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Research Article

Applications of Magnetic Method in Mapping Subsurface Structures in the Ziway Langano Corridor Central Main Ethiopian Rift

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ABSTRACT

This paper aimed to map subsurface structural influences on groundwater flow in the Ziway- Langano Corridor area, located in the central main Ethiopian rift using the magnetic method. It is determined that the tectonic setting and rock types of an area is important in establishing the distribution of the groundwater flow. The existence of subsurface structures which include faults, fractures, and veins have been investigated in the Ziway-Langano Corridor using a tilt derivative magnetic map compiled for the study area. These geophysical investigation results have identified subsurface geologic structures that are responsible for the flow of groundwater from Lake Ziway towards Lake Langano. This conclusion is also confirmed by the existence of hot springs at the northern shore of Lake Langano which is missing at the southern shore of Lake Ziway. This paper has shown that there are no east-west structures that favor the flow of groundwater. Hence, the direction of groundwater flow in the study area takes place from Lake Ziway towards Lake Langano being controlled by the N-S and NE-SW oriented faults and fractures mapped in the Ziway-Langano corridor.

Keywords: Groundwater; Tilt derivative; Subsurface geological structures

INTRODUCTION

Background

This paper mainly investigated subsurface structural influences on groundwater flow in the Ziway Langano corridor area, located in the central main Ethiopian rift. Groundwater is water that occurs in the subsurface, in the pore spaces between mineral grains or weathering, cracks, and fractures in the rock. This paper was mainly aimed to map subsurface structures that control the movement of groundwater along the Ziway-Langano corridor using magnetic data. In this study, magnetic data were collected, reviewed, analyzed, and interpreted to examine the subsurface geological structures and groundwater flow in the Ziway-Langano Corridor. Further, based on the results of magnetic anomaly maps, this paper attempts to describe the tectonic and geologic implications of the study area. The results show that the tectonic setting and rock types of an area is important in establishing the spatial distribution of the groundwater flow. The study area is located in the Central Main Ethiopian Rift (CMER). The area ranges in elevation between 1500 and 2150 m above sea level. Geographically the study area is bounded between7045′ N-800′ N latitude and 38030′ E-39000′ E longitude.

Description of the study area

Location and accessibility: The study area is located about 190 km southwest of Addis Ababa, in the Central MER. As shown in the Figure 1, the study area is situated within the Lakes District region, between Lake Ziway to the north and Lake Langano to the south and forming some sort of corridor between the two lakes. Meki, Kator, and Bulbla rivers are the major rivers that flow to Lake Ziway and Lake Langano. The study area covers an area of approximately 1800 square km.

Geographically, the study area is bounded between7045′ N-80 0′ N longitude and 38030′ E-390 00′ E latitude. The study area can be accessed through two roads passing from Adami Tulu to the Aluto geothermal to Lake Langano, passing through the Aluto

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geothermal base camp and it joins again the asphalted road at Bulbula.

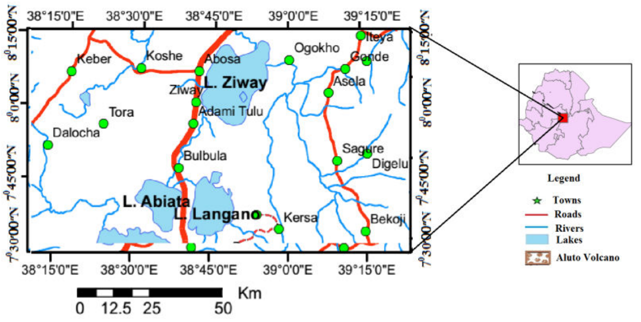

Figure 1: Location map of the Ziway-Langano corridor.

Physiography: The Ethiopian sector of the East African Rift system extends for more than 1000 km in a NE-SW to N-S direction from the Afar depression, at the Red Sea-Gulf of Aden junction, southwards to the Turkana depression. The MER which is estimated to be about 80 Km wide, separates uplifted Somalia and Ethiopian plateau and these plateaus rise more than 2000 m above mean sea level. The rift floor increases in elevation from the Turkana depression up to the main watershed between the Meki and Awash rivers north of Lake Ziway. In the north direction, the elevation of the rift floor decreases as we move to the Afar depression (Figure 2).

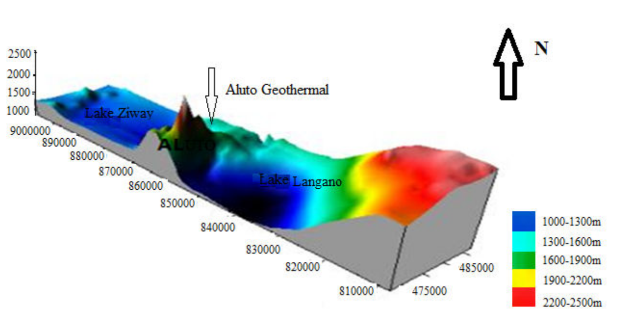

Figure 2: Physiographic map of the study area.

Climate and vegetation cover: The study area is characterized by a warm to cool, semi-humid zone, where the annual rainfall is more than 1000 mm and it is a semi-humid to an arid zone. Vegetation on the floor of the rift is dominated by the spiny acacia trees and some short bushes. The top part of Aluto, is covered by denser vegetation consisting of a variety of trees and bushes.

Objectives of the study

General objective: The general objective of this study was to map subsurface structures that control the movement of groundwater along the Ziway-Langano corridor using magnetic data.

Specific objective: The specific objectives of this study were to:

Compile the total magnetic field anomaly map and its derivative maps of the study area.

Translate geophysical anomalies revealed by the compiled maps into geologic and tectonic structures of the study area.

Map locations and estimate depths of the geological structures that control groundwater flow in the study area.

MATERIALS AND METHODS

The selection of the appropriate geophysical method is determined by the physical contrasts of a hydrological unit/ contrast. Typical physical properties measured are the susceptibility of the rock unit. Therefore, the geophysical methods used in this survey were selected based on the prominent physical characteristics of the subsurface geological structures that control the movement and storage of groundwater. The magnetic data utilized in this study were collected using a Proton Precession Magnetometer of MP2 type that measures the total intensity of earth's magnetic field at a given observation point, with an accuracy of one Gamma (1γ). The survey was conducted in a random type, with the geographic coordinates and elevation of each observation point determined using a handheld GPS of Garmin 12 type. Before any measurement was made, a base station for all the observations occupied was established to correct the diurnal effect. Accordingly, all the primary magnetic data were collected from the survey and were made available for further reduction and processing steps. The collected data were processed and analyzed using different software (Arc GIS V10.3.1 and Geosoft oasis montaj V 6.4.2).

Geologic and tectonic setting of the study area

Regional geological setting: The main Ethiopian rift system being Active rift type, up-doming was followed by volcanism and rifting. The earliest episodes took place in the Southern Ethiopia Rift (SER) and the Afar Rifts, before 25 Ma. Rift propagation proceeded both from the south and north directions towards the MER [1]. Rifting in the MER did not start until about 8 Ma [2], possibly due to the presence of transversal structures (GBL and YTVL to the south and the north of MER, respectively), that stopped the propagation of rifting for a long geological period. During the early stages of the MER, several central volcanoes erupted forming very thick pyroclastic deposits, thought to have been partially produced from fissures. These volcanic products have about 5 Ma and are known as the Nazret group [3-6]. Formation of the important rift margins of the Central MER took place about 3.5 Ma ago when the Munesa and Guraghe escarpments were formed. Lithologies with age younger than 1.6 Ma are related to the NE-SW trending fracture systems together with their transversal structures that are NW-SE and ENE-WSW oriented. After 1.6 Ma the Somalian plate drifting direction changed from SE towards nearly [7], causing the development of N-S/NNE-SSW trending fracture systems known as the Wonji Fault Belt (WFB).

Structural description of the study area: The Main Ethiopian Rift (MER) is generally NE-trending sector of the largest East African Rift system that includes a series of different rift segments that extend from the Afar depression at the Red Sea-Gulf of Aden intersection to the Kenyan Rift [1]. The Main Ethiopian Rift (MER) is among the few places that are volcanically active [8].

Generally the MER encompasses three different parts: The first part of MER is Northern main Ethiopian Rift (NMER) which is situated at the northern part of the main Ethiopian rift. The NMER generally covers areas from the Afar depression to the Lake of Koka region [1]. As indicated by [6,8] the early volcanism in NMER has been started at 10–11 Ma. The second part of MER is the central MER, which is bounded between the Northern and Southern main Ethiopian Rift [8]. This sector separates the wide uplifted Ethiopian volcanic province into the northwest and southeast plateaus [4], and the third part of MER is called the Southern MER, that extends from Lake Awasa to the overlapping area between the Ethiopian and Kenya Rifts [1,6]. Generally the Main Ethiopian Rift (MER) is characterized by NE-trending sector of the East African Rift system that includes different rift segments [1]. The Main Ethiopian rift is one of volcanically active places in the world [9]. These three segments represents different stages of extensional process, from early rifting in the Southern MER to more evolutes stages in the Central and Northern MER preceding the incipient seafloor spreading in Afar [10].

Hydrology of the study area: The Main Ethiopian rift is one of a volcanically active region in the world [9]. The MER encompasses different lakes that differ in size, hydrological and hydrogeological settings. The central main Ethiopian Rift (CMER) which is part of MER encompasses Lake Ziway, Lake Abijiata, Lake Langano, and Lake Shala. Those Lakes forms a complex and vulnerable hydrological system with unique ecological characteristics. The main rivers that fed these lakes are Meki and Ketar Rivers. Meki and Keta Rivers flows into Lake Ziway and, the Lake Ziway water flows into the Bulbula River [11]. In recent years the levels of some of these lakes have decreased dramatically [12]. A significant change has been observed in the water level of Lake Ziway in Ethiopia [13]. As the result of the expansion of irrigational activities, the size of Lake Ziway decreases approximately by 0.5 m [13]. Additionally some lakes have shrunk due to excessive abstraction of water and others have expanded due to increasing of surface runoff and groundwater variation from percolated irrigation water.

Annually over 37 × 106 m3 amount of water are discharged from the level of Lake Ziway due to irrigational purposes. Generally this led to a decreasing of lake level by 0.36 m which corresponded to 18 km2 reductions in the lake surface area [14]. The results indicate that abstraction from the lake is a significant contributor to the decreasing of water in the level of Lake Ziway [14].

However, the contribution of subsurface geological structures and their impact on the lake water level variation has not been quantified yet. This paper addresses the contributions of subsurface structures on groundwater flow from Lake Ziway towards the Lake Langano corridor using a magnetic method. The results reveal that Lake Ziway is flowing towards Lake Langano. Generally, the reduction in the water level of Lake Ziway is mainly attributed to natural and anthropogenic factors and subsurface geological structures that favor the flow of groundwater from Lake Ziway towards Lake Langano.

Data acquisition and reduction

Magnetic data acquisition: The magnetic data utilized in this study which amount to a total of 130 (as indicated in the magnetic data location plot map (Figure 3) were collected using a Proton Precession Magnetometer of MP2 type that measures the total intensity of earth's magnetic field at a given observation point, with an accuracy of one Gamma (1γ). The survey was conducted in a random type, with the geographic coordinates and elevation of each observation point determined using a handheld GPS of Garmin 12 type. Before any measurement was made, a base station for all the observations occupied was established to correct the diurnal effect. Accordingly, all the primary magnetic data were collected from the survey and were made available for further reduction and processing steps.

Magnetic data reduction: The raw magnetic data collected in the field are transformed to total magnetic field anomaly values by applying diurnal correction and IGRF correction using the standard ground magnetic data reduction procedures to compute the total magnetic anomaly values of all the stations considered in the study area. The computed total magnetic field anomaly values of the stations considered in the study area were plotted to compile the total magnetic field anomaly map (Figure 4) of the study area, which is the sum of the effects of both the regional and residual fields was then used for further processing; for example in separating the regional and residual field effects. Consequent processing and enhancements were based largely on the residual magnetic field anomaly map generated using the low and high pass filtering techniques applied in Oasis Montaj Software (V.6.4.2).

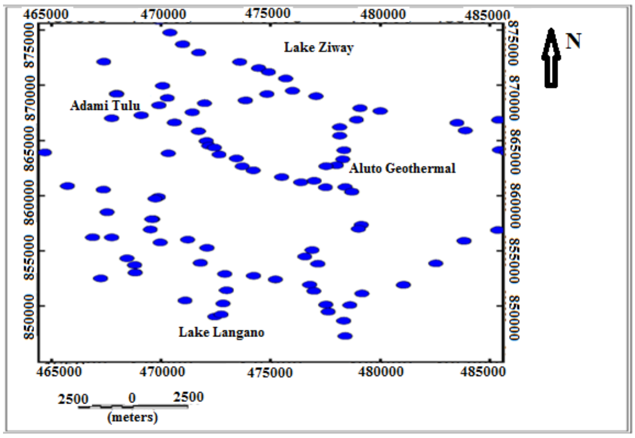

Figure 3: Magnetic data distribution map of the study area.

Data processing and presentations: The magnetic data utilized in the present work have undergone a series of data reduction steps before they were subjected to the data processing and presentation phases. Accordingly, corrections on the daily variations (Diurnal correction) and the effect of the core field (IGRF- removal) on the measured (Observed) total magnetic intensity anomaly values have resulted in diurnally corrected total intensity anomaly and IGRF corrected total intensity anomaly values, respectively. It was the IGRF corrected anomaly values taken as final and base anomaly values for generating the IGRF corrected anomaly map using the Geosoft Oasis Montaj

Software (V 6.4.2) in which, further enhancements, filtering operations, and interpretations have been based.

The IGRF corrected total magnetic intensity anomaly map, like the complete Bouguer anomaly map in the gravity survey, represents the sum of the effects of the shallow depth, short wavelength, and deep-seated, long-wavelength source effects. Hence, effective interpretations of the magnetic data necessitate the separation of the regional and residual responses from the IGRF corrected total magnetic intensity anomaly values. Following the separation of the regional and residual magnetic anomalies using the same procedures as applied in the gravity data, further filtering techniques and enhancements were performed as per the procedures of the magnetic data processing steps.

RESULT AND INTERPRETATIONS

The results of the magnetic survey are compiled in the form of different maps that have been generated after the field raw data have undergone different mathematical corrections. It was using the IGRF corrected magnetic field anomaly values that the Total Field Magnetic Anomaly Map (TFMAM) was derived and gridded with the help of Geosoft Oasis Montaj software (V. 6.4.2).

The residual magnetic field anomaly map was generated after separating the regional anomaly from the TFMAM following the use of the high pass filtering methods. Based on the residual anomaly map, different derivative maps are generated. The results of all magnetic anomaly maps included in the present work are discussed as follows:

Total magnetic field anomaly map

This anomaly map (Figure 4), as mentioned above was generated after the field raw data have been corrected for the effects of daily and main (core) field variations in the earth's magnetic field strength during data acquisition. As can be seen from the map, high magnetic field anomalies in the range of greater than 78 Gammas characterize the eastern and northeast part of the study area. Superimposed on these are, very high magnetic anomaly areas as depicted in the Central southeast part of the mapped area, coinciding with the locations of the volcanic centers. The highest magnetic anomalies recorded are observed in the north and North-East part of the study area associated with the Aluto volcanic complex.

The largest part of the mapped area is characterized by medium to low total magnetic field anomaly values. These include areas close to the volcanic centers of the region and located on the slopes of the volcanic centers in the North as in Aluto area volcanic centers, respectively. Very low total magnetic anomaly values characterize the Northeastern and southern parts of the study area. These areas are relatively low lands in the study area, filled with sediments, and are largely covered by the lakes of the area, lakes Ziway and Langano respectively.

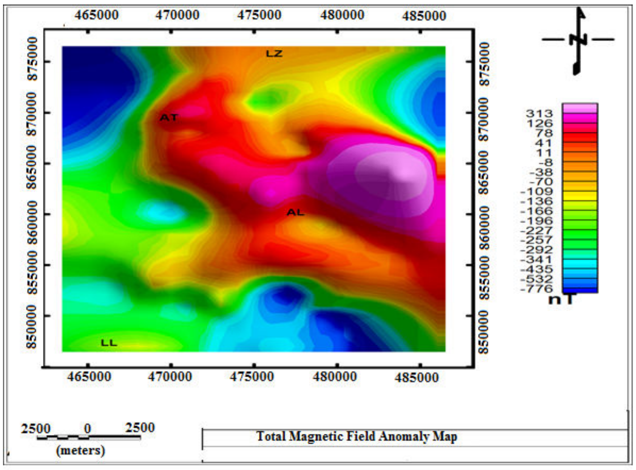

Figure 4: Total magnetic field anomaly map. where LZ (Lake Ziway), AT (Adami Tulu), AL (Aluto), and LL (Lake Langano).

Regional magnetic field anomaly map: The regional magnetic anomaly map of the study area was generated after a low pass filtering technique has been computed using the Geosoft Oasis Montaj Software (V.6.4.2). Generally, magnetic anomalies increase in eastwards from the South/SW part of the study area, with the Northern Central Northern part being characterized by high to very high anomalies are observed in the study area. The magnetic susceptibility of geologic materials may explain the observed regional increase in the magnetic anomaly, high magnetic anomaly readings being interpreted as the responses of low magnetically susceptible earth materials, such as observed with the silicic volcanic centers of Aluto in the study area.

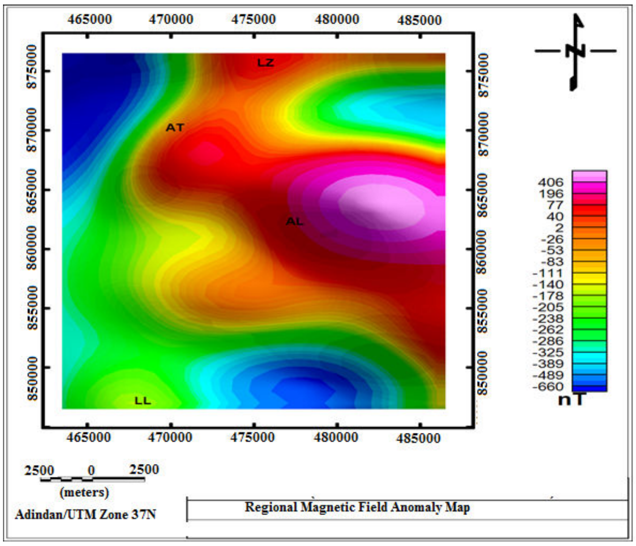

Figure 5: Regional magnetic field anomaly map of the study area. Where LZ (Lake Ziway), AT (Adami Tulu), AL (Aluto), and LL (Lake Langano).

Residual magnetic field anomaly map: The residual magnetic anomaly map (Figure 6) was generated after the separation of the regional anomaly from the total Magnetic Field data. The map depicts detailed features better than those revealed by the observed total magnetic field map. High to very high residual anomalies characterize the Southern and the Northern part of the study area. Very elongated, trending approximately N-S high anomaly segment characterizes the Central Western part of the mapped area. The very high residual anomalies observed in this area are in the form of mostly patches and elongated features. As depicted in the map, the northeastern, central, and southwestern parts of the study area are characterized by low to very low magnetic anomaly values. These regions are largely occupied by the major lakes and their surroundings which are filled with Quaternary sediments.

It is determined that there exists an inverse relationship between the magnetic susceptibility behavior of geologic materials and their magnetic anomaly responses in equatorial areas. As the present study area is located very close to the magnetic equator, the high magnetic anomaly observed over the volcanic complexes are associated with the low susceptibility volcanic materials that resulted from the high heat flow associated with the volcanoes. (In other words, the observed high magnetic anomalies over the volcanic complexes are due to low susceptibility materials that are magnetized by the earth's equator magnetic field). Conversely, the observed negative anomalies could be thought to result from the relatively high susceptibility sedimentary rocks (not affected by high heat flow) derived from the neighboring volcanic complexes

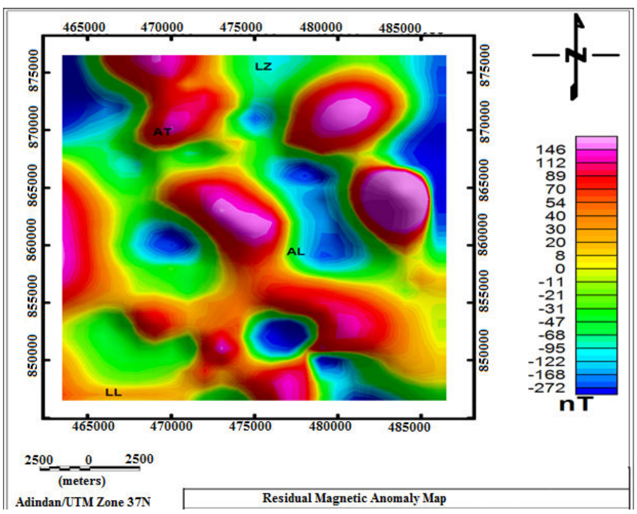

Figure 6: Residual magnetic field anomaly map. Where LZ (Lake Ziway), AT (Adami Tulu), AL (Aluto), and LL (Lake Langano).

Analytical signal (total gradient): The Analytical signal of a potential field, such as a magnetic field, is generated by combining the 3-directional gradients of the potential field at the location (X, Y) in use and is given by the following formula [15].

$$AS(x,y) = \sqrt{\left(\frac{\partial \Delta B}{\partial x}\right)^2 + \left(\frac{\partial \Delta B}{\partial y}\right)^2 + \left(\frac{\partial \Delta B}{\partial z}\right)^2}$$

Where, is the residual magnetic field anomaly.

The Analytical signal has the form of the ridge located above the vertical contact and is slightly displaced when the contact is dipping with the crest of the ridge delineates the edge of the top surface. The width of a maximum or ridge is an indicator of the depth of the contact, as long as the signal arising from a single contact can be resolved [16]. The analytical signal map of the study area is generated after performing analytical enhancement filtering on the residual magnetic anomaly map already produced.

As can be seen from the map (Figure 5), forms of ridges, with magnetic anomaly peaks are observed both on the NE, SW, and central part of the mapped area. These observations seem to coincide with the magnetic anomaly highs identified in the residual magnetic anomaly map. These zones are also coincident with the zones where magmatic intrusions are associated with.

Accordingly, there are two evident structural contacts identified in Figure 7 with a general trend of NW-SE, and NE–SW, with the majority of these structural contacts aligned in an NW–SE trend.

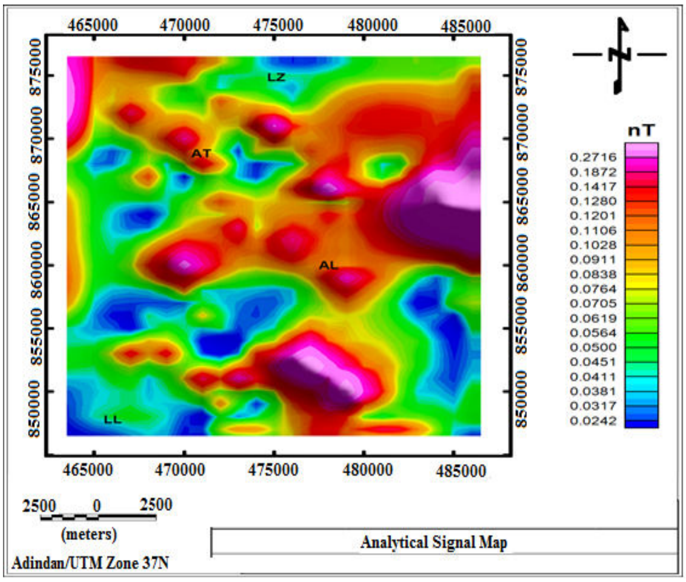

Figure 7: Analytical signal magnetic map. Where LZ (Lake Ziway), AT (Adami Tulu), AL (Aluto), and LL (Lake Langano).

Tilt derivative magnetic map: According to Miller and Singh the Tilt Derivative maps are used to locate the edges/ boundaries of geologic structures prevailing in a given area of study [17].

In the present work, the Tilt derivative of the Analytical signal map is generated and the map as depicted in (Figure 8), shows a more refined and detailed structural contacts/ boundaries (as delimited by the black broken lines, Figure 8) than was observed in the residual magnetic anomaly map and its counter analytical signal map.

According to the rules of interpretations of Tilt Derivative Maps, the maximum (peak) values in the map correspond to the contact or boundaries of geologic structures. As can be seen from the Tilt Derivative map of the Analytical Signal map generated in the present work, the study area is characterized by numerous structures delineated by contact/

boundaries. The result is in good agreement with the geologically studied surface results that the study area has been subjected to extensive faulting and fracturing activities throughout its geological history.

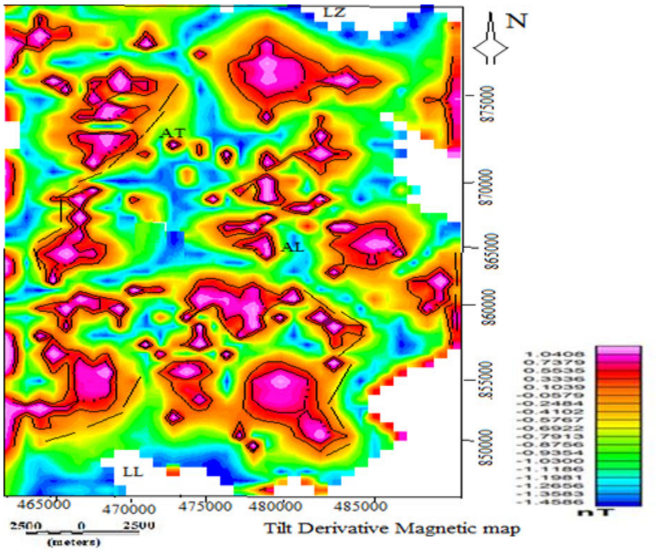

Figure 8: Tilt derivative magnetic map. Where LZ (Lake Ziway), AT (Adami Tulu), AL (Aluto), and LL (Lake Langano).

Euler deconvolution magnetic map: Euler deconvolution technique is applied in order to estimate the depth and location of the magnetic source. In standard Euler deconvolution process, each model contains solutions of a particular structural type defined by the structural parameter. The optimal structural index is selected by a visual inspection of maps which compiled using various structural indices until the best clustering of solutions is obtained. Based on this procedure, a structural index of 0 was determined and applied to the residual magnetic anomaly map to derive the Euler deconvolution map. The Euler deconvolution gravity map (Figure 9) of the study area is compiled by applying a standard 3D Euler deconvolution filter using the Geosoft Oasis Montaj software. The map reveals magnetic anomaly sources of different depths marked by different colored symbols plotted on the map. These include; a red circle indicating magnetic sources with depth greater than 900 m. The yellow circle indicates magnetic sources that range from 600-900 m depth. The blue triangles represent sources that range from 200-600 m in depth. The light green circles represent sources that are less than 200 m in depth. Generally, the magnetic Euler depth map shows that the prevailing geological features are located close to the surface with a depth range of fewer than five kilometers.

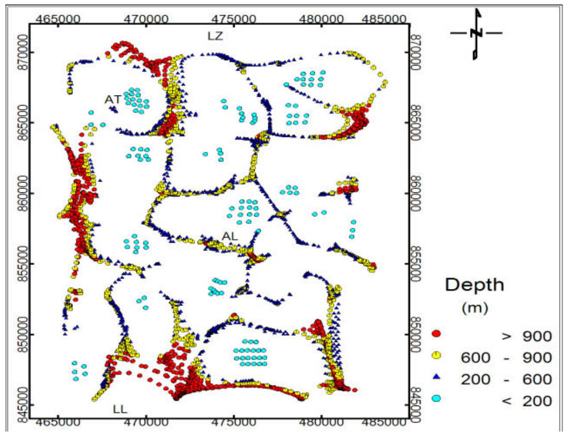

Figure 9: Euler deconvolution magnetic depth map for SI=0, Where LZ (Lake Ziway), AT (Adami Tulu), AL (Aluto), and LL (Lake Langano).

CONCLUSION

This Paper aimed to map subsurface structural influences on groundwater flow in the Ziway – Langano Corridor area, located in the central main Ethiopian Rift using a magnetic method. The conclusion is also confirmed by the existence of hot springs at the northern shore of Lake Langano which is missing at the southern shore of Lake Ziway. This work has shown that there are no east-west structures that favor the flow of groundwater. Hence, the direction of groundwater flow in the study area takes place from Lake Ziway towards Lake Langano being controlled by the N-S and NE-SW oriented faults and fractures mapped in the Ziway – Langano Corridor.

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