface structure beneath Arta, which could contribute to geothermal exploration. The horizontal gradient delineated subsurface faults that have no evidence on the surface and would hence not be discovered by geological mapping. Some geologic faults are confirmed and others are delineated. The interesting result is that the hot springs are well correlated with high horizontal gradient anomalies that are interpreted as boundaries or faults. This indicates that the geothermal manifestations for Arta are structurally controlled. The results of the present study lead to an understanding of subsurface structure, which may aid in future geothermal exploration of the Arta area.

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