



Investigation of seepage paths from dam embankments using magnetic methods: case study of Jebba earth dam, Nigeria

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Abstract

This study aims to detect possible seepage paths from the dam embankment and describe structural defects such as faults, joints resulting from fracturing, and their antagonistic effect on the dam embankment. The land magnetic survey was conducted to identify the chief structure and the depth to the basement along the embankment part of the Jebba dam. Data were acquired with a proton precession magnetometer G-857 along three parallel profiles oriented NS with a length of 1.21 km along the dam embankment at an interval of 10 m apart. The Analytical Signal map against the total magnetic intensity (TMI) map indicated a fault at 48 m distance from the beginning of profile 1 closest to the dam axis, and an intrusion at 34 m distance. Faults were detected around horizontal distance 12 m, 38 m and there is an intrusion at 4 m and 54 m distance along with profile 2. No faults were observed but an intrusion was observed at a 95 m distance along with profile 3. Reduction to Pole map was produced to show the correct position of the magnetic susceptibility over profile distance. The correlation of the upward modeling maps and first derivative maps shows that the geological structures are continuous from shallow depth to a deeper depth. Thus, this study shows that beneath the embankment (i) there exist fractures and intrusions (ii) the geological structures are continuous from shallow depth to the deeper depth, (iii) there is enough evidence to suspect seepage in the dam area. Therefore, the magnetic investigation revealed the present condition of the Jebba dam.

Keywords Jebba dam · Abnormal seepage · Dam embankment · Land magnetics · Geological structures

Introduction

Seepage from a dam simply refers to the process by which water outflows from its reservoir. Seepages can be categorized as normal or abnormal. Normal seepages refer to the pathways created during the dam designs, these include the spillway and the filter bed. Islam et al (2021) hinted that developing countries, Nigeria inclusive, are affected by floods such as flash floods. Such floods that could overflow the dam and possibly cause a collapse are controlled with spillways. The spillway is a path for water flow, to mitigate possible overflows of dams in the event of floods of any type. It serves remedial solution to dam collapse in the event of floods. Abnormal seepages may arise from geological

hazards, animal and plant activities, the effects of which are inimical to the stability of the dam embankment. Thus, abnormal seepages especially from the embankment need to be detected early to avoid dam failure. Olorunfemi et al. (2000) reiterated that the slow release of water that ought to stay in the reservoir, through conduits to the dam's flank is unfavorable to the stability and functionality of a dam. It reduces the amount of water that is likely to be available and harms dam gates. Soil such as laterite swells if they get saturated with the seeping water and when there is a loss of water in them, they shrink significantly and possibly result in cracks. Cracks and collapse in the dam can, therefore, be activated by these expansions and shrinkages of soils, if not addressed in time. Seepage is one of the most common causes of embankment dam failures, and it has the potential to cause substantial social disruption such as displacement of people, loss of precious lives and properties, among others.

The studied dam Jebba dam, located between latitudes 9° 8' 08" N and longitude 4° 47' 16" E, was built between 1981 and 1983, and became operational in 1984 (i.e. about 39 years old). It is a typical earth fill, rockfill, and concrete

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structures sort, attached with numerous secondary dams and infrastructure (Mainstream 2017). The main rockfill dam and a saddle dam, as well as four auxiliary dams consisting of an embankment dam and three gravity concrete structures, make up the civil structure of the dam. It is envisioned for hydroelectric power generation, provision of flood protection, and, originally, support navigation (among the benefits of the dam). Actually, regular maintenance is imperative for the sustenance of any structure of this type. Age and subsurface geological structures are imminent to the survival of a dam. Jebba dam constructed about 4 decades ago, cum the quest for the knowledge of the underline geology prompted this study for its sustainability. Furthermore, the dam hosts a community of about 1 million population, living in Jebba town located at the downstream side of the dam. Thus, the event of failure, if not detected in time, could result in a colossal loss of lives and property. Thus, this work aimed to identify potential abnormal seepage paths from the dam embankments, as a consequence of structural problems such as faults, fracture, and joints; this is done through the following objectives (i) acquiring Land magnetic data using a proton precession magnetometer (G-857) (ii) processing magnetic data collected and enhancing it to map the lithology and geological structures of the Jebba dam (iii) generating filtered data to define the lithological boundaries, the intersection of geological structures, faults, and contacts.

The magnetic method is suitable to study subsurface geology on the premise of the anomalies in the earth's magnetic field (Nicolas 2007). The shape and amplitude among others of the anomalies are a function of the orientation, and magnetic susceptibility among others of the body as well as the intensity and inclination of the earth's magnetic field in the survey area (Oladunjoye et al. 2014). They furthered that magnetic anomalies can be used to identify faults and intrusions on the dam site. The magnetic survey has been widely employed in basement mapping and the delineation of subsurface linear geologic formations that may be associated with groundwater accumulation by detecting rocks or minerals with peculiar magnetic properties that manifest as anomalies in the earth's magnetic field intensity (Abderahman and Essa 2005; Olasunkanmi et al. 2018). Thus, magnetic methods are considered suitable and adopted for this study, to determine seepage paths through faults, fractures, and joints in the subsurface lying under the Jebba dam embankments.

The investigation of dam failure globally has shown that 25% of the failures were related to geotechnical problems that are related to abnormal seepages, inadequate seepage cut-off, faults, settlements, and land-slides among others (Biswas and Charttergee 1971). Therefore, it is imperative to carry out routine checks on the embankments, such as geophysical surveys of this type to ascertain security and safety.

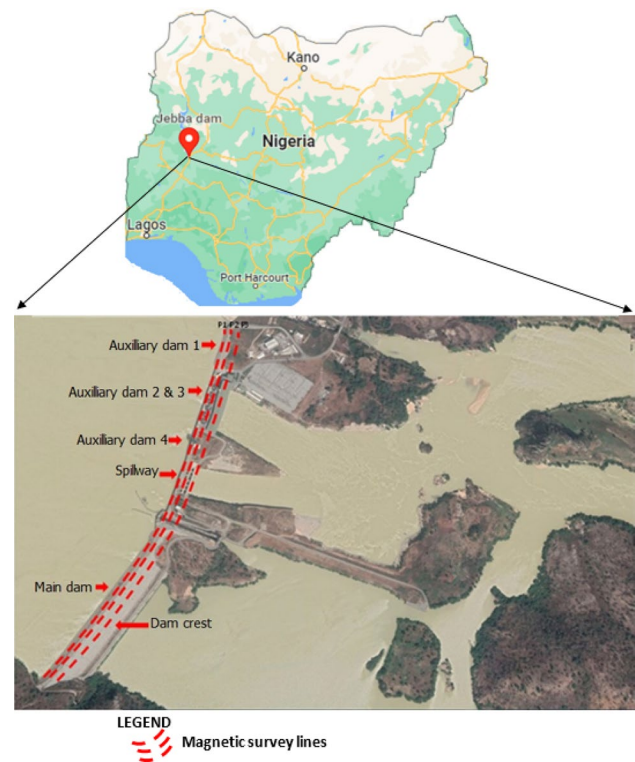


Fig. 1 Jebba dam (study area) with inset of Nigeria

The study area

Jebba Dam (Fig. 1) is along River Niger, Nigeria, situated between latitudes $9^{\circ} 10' N$ to $9^{\circ} 55' N$ and longitudes $4^{\circ} 30' E$ to $5^{\circ} 00' E$ at elevation 76 m above sea level (about 100 km downstream of Kanji dam). The study area is primarily rippling at either side of the channel near the dam site. The human population density is low in the areas adjacent to the lake and generally low throughout the drainage basin. Intensive agriculture is carried out in a few places. Except in a few places population density is in the order of 10–20 per square mile. The station is one of the most cost-effective sources of electricity in Nigeria. It has a maximum length of 100 km (km), a maximum depth of 32.5 km, a maximum width of 10 km, and a mean depth of 3.3 m. The surface area is 350 km^2 , the maximum volume of $1000 \times 106 \text{ m}^3$, operating head of 27.6 m and maximum flow per unit of $380 \text{ m}^3/\text{s}$. The floristic composition of the arboreal vegetation in the study area is strikingly uniform and is little influenced by the difference in physiognomy. The majority of species are adapted to a savanna environment in that they are resistant or tolerant to fire and regenerate easily from coppice or root sucker. Fire-tender species, which in some parts of the Southern Guinea Zone grow in the lower strata of mature savanna woodland are

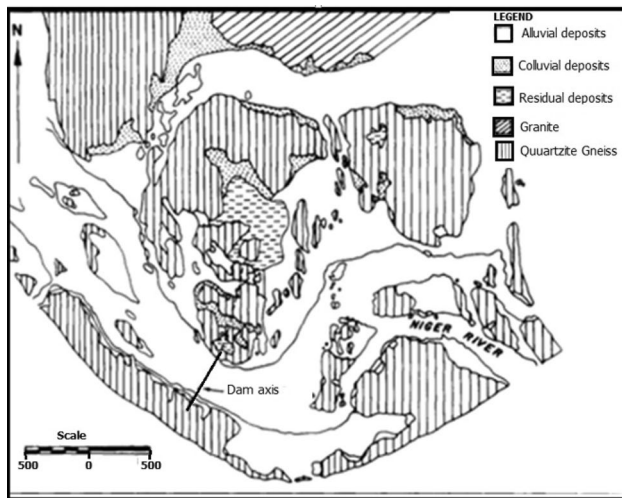


Fig. 2 Geological map of Jebba dam site (Malomo 1984)

absent or rare. However, the major factor contributing to this floristic uniformity appears to be the narrow range of variation in moisture conditions in most of the habitats; many soils tend to be deep, permeable, and well-drained and provide a good medium for growth.

The area of investigation is being built in the town of Jebba, on the Niger River, just upstream of a freshly completed railway bridge. Close to the dam site, the topography is often undulating on both sides of the river. On both sides of the canal, however, the bedrock outcrops into hills that rise to 200 m above sea level along the dam axis. It can be found in depths of 10–40 m within the river.

Concise geology of the study area

The research region (Fig. 2) is located on Nigeria's basement complex rocks. Several rock types are seen in the research region, including granitic, dioritic, and hornblende-biotite gneiss, diorite, mica quartzite, pegmatite, and dolerite (the last two as intrusive). Massive outcrops of granite gneiss cover over half of the region, with diorite and quartzite accounting for the remaining 10%. The remaining 30% of the area is made up of dioritic and hornblende-biotite gneiss. The gneiss is said to have both concordant and discordant pegmatite veins that are 3–25 cm broad. Dolerite, the other intrusive rock, is mostly found as veins.

The presence of a three-joint system—porphyritic granite, mica quartzite, and diorite—distinguishes these rocks. The quartzite is strongly jointed. The tectonic origin of these joints is supported by their structural link with the axis of the folds, however, small, in the vicinity. The gneisses and schists' foliation is mostly north–south with a few exceptions. They have a sharp westward inclination

(Fig. 2). At the perimeter, foliation is poorly defined, with the appearance of a flow pattern that is likely 85–10 tied to its origin (NGSA 2006). Landsat images (Kogbe et al. 1983), 16 variable drilling investigations at an old railway bridge for a former dam axis (Henderson 1973), and the new railway bridge (Kogbe et al. 1983) all point to linear faulting near the river channel near Jebba.

Materials and methods

The studies began with a site assessment; we avoided high-tension transmission lines as well as grounded metallic structures such as metal fences, pipes, and other sources of data noise. The magnetic measurements were made with a G-857AX proton precession. The base map needed for data collection profiles was obtained with the aid of the google earth application, using the global coordinate of a point on the crest of the embankment. A profile is 1.21 km long, 3 of which were established on the dam embankment at a regular interval of 5 m. The data were recorded along with magnetic profiles as Intensity (nanoTesla) against distance (meters). Oasis montaj software was employed to derive the following fields: total magnetic intensity (TMI), analytical signal/total gradient (TG), reduction to pole (RTP), first vertical derivative (FVD), and upward continuation. These were used to produce maps utilized for interpretations. The GPS was utilized to record the coordinates of each station point, as well as to establish a straight line on each profile. To remove the diurnal variable effects of the earth's magnetic field from the data, a separate magnetically clean base station was set up roughly 50 m distant from the survey area, where magnetic readings were obtained at 60 min time intervals.

The superposition of the TMI on TG revealed faults and intrusions. Reduction to the pole aids the positioning of magnetic anomalies in the correct position. FVD enhances shallow causative bodies and the upward continuation process enhances deep-sited bodies.

Results and discussion

The interpretation of the magnetic map was both qualitative and quantitative. The qualitative interpretation involved the examination of the map for patterns and characteristics that are typical of linear features (lineaments) such as faults and fracture zones, lithological contacts, etc. The quantitative interpretation of magnetic profiles along and across identified lineaments was done using the Werner deconvolution technique (Birch 1984), modified for this low magnetic latitude by taking the magnetization at the equator to be

horizontal and parallel to the normal terrestrial field, instead of vertical as in the high magnetic latitudes.

Total magnetic intensity (TMI) results

TMI data are frequently available at very fine scales. When preparing a survey, a region's magnetic and geology maps are now considered essential information. From region selection through target selection, magnetic data are employed at every stage of the survey. This is especially true for magnetic latitudes ranging from middle to high. At low latitudes, changes in anomaly shapes, reductions in total amplitude, and changes in map textures make geology interpretation from magnetic data problematic. At high magnetic latitudes, litho-magnetic "markers" are used to trace complex structures from aeromagnetic maps. At low magnetic latitudes, these litho-magnetic markers are typically associated with lows (and small, marginal highs) rather than highs or high-low combinations. Mapping magnetic units and structures at low latitudes are therefore that much harder. These problems are worst for regions closer to the magnetic equator e.g. Africa. The two most commonly used solutions applied to the "low latitude problem" are to use reduction to the equator or the Analytic Signal. Reduction to the equator is the transformation of the TMI data to the magnetic pole (Baranov and Naudy 1964). Ideally, reduction to the equator (RTE) removes the effect of induced magnetization and strike on the shape of magnetic anomalies.

TMI for profile 1

The magnetic anomalies revealed series of positive peaks (magnetic highs) alternated fairly with troughs (magnetic lows) along the profile showing that the location is generally of undifferentiated basement rock with rock contacts; inferred from the TMI map. The magnetic field intensity map for profile 1 is presented in Fig. 3. The figure shows the variations in the intensity of magnetics that reflect the susceptibility of various rocks across the different terrains as displayed on the map. From the TMI map, a group of positive peaks of magnetic susceptibility along the horizontal distance of 35–60 m ranging from 1000 to 4200 nT can be identified and it signifies conductive zones which are indicative of a series of fractures. The Magnetic Intensity distributions for profile 1 range from -2000 to 4000 nT on the Total Magnetic Intensity map. The acute shape of a positive anomaly (4000 nT) is visible in the NNE trending directions along with the profile.

TMI for profile 2

The magnetic anomalies revealed series of positive peaks (magnetic highs) alternated fairly with troughs (magnetic lows) along the profile showing that the location is generally of undifferentiated basement rock with rock contacts; inferred from the TMI map. The magnetic field intensity map for profile 2 is presented in Fig. 4. The figure shows the variations in the intensity of magnetics that reflect the

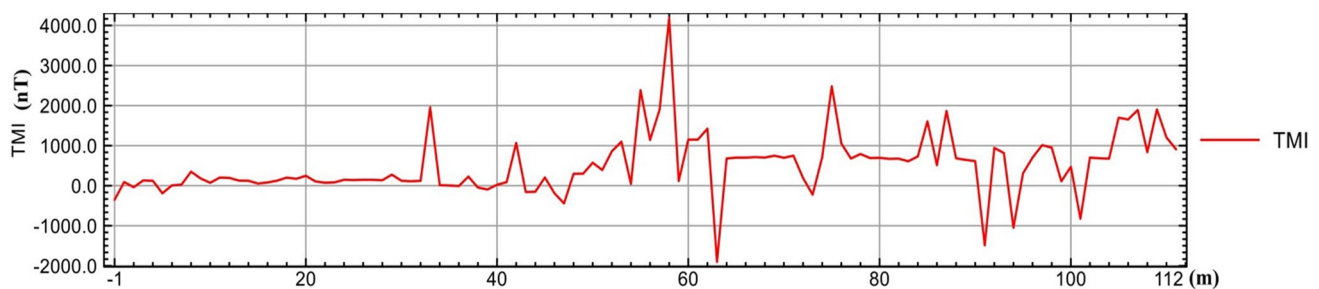


Fig. 3 TMI anomaly for profile 1, along NNE and N-trending direction

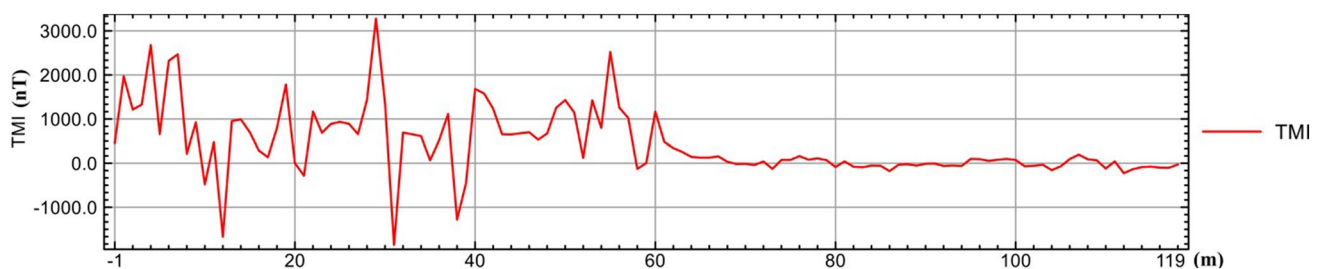


Fig. 4 TMI anomaly for profile 2, along NNE and N-trending direction

susceptibility of various rocks across the different terrains as displayed on the map. From the TMI map, the magnetic response is distinguished into magnetic highs (2 m, 6 m, 28 m, 58 m), magnetic intermediates (8–10 m; 16–26 m; 34 m, 40–54 m; 60–120 m), and magnetic lows (12 m, 31 m, 38 m).

A group of positive peaks of magnetic susceptibility along the horizontal distance of 26–30 m ranging from –1000 to 3000 nT can be identified and it signifies conductive zones which are indicative of a series of fractures. The Magnetic Intensity distributions for profile 2 range from –2000 to 4000 nT on the total magnetic intensity map. The acute shape of a positive anomaly (4000 nT) is visible in the NNE trending directions along with the profile.

TMI for profile 3

The magnetic anomalies revealed series of positive peaks (magnetic highs) alternated fairly with troughs (magnetic lows) along the profile showing that the location is generally of undifferentiated basement rock with rock contacts; inferred from the TMI map. The magnetic field intensity map for profile 3 is presented in Fig. 5. The figure shows the variations in the intensity of magnetics that reflect the susceptibility of various rocks across the different terrains as displayed on the map. From the TMI map, the magnetic response is distinguished into magnetic highs (64 m, 94 m), magnetic intermediates (0–60 m; 104–122 m), and magnetic lows (67–92 m, 102 m, 125 m).

A group of positive peaks of magnetic susceptibility along the horizontal distance of 90–96 m ranging from –3000 to 3000 nT can be identified and it signifies conductive zones which are indicative of a series of fractures. The magnetic intensity distributions for profile 3 range from –2000 to 4000 nT on the total magnetic intensity map. The acute shape of a positive anomaly (3000 nT) is visible in the NNE trending directions.

The magnetic anomalies revealed series of positive peaks (magnetic highs) alternated fairly with troughs (magnetic lows) along the three (3) profile lines showing that the location is generally of undifferentiated basement rock with rock

contacts along the study area. The derivatives are sensitive to rock susceptibility near the ground surface rather than at depth.

Total gradient/analytical signal (TG) results

Magnetic gradients determine the Analytic Signal (Nabighian 1972, 1984). It is almost, but not totally, unaffected by the direction of magnetization (Rajagopalan 1997). It causes the anomaly peak to align (roughly) with either the magnetic source's center or its edges. At low magnetic latitudes, both Reductions to the Equator and the Analytic Signal are currently utilized to facilitate interpretation, although neither is a perfect answer. Several diagnostic characteristics have been used to compare them.

Reduction to the equator, on the other hand, can be accurately and easily carried out at intermediate to high latitudes but usually results in declination-parallel noise and incomplete reduction, especially of declination-parallel sources, at low magnetic latitudes. When analytical amplitude increases before an increase at the TMI value, it indicates a fault but when it increases directly at an increase of the TMI amplitude it indicates an intrusion e.g. a dyke.

Analytical signal/(TG) for profile 1

The magnetic anomalies revealed series of positive peaks (magnetic highs) alternated fairly with troughs (magnetic lows) along profile one line showing that the location is generally of undifferentiated basement rock with rock contacts; inferred from the analytic signal amplitude (ASA), horizontal and vertical derivatives model on the submenu of SignProc Geosoft. These derivatives are sensitive to rock susceptibility near the ground surface rather than at depth.

Ridges or peaks in analytical signal total magnetic intensity anomaly map occurs mostly on geological targets such as faults, volcanic plugs, dykes, shear zones, lithological contacts, discrete bodies and their edges, magnetization's directions notwithstanding (Anudu et al. 2014). Analysis of analytical signal over the magnetic data of the study area

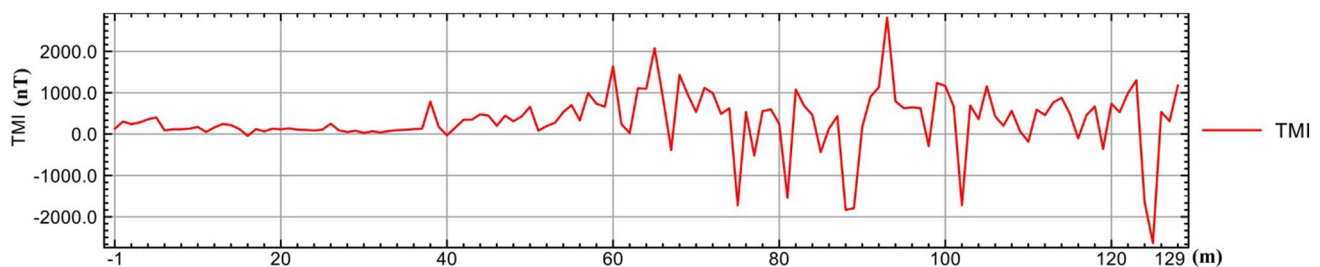


Fig. 5 TMI anomaly for profile 3, along NNE and N-trending direction

confirms the anomalies' peaks' existence in the form of causative bodies.

The figure below shows a graph of an analytical signal and TMI plots, from Fig. 2 below the analytical signal ranges from 0 to 400 nT/M the highest value is 400 nT/M. From Fig. 6 below, the analytical graph indicates faults and fractures the maximal the are formed before an increase in the TMI values are most likely to indicate a fault which is experienced at 48 m, while the ones formed directly on the TMI amplitudes indicate an intrusion which is experienced at 34 m.

Analytical signal/(TG) for profile 2

The magnetic anomalies revealed series of positive peaks (magnetic highs) alternated fairly with troughs (magnetic lows) along the profile showing that the location is generally of undifferentiated basement rock with rock contacts; inferred from the analytic signal amplitude (ASA), horizontal and vertical derivatives model on the submenu of SignProcGeosoft. These derivatives are sensitive to rock susceptibility near the ground surface rather than at depth.

The Analytical signal map was cross-plotted with the Total Magnetic Intensity map in order to identify subsurface structures. On the map, Ridges or peaks occurs mostly on geological targets such as faults, volcanic plugs, dykes, shear zones, lithological contacts, discrete bodies and their edges, magnetization's directions notwithstanding (Anudu et al. 2014). Analysis of analytical signal over the magnetic data

of the study area confirms the anomalies' peaks' existence in the form of causative bodies. Maximals formed directly on the TMI amplitudes indicate an intrusion, while the ones formed before or after the TMI are like faulted zone and those faults are possible seepage zones.

Figure 7 below shows a cross-plot of the analytical signal and TMI chart. The analytical signal ranges from 0 to 400 nT/m in which the highest value is 400 nT/M. The total gradient maximals that are not directly on the TMI indicate faults and fractures which can be found around the horizontal distance between 14 and 18 m, 24 and 26 m, 32 and 36 m, and 42 and 50 m, respectively. While the total gradient maximal that are directly on the TMI indicates possible intrusions which can be seen around 2 m, 38 m, respectively.

Analytical signal/(TG) for profile 3

The magnetic anomalies revealed series of positive peaks (magnetic highs) alternated fairly with troughs (magnetic lows) along the profile showing that the location is generally of undifferentiated basement rock with rock contacts; inferred from the analytic signal amplitude (ASA), horizontal and vertical derivatives model on the submenu of SignProc Geosoft. These derivatives are sensitive to rock susceptibility near the ground surface rather than at depth.

The Analytical signal map was cross-plotted with the Total Magnetic Intensity map in order to identify subsurface structures. On the map, Ridges or peaks occurs mostly on geological targets such as faults, volcanic plugs, dykes, shear

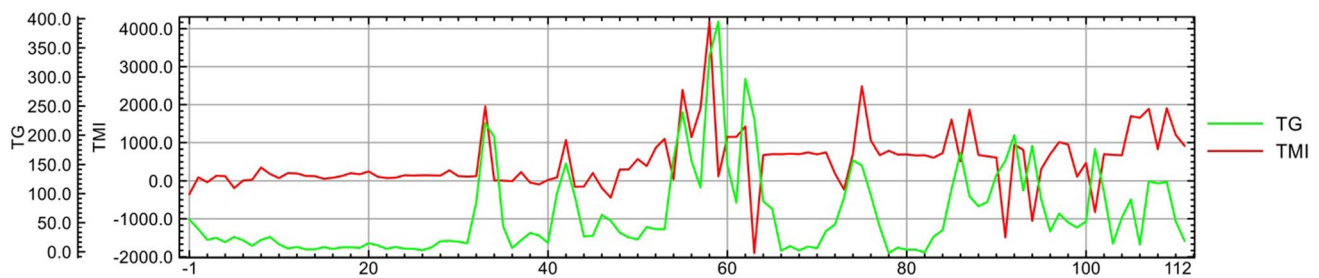


Fig. 6 Total gradient profile one produced from the magnetic data of the study area for profile one

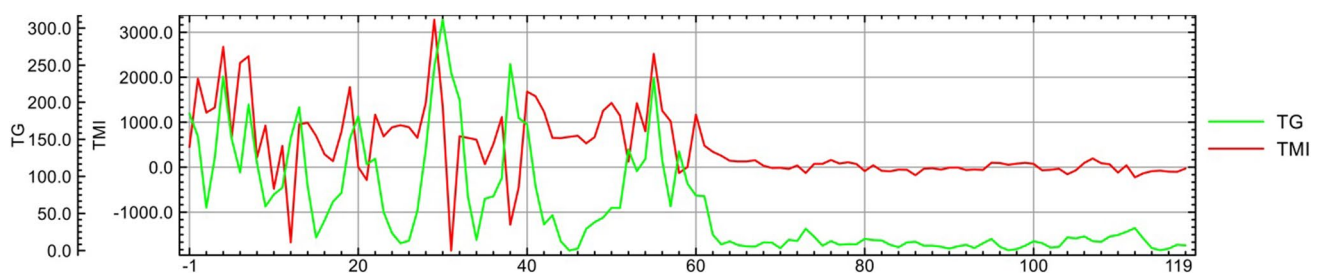


Fig. 7 Total gradient response on profile 2

zones, lithological contacts, discrete bodies and their edges, magnetization's directions notwithstanding (Anudu et al. 2014). Analysis of analytical signal over the magnetic data of the study area confirms the anomalies' peaks' existence in the form of causative bodies. Maximal formed directly on the TMI amplitudes indicate an intrusion, while the ones formed before or after the TMI are like faulted zone and those faults are possible seepage zones.

Figure 8 below shows a cross-plot of the analytical signal and TMI chart. The analytical signal ranges from 0 to 400 nT/m in which the highest value is 400 nT/M. The total gradient maximals that are not directly on the TMI indicate faults and fractures which can be found around the horizontal distance between 68 and 72 m, 76 and 78 m, 102 and 120 m, respectively. While, the total gradient maximal that are directly on the TMI indicates possible intrusions which can be seen around 74 m, 82 m, and 102 m, 125 m, respectively.

The maximal value indicates faults, fractures, or intrusion, the interpretation of analytical signals with determining the type of structures in the subsurface. Analytical signal measures as a function of distance and the unit are nT/M. the analytical signal is majorly used to identify geologic structures.

Reduction to the equator (RTE) results

Reduction to the pole (RTP) transforms an observed TMI anomaly into an anomaly that would be measured at the north magnetic equator. Accordingly, it is an object of the invention to provide a method of processing magnetic data recorded within about 25 of latitude above or below the magnetic equator to yield a more realistic picture of the magnetic structure of the earth. It is accordingly an object of the invention to provide a method of processing magnetic data recorded in the vicinity of the magnetic equator so that anomalies in the magnetic field are recorded correspond to the geologic body which causes them. It is a further object of the invention to provide a way in which magnetic data recorded concerning geologic anomalies in the vicinity of the magnetic equator can be reprocessed to

yield a map resembling one which would be generated if the data had been recorded concerning geologic anomalies near the magnetic poles. One important method of such processing is referred to a reduction-to-the-equator processing. This method refers to the well-known fact that the accuracy of the results of plotting the measurements of the magnetic field concerning the actual geologic structure is influenced by the magnetic latitude at which the measurements are taken. That is to say, the magnetic field recorded concerning a particular geologic anomaly, i.e., local variation from the mean amount of magnetic material present in the earth's crust at the area of exploration, is influenced by the latitude concerning the magnetic equator at which the survey is flown. If the anomaly is located at or near the north or south magnetic pole and corresponds to an increase in magnetic material in the area of exploration, the magnetic field will show its peak value concerning the ambient field when the magnetometer is directly over the geologic body producing the magnetic anomaly. As the exploration moves toward the magnetic equator, the simple peak shape of the anomaly when recorded concerning a magnetic body at the pole becomes instead a positive peak and a negative trough in the magnetic field recorded.

The relative intensities of the peak and trough vary with latitude. Furthermore, the zero points of the paired peaks do not in general coincide with the epicenter of the magnetic material in the geologic body. Therefore, to reduce magnetic anomaly data to its version at the equator so that the negative-going trends in the magnetic data are centered concerning the geographic anomalies which produce them.

RTP result for profile 1

To find the observed magnetic disturbances directly over the magnetic source bodies that produced the anomaly, a reduce to the pole (RTP) filter was added to the TMI grid. It was also used to eliminate the effect of magnetic latitude on magnetic anomalies. The TMI grid was converted to a reduction to the pole (RTP) grid using the 2D-FFT (Fast Fourier Transform) filter. The parameters for the transition are a -9.74° inclination and a -1.4θ declination, which

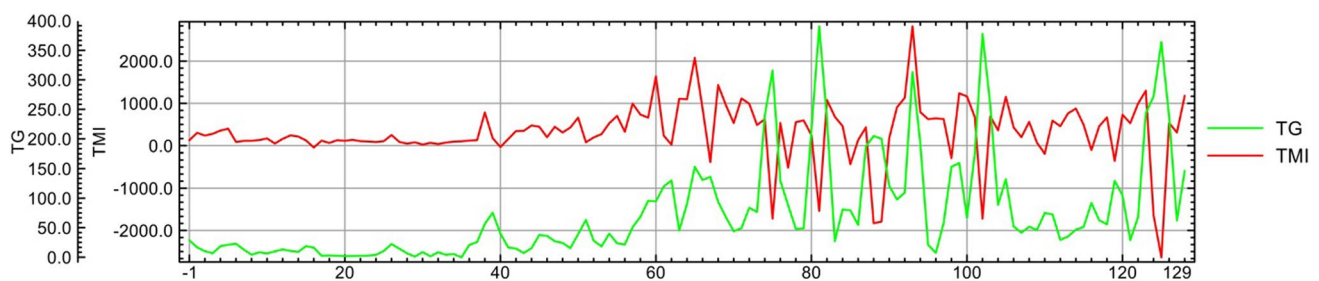


Fig. 8 Total gradient response on profile 3

reflect the area's mean value. Low and high magnetic frequencies on the TMI map represent points with high and low magnetic signatures, respectively, on the RTP magnetic anomaly map which is seen in Fig. 9. The magnetic peaks of the TMI are seen as lows in the RTP image. The Reduction to Pole map has a susceptibility range between -2000 to 4000 nT on the Reduction to Pole map for the profile.

RTP result for profile 2

To find the observed magnetic disturbances directly over the magnetic source bodies that produced the anomaly, a reduce to the pole (RTP) filter was added to the TMI grid. It was also used to eliminate the effect of magnetic latitude on magnetic anomalies. The TMI grid was converted to a reduction to the pole (RTP) grid using the 2D-FFT (fast Fourier transform) filter. The parameters for the transition are a -9.74° inclination and a -1.40 declination, which reflect the area's mean value. Low and high magnetic frequencies on the TMI map represent points with high and low magnetic signatures, respectively, on the RTP magnetic anomaly map which is seen in Fig. 10. The magnetic peaks of the TMI are seen as lows in the RTP image. The reduction to pole map has a susceptibility range between -2200 to 3100 nT on the reduction to pole map for the profile. From the RTP map, it can be interpreted that distances 12 m, 21 m, 38 m rep high magnetic susceptibility associated with structures like faults, fractures; distances 19 m, 57 m for areas with low magnetic susceptibility.

RTP result for profile 3

To find the observed magnetic disturbances directly over the magnetic source bodies that produced the anomaly, a reduce to the pole (RTP) filter was added to the TMI grid. It was also used to eliminate the effect of magnetic latitude on magnetic anomalies. The TMI grid was converted to a reduction to the pole (RTP) grid using the 2D-FFT (fast Fourier transform) filter. The parameters for the transition are a -9.74° inclination and a -1.40 declination, which reflect the area's mean value. Low and high magnetic frequencies on the TMI map represent points with high and low magnetic signatures, respectively, on the RTP magnetic anomaly map which is seen in Fig. 11. The magnetic peaks of the TMI are seen as lows in the RTP image. The reduction to pole map has a susceptibility range between -3000 to 5000 nT on the reduction to pole map for the profile. From the RTP map it can be interpreted that distances 89 m, 102 m, 125 m represent high magnetic susceptibility associated with structures like faults, fractures; distances 60 – 68 m, 93 m, and 123 m for areas with low magnetic susceptibility.

Upward continuation

Upward continuation is a method to separate a regional magnetic anomaly resulting from deep sources from the observed magnetic. This is a mathematical technique that projects data taken at an elevation to a higher elevation. The effect is that short-wavelength features are smoothed

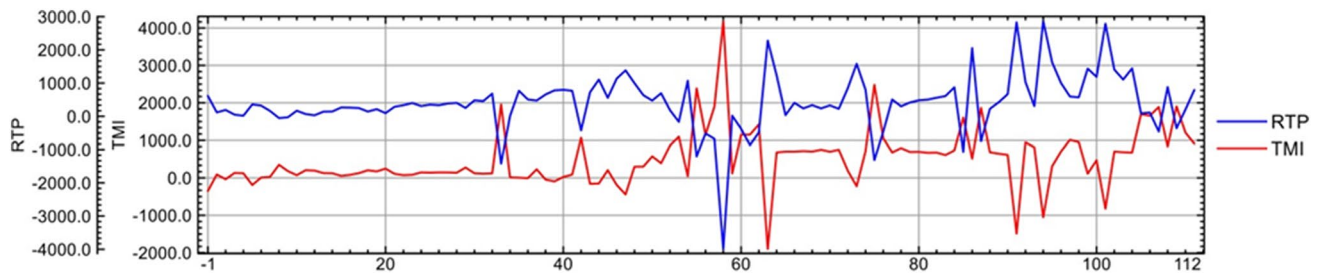


Fig. 9 RTP anomaly on profile 1

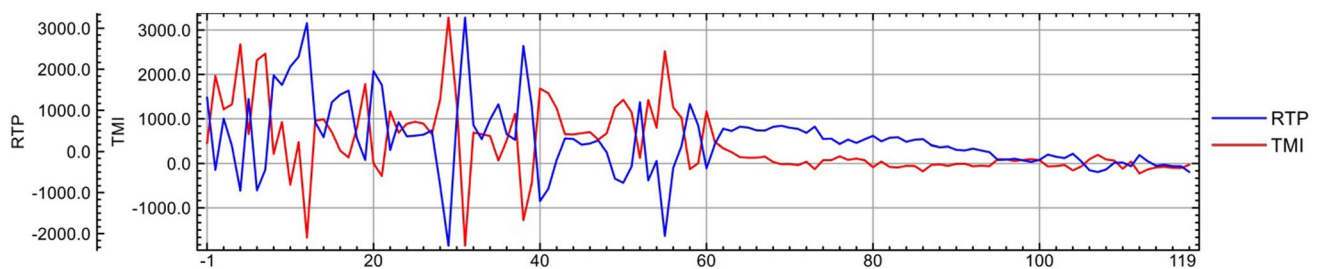


Fig. 10 RTP anomaly on profile 2

out because one is moving away from the anomaly. Upward continuation is a way of enhancing large-scale (usually deep) features in the survey area. The upward continuation attenuates anomalies concerning the wavelength of the output; the shorter the wavelength feature, the higher the attenuation of the feature. It is a way of enhancing large-scale (usually deep) features in the survey area. Also, upward continuation tends to accentuate anomalies caused by deep sources at the expense of anomalies caused by shallow sources (Li et al 2019). This is considered a clean filter, because it produces almost no side effects that may require the application of other filters or processes to correct. Because of this, it is often used to remove or minimize the effects of shallow sources and noise in grids. Also, upward continued data may be interpreted numerically and with modeling programs. This is not the case for many other filter processes.

Upward continuation result for profile 1

The appropriation of the magnetic intensities from deeper structures led to applying the UC filter to suppress the effects of shallow anomalies. This helped high-frequency anomalies relative to low-frequency anomalies to be smoothed out. The upward susceptibility ranges between -2000 and 3000 nT. In Fig. 12 below, high magnetic susceptibility can be observed for deep-sited conductive zones which are indications of major faults along 88–140 m.

Upward continuation result for profile 2

The appropriation of the magnetic intensities from deeper structures led to applying the UC filter to suppress the effects of shallow anomalies. This helped high-frequency anomalies relative to low-frequency anomalies to be smoothed out. An almost identical data plot is obtained in Fig. 13 signifying

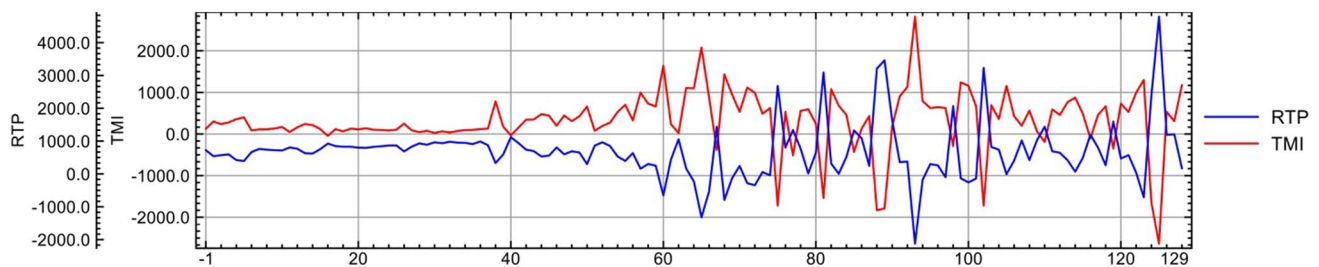


Fig. 11 RTP anomaly on profile 3

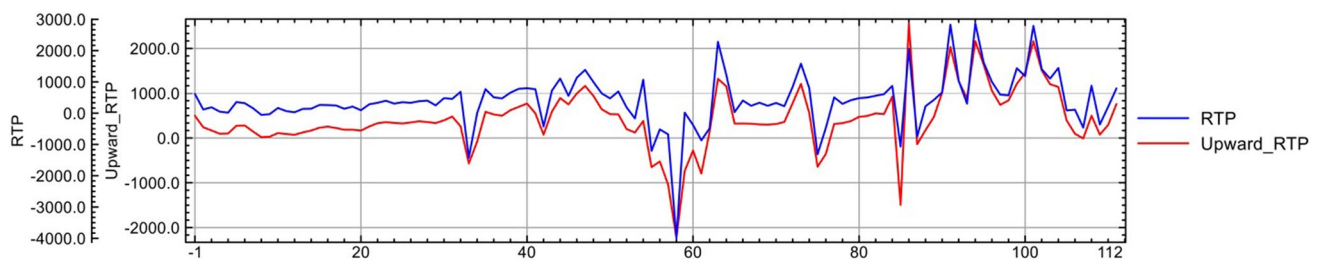


Fig. 12 Upward continuation anomaly on profile 1

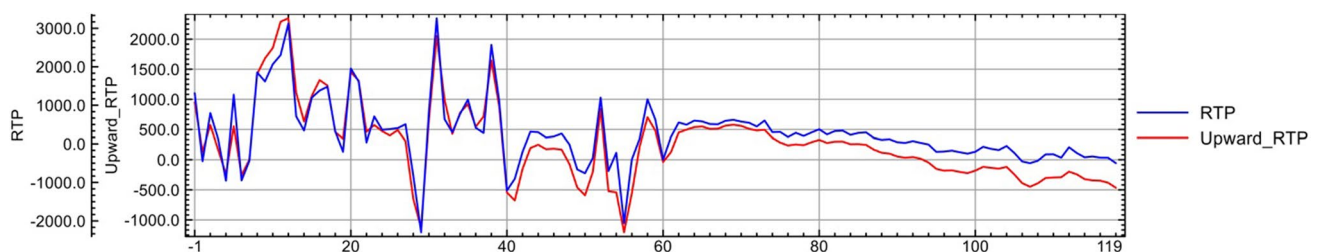


Fig. 13 Upward continuation anomaly on profile 2

continuity of structures detected at the shallow surface to deep depths.

Upward continuation result for profile 3

The appropriation of the magnetic intensities from deeper structures led to applying the UC filter to suppress the effects of shallow anomalies. This helped high-frequency anomalies relative to low-frequency anomalies to be smoothed out. An almost identical data plot is obtained in Fig. 14 signifying continuity of structures detected at the shallow surface to deep depths. The first vertical derivatives range from -1000 to 3500 nT. An almost identical data plot is obtained in Fig. 14 signifying continuity of structures detected at the shallow surface to deep depths.

First vertical derivative (FVD)

According to Telford et al. (2004), the first vertical derivative (FVD) is the most usual type of vertical gradient (or derivative) maps produced during aeromagnetic magnetic data analysis. It is one of the vertical derivatives commonly applied to total magnetic field data to enhance the shallowest geological sources in the data. As with other filters that enhance the high wavenumber components of the spectrum, it is often necessary to apply an additional low-pass filter to remove high wavenumber noise. The high wave number anomalies associated with the surface, near-surface, and local geological structures (such as faults) are the major

emphasis of first and second vertical derivatives and are greatly enhanced.

FVD result for profile 1

According to Telford et al. (2004), the first vertical derivative (FVD) is the most usual type of vertical gradient (or derivative) maps produced during magnetic data analysis. Figure 15 shows the first vertical derivatives of the total magnetic intensity (TMI) anomaly maps produced from magnetic data. The high wave number anomalies associated with the surface (fault), near-surface, and local geological structures are the major emphasis of first vertical derivatives and it is greatly enhanced. The magnetic susceptibility of the FVD ranges from -380 to 360 nT. This indicated that the near-surface structure is of low conductivities as opposed to the Upward Continuation map in Fig. 12 above which can be interpreted as minor faults and fractures.

FVD result for profile 2

Figure 16 shows the first vertical derivatives of the total magnetic intensity (TMI) anomaly maps produced from magnetic data. The high wave number anomalies associated with the surface (fault), near-surface, and local geological structures are the major emphasis of first vertical derivatives and it is greatly enhanced. The first vertical derivatives range from -150 to 150 . The almost identical data plots indicate minor differences in the geological structures present at the surface and at deep depths in that area.

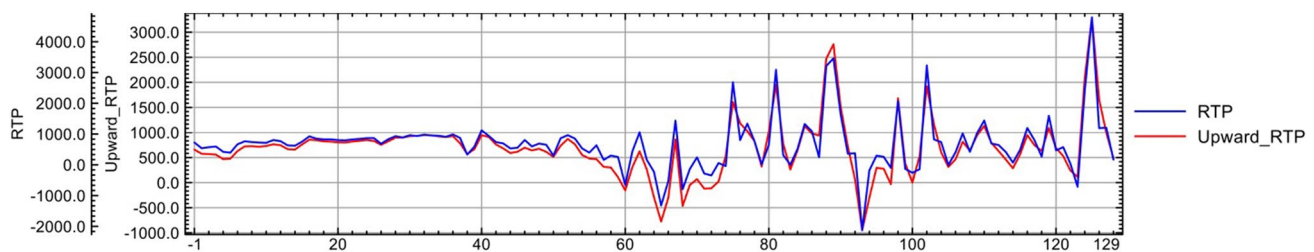


Fig. 14 Upward continuation anomaly on profile 3

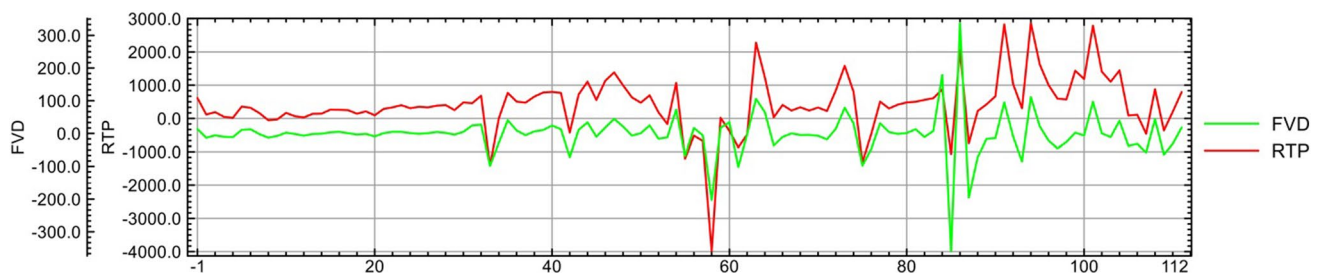


Fig. 15 FVD anomaly on profile 1

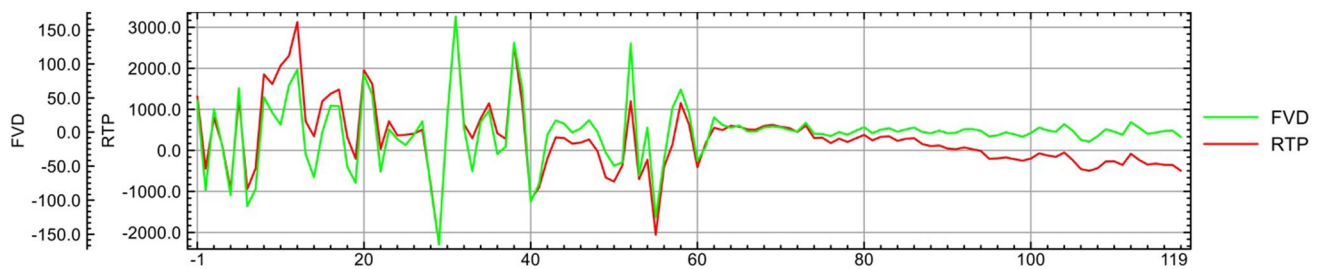


Fig. 16 FVD anomaly on profile 2

The magnetic map used for this study was obtained from the data that was acquired on three parallel profiles using Proton Precision Magnetometer. The map represents the Northern–Southern and Eastern–Western study areas. The data were presented in magnetic profiles, as well as TMI, Upward Continuation map, FVD, and reduction to the pole map.

FVD result for profile 3

Figure 17 shows the first vertical derivatives of the total magnetic intensity (TMI) anomaly maps produced from magnetic data. The high wave number anomalies associated with the surface (fault), near-surface, and local geological structures are the major emphasis of first vertical derivatives and it is greatly enhanced. The first vertical derivatives range from -150 to 50. The almost identical data plots indicate minor differences in the geological structures present at the surface and at deep depths in that area.

Quantitative analysis

TMI map

The textual content of TMI maps aids the extraction of geological information. The RTP grid ideally contains the same frequency distribution as the original TMI grid. It also retains dip information while removing the effect of magnetization direction (provided there is no remanence) and

geological strike. Therefore, it should be equally possible to map structures, divide the region into geologic terrains, etc. The Analytic Signal grid enhances the effect of shallow sources, widens anomalies, and removes the effect of magnetization direction (almost completely), geological strike, and geological dip. The resultant map is generally noisy in appearance, with significantly less textural information, thus also making it harder to extract geological information from it. For even lower magnetic inclinations, the textural content of RTP grids is compromised by the increasing signal noise and the inadequate reduction of declination signals.

The variations are in three categories, namely magnetic highs, magnetic intermediates, and magnetic lows. The magnetic highs values of intensity range between 957.0 and 1492.0 nT are the most dominant in the central part and around the northern part of the study area. This indicates the presence of rocks of high magnetic susceptibility of typical Basement Complexes. Magnetic intermediates range from 459.7 to 908.5 nT dominated the western and eastern part of the study area, which also formed the boundaries for shallow sources in the western part. This indicates the presence of metamorphic rocks. Magnetic lows with a magnetic intensity value range between -206.7 and 449.7 nT are mainly dominated in the southern part of the study area, signifying the presence of materials of low magnetic susceptibility which is of sedimentary rock origin. Figure 18 clearly shows three major rock types that exist in the study area, namely sedimentary rock which is of high dominance in the southern part of the study area, metamorphic rock dominates in the

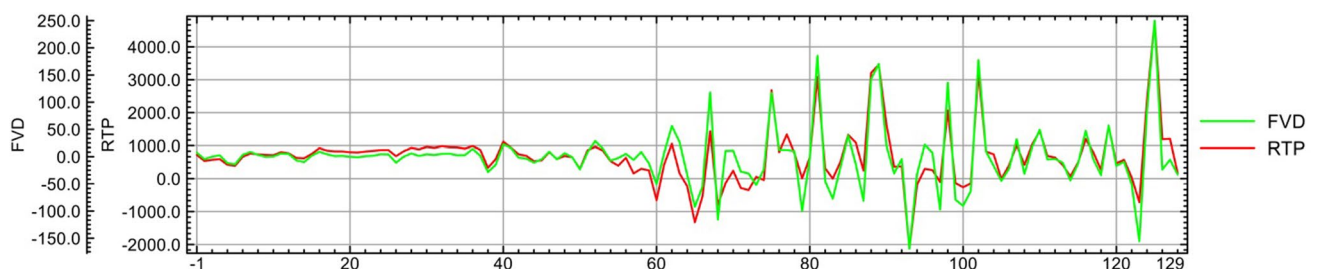


Fig.17 FVD anomaly on profile 3

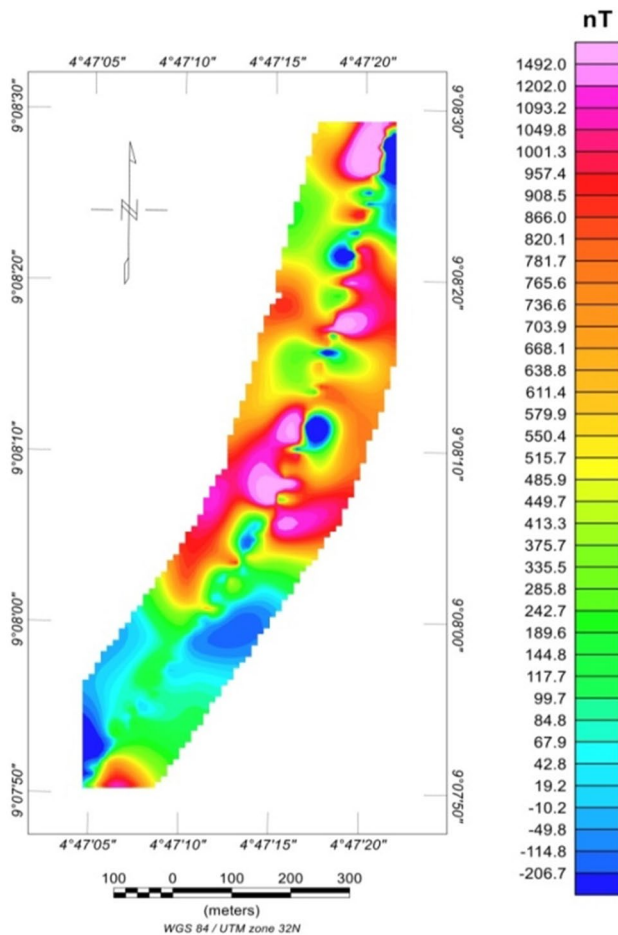


Fig. 18 TMI anomaly map of the study area

western and eastern, and igneous rock as an anomaly in the northern and the central part of the study area. Also, the acute shape of a positive anomaly (1492 nT) is visible in the central area.

RTP map

To find the observed magnetic disturbances directly over the magnetic source bodies that produced the anomaly, a reduce to the pole (RTP) filter was added to the TMI grid. It was also used to eliminate the effect of magnetic latitude on magnetic anomalies (Murphy 2007). The TMI grid was converted to a reduction to the pole (RTP) grid in the Geosoft Oasis Montaj program using the 2D-fft (fast Fourier transform) filter. The parameters for the transition are a -9.74° inclination and a -1.40° declination, which reflect the area's mean value.

Low and high magnetic frequencies represent points with low and high magnetic signatures, respectively, on the RTP magnetic anomaly map (Fig. 19). The magnetic peaks (pink color) of the TMI (Fig. 18) are seen as lows in the RTP

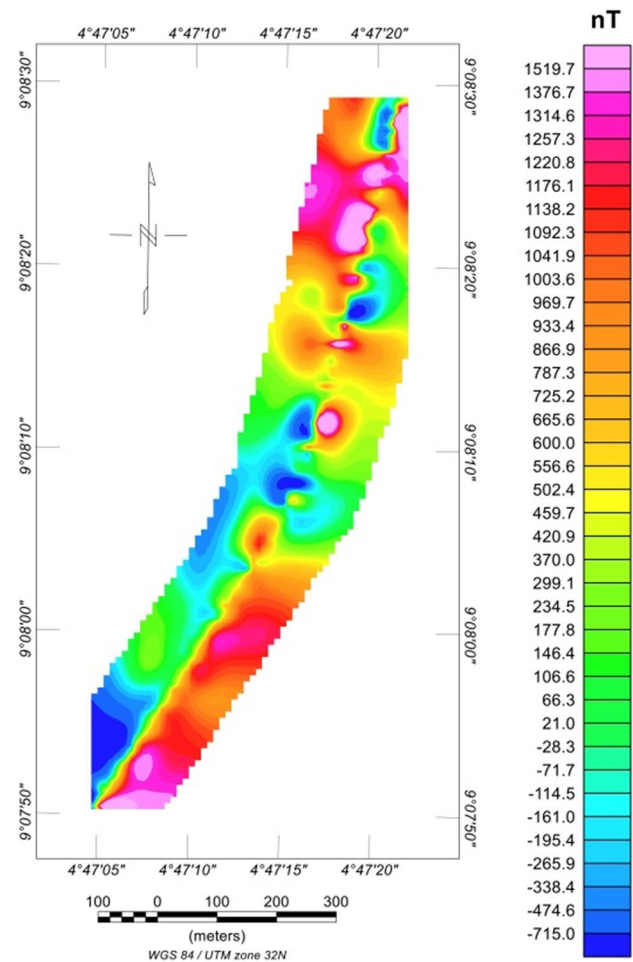


Fig. 19 RTP anomaly map of the study area

image, but the magnetic highs (pink color) of the TMI are seen as lows in the RTP image (blue color). The RTP chart displays more important characteristics of the magnetic signature, such as structures and lithology than the residual magnetic strength map.

Conclusion

The geophysical investigation involved the application of the magnetic method to the Detection of seepages and fracture zone on Jebba dam using the magnetic method. A total of three (3) profiles were obtained and after careful study and interpretation of the magnetic data, we generated several maps and plots which described the lithology distribution and geological structures dominating the area. The susceptibility map detected the presence of magnetic variations in values scattered along with the profiles.

The investigation has depicted the presence of magnetic highs and low across each profile. For profile one, the

Analytical Signal map superimposing TMI map indicated a fault at 48 m distance and an intrusion at 34 m distance. For profile two, some faults at 12 m, 38 m distance, and intrusions at 4 m, 54 m distance. For profile three, no faults were observed and an intrusion was observed at a 95 m distance. Reduction to pole shows the correct position of the magnetic susceptibility over profile distance and correlation in the upward modeling maps improved shallow causative bodies and first derivative maps improved deep-seated bodies show that the geological structures are continuous from shallow depth to a deeper depth. These results show there is a presence of unexpected/abnormal seepages in the N–S and E–W parts of the study area.

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Code availability Not applicable.

Declarations

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Consent for publication All authors have agreed to publish the article in 'Sustainable Water Resources Management'.

References

- Abderahman EM, Essa KS (2005) Magnetic interpretation using a least-squares depth shape curves method. *Geophysics* 70(3):L23–L30
- Anudu GK, Stephenson R, Macdonald D (2014) Using high-resolution aeromagnetic data to recognize and map intra-sedimentary volcanic rocks and geological structures across the Cretaceous middle Benue Trough, Nigeria. *J Afr Earth Sci*. <https://doi.org/10.1016/j.jafrearsci.2014.02.017>
- Baranov V, Naudy H (1964) Numerical calculation of the formula of reduction to the magnetic pole. *Geophysics* 29:67–79. <https://doi.org/10.1190/1.1439334>
- Birch FS (1984) Bedrock depth estimates from ground magnetometer profiles. *Groundwater* 22:427–432
- Biswas AK, Chatterjee S (1971) Dam disasters—an assessment. *Eng J (canada)* 54(3):3–8
- Henderson F (1973) Nigeria–Kainji Lake project: a limnological description of Kainji Lake 1969–1971. A report prepared for the Kainji Lake Project. FI: DP/NIR 66/524/10
- Islam AM, Talukdar S, Mahato S, Kundu S, Eibek KU, Pham QB, Kuriqi A, Linh NT (2021) Flood susceptibility modeling using advanced ensemble machine learning models. *Geosci Front* 12(3):101075. <https://doi.org/10.1016/j.gsf.2020.09.006>
- Kogbe CA, Ajakaiye DE, Matheis G (1983) Confirmation of a rift structure along the mid-Niger Valley, Nigeria. *J Afr Earth Sci* 1:127–131
- Li H, Li Z, Xu H, Zhou N, He Y (2019) Embankment dam leakage detection by the joint use of magnetic resonance sounding and electrical resistivity imaging. *IOP Conf Ser Earth Environ Sci* 304:042005. <https://doi.org/10.1088/1755-1315/304/4/042005>
- Mainstream Energy Solution (2017) <https://mainstream.com.ng/jebba-plant.html>
- Malomo S (1984) Engineering geology of dam sites in parts of the Niger River Basin Netherlands Development Company (NEDECO) 1961. Niger dams project report. Vol. 3 Geology. Submitted to National Electric Power Authority (NEPA), Lagos
- Murphy BSR (2007) Airborne geophysics and the Indian scenario. *J Ind Geophysics Union* 11(1):1–28
- Nabighian MN (1972) The analytic signal of two-dimensional magnetic bodies with polygonal cross-section: its properties and use for automated anomaly interpretation. *Geophysics* 37:507–517
- Nabighian MN (1984) Toward a three-dimensional automatic interpretation of potential field data via generalised hilbert transforms: fundamental relations. *Geophysics* 49:780–789. <https://doi.org/10.1190/1.1441706>
- NGSA-Nigeria Geological Survey Agency (2006) Geological and mineral resources map of Kwara State, Nigeria
- Nicolas MO (2007) The magnetic method. Presented at Short Course II on Surface Exploration for Geothermal Resources, organized by UNU-GTP and KenGen, at Lake Naivasha, Kenya, 2–17 Nov 2007
- Oladunjoye HT, Olasunkanmi NK, Olaleye AO (2014) geophysical evaluation of magnetic data of Okenugbo Area, Ago-Iwoye, Southwestern, Nigeria. *Academic Journal of Interdisciplinary Studies*. MCSER Publishing, Rome (E-ISSN 2281–4612, ISSN 2281–3993)
- Olasunkanmi NK, Aina A, Olatunji S, Bawalla M (2018) Seepage investigation on an existing dam using integrated geophysical methods. *J Environ Earth Sci* 8(5) (ISSN 2224–3216 (Paper) ISSN 2225–0948 (Online))
- Olorunfemi MO, Ojo JS, Sonuga F, Ajayi O, Oladapo MI (2000) Geoelectric and electromagnetic investigation of the failed Koza and Nasarawa Earth Dams around Katsina, Northern Nigeria. *J Min Geol* 36:51–65
- Rajagopalan S (1997) The 3D analytic signal: a creative solution or a waste of time?: Preview, 66, 63–64. Nigerian Geological Survey Agency, N.G.S.A. 2006. Geological and Mineral Resources Map of Cross River State, Nigeria
- Telford WM, Geldart LP, Sheriff RE (2004) Applied geophysics, 2nd edn. Cambridge University Press, New York

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