Posted on 28 Nov 2022 — The copyright holder is the author/funder. All rights reserved. No reuse without permission. — https://doi.org/10.1002/essoar.10503775.1 — This a preprint and has not been peer reviewed. Data may be preliminary.

Magnetic anomaly patterns and volcano-tectonic features associated with geothermal prospect areas in the Ziway-Shala Lakes basin, Central Main Ethiopian Rift

Hailemichael Kebede[1] and Abera Alemu[1]

[1]Addis Ababa University

November 28, 2022

Abstract

The Ziway-Shala Lakes Basin is a structural depression found in the Main Ethiopian rift being associated with Cenozoic volcanism, faulting and sedimentation activities. The Aluto-Langano volcanic complex is one of the geothermal prospect sites found in this basin and is currently being exploited for geothermal power production. Although it contradicts with the previous research results, recent observations using magneto-telluric method reveal nonexistence of a heat source beneath the Aluto volcano. Instead existence of a strong conductor possibly a magmatic heat sources claimed to occur beneath the Silti Debre Zeyet Fault Zone that lays far NW of the Aluto volcanic complex. In this study, ground based magnetic survey is carried out to map magnetic anomaly patterns and structural features associated with the Aluto-Langano. The volcano-tectonic features are extracted from the differentially pole reduced total magnetic field anomaly map and its derivative maps compiled by applying upward continuation, first vertical derivative and tilt derivative filters. Interpretation of the complied anomaly maps reveal existence of a heat conduction structural path along a traverse running from the Aluto-Langano geothermal to the Silti Debre Zeyte Fault zone and laying between 1.5 km and 3 km depths. This result could be taken to prove the most likely heat source feeding the Aluto-Langano geothermal field is found at about the locality of the Silti Debre Zeyte Fault Zone. The research work also identified magnetic lineaments most of which oriented in the direction of pre-existing Mesozoic structures and in the direction of thermally altered structures.

Magnetic anomaly patterns and volcano-tectonic features associated with geothermal prospect areas in the Ziway-Shala Lakes basin, Central Main Ethiopian Rift.

Hailemichael Kebede[1*], Abera Alemu[1]

[1]School of Earth Science, Addis Ababa University, P.O. Box 1176, Addis Ababa, Ethiopia

[*]Corresponding author: E-mail: hailekebede1995@gmail.com/hailemichael.kebede@aau.edu.et

Keywords: Magnetic anomalies, geologic structures, geothermal energy, magnetic lineaments, mathematical filters, thermal alteration

Abstract

The Ziway-Shala Lakes Basin is a structural depression found in the Main Ethiopian rift being associated with Cenozoic volcanism, faulting and sedimentation activities. The Aluto-Langano volcanic complex is one of the geothermal prospect sites found in this basin and is currently being exploited for geothermal power production. Although it contradicts with the previous research results, recent observations using magneto-telluric method reveal nonexistence of a heat source beneath the Aluto volcano. Instead existence of a strong conductor possibly a magmatic heat sources claimed to occur beneath the Silti Debre Zeyet Fault Zone that lays far NW of the Aluto volcanic complex. In this study, ground based magnetic survey is carried out to map magnetic anomaly patterns and structural features associated with the Aluto-Langano. The volcano-tectonic features are extracted from the differentially pole reduced total magnetic field anomaly map and its derivative maps compiled by applying upward continuation, first vertical derivative and tilt derivative filters. Interpretation of the complied anomaly maps reveal existence of a heat conduction structural path along a traverse running from the Aluto-Langano geothermal to the Silti Debre Zeyte Fault zone and laying between 1.5 km and 3 km depths. This result could be taken to prove the most likely heat source feeding the Aluto-Langano geothermal field is found at about the locality of the Silti Debre Zeyte Fault Zone. The research work also identified magnetic lineaments most of which oriented in the direction of pre-existing Mesozoic structures and in the direction of thermally altered structures.

1. Introduction

The reasons for the ever-growing need in consumption of energy worldwide are due to the increase in world population, industrialization and improvement in the standard of living (Gupta & Roy, 2007). Development strategy of countries worldwide are thus depends on the availability of the energy sources (Teklemariam & Kebede, 2010) which could include hydropower, geothermal, solar, wind, petroleum and coal energy. Ethiopia as a country has locational advantages where all these resources exist in plenty. These resources are either partly exploited or being under studies. Utilization of such natural resources generally requires understanding of the geology and geologic structures. Volcanisms, tectonism and sedimentation processes are responsible for such structures (Woldegabriel et al., 2000). Extensional tectonic activities in great East African Rift system (EARS) divide the Horn region in to two (Paola, 1972) and the dividing region in Ethiopia is called the Main Ethiopian Rift (MER). Associated with this tectonics, this region is volcanically active and is characterized by a number of volcanoes which could be the main source of geothermal energy. For example, the Aluto-Langano geothermal field has been established by drilling an eight exploration wells having depths ranging from 1300 m to 2500 m (Abera & Mizunaga, 2018) and a temperature ranging from ∼100 ◦C to ∼350 ◦C. The heat sources used for the geothermal energy were investigated using local seismic study conducted at Aluto volcano and was found below 9 km deep (Wilks et al., 2017). However, using Mageto-telluric (MT) data Samrock et al., (2015) arrived at a conclusion that no indication of an active deep magmatic system under Aluto. Following, the conclusion reached by Samrock et al., (2015); Hübert et al. (2018) generate 2-D electrical resistivity model of the crust using profile magnetotelluric data. The model was constructed along a 110 km transect crossing the whole rift and passing over Aluto volcanic center. The finding showed, the existence of a strong conductor near the Silti Debre Zeyt Fault Zone (SDFZ) (Fig. 1) approximately 40 km to the northwest of Aluto volcanic center (Hübert et al., 2018). It can be deduced from these observations that, there should be geology and geologic structures that is suitable for heat conduction between the claimed source location found nearby SDFZ and Aluto-langano geothermal field.

One of the scientific foundation for geothermal energy resource exploration in any given region is the knowledge of the geology (Weiler, 2007) and geologic structures (Moeck, 2014). These geology and geologic structures can be studied indirectly using geophysical methods through characterizing physical properties of rocks and layers geometries. Many rocks exhibit magnetic properties which are induced by the geomagnetic field or a remnant magnetization or a combination of both (Weiler, 2007). These rocks magnetic properties result in magnetic data collected on the surface to show diverse magnetic anomaly patterns. The anomalies could show varied anomaly signatures (low, intermediate or high) depending on underlying rocks type as sedimentary, igneous and metamorphic. However, at all study locations simple interpretation of magnetic anomalies may not reflect the causative sources beneath. For example, the Ziway-Shala lakes basin (Fig. 1) is found at geomagnetic equator where magnetic data interpretation and information extraction found to be difficult. At low geomagnetic latitude, the inducing field direction is horizontal and smaller in strength which complicates interpretation of the magnetic anomaly data (Hansen & Pawlowski, 1989). The magnetic data collected in this area doesn't reflect the causative source bodies beneath. One solution to these problem is to make use of mathematical filtering and pole reduction algorithms (Nabighian,1972; Hansen & Pawlowski, 1989; Li & Oldenburg, 2001; Cooper & Cowan, 2005; Arkani-hamed, 2007, Ellis et al., 2012; Aisengart, 2013) which will help to get rid of the problems encountered and make geophysical magnetic methods usable and interpretable in the area.

The environments in which the rocks are found also affect the magnetic anomalies signal intensity. For example, in a geothermal environment where temperatures is high, rocks-fluid interactions result in mineral transformations (alteration) (Tapia et al., 2016) and decreases rocks susceptibility values (Mariita, 2007). Analyses of magnetic data are therefore useful in mapping high-temperature hydrothermal/geothermal systems because hydrothermal processes can significantly alter and reduce the rock magnetic susceptibilities (Mariita, 2007) which intern signify low magnetic anomalies. The analyses include data processing, correction/reduction, gridding, pole reduction with low latitude problems into consideration (Cooper & Cowan, 2005) and the other filtering techniques (Werner, 1953; Spector & Grant, 1970;Verduzco et al., 2004; Mammo, 2012; H. Kebede et al., 2020).

The objective of this study is thus to map magnetic anomaly patterns and structural features related to geothermal activities in low latitude area of the Ziway-Shala lakes basin. This is performed through analysis and interpretation of differentially pole reduced total magnetic field anomaly map.

2. The Study Area Location, Geologic and Structural Settings

Ziway-Shala lakes basin is found in central Main Ethiopian rift (CMER) within Latitudes 7^{0}00’N-8^{0}30’N and Longitudes 38^{0}00’E-39^{0}30’E. It is surrounded by two adjacent basins and two adjacent plateaus (Fig. 1). Hawasa basin is found south of Ziway-Shala Lakes basin, in Southern Main Ethiopian Rift (SMER) and Awash basin is found north of Ziway-Shala Lakes basin, in Northern Main Ethiopian Rift (NMER). The two adjacent plateaus are called North-West and South-East plateaus (Fig. 1). The Ziway-Shala Lakes basin is bounded by alternating boundary faults that give rise to major fault escarpments separating the rift floor from the Ethiopian and Somalian plateaus (Fig. 1).

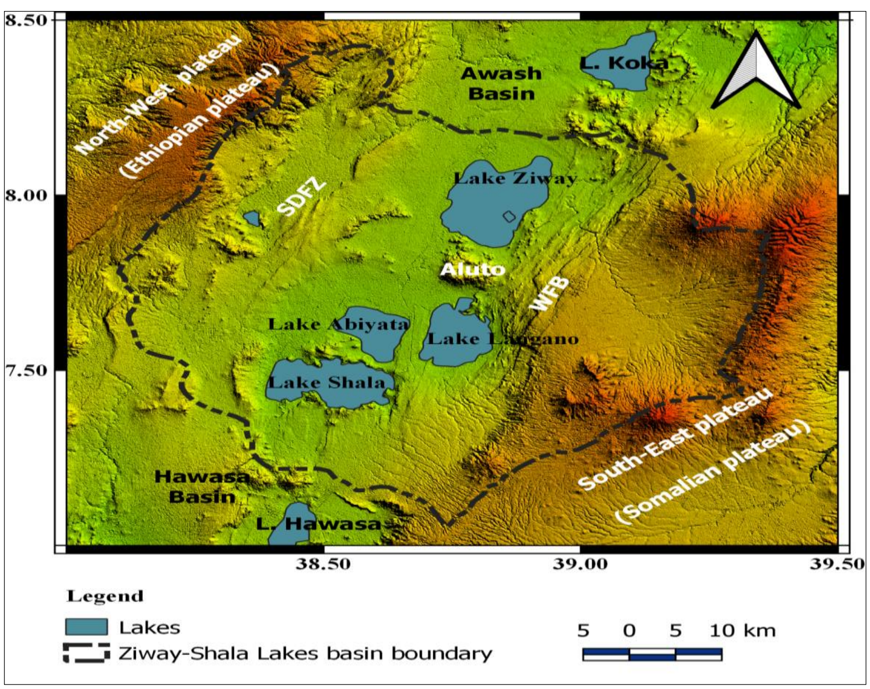

Fig. 1 Location and Elevation (Physiographic) map of the Ziway-Shala Lakes basin and surroundings, CMER

The geological map (Fig. 2 (a)) constructed by Ethiopian Geological Survey (EGS) shows outcropped rock distributions which is considered surface geology of the region (Tefera et al., 1996). The region is known by active extensional tectonics and associated volcanic activities as well as sedimentation processes (Woldegabriel et al., 2000). The processes have generated complex geological structures (Fig. 2(a)), geology (Fig. 2(a)) and geomorphology (Fig. 1). A non-volcanic rocks (Lacustrine sediments) (Paola, 1972), ignimbrites, basalt, tuff, pumice fall deposits, trachyitic and rhyolitic lava flows are the main rock types observed in the area (Fig. 2)(Paola, 1972) (Tefera et al., 1996). The geological map is overlaid by structural (faults) map and is shown in (Fig. 2(a)). These Cenozoic surface structures are orientated SSW-NNE to SW-NE, N-S and NW-SE (Agostini et al., 2011) (Molin & Corti, 2015) (Fig. 2 (a)).

The normal faults shown in Fig. 2(a) trends parallel to the rift axis and separates the NW and SE plateaus. These fault system are called Wonji Fault Belt (WFB) (Mohor, 1962) and Silti Debre Zyte Fault Zone (SDFZ) and their associated boarder faults (Fig. 2 (a)).

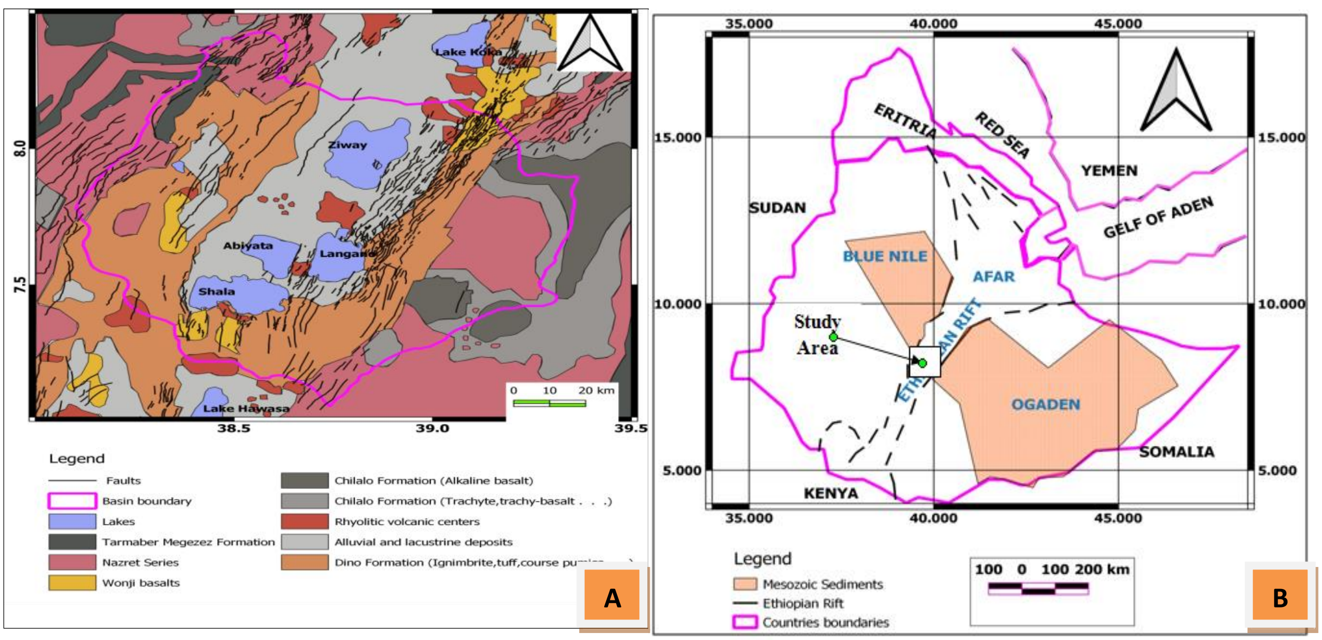

Fig. 2 Geological map modified from Tefera et al.(1996) and structural map modified from Agostini et al.(2011) and Molin and Corti (2015) (a) Map showing the pre-existing Mesozoic structures crossing the Cenozoic Main Ethiopian rift perpendicularly (modified after Mammo, 2010) (b)

The previous studies also show, the subsurface pre-existing Mesozoic structures which crosses the Cenozoic structures perpendicularly (Fig. 2(b)) and trends SSE-NNW to SE - NW (Fig. 2(b)) (Korme et al., 2004) (Abebe et al., 2007). These subsurface structures were identified through analysis of gravity data (Korme et al., 2004).

Massive and voluminous mafic and silicic volcanisms characterize the Cenozoic geological history (Ayenew, 2001) in the area. Several shield volcanoes were developed on the plateaus (Woldegabriel et al., 1990) and various volcanic episodes formed thick volcanic rock sequences (Ayenew, 2001). Though the MER is known by number of volcanoes, within the Ziway-Shala Lakes basin depression only Aluto volcanic center is active and currently productive geothermal resources. Volcanisms, tectonizm, sedimentation processes and reactivated pre-existing structures in the region formed the current complex geology and geological structures (Fig. 2(a)). These resulted in geophysical data collected in the region to show varied anomaly signatures (e.g. Fig. 6).

Seismic studies in Aluto-Langano geothermal indicated that the upper 2 km is interpreted in terms of hydrothermal system (Wilks et al., 2017). High seismicity and high b-values was observed which indicate a high fluid saturation and circulation. This fluid circulation is governed by subsurface geologic structures observed in the area (Saibi et al., 2012).

3. The Mathematical Filtering Methods used

Reduction to pole (RTP) is a filter where gridded observed magnetic anomalies are input to the operator to change asymmetric anomalies to a symmetric form (Cooper & Cowan, 2005). The operator is expressed in frequency domain given as (Eq. 1)

$$\boldsymbol{A}'(u,v) = \frac{A(u,v)}{(\boldsymbol{sin\theta} + \boldsymbol{i}\ \boldsymbol{cos}\ \boldsymbol{\theta}\ \boldsymbol{sin}(\emptyset + \boldsymbol{\alpha}))^2}. \quad (1)$$

Where, $A(u,v)$ is the amplitude at frequencies(u,v), θ and $\emptyset$ are the geomagnetic inclination and declination respectively and α is $\tan^{-1}(v/u)$

This is the standard operation which transforms magnetic anomaly caused by an arbitrary source into the anomaly that the same source would produce if it is located at the pole and magnetized by induction only. However, at low geomagnetic latitudes (with small inclination) where magnetic source bodies possess remnant magnetization, the operator (Eq. 1) amplifies the noise present in the data and produces unacceptable result (Fig. 3).

A new algorithm suggested (Cooper & Cowan, (2005)) is a Taylor series expansion in space domain (Eq. 2) and is called Differential Reduction to Pole (DRTP). This method solves the problems encountered in standard reduction to pole (RTP) **(Fig. 3).** The mathematical expression that solves the problem of standard reduction in low latitude area is the algorithm given by Cooper & Cowan, (2005) (Eq. 2)

$$RTP_{var} = RTP_{mean} + \Delta inc \frac{\partial RTP}{\partial inc} + 0.5\,\Delta inc^2 \frac{\partial^2 RTP}{\partial inc^2} + \Delta dec \frac{\partial RTP}{\partial dec} + 0.5\,\Delta dec^2 \frac{\partial^2 RTP}{\partial dec^2} + \ldots (2)$$

Where,

$\boldsymbol{RTP_{mean}}$ is the dataset reduced to pole using the average field inclination and declination of the area

$\Delta \boldsymbol{inc}$ is the difference between the inclination at a given point and the average inclination

$\Delta \boldsymbol{dec}$ is the difference between the declination at a given point and the average declination

The accuracy required by the space domain Taylor series expansion (Eq. 2) is guaranteed by analysis of remainder term of the Taylor series expansion of n terms given by (Eq.3(a) and Eq.3(b))

$$R_n = \frac{(x-x_0)^{n+1} f^{n+1} x^*}{(n+1)!} \quad (3(a))$$

where x^* lies between x and x_0. In terms of the pole reduction problem this becomes

$$R_n = \frac{\Delta inc^{n+1}}{(n+1)!} RTP_{MEAN}^{n+1} \quad inc^* + \frac{\Delta dec^{n+1}}{(n+1)!} RTP_{MEAN}^{n+1} \quad dec^* \quad (3(b))$$

Where, inc^* lies between 0 and Δinc, and dec^* lies between 0 and Δdec.

This algorithm is computationally simple as the derivative in the series is approximated by differencing and that might be the reason for the name Differential Reduction to Pole (DRTP) (Cooper & Cowan, 2005). In this study, the calculation of pole reduction using this algorithm is made using Oasis Montaj Geosoft software version 8.4.

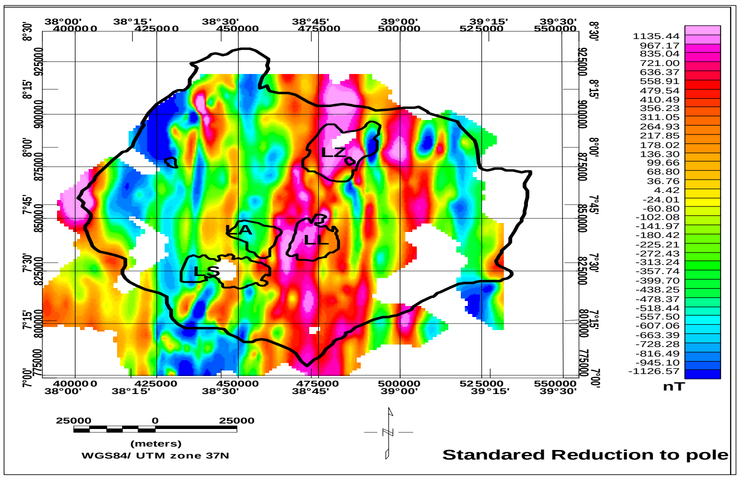

Fig. 3 Map showing the action of the standard reduction to pole operator on total magnetic field anomaly and instability of the standard RTP computation in Ziway-Shala lakes basin.

The first vertical derivative of gridded total magnetic field anomaly ($F = f(x, y, z)$) is defined mathematically as (Eq. 4)

$$FVDR = -\frac{\partial f}{\partial z} \tag{4}$$

The filter helps to locate magnetic susceptibility boundaries (edges of anomalies) of shallow earth origin by accentuating high frequency signals and obscuring broader regional (low frequency). The derivative grid map is compared with differentially pole reduced residual anomalies of the area for shallow Earth interpretation.

The tilt derivative (θ) of magnetic anomaly, **F**, is expressed as a ratio of its first vertical derivative to total horizontal derivative (Verduzco et al., 2004) (Eq. 5):

$$\theta = TDR = tan^{-1} \frac{\frac{\partial F}{\partial z}}{\sqrt{\left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2}} \qquad (5)$$

Where, $\frac{\partial F}{\partial x}, \frac{\partial F}{\partial y}$ and $\frac{\partial F}{\partial z}$ are the derivatives of the pole reduced magnetic anomaly, **F,** with respect to $x, y\ and\ z$ directions.

A mathematical property of arctan restricts the value of θ to lie between $-\frac{\pi}{2}$ and $-\frac{\pi}{2}$ or between-90^0 and 90^0.

This filter enhances and sharpens the anomalies with zero value contours (zero crossing) which indicate lithological /structural contacts. In this research, tilt derivative operator acted on differentially pole reduced residual magnetic anomaly grid to extract magnetic lineaments in the study region considered in this research work.

The derivative filters generally enhance effect of the shallower earth but not necessarily effect of the deeper earth. The regional anomaly resulting from the deeper earth is approximated using the upward continuation filter which is mathematically expressed by Gupta and Ramani (1980) and Jacobsen (1987) (Eq. 6) as:

$$H_{reg}(k) = S_0(k)\, e^{-2\pi k z_0} \qquad (6)$$

Where $S_0(k)$ is Bouguer anomaly, k is the wave number and $\boldsymbol{z_0}$ is the continuation height

The magnetic source signatures at different depth levels are isolated by upward continuing the observed differentially pole reduced magnetic field anomalies to a higher elevations. This is performed based on Jacobsen (1987) statement, stating when the potential field data is upward continued to a height $'\boldsymbol{z}'$; it maps the sources found at and below the depth $'\boldsymbol{\frac{z}{2}}'$.

4. Magnetic and Well-log Dataset

4.1 Magnetic Dataset

4.1.1 Total Magnetic Field Anomaly

A total of 855 ground based total magnetic field intensity data with their distribution shown in Fig. 4(a) were collected between the years 2014 and 2018 using Proton precession magnetometer. Out of 855 ground-based magnetic data collected 592 are secondary data collected by Dr. Abera in connection to MSC thesis works (Kebede, 2014) (Kelemework, 2016) and 263 are primary data collected by the principal author of this manuscript. These data sets are merged and a correction for main field was jointly made for the IGRF 2005 epoch. Finally, the reduced total magnetic field values are gridded to generate the total magnetic field anomaly map of the study area (Fig. 4 (b)). These anomalies reveal important information about crustal structures of the regions (Gabriel et al., 2011).

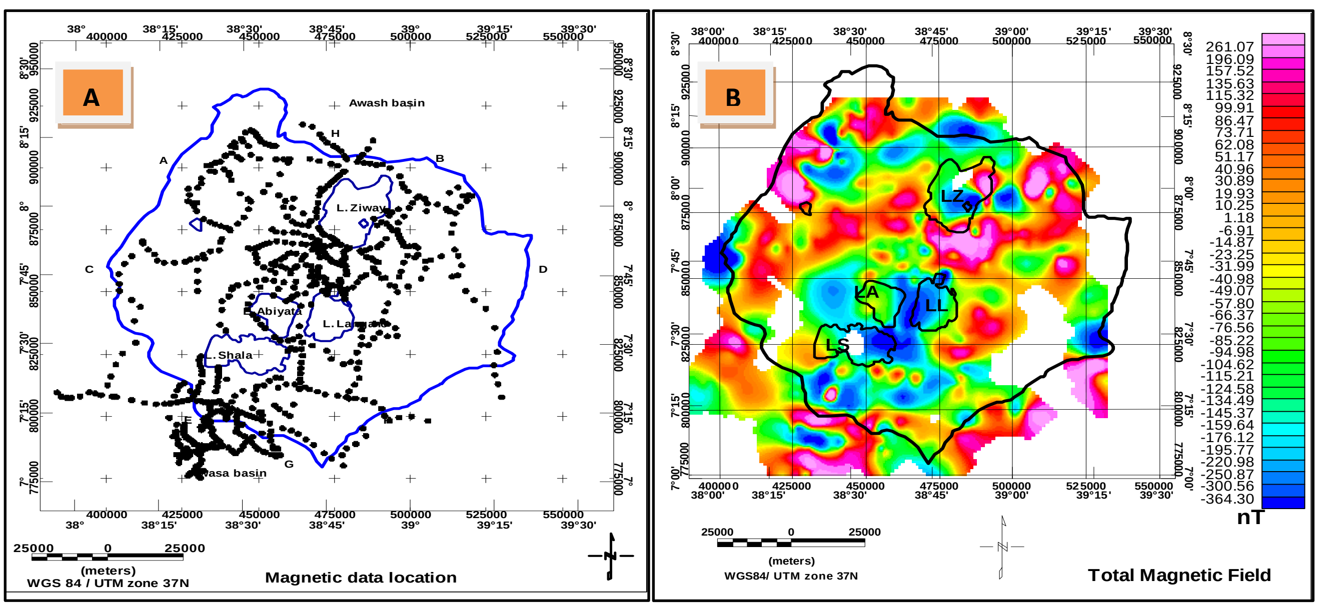

Fig. 4 Magnetic data stations distribution map (a) Total field magnetic anomaly map of the Ziway-Shala Lakes basin (b)

4.1.2 Magnetic Anomalies and causative geological source matching through Reduction to Pole

The magnetic anomaly map (Fig. 4(b)) shows a color contrast reflecting the subsurface geology in the region considered. However, the highs and lows shown may not occur over the sources generating them. This could be due to the fact that the survey area is located at low magnetic latitude where the direction (inducing field direction is horizontal) and strength of inducing field (magnetic field intensity is smaller) complicates interpretation of the magnetic anomaly data (Hansen & Pawlowski, 1989). These problems are solved through reduction to pole (RTP) filtering method. The standard RTP (SRTP) method can only be used for the region outside ±15° inclination. If used for regions lying within ± 15° latitudes (Silva, 1986) (Telford et al., 1990), it would mislead the interpretation by amplifying the noise present in the data (Rajagopalan, 2003); (Cooper & Cowan, 2005). To solve the problem of low latitude effects several researchers used methods such as Reduction to Equator (RTE)(Yao et al., 2010), FFT filtering (Li & Oldenburg, 2001), Wiener Filtering (Hansen & Pawlowski, 1989), Analytic signal (Nabighian, 1972), Differential reduction to pole (DRTP) (Arkani-hamed, 2007)(Cooper & Cowan, 2005) and Magnetic vector inversion (MVI) (Aisengart, 2013; Ellis et al., 2012) to substitute the standard RTP method. Though, each of the methods mentioned has a merit and demerit, each transformation technique has an advantage in magnetic data interpretation at low magnetic latitudes. For example, RTE is a filter which helps to centre anomalous bodies over their exact positions (Fig. 5), with the anomalies signatures switched. The lows become highs and the highs become the lows. In case of RTE (Fig. 5), the anomalies over magnetically susceptible bodies tend to show negative anomalies instead of positive anomalies.

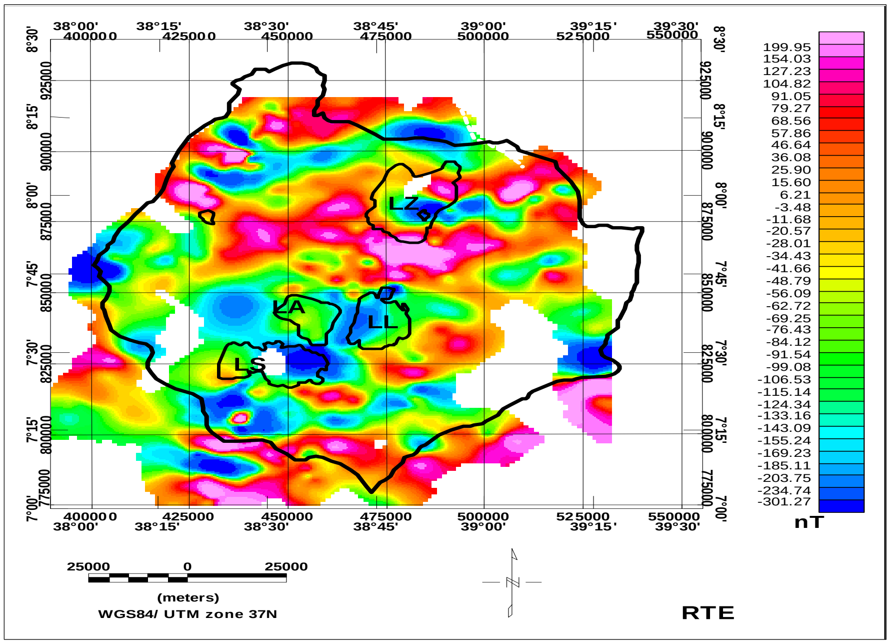

Fig. 5 Reduction to equator as estimation to RTP

The action of standard RTP operator at this area produces noised anomalies (Fig. 3) and the result produced doesn't reflect underlying geology and is unacceptable. Therefore, in this paper differential reduction to pole (DRTP) operator is applied to the total magnetic field anomaly for generating anomalies which are related with the causative sources locations. In other words, DRTP method can be used to reliably relocate magnetic anomalies over their sources (Fig. 6).

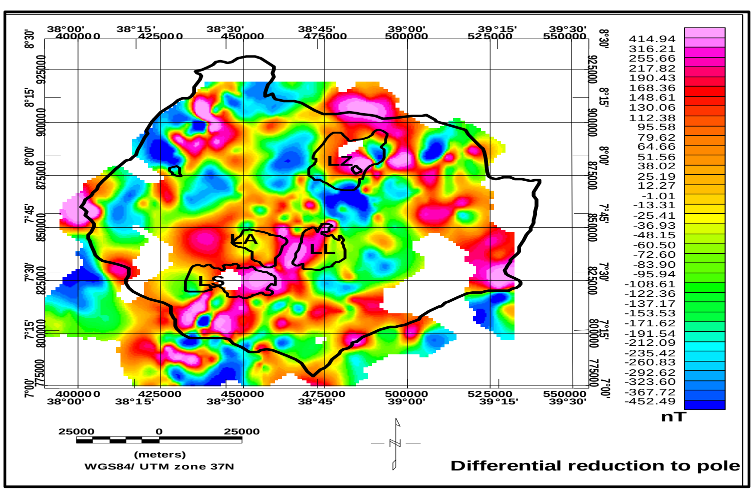

Fig. 6 Total magnetic field anomaly reduced to magnetic pole using DRTP

4.1.3 Magnetic Anomaly Causative Sources Signifying Deep and Shallow Subsurface Geology

Differentially pole reduced total magnetic field (Fig. 6) anomaly need to be separated in to regional (Fig. 9(a)) and residual (Fig. 9(b)) anomaly components to delineate the deep and shallow magnetic causative sources location respectively. The separation process is subjective and non-unique as there is no single best approach to approximate the low frequency signature (H. Kebede et al., 2020). Though there exist different methods (Keating et al., 2011), (Mammo, 2010), (V. K. Gupta & Ramani, 1980)(Xu et al., 2009), the most frequently used upward continuation is used to estimate the regional anomaly of the region. Therefore, differentially pole reduced total magnetic anomaly is upward continued to different continuation heights of 250 m, 1000 m, 2000 m, 3000 m, 4000 m, 5000 m and 6000 m (Fig. 7) to filter out the regional magnetic field trend. As the continuation heights increases the shallow magnetic field signatures get attenuated and the regional magnetic field signatures get magnified. Visually it is observed that (Fig. 7) at upward continuation height of 6 km, most of the shallow signatures removed.
This is also proved by extracted profile anomaly taken at $7^{0}45'$ latitude (Fig. 8). As the continuation heights increases the estimated regional anomalies signatures get smoothened. Therefore, the continuation height of 6 km is chosen as an estimate to the regional magnetic anomaly of the region (Fig. 7 (h)).

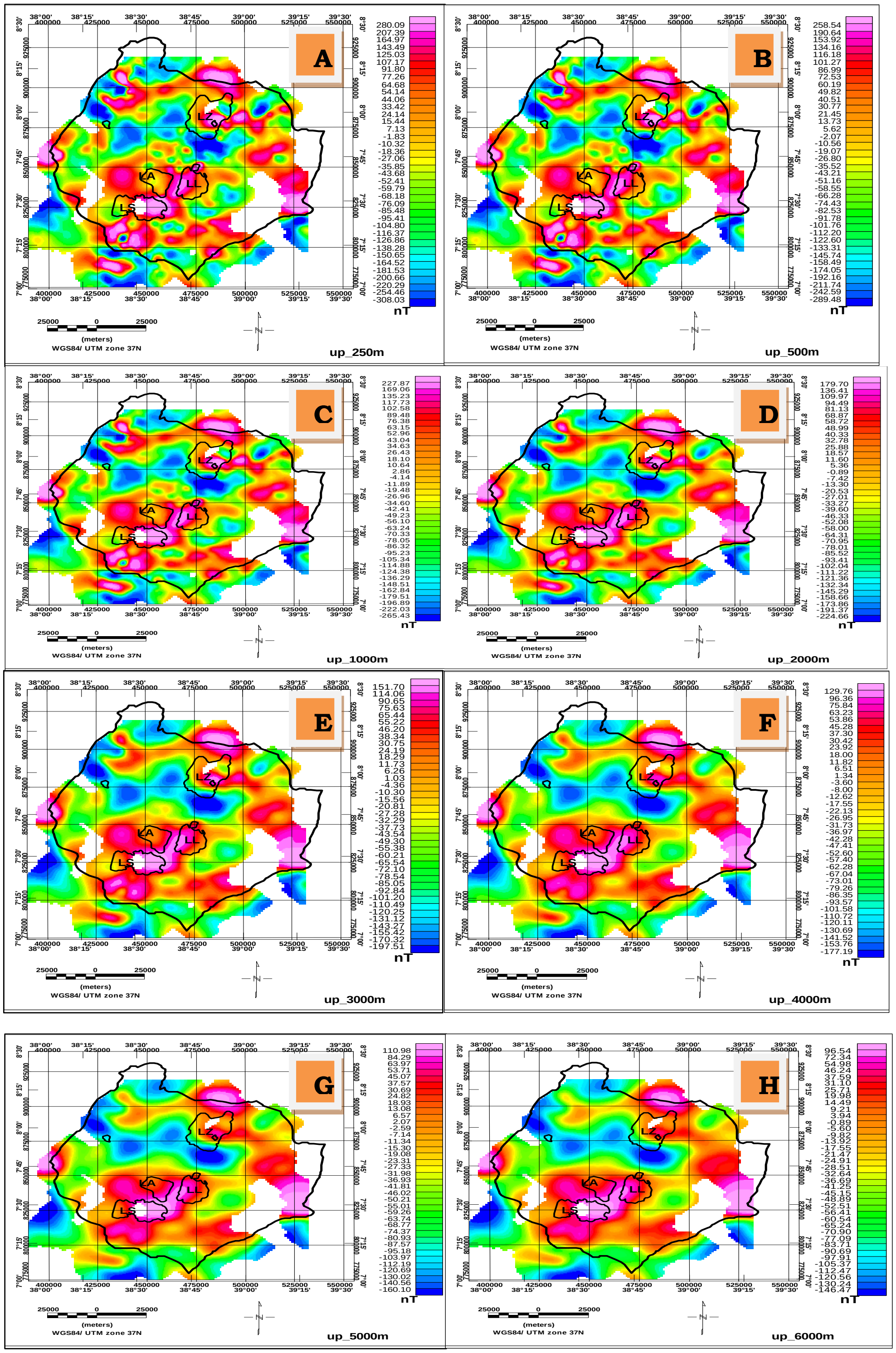

Fig. 7 Differentially pole reduced total magnetic anomaly upward continued to height of 250 m (a) to height of 500 m (b) to height of 1.0 km (c) to height of 2 km (d) to height of 3 km (e) to height of 4 km (f) to height of 5 km (g) to height of 6 km (h)

It is observed that the continuation height (6 km) used in gravity data decomposition (Kebede et al., 2020) is adopted to equally apply here for estimation of the regional magnetic anomaly. The estimated regional magnetic anomaly is then subtracted from differentially pole reduced total magnetic anomaly to compile the differentially pole reduced residual magnetic anomaly map (Fig. 9(b)) of the study area. These magnetic anomalies are then subjected to filtering operators to extract information of the subsurface.

4.2 Geologic Section constructed from Well-log Data

The results obtained from magnetic data analysis and interpretations are validated by well-log data drilled in the center of Ziway-Shala lakes basin. The geologic section shown in Figure 10 was assembled from core-samples obtained from eight boreholes drilled for the purpose of studying the geothermal resources at Aluto-Langano geothermal field. This west-east extending section were constructed by (Abera and Mizunaga, 2018; Wilks et al., 2017; Hutchison et al., 2016). The topmost layer is pyroclastic and lava flows, the second thin layer is lacustrine sediments which are used as clay cap over the hydrothermal system to seal the reservoir (Wilks et al., 2017), the third layer constituting Bofa basalt, tuff and berecia overlie the ignimrite formation and the lowermost and oldest layer is Tertiary ignimrite layer. This ignimbrite unit believed to hold geothermal reservoir (Wilks et al., 2017) in the area.

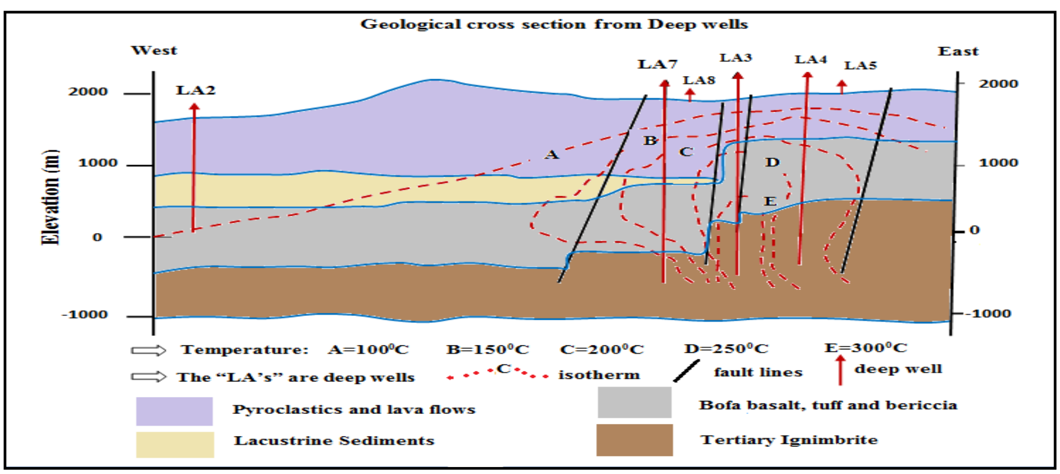

Fig. 10 West-east geologic cross-section derived from core samples of the deep geothermal wells drilled in the Aluto-Langano geothermal field modified from Abera and Mizunaga (2018).

5. Results and Discussion

5.1 Geothermal Related Structural Features

The geology and geologic structures of the region is identified by a simple visual observation (or qualitative interpretation) of the magnetic anomaly maps (Fig. 9 (a) and Fig. 9 (b)). As the study area lies in a rift environment where tectonic, volcanic and sedimentation processes are active, the magnetic anomalies arising from these features are observed to show widely ranging anomaly patterns consisting of positive and negative anomaly signatures. These patterns can be observed on the differentially pole reduced total magnetic field map (Fig. 6), regional magnetic anomaly map (Fig. 9(a)) and residual magnetic anomaly map (Fig. 9(b)). Particularly, the residual magnetic anomaly map (Fig. 9(b))) shows that the WFB and SDFZ are marked by maximum magnetic anomalies ranging from 103 - 333 nT (Fig. 9(b)). On the other hand, the minimum residual magnetic anomalies mark Silicic strata over which heat-flux in the form of surface hydrothermal activities are manifested. For example, the Aluto–Langano geothermal field is a well developed hydrothermal field associated with low magnetic anomaly patterns. The low magnetic anomaly observed on the total magnetic anomaly map over the Aluto geothermal field is seen to be extending down to a depth of 3 km. The magnetic anomaly lows beginning at Aluto and extending NW towards SDFZ and Western plateau border (Fig. 10 (a)) is thought to link thermally altered geologic structures. The temperature at Aluto volcanic center is increasing downward (Fig. 10) to the bottom most ignimbrite layer suggesting that the source of the hot water is directly below the area being exploited. However, the existence of the source beneath Aluto was disproved by Samrock et al. (2015) and the source was identified some 40 km NW of Aluto near SDFZ (Hübert et al., 2018). According to Wilks et al., (2017) the bottom most ignimbrite layer is used as geothermal reservoir. This layer is one of the linking structures that connect the Aluto with SDFZ (where the source clamed to exist). This study estimated thermally altered structures at shallow depth of 1.5 km and extending down to depth of 3 km where the reservoirs believed to reside. The depths range are read from upward continuation of differentially pole reduced total magnetic anomalies to heights of 3km, 4km, 5km and 6km. Ignimbrite geologic unit constitutes one of the top layer reservoir identified in magnetic data analysis in this research. The low anomaly observed along the traverse from Aluto to SDFZ is thought to be the effect of a heat source tending to decrease the magnetic susceptibility (rock magnetization) of the rocks by thermally altering susceptibility of magnetic minerals to have low values. A heat source (magma) occurring near SDFZ was discovered by Hübert et al. (2018) using Magneto-telluric (MT) data. Our investigation result reveals the existence of a heat conduction path along the traverse from the Aluto-Langano geothermal field to the SDFZ which might prove the existence of the heat source discovered by Hübert et al. (2018).

5.2 Magnetic Anomaly Patterns reflecting shallow and deep sources

The study area is located in an equatorial region where the inducing magnetic field is low and direction of an inducing field is horizontal. These phenomenons make magnetic interpretation made in the region difficult. However, with mathematical filtering techniques mentioned in section 2, the low latitude problems get resolved and the magnetic anomalies reflects the surface and subsurface geology of the region.

The rock magnetic properties of the shallow Earth, subsurface geologic structures and near-surface alteration in the study area cause the magnetic anomalies. Relationship between the near surface geology (Fig. 2(a)) and residual magnetic anomalies (Fig. 9 (b)) was made for better understanding of whether the anomalies pattern reflects the underlying surface geology or not. The first vertical derivative (Fig.11) filter of differentially pole reduced total magnetic anomalies is equally used to map the near surface geology (high frequency signature) of the area by suppressing the low frequency trend. Accordingly, the Silicic stratum at Aluto and Corbeti volcanic centers shows low magnetic anomalies signatures. The low magnetic anomalies are associated with heat effect in altering and reducing magnetic susceptibilities of rocks in the region considered. South of Shala Lake for example, low anomalies observed in between two high anomalies. The highs are because of Wonji basaltic lava flows and the low is because of ignimbrite, tuff and course pumice rock origin. At plane of Butajira the highs are due to Wonji basaltic lava flows. Though the interpretation of the magnetic anomalies is made with respect to surface geology, the anomalies also reflect the subsurface geology of the area. For example, North of Ziway Lake shows high magnetic anomalies. The highs are because of deep seated causative source (magnetic basement) than the shallow one. Similar interpretation is made for the remaining anomalies in the region considered.

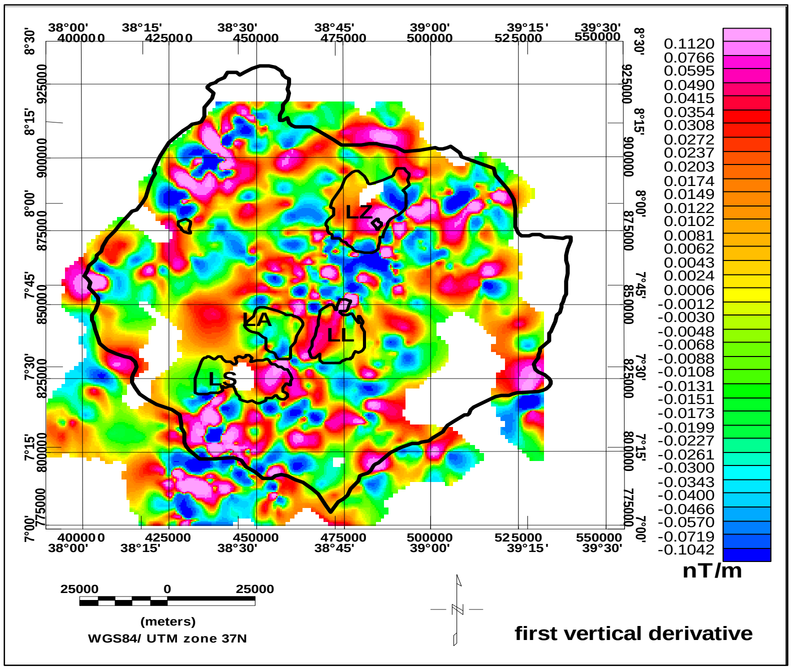

Fig. 11 The first vertical derivative of differentially pole reduced total magnetic anomaly showing the shallow magnetic sources

5.3 Magnetic Lineaments reflecting subsurface structures

Differentially pole reduced residual magnetic anomalies (Fig. 6) are subjected to various filtering algorithms in order to extract the subsurface (magnetic) lineaments in the study area. The tilt derivative operator is applied to differentially pole reduced total magnetic anomaly to compile the tilt derivative magnetic map (Fig. 12(a)). The map shows a tilt derivative values ranging between -1.35 and +1.33 rad. The zero contours values of tilt derivative map indicate geologic structures (susceptibility contacts) that are seen as linear features commonly known as magnetic lineaments. The map also shows subsurface structural features dominantly oriented NW-SE and NE-SW directions. Most these linear features are not visible on the structural map of the area (Fig. 2(a)). Moreover, the lineaments reveled on the tilt derivative map (Fig. 12 (a) or Fig. 12

(b)) can be observed to generally coincide with structural orientation of the Mesozoic pre-existing Ogaden rift (Fig. 2(b)).

The tilt derivative filter applied to differentially pole reduced total magnetic anomaly (Fig. 12 (a)), magnetic lineaments extracted from differentially pole reduced total magnetic field (Fig. 12 (b)) and the structural trend analyses using line direction histogram show that the main subsurface structures oriented SSE-NNW to SE-NW direction (Fig. 12(c)). The structural orientation is nearly similar to that of thermal structural orientation which trends NW from Aluto volcanic center (Fig. 9 (a)).

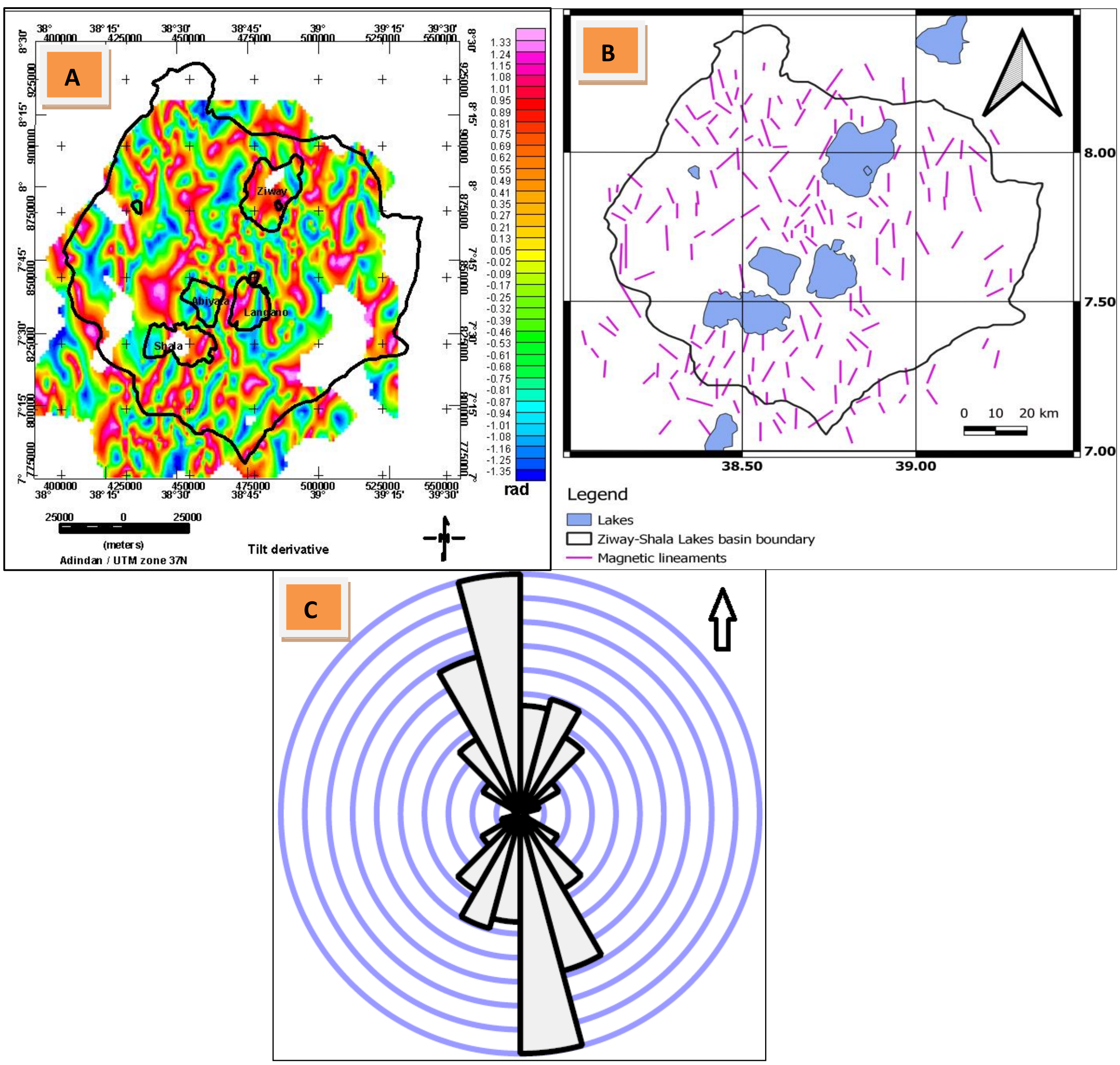

Fig. 12 Tilt derivative map compiled from differentially pole reduced total magnetic anomaly (a) showing magnetic lineaments of the Ziway-Shala Lakes basin extracted with zero contour tilt derivatives (b) and rose diagram (c) constructed based on magnetic lineaments (b) as an input to Line direction histogram algorithm.

Generally, the rock units in Aluto-Langano geothermal system (Fig. 10) are important parameters in governing the resource exploration and exploitation activities in Aluto-Langano geothermal field. Equally, the identified structural lineaments (Fig. 12 (b)) are important factors in governing the resource exploration works in the area. The study then claim the geothermal reservoirs at Aluto-Langano geothermal field are closely associated with heat flow systems. The role such geological structure play in controlling fluid flow in geothermal systems is documented in different research work in different study area (Siler et al., 2019).

6. Conclusion and recommendation

In such areas where volcanic, tectonic and sedimentation processes are active the geology and geologic structures observed in the region is very complex and shows a varying magnetic anomalies. The pre-existing Mesozoic rift structures crossing the region perpendicularly also add further complexity. Such complexities result in different geophysical data to be analyzed differently. For example, the ambiguous results among researchers on the existence of heat sources beneath Aluto-Langano geothermal field. Though it contradicts with the previous research result, recent observations reveal the non existence of heat source (magma) beneath the Aluto-Langano geothermal field. Using MT data a heat source (magma) was identified in Western side of the rift near SDFZ. Our investigation reveals the existence of a heat conduction structural path that conduits heat sources along the traverse from the SDFZ to the Aluto-Langano geothermal field. The results might prove the most probable heat source location near SDFZ and which could be used as a heat source for Aluto-Langano geothermal field. This path is recognized by low magnetic anomalies resulted from temperature induced reduction in rock's magnetic mineral content (magnetic susceptibility). Finally, the conclusions made in this manuscript are limited to the extent and distribution of magnetic data used. It is therefore, for better shallow Earth magnetic anomalies interpretation in the region it is recommended to consider a more refined and gridded magnetic data collection either airborne or ground based.

Acknowledgments

This manuscript is a part of PhD dissertation undertaken by the corresponding author at School of Earth Sciences, College of Natural Sciences in Addis Ababa University, under the supervision of co-author. Archiving the raw magnetic data used in this study is underway.

Authors' contributions

The principal author made magnetic data processing, analysis of the data, review literature, generates maps and wrote and edits the manuscript. The second author acts as a supervisor for the research and edits the results.

Competing interests

The authors declare that they have no competing interests.

References

Abebe, B., Acocella, V., Korme, T., & Ayalew, D. (2007). Quaternary faulting and volcanism in the Main Ethiopian Rift. *Journal of African Earth Sciences*, *48*(2–3), 115–124. https://doi.org/10.1016/j.jafrearsci.2006.10.005

Abera, B., & Mizunaga, H. (2018). Resistivity imaging of Aluto-Langano geothermal field using 3-D magnetotelluric inversion. *Journal of African Earth Sciences*, *139*, 307–318. https://doi.org/10.1016/j.jafrearsci.2017.12.017

Agostini, A., Bonini, M., Corti, G., Sani, F., & Manetti, P. (2011). Distribution of Quaternary deformation in the central Main Ethiopian Rift, East Africa. *Tectonics*, *30*(4), 1–21. https://doi.org/10.1029/2010TC002833

Arkani-hamed, J. (2007). Differential reduction to the pole : Revisited. *Geophysics*, *72*(1), 13–

20.

Ayenew, T. (2001). Numerical Groundwater flow Modeling of the Central Main Ethiopian rift Lakes basin. *SINET: Ethiopian Journal of Science*, *24(2)*(ISSN:0379-2897), 167–184.

Cooper, G. R. J., & Cowan, D. R. (2005). Differential reduction to the pole. *Computers and Geosciences*, *31*(8), 989–999. https://doi.org/10.1016/j.cageo.2005.02.005

Ellis, R. G., Wet, B. de, & Macleod, I. N. (2012). Inversion of Magnetic Data from Remanent and Induced Sources. In *22 nd International Geophysical Conference and Exhibition, 26-29 February 2012 - Brisbane, Australia* (pp. 1–4).

Gabriel, G., Vogel, D., Scheibe, R., Lindner, H., Pucher, R., Wonik, T., & Krawczyk, C. M. (2011). Anomalies of the Earth's total magnetic field in Germany – the first complete homogenous data set reveals new opportunities for multiscale geoscientific studies. *Geophysical Journal International*, *184*, 1113–1118. https://doi.org/10.1111/j.1365-246X.2010.04924.x

Gupta, H., & Roy, S. (2007). *Geothermal Energy: An Alternative Resource For The 21st Century* (First edit). Elsevier B.V.

Gupta, V. K., & Ramani, N. (1980). Some aspects of regional- residual separation of gravity anomalies in a Precambrian terrain. *Geophysics*, *45*(9), 1412–1426. https://doi.org/10.1190/1.1441130

Hansen, R., & Pawlowski, R. S. (1989). Reduction to the pole at low latitudes by Wiener filtering. *Geophysics*, *54*(12), 1607–1614.

Hübert, J., Whaler, K., & Fisseha, S. (2018). The Electrical Structure of the Central Main Ethiopian Rift as Imaged by Magnetotellurics : Implications for Magma Storage and Pathways. *Journal of Geophysical Research: Solid Earth*, *123*, 6019–6032. https://doi.org/10.1029/2017JB015160

Hutchison, W., Pyle, D. M., Mather, T. A., Yirgu, G., Biggs, J., Cohen, B. E., et al. (2016). The eruptive history and magmatic evolution of Aluto volcano: new insights into silicic peralkaline volcanism in the Ethiopian rift. *Journal of Volcanology and Geothermal Research*, *328*, 9–33. https://doi.org/10.1016/j.jvolgeores.2016.09.010

Jacobsen, B. H. (1987). A Case for Upward Continuation As a Standard Separation Filter for Potential-Field Maps. *Geophysics*, *52*(8), 1138–1148. https://doi.org/10.1190/1.1442378

Keating, P., Pinet, N., & Pilkington, M. (2011). Comparison of some commonly used regional residual separation techniques. *The Society of Exploration Geophysicists and the Chinese Geophysical Society*, (April 2016), 14–14. https://doi.org/10.1190/1.3659055

Kebede, B. (2014). Application of Gravity, Magnetic and Electrical Resistivity Methods for Geothermal Investigation at the Corbetii Caldera, Main Ethiopian Rift, Ethiopia. *MSC Thesis Work, Addis Ababa University*.

Kebede, H., Alemu, A., & Fisseha, S. (2020). Upward continuation and polynomial trend analysis as a gravity data decomposition , case study at Ziway-Shala basin , central Main Ethiopian rift. *Heliyon*, *6*, e03292. https://doi.org/10.1016/j.heliyon.2020.e03292

Kelemework, Y. (2016). *Integrated Geophysical Investigations of the Central main Ethiopian Rift and Adjacent Plateaus: An implication to Crustal Structure and Moho Depth Determinations. MSC thesis*.

Korme, T., Acocella, V., & Abebe, B. (2004). The Role of Pre-existing Structures in the Origin, Propagation and Architecture of Faults in the Main Ethiopian Rift. *Gondwana Research*, *7*(2), 467–479.

Li, Y., & Oldenburg, D. W. (2001). Stable reduction to the pole at the magnetic equator. *Geophysics*, *66*(2), 571–578.

Mammo, T. (2010). Delineation of sub-basalt sedimentary basins in hydrocarbon exploration in North Ethiopia. *Marine and Petroleum Geology*, *27*(4), 895–908. https://doi.org/10.1016/j.marpetgeo.2009.12.009

Mariita, N. O. (2007). The magnetic method. In *Presented at Short Course II Surface Exploration for Geothermal Resources, organized by UNU-GTP and KenGen, at Lake Naivasha, Kenya* (pp. 2–17).

Moeck, I. S. (2014). Catalog of geothermal play types based on geologic controls. *Renewable and Sustainable Energy Reviews*, *37*, 867–882. https://doi.org/10.1016/j.rser.2014.05.032

Mohor, P. (1962). *The Ethiopian Rift System*. Bull. Geophys. Observ., Addis Ababa, 5, 33–62.

Molin, P., & Corti, G. (2015). Topography, river network and recent fault activity at the margins of the Central Main Ethiopian Rift (East Africa). *Tectonophysics, 664*, 67–82. https://doi.org/10.1016/j.tecto.2015.08.045

Nabighian, M. N. (1972). The Analytic Signal of Two Dimensional Magnetic Bodies With Polygonal Cross-Section: Its Propertices And Use For Automated Anomaly Interpretation. *Geophysics*, *37*(3), 507–517.

Paola, G. M. D. I. (1972). The Ethiopian Rift Valley (Between 7 ° Off and 8 ° 40 ’ lat . North).

Rajagopalan, S. (2003). Analytic signal vs . reduction to pole : Solutions for low magnetic latitudes. *Exploration Geophysics*, *34*(4), 257–262.

Saibi, H., Aboud, E., & Ehara, S. (2012). Analysis and interpretation of gravity data from the Aluto-Langano geothermal field of Ethiopia. *Acta Geophysica*, *60*(2), 318–336. https://doi.org/10.2478/s11600-011-0061-x

Samrock, F., Kuvshinov, A., Bakker, J., Jackson, A., & Fisseha, S. (2015). 3-D analysis and interpretation of magnetotelluric data from the Aluto-Langano geothermal field, Ethiopia. *Geophysical Journal International*, *202*, 1923–1948. https://doi.org/10.1093/gji/ggv270

Siler, D. L., Faulds, J. E., Hinz, N. H., Dering, G. M., Edwards, J. H., & Mayhew, B. (2019). Three ‐ dimensional geologic mapping to assess geothermal potential : examples from Nevada and Oregon. *Geothermal Energy*. https://doi.org/10.1186/s40517-018-0117-0

Silva, J. B. C. (1986). Reduction to the pole as an inverse problem and its application to low-latitude anomalies. *Geophysics*, *51*(2), 369–382.

Tapia, J., Townley, B., Córdova, L., Poblete, F., & Arriagada, C. (2016). Hydrothermal alteration and its effects on the magnetic properties of Los Pelambres , a large multistage porphyry copper deposit. *Journal of Applied Geophysics*, *132*, 125–136. https://doi.org/10.1016/j.jappgeo.2016.07.005

Tefera, M., Chernet, T., & Haro, W. (1996). Geology of Ethiopia. *Geological Survey of Ethiopia*. Retrieved from www.gse.gov.et/index.php/geology-of-ethiopia

Teklemariam, M., & Kebede, S. (2010). Strategy for Geothermal Resource Exploration and Development in Ethiopia. In *Proceedings World Geothermal Congress* (pp. 25–29).

Telford, W. M., Geldart, L. ., & Sheriff, R. . (1990). *Applied geophysics (2nd ed.) Cambridge*. Cambridge University Press.

Verduzco, B., Fairhead, J. D., Green, C. M., & Mackenzie, C. (2004). New insights into magnetic derivatives for structural mapping. *Leading Edge*, (13), 116–119.

Weiler, P. D. (2007). Cross-references MAGNETIC ANOMALIES FOR GEOLOGY. *Encyclopedia of Geomagnetism and Paleomagnetism*, 477–482. https://doi.org/http://www.springer.com/978-1-4020-3992-8

Werner, S. (1953). Interpretation of Magnetic Anomalies of Sheet-like Bodies. *Sveriges Geologiska Arsbok, Stockholm*, *43*.

Wilks, M., Kendall, J. M., Nowacki, A., Biggs, J., Wookey, J., Birhanu, Y., et al. (2017). Seismicity associated with magmatism, faulting and hydrothermal circulation at Aluto Volcano, Main Ethiopian Rift. *Journal of Volcanology and Geothermal Research*, *340*(November), 52–67. https://doi.org/10.1016/j.jvolgeores.2017.04.003

Woldegabriel, G., Aronson, J., & Walter, R. C. (1990). Geology , geochronology , and rift basin development in the central sector of the Main Ethiopian Rift. *Geological Society of America Bulletin*, *102*, 439–458. https://doi.org/10.1130/0016-7606(1990)102<0439

Woldegabriel, G., Heiken, G., White, T. D., Hart, W. K., & Renne, P. R. (2000). Volcanism, tectonism, sedimentation, and the paleoanthropological record in the Ethiopian Rift System. *Geological Society of America*, *345*(January). https://doi.org/10.1130/0-8137-2345-0.83

Xu, Y., Hao, T., Li, Z., Duan, Q., & Zhang, L. (2009). Regional gravity anomaly separation using wavelet transform and spectrum analysis. *Journal of Geophysics and Engineering*, *6*(3), 279–287. https://doi.org/10.1088/1742-2132/6/3/007

Yao, L., Dian-Jun, X., & Ming, W. (2010). *Reduction to the Pole at the Geomagnetic Equator*. *CHINESE JOURNAL OF GEOPHYSICS* (Vol. 53). https://doi.org/10.1002/cjg2.1578