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Full Length Research

Qualitative aeromagnetic interpretation over Ikogosi Warm Spring, southwestern Nigeria

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ABSTRACT: In this paper, lineaments of Ikogosi warm spring and its environs have been delineated using qualitative methods. Boundary structures or lineaments between magnetic units were delineated using the first horizontal derivative map and skeletonization of derivative-based data. Also, the residual anomaly contour map was digitized into ten profiles, profiles' plots were made and used for interpretation. Dominant lineaments suspected were elongated features trending North East-South West direction and are housed by the shallow basements beneath the study area and surroundings.

Keywords: Lineament, magnetic induction ($B(R)$), observation and source locations (R and R_o), permeability of free space (μ_0), reduction to equator (RTE).

INTRODUCTION

Lineaments are a reflection of features such as fractures and faults. A fault is planar fracture or discontinuity in rock volume across which there is a significant displacement when there is a rock mass movement while the fracture is a form of separation or break in a rock formation that could form when lithosphere is pulled apart.

The term, lineament, is defined as a significant line of the landscape caused by joints and faults, revealing the architecture of the rock basement (Hobbs, 1904; Hobbs, 1912). And these features are mapped out at various scales, from local to continental. Lineaments are naturally occurring, linear topographic features in the earth crust unearthed via aeromagnetic imagery (Hobbs, 1904; Hobbs, 1912). They are also indication of prevailing tectonic activities in their embedded areas. The spring under investigation is attributed to the warm issue of water and is underlain by a very shallow basement that intruded from a profound depth to a near surface position. Tectonic activities are always accompanied by heat and the flow is channeled through the lineament which could add up to the subjacent heat source (radioactive isotopes) to cause the surface manifestation of heat and raise the temperature of the spring.

The features such as depth to basement, lineaments and the temperature of the issue are often used to characterize the settings of any potential geothermal reservoir. It is no doubt that the identification of shallow lineaments or lineaments near the surface or mean ground level of the studied area will provide clues on the tectonic activities of the area and consequently how the warm groundwater flows from profound depths to the surface. Some findings have been made earlier on Ikogosi warm spring which include studies to determine the curie depths (Olorunfemi et al., 2013; Abraham et al., 2014b) and describe the subsurface geological succession (Ojo et al., 2011). Curie point depths ranging from 5 to 16 km were obtained around Ikogosi warm spring by Abraham et al. (2014b). Ayobami and Lateef (2019) investigated depth to shallow basement which could accommodate the channels to the warm spring using aeromagnetic data with depths in between 2.98 to 290 m for Euler De-convolution method and 2.1 to 1311.4 m for Local Wave Number method.

Therefore, there is a need to further investigate this area using suitable techniques in order to reveal the trends and proximities of the basements of the study area.

Location of study area

The Ikogosi Warm Spring is located in the southwestern part of Ekiti State of Nigeria. It is situated between steep-

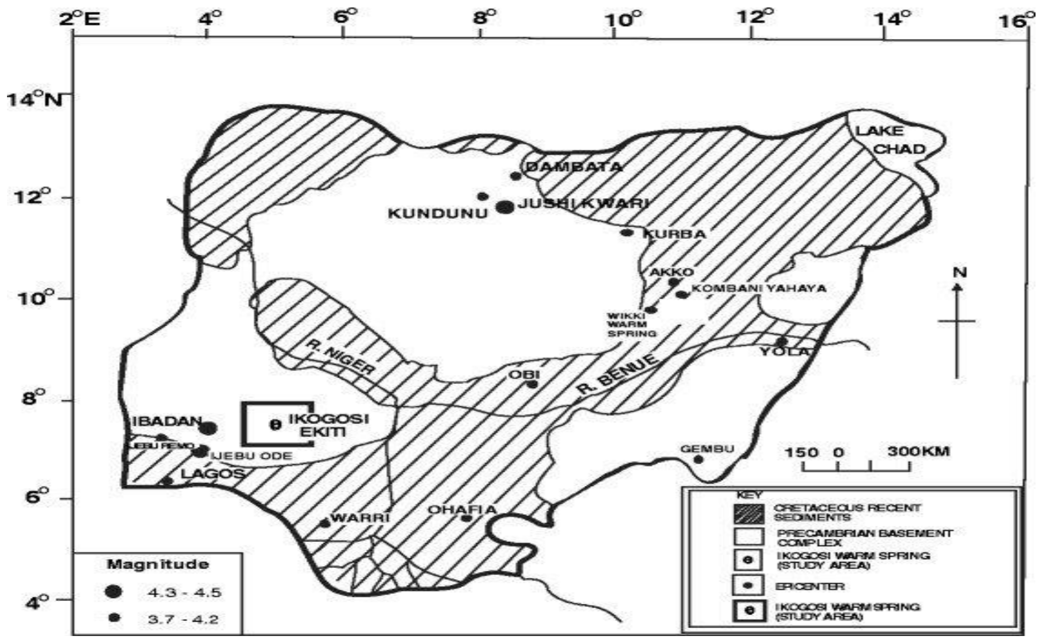

Figure 1. Location of Ikogosi Warm Spring in the basement complex of Nigeria (Adegbuyi and Abimbola, 1997).

sided and heavily wooded, north-south trending hills about 17 miles (approximately 27.4 km) east of Ilesha, and about 6.5 miles (approximately 10.4 km) southeast of Effon Alaye (Rogers et al., 1969). It lies on the geographic latitude of 7°35′N and longitude 5°00′E (Figure 1) within the central region of the area covered by this study. Located within the Precambrian basement complex of southwestern Nigeria, it is at an altitude of 450 to 500 m (Adegbuyi and Abimbola, 1997). The area is covered by the aeromagnetic map sheet 243 (Ilesha).

Geological setting of the study area

The warm spring issues with a temperature of 38°C near the foot of the eastern slope of the north-south trending ridge from a thin quartzite unit within a belt of quartzite which includes quartz-mica schist and granulitic migmatite east of Ilesha (Figure 2). The Okemesi quartzite member is characterized by a north-south trending ridge called the Effon ridge (Elueze, 1988; Oyinloye, 2011). The quartzitic rocks are composed of dominant quartz with muscovite, chlorite and sericite occurring in minor proportions (Adegbuyi and Abimbola, 1997). It was suggested that the source of springs in the Effon Psammite formation is associated with a faulted and fractured quartzite band sandwiched between schists (Rogers et al., 1969). Chemical data show that quartzite is largely metamorphosed sandstones containing minor arkosic intercalations (Elueze, 1988). On the basis of petrology, a medium pressure Barrovian and low medium pressure types of metamorphism had been suggested for the Precambrian basement rocks in southwestern Nigeria (Oyinloye, 2011).

It is believed that the intersections of the North North East-South South West epeirogenic belts with the North West-South East fracture trends in Nigeria coincide with the centres of warm springs like the Wikki (Bauchi State) and Ikogosi (Ekiti State) springs (Mbonu, 1990). The issue of the springs is controlled by permeability developed within the quartzite as a result of intergranular pore spaces coupled with the fracturing of the relatively competent quartzite (Rogers et al., 1969). The Effon Psammite formation is associated with the faulted and fractured quartzite band sandwiched between schists (Effon Alaiye location) as seen on the map (Figure 2). The Precambrian basement rocks of the region are composed of a migmatite-gneissic-quartzite complex and date from the Archean to the early Proterozoic (Oyinloye 2011). Granulitic migmatite together with quatz-mica schist (Figure 2) are also constituents of the quartzite belt. The dominant geology of Nigeria made mainly by crystalline (Precambrian basement complex) and sedimentary rocks (Cretaceous recent sediments) are also represented. The map also shows the locations of seismicity. The Ibadan and Ijebu Ode locations of seismicity appear closest to the study area (Figure 1). Rogers et al. (1969) stated that the source of the spring was related to a faulted as well as fractured quartzite band placed between schists.

THEORETICAL BACKGROUND

Earth's magnetic field

The largest component (80 to 90%) of the earth's magnetic field is believed to originate from convection of liquid iron

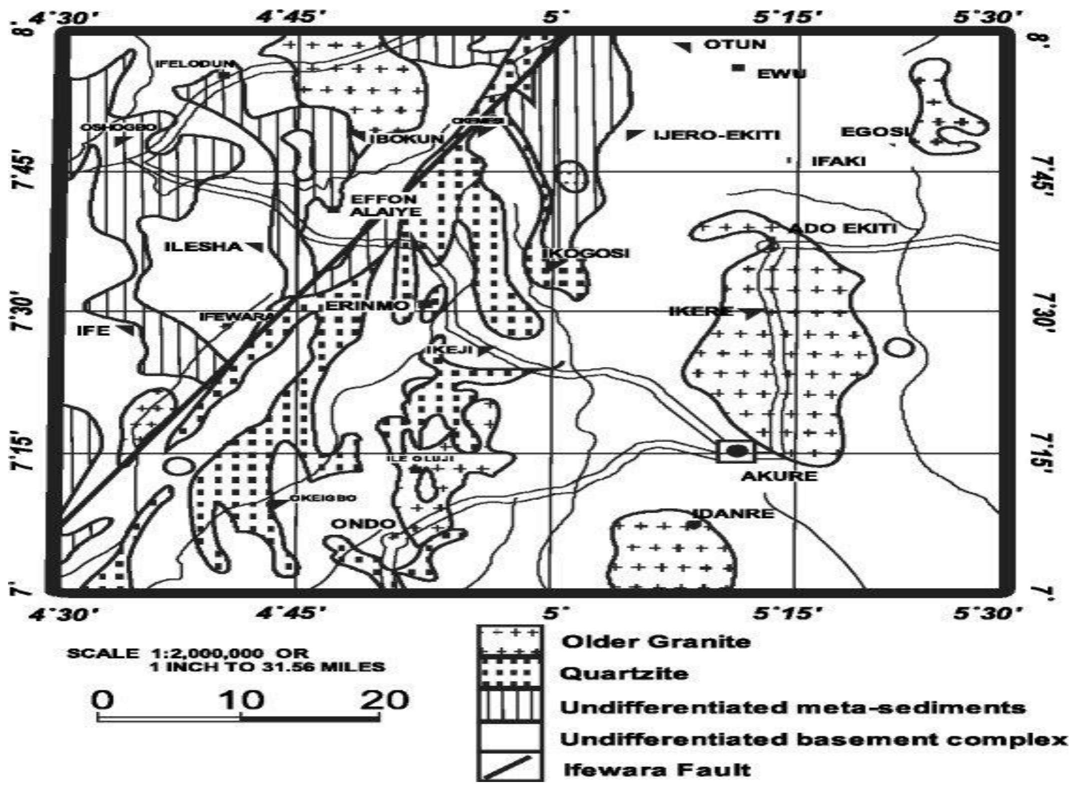

Figure 2. Geological map of the study area (Abraham et al., 2014).

in the earth's outer core. Also, currents induced in the earth by external field variations, permanent (remanent) and steady-state induced magnetizations of the crustal; rocks contribute to the overall geomagnetic field. The components of the geomagnetic field affect exploration surveys in a variety of ways.

The main dipole field

The prevailing component of the geomagnetic field to first-order approximation acts like a bipolar electromagnet located at the center of the earth but inclined at 11.50^o to the rotational axis. Geomagnetic poles are not the same as the magnetic or dip poles. Geomagnetic dipoles are located at the position where the magnetic field is directed vertically. The geomagnetic field is produced by electric currents induced within the conductive liquid outer core as a result of slow convective movements within it. With the exception of power lines and cathodically protected pipelines in which the magnetic fields are generated by currents, the bulk behaviour of these fields can be characterized by a vector quantity known as magnetization, M. The magnetic induction B, which is composed of the ambient earth's field and magnetic material in the subsurface is related to M by:

$$B(R) = \frac{-\mu_O}{4\pi}\int M\,(R_O).\ddot{\nabla}_o \frac{1}{R - R_o}\,dV_o \qquad (1)$$

Where μ is known as the permeability of free space and R and R_o are the observation and source locations, respectively.

The unit of magnetic induction is Tesla but nanotesla (nT) is used because of the varying large values of Tesla. Nearly all magnetometers used to measure the total magnetic intensity T, which is just the magnitude of the magnetic induction;

$$T = /B/ \qquad (2)$$

The magnetic induction in turn can be considered as being composed of the ambient earth's field, B_0 and a component ΔB due to the magnetic material in the subsurface. Generally, but not always, ΔB is much smaller than B_0, so we can approximate to first order in $\Delta B/Bo$:

$$T = /B/ + \frac{B_0}{/B_O/} * \Delta B = T_O + \Delta T \text{ T\_O+ } \Delta T \qquad (3)$$

The Total Magnetic Field B represents the sum of the magnetizing field strength and the magnetization of the medium:

$$B = \mu_0(1-k)H = \mu\mu_0 H \qquad (4)$$

Where: μ_0 is the permeability of free space (4×10^{-7} H/m)

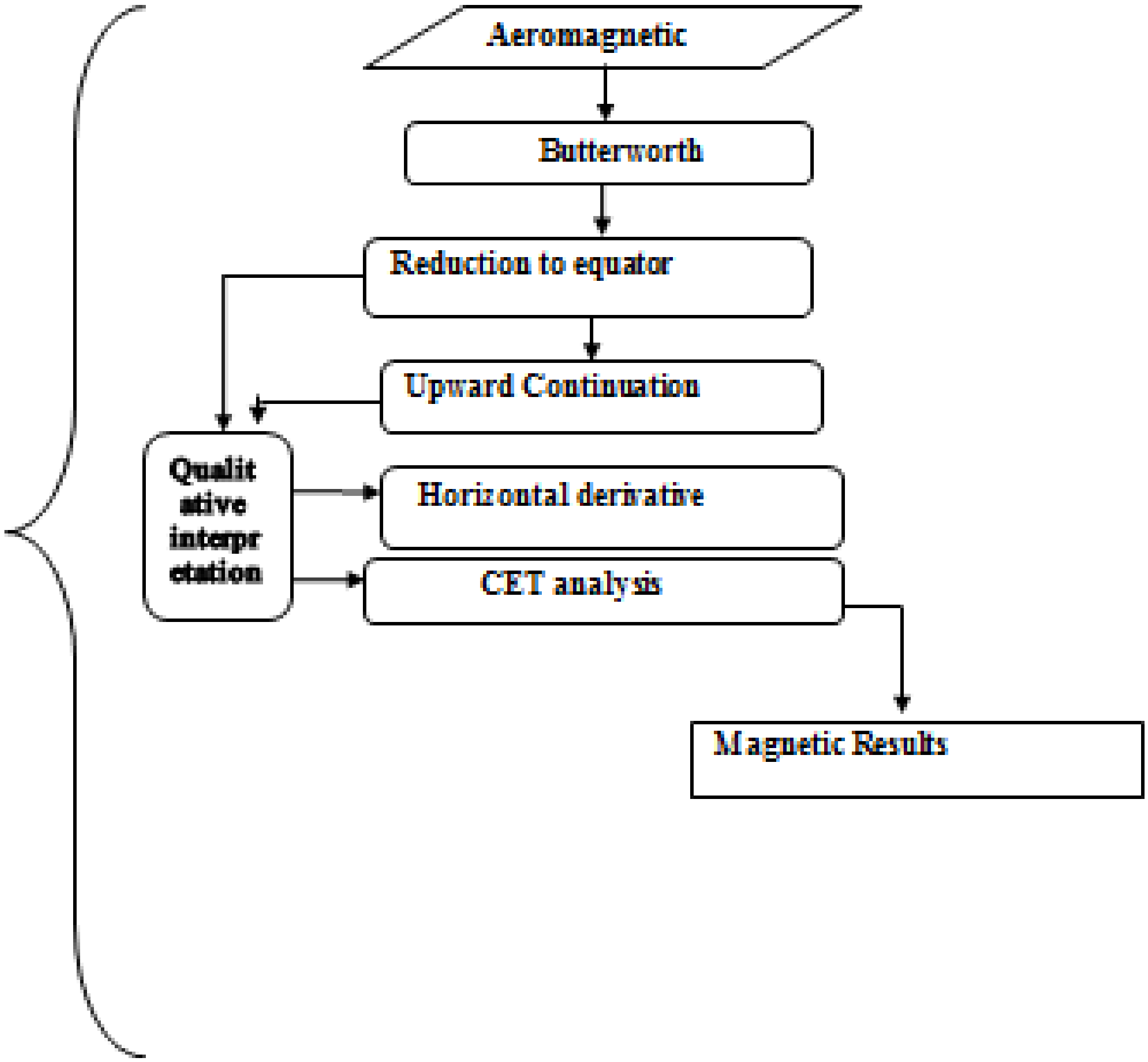

Figure 3. Study methodological flow chart (Lateef, 2017).

and B is also called the magnetic flux density or magnetic induction.

In geophysics, magnetic fields are small and measured in nT. Earth's magnetic field varies between 20,000 nT in the equator and 60,000 nT at the pole (Reynolds, 1997).

METHODOLOGY

The totality of magnetic processes involved in this study is summarized in a flow chart (Figure 3). A high resolution aeromagnetic data which are part of the airborne geophysical data of Nigeria acquired by Fugro Exploration in 2008 and published by the Geological Survey Agency of Nigeria (GSN) on a total magnetic intensity map scale of 1:100,000 were processed and interpreted to yield the set objectives. The data were leveled, cultural-edited, high frequency noise filtered before further processing. Error correction, spike removal, gridding were carried out prior to other filtering operations to yield the proposed target.
Subsequently, the general description of the survey results and the explanation of the major features called anomalies which can be geological formation and/or structures were discussed. As explained in the research methodology flow chart, the qualitative interpretation was performed using grids of residual field of the total magnetic intensity, reduction to the equator, upward continuation to 1km, horizontal derivatives and CET (centre for exploration targets) analysis for a lineament map. The aeromagnetic data were input into the Geosoft Oasis Montaj software that processed them into grids and maps after which the gridded data was contoured on Surfer. The output results were then interpreted qualitatively.

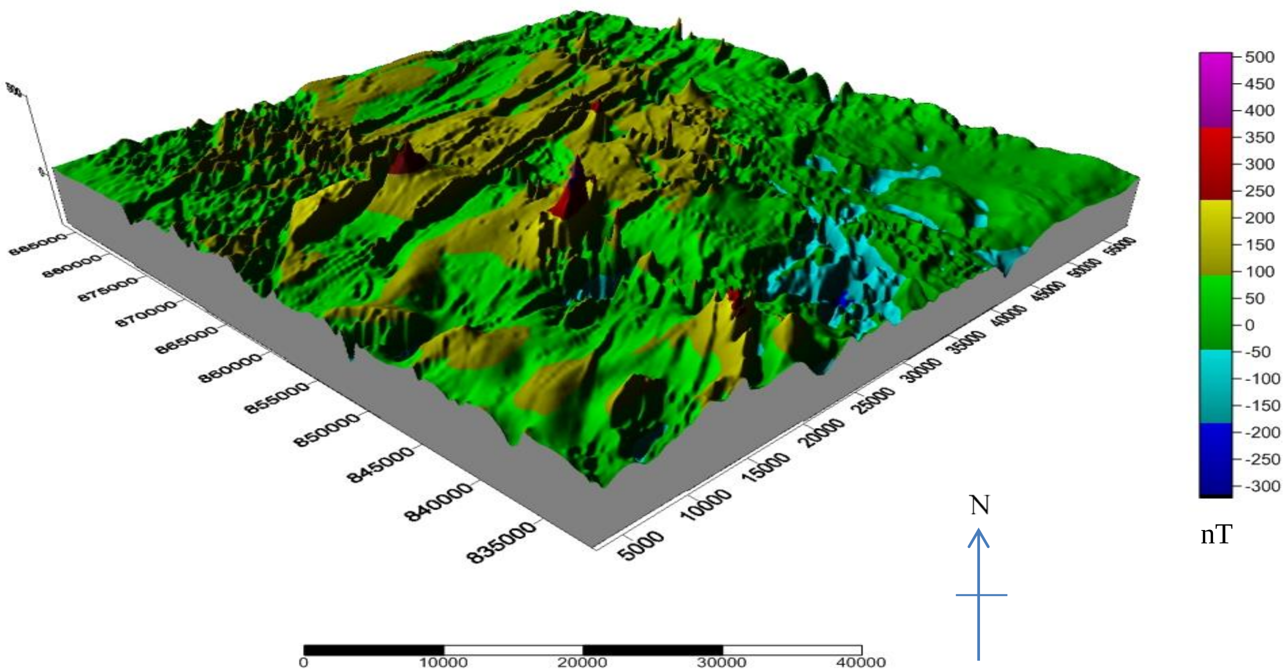

Figure 4. 3-D surface map of study area.

RESULTS AND DISCUSSION

Presentation and Interpretation

Interpretation of aeromagnetic data is better done using a 3-D image (Figure 4). The 3-D image was used together with Figure 2 to make the following inferences. The regions (shaded purple/dark red) with spikes have high magnetic intensities indicating features that are rich in ultra-mafic minerals and are suspected to be igneous rock (undifferentiated). The regions (shaded green) with low positive anomalies are indicating features with low magnetic contents and correlates well with undifferentiated meta-sediment. The regions (shaded deep yellow) have moderate magnetic intensities. These are indicating features with appreciable magnetic contents and are suspected to be igneous rocks.

The regions (shaded with either light blue or deep blue surrounded by green) have low negative anomalies and are indicating features with very low magnetic contents (Figure 4). This shows that these low negative anomaly features (light/deep blue) are rimmed by the low positive anomaly features (green). And these regions are suspected to be differentiated (fractured/faulted) metasediment basement rocks.

Profile plots presentation and interpretation

The residual anomaly field data were digitized into ten profiles as shown in Figure 5 and profile data were plotted. The profile plots of the digitized residual anomaly field data are presented here for qualitative interpretation.

Profile AA^{I} has positive anomaly amplitudes of 0.045nT and 20.56nT (Figure 6a). This correlates well with a deep magnetic source (quartzite basement).

Profile BB^{I} has positive anomaly amplitude of 69.33nT and low negative anomaly amplitude of -114.60nT (Figure 6b). The positive anomaly correlates well with shallow magnetic source/basement with appreciable magnetite content (undifferentiated metasediment). The low negative anomaly correlates well with intensely fractured/faulted zone sandwiched in a quartzite basement.

Profile CC^{I} has positive and low negative anomaly amplitudes of 47.27nT and -105.50nT (Figure 6c). The positive anomaly correlates with a source having appreciable magnetite content (undifferentiated metasediment) while the low negative anomaly suggests intensely fractured/faulted zone sandwiched in a shallow quartzite basement.

Profile DD^{I} has positive and low negative anomaly amplitudes of 93.60nT and -123.32nT (Figure 6d). The positive anomaly suggests deep magnetic source with high magnetite content while the very low negative anomaly sloping down the profile and enveloped by positive anomaly is suspected to be a fractured/faulted zone rimmed by a shallow quartzite basement.

Profile EE^{I} has high positive anomaly of 147.73nT and low

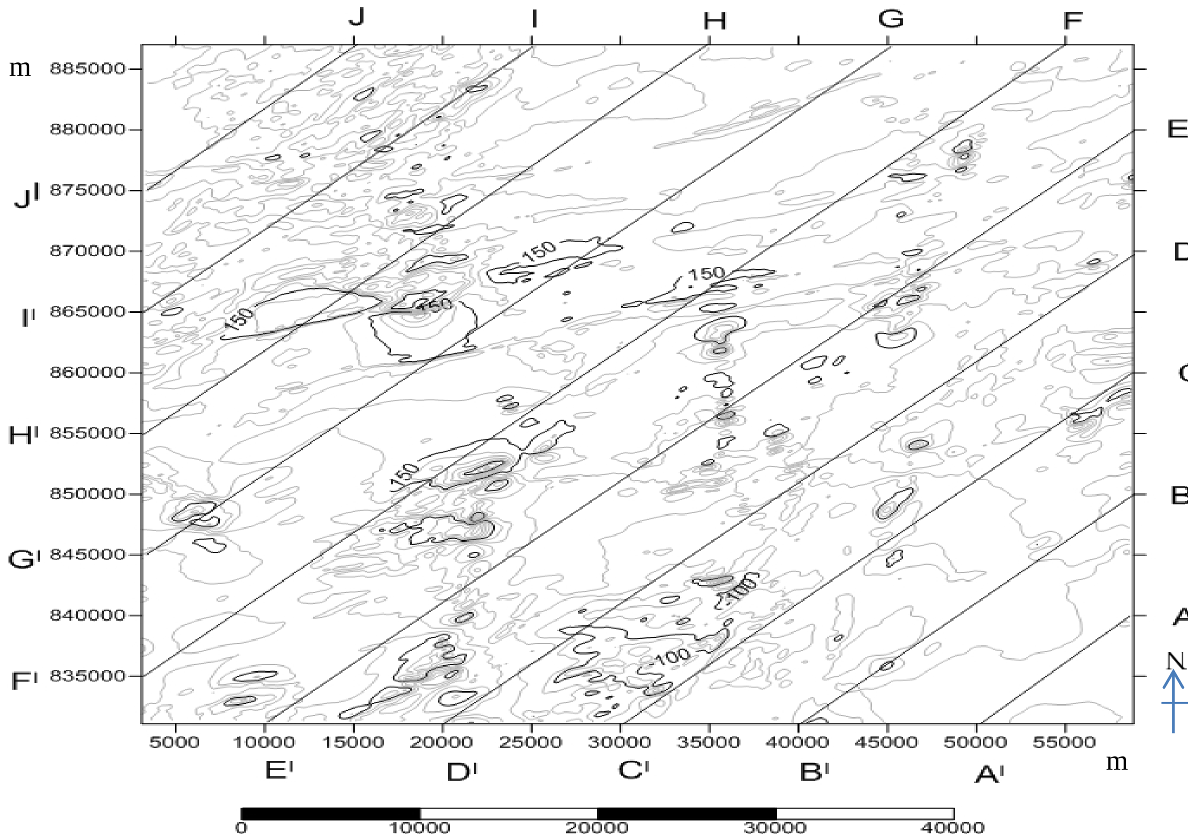

Figure 5. Residual anomaly contour map showing the profile lines made in the directions NE-SW.

negative anomaly amplitude of -121.03nT (Figure 6e). The positive anomaly correlates well with shallow magnetic source/feature that is rich in magnetite content (igneous). The low negative anomaly is rimmed by a positive anomaly and it correlates well with intensely fractured/faulted zone sandwiched in a shallow quartzite basement.

Profile FF^{I} has a very high positive anomaly and high negative anomaly amplitudes of 250.30nT and -8.11nT (Figure 6f). The positive anomaly suggests shallow magnetic basement with very high magnetite minerals (undifferentiated igneous) while high negative anomaly suggest a slightly fractured basement.

Profile GG^{I} has high positive and very low negative anomaly amplitude of 199.12nT and -129.31nT (Figure 6g). The positive anomaly suggests magnetic basement with high magnetite minerals (undifferentiated igneous) while negative anomaly suggests an intensely fractured/faulted shallow basement (metasediment).

Profile HH^{I} has low negative and high positive anomaly amplitude of 217.16nT and -41.81nT (Figure 6h). The positive anomaly suggests undifferentiated shallow magnetic basement (igneous) while the negative anomaly suggests slight fractured basement (metasediment).

Profile II^{I} has high positive and low negative anomaly amplitudes of 163.nT and -113.56nT (Figure 6i). The positive anomaly suggests undifferentiated shallow magnetic basement (igneous) while the low negative anomaly suggests intensely fractured/faulted basement (metasediment).

Profile JJ^{I} has positive and high negative anomaly amplitudes of 92.55nT and -14.52nT (Figure 6j). The positive anomaly suggests deep magnetic basement with high magnetite contents (igneous) while the high negative anomaly suggests a slightly fractured basement.

Low/negative magnetic peak profiles represent typical anomaly- signatures in low-latitude magnetic regions (around the equator where Nigeria is located) (Parasnis, 1986). Correlating these low/negative peaks from profile to profile may delineate fault line/fault zone or magnetic bearing fault zone.

Profile BB^{I}, CC^{I}, DD^{I}, EE^{I}, GG^{I} and II^{I} have linear trend of low /negative magnetic peaks as suggested earlier, shallow seated anomaly sources were suspected and correlated to features that are intensely fractured/faulted elongating in North East-South West direction and are sandwiched in the quartzite basements/basement complex.

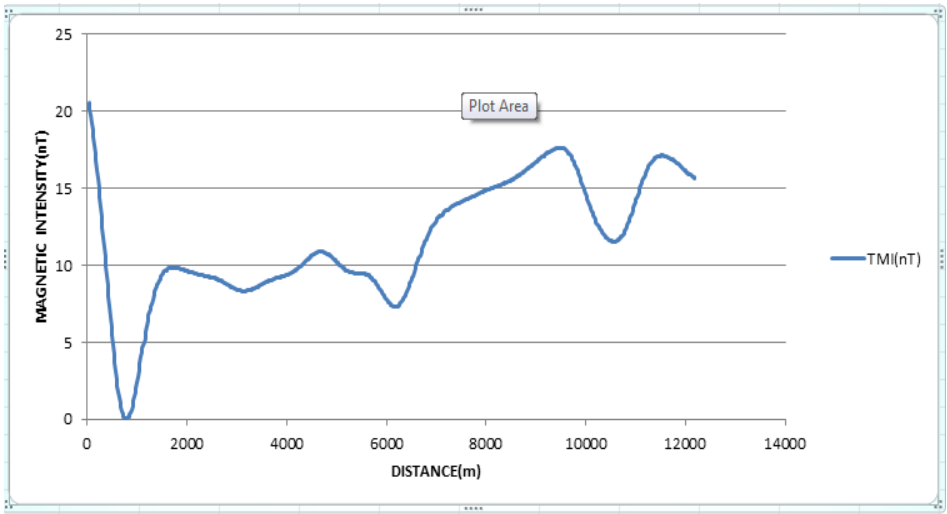

Figure 6a. Profile line AA^{I}.

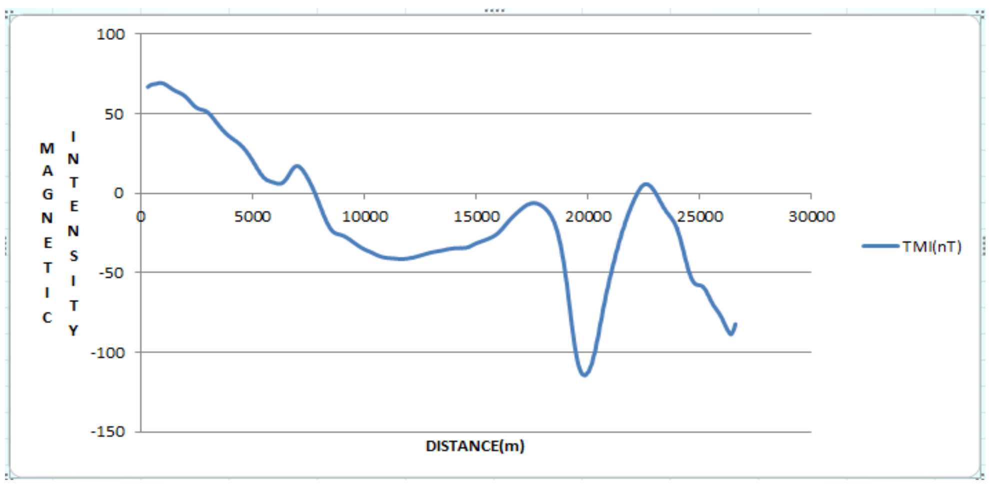

Figure 6b. Profile line BB^{I}.

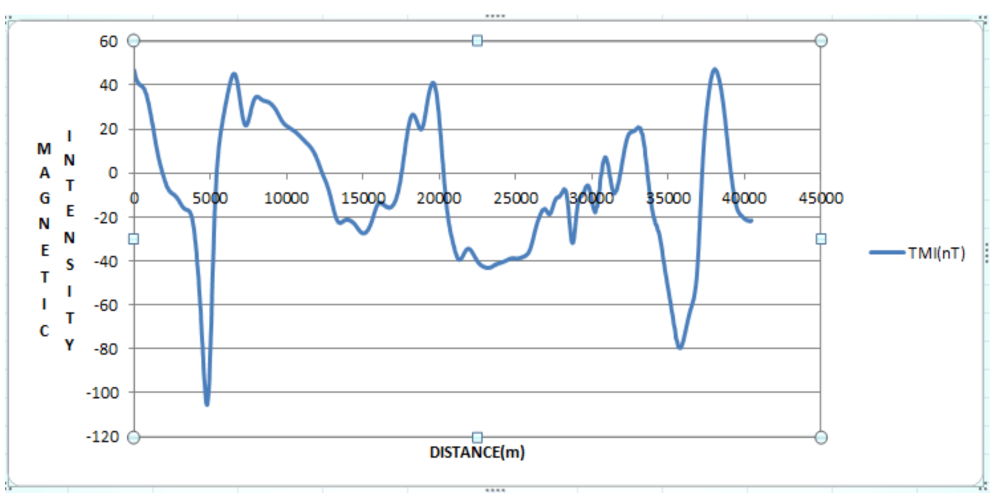

Figure 6c. Profile line CC^{I}.

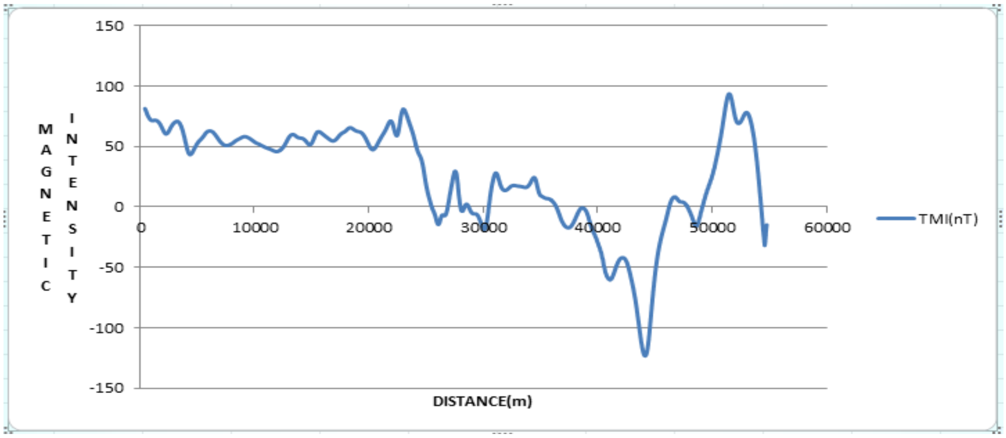

Figure 6d. Profile line DD^{I}.

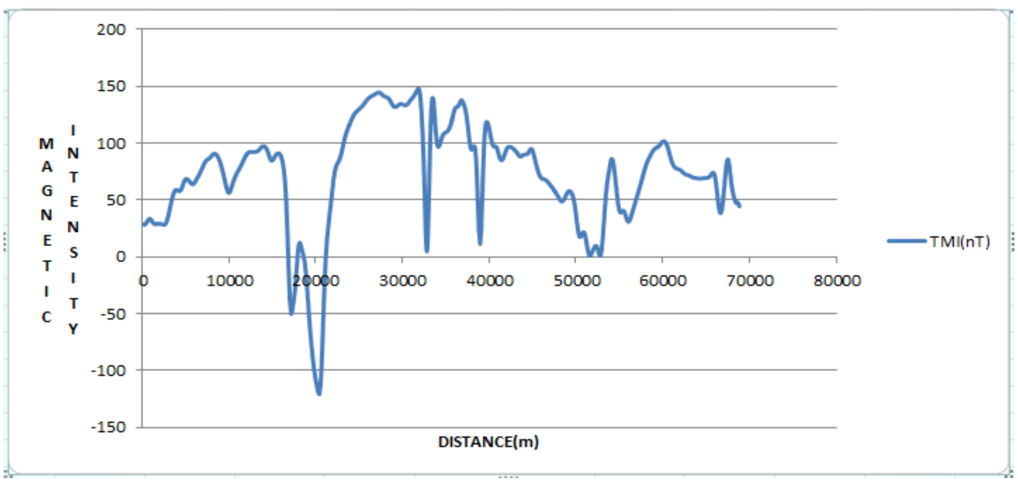

Figure 6e. Profile line EE^{I}.

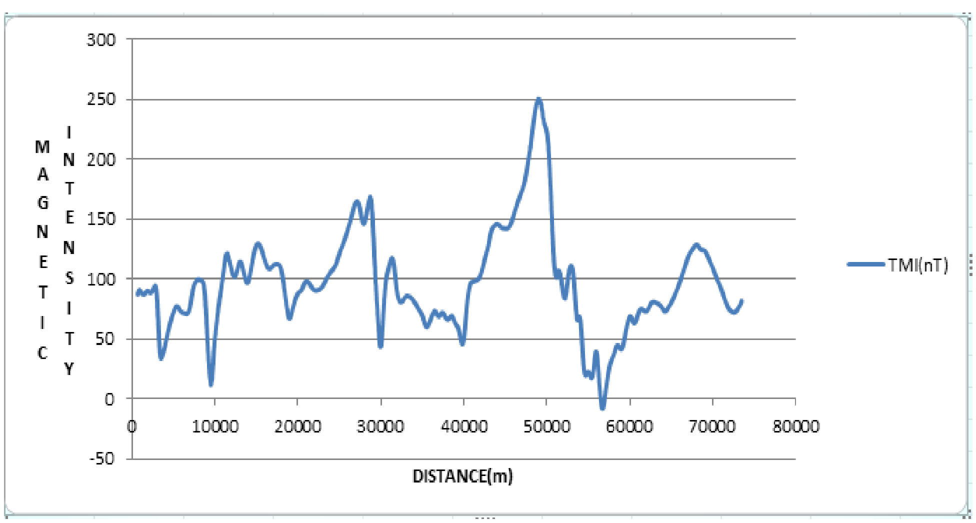

Figure 6f. Profile line FF^{I}.

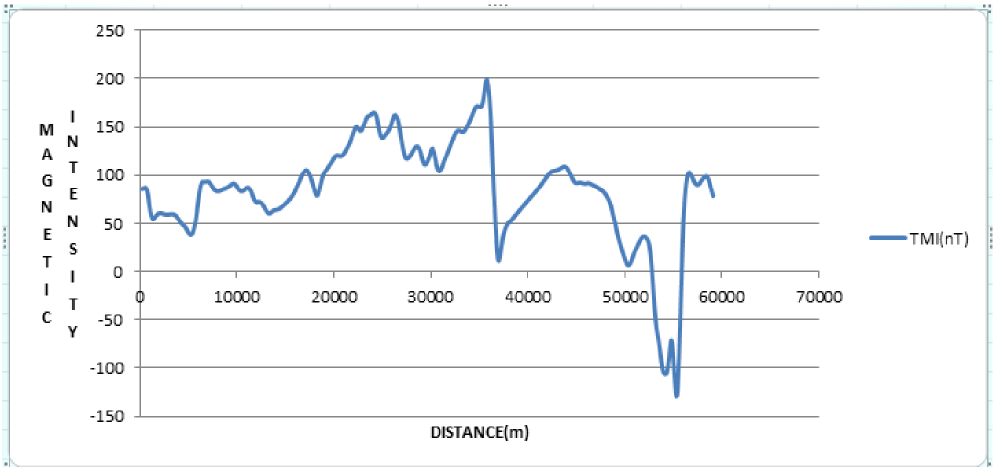

Figure 6g. Profile line GG^I.

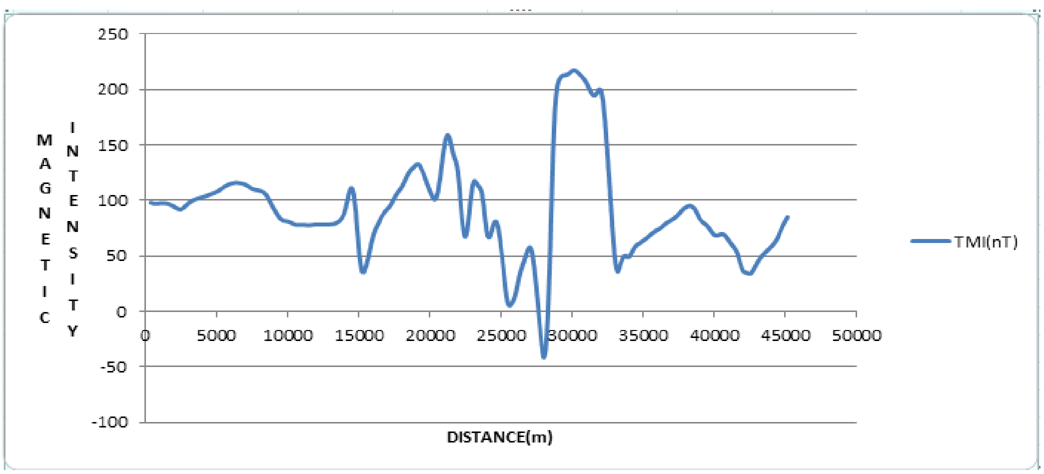

Figure 6h. Profile line HH^I.

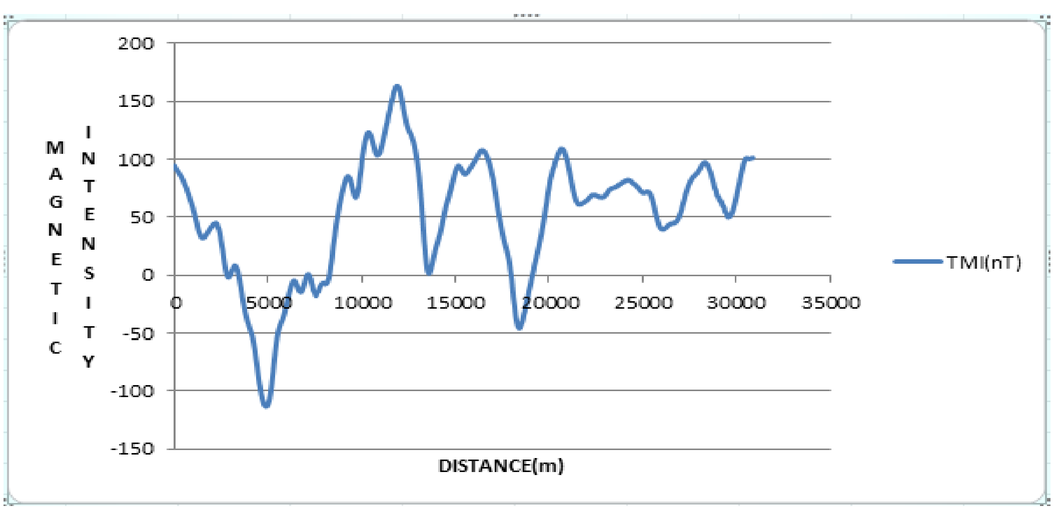

Figure 6i. Profile line II^I.

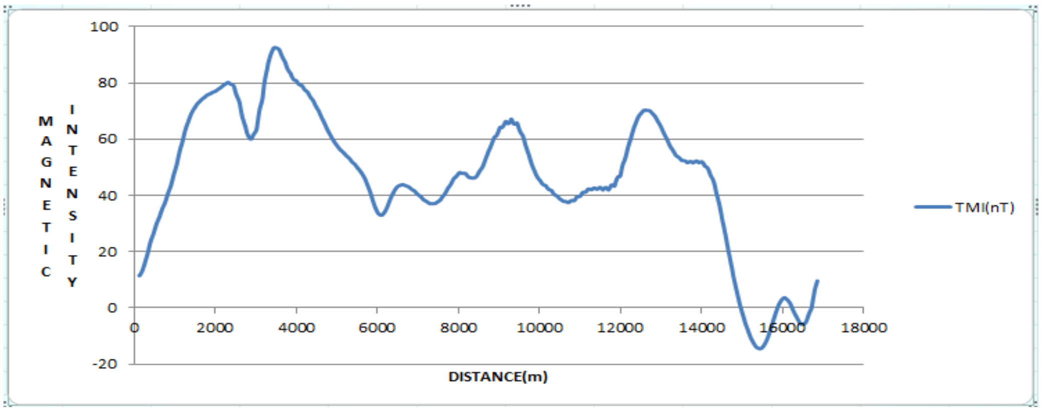

Figure 6j. Profile line JJ[I].

In the residual map (Figure 5), it is obvious that profiles cut across anomalous zones with approximately north easterly and south westerly trends. So, among the negative anomalies are those of profile BB[I] and CC[I] seated at lower latitude and lower longitude locations (i.e. Ikogosi environs) have their lines of anomaly (contour lines) widely spaced. This correlates well with intensely fractured/ faulted zone beneath Ikogosi area. Base on the magnetic anomaly field peak trend, the spring outlet is also suspected to be at the interface of low negative and high positive magnetic peak zone (lineament interface).

From the discussions above, most of the profiles have both relatively low negative and high positive magnetic anomaly field strengths. Those with low negative magnetic anomalies are suspected to be the embedded features (faults/fractures) and those with positive anomalies are suspected to be massive quartzite/basement complex embedding the embedded features.

The contour lines of profile BB[I] and CC[I] are widely space as mentioned earlier, indicate shallow slope, which is an area with lower magnetic susceptibility. The prominent sudden change in the contour over an appreciable distance that trends frequently in the south-west direction of the studied area implies discontinuity in depth. This could be subsurface major faults. The trends and the prevailing shallow depths suggested qualitatively here are consistent with Ojoawo et al. (2016) that predicted qualitatively, the subsurface major faults and quantitatively, the depths to shallow magnetic sources which ranged from 8 to 14 m and may have accommodated the channels or passages of the heat in the area of the warm spring.

This research was a reconnaissance study to the work of Ayobami and Lateef (2019) which predicted the shallow basements which may have accommodated the channels to the warm spring using aeromagnetic data with depths in between 2.98 to 290m for Euler De-convolution method and 2.1 to 1311.4 m for Local Wave Number method. Therefore, it I s obvious that trends predicted above are consistent with their obtained results.

Horizontal derivative map

Figures 7 and 8 are the horizontal derivative map of the RTE anomaly field and horizontal derivative map of upward continued RTE anomaly field, respectively. Both are presented here for qualitative interpretation. Figure 7 shows short wavelength anomalies whose visibility is enhanced by shaded relief image. A further enhancement of the short wave-length trends in the data set is achieved in the first horizontal derivative of the reduce-to-equator magnetic field. A system of North East-South West trending low negative anomalies of the short wavelength which are rimmed by positive anomalies is clearly visible in Figure 7, extending from Ikogosi town to the boundary shared by Ife and Ilesha. This correlates well with the existence of fractured/faulted zones and all the areas spanned by the trending anomalies are suspected fractured/faulted zones.

Figure 8, the horizontal derivative of the upward continued total magnetic intensity shows a better enhancement of high wave-length anomalies sources and is as expected because upward continuation is known for enhancement of deep seated anomaly sources at the expense of shallow anomaly sources. So, in this fashion, the shallow anomaly sources were suppressed. The North East-South West trending negative anomalies are more pronounced than in Figure 7 and the positive anomalies that rimmed low negative anomalies were suppressed making the North East-South West low/negative peak anomalies more conspicuous. This is indicating that the faulted/fractured zone is extending from a profound depth into the shallow basement.

Though, the peaks (magnitudes) of the North East-South West anomalies reduced as seen in the legend bar. It is as expected because the magnetic field decreases with the distance between the magnetometer sensor and magnetic source. Deeper anomalies (low negative anomalies) were enhanced (pronounced) in this process. And this North East-South West trending anomalies are most pronounced in the surroundings of the area of study. This suggests that

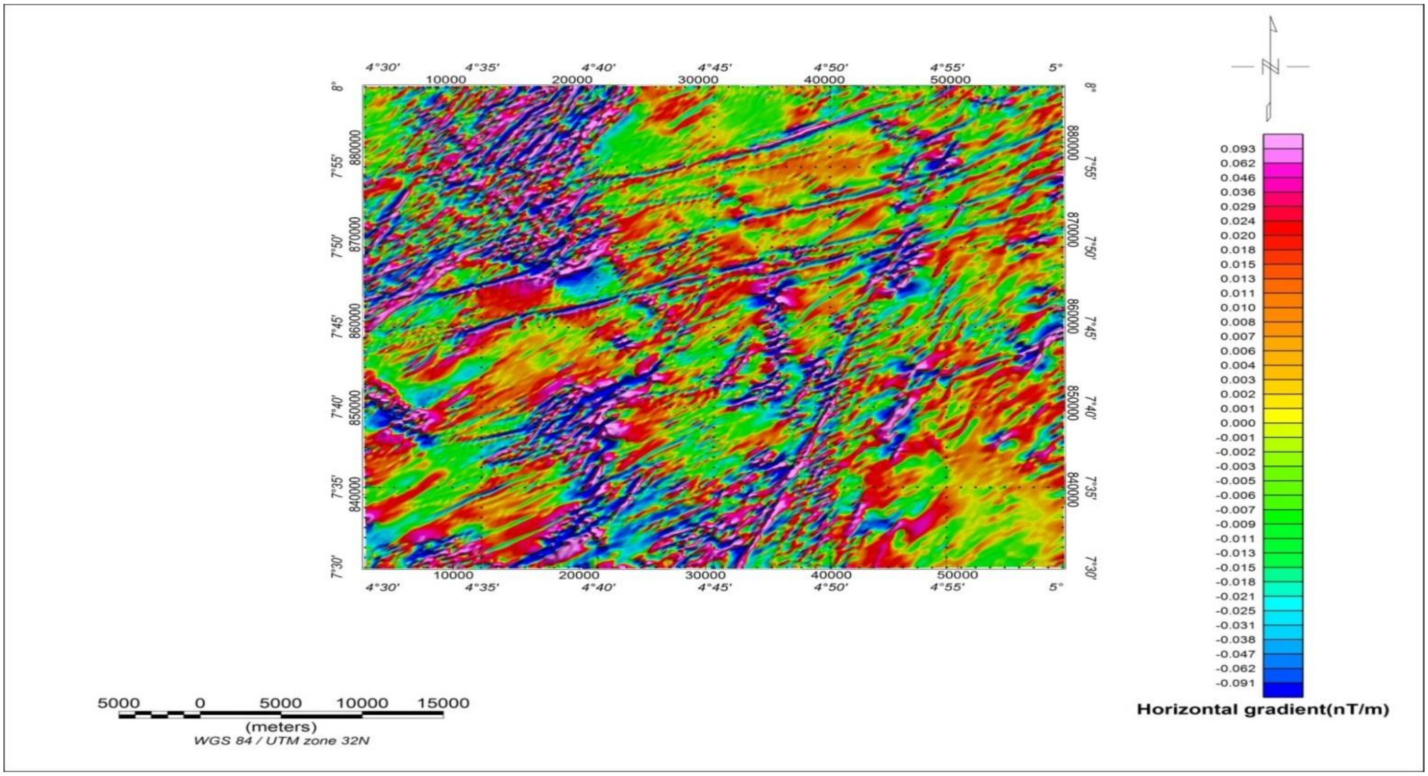

Figure 7. Horizontal derivative map of the RTE field.

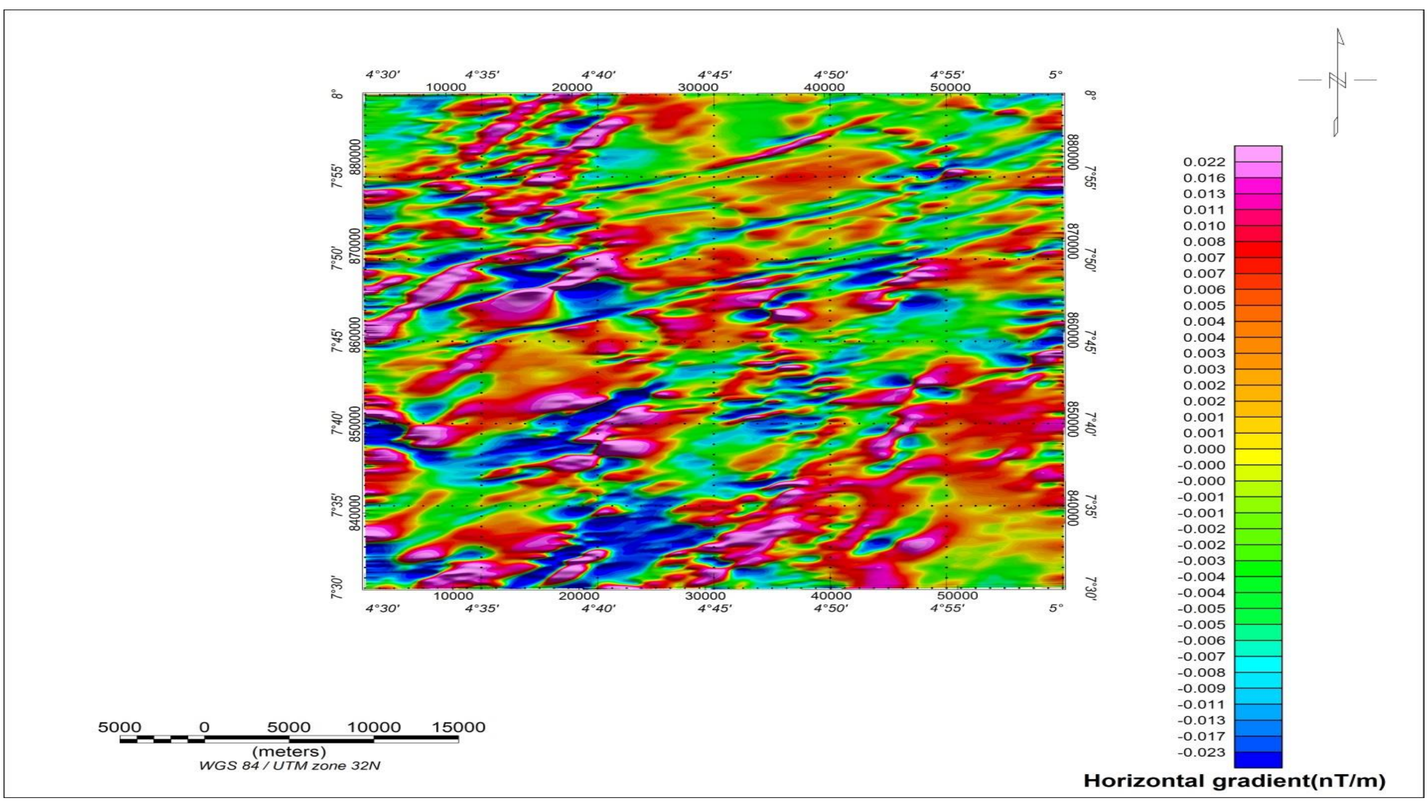

Figure 8. Horizontal Derivative Map of the 1km upward continued RTE anomaly field.

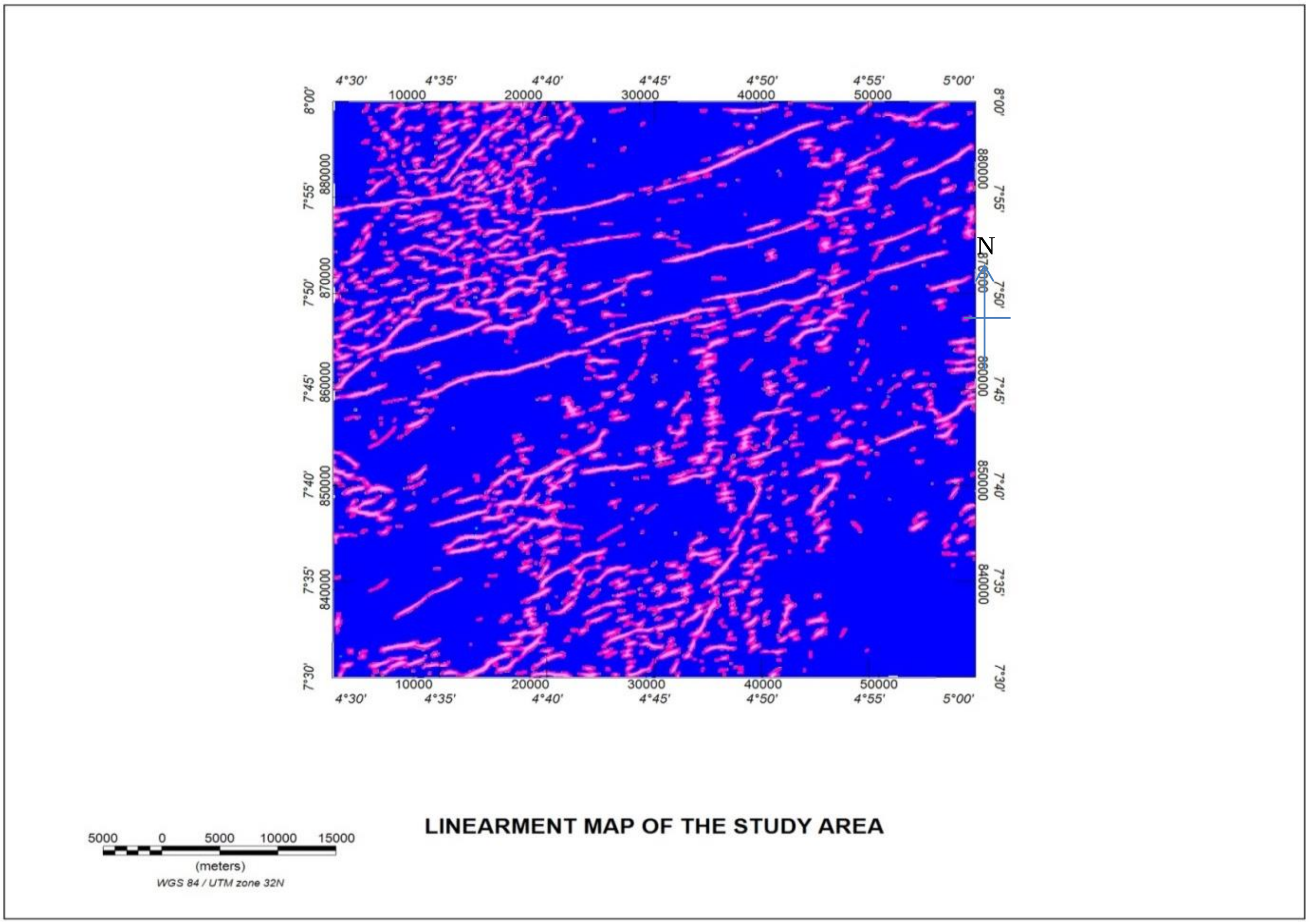

Figure 9. Lineament map of Ikogosi warm spring and its environs.

the study area and its surroundings were subjected to more tectonic event than other areas in the map and could be attributed significantly to a faulted zone.

So the predicted shallow depths suggested in this section may have resulted from magmatic intrusion into a point near the mean ground level where it got solidified and later affected due to tectonic activities which faulted or fractured it and ever since may have made it a channel or passage for heat flow from a subjacent heat source (at Curie depth) to get to the surface. Abraham et al. (2014a) research work on this area highlighted depths to the points where the sources may have completely lost their magnetic properties due to their possession of temperatures greater or equal to Curie temperature. The sources mapped out in his work were significantly deeper sources which could be the roots or deeper parts of the predicted sources in this current paper and also his work suggested radioactive isotopes as the source of the heat that activated the Curie temperature.

Lineament map

The map (Figure 9) shows the skeleton of the geological features (faulted zones, fractured zones or both) that are elongated in North East-South West directions. The lineaments bounded from (7^{0}35’, 4^{0}55’), (7^{0}35’, 5^{0}) to (7^{0}40’, 4^{0}55’), (7^{0}40’ 5^{0}) (Figure 9) are sandwiched in the quartzite formation of the basement complex of the study area (Figure 2).

The profiles’ anomalies AA’ to GG’ (Figure 5) span the area under investigation and its surroundings and are fractured sources as explained in the earlier section and the regions spanned by the anomalies are seen to have prominent lineaments predicted by their negative peak anomalies and positive peak anomalies.

BB’ and CC’ profiles’ anomalies (Figure 5) are sharp negative peak anomalies to positive peak anomalies which could suggest fault bearing zones spanning through area of over 3 km for both profiles’ anomalies while others are not as prevalent as both are but are also fractured sources (lineaments). The aforesaid statements corroborate the distribution of lineaments and its prevalence in the Ikogosi warm spring area and its surroundings as seen on the lineament map (Figure 9).

The lineaments as seen on the lineament map are not as prominent as that of its surroundings and they suggest that the study area was subjected to less tectonic events. So, the heat flow must have probably been reinforced by the area's subjacent heat source (radioactive isotopes) and its more tectonic active surroundings. The orientation of the prominent lineament is obviously North East- South West direction as appeared on lineament map (Figure 9). Though, this research is a qualitative interpretation showing the trends of the lineaments using the explained filters and method.

The skeletonization (Figure 9) of the areas shows the lineaments and their trends. The prevailing lineaments in the study area and surroundings are oriented in a North East-South West direction which is consistent with Abraham et al. (2014b) and Ojo et al. (2011) research works. Therefore, this research is closely in line with the previous research done on this area.

Conclusion

The analysis of aeromagnetic data from this region revealed fascinating patterns and depth information to the respective geologic sources. Lineaments which could be fracture or fault or both have been delineated with their respective trends indicated. Dominant trends mapped out in the region are elongated in the North East-South West directions. The predicted source depths are shallow. The revelation of these trending features would make quick recognition of the geologic patterns embedded in this region and also contribute to the proper characterization of geothermal settings in this region.

The delineated relatively shallow magnetic basement which was suspected to be faulted and fractured could be an indication of magma intrusion which solidified to form a basement rock and thus has several implications on geothermal resources and tectonic activities of the study area and its surroundings. The heat flow in the study area that is consequent to its tectonically active surroundings and radioactive isotopes is enough to cause the surface manifestation of heat.

It is also suspected that the probable fractured/faulted zones mapped out may have acted as channels for movement of warm ground water from profound depths to the surface and the spring outlet is located on a lineament interface. Results presented here would provide a possible tool to further geothermal energy exploration activity in this region.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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