

## Research Article

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# Aeromagnetic mapping of fault architecture along Lagos–Ore axis, southwestern Nigeria

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**Abstract:** A seismic wave is released when there is sudden displacement on a fault plane. The passage of this wave along the fault plane or within the lithosphere could result in ground shaking or vibration at the surface of the Earth. To provide a geophysical explanation to this phenomenon, the high-resolution aeromagnetic data of the sedimentary terrain and part of the Basement Complex of Southwestern Nigeria were processed and interpreted to provide fault architecture of the area, which could serve as conduit for the passage of seismic energy in the study area. High-resolution aeromagnetic data along the Lagos–Ore axis are processed for fault mapping in the study area. The reduced-to-equator (RTE) residual aeromagnetic data used were enhanced using the total horizontal derivative (THD) and upward continuation (UC) filtering techniques on Oasis Montaj 6.4.2 (HJ) software. The resultant maps were overlaid and compared with the plotted RTE residual maps for relevant interpretations. Varying signatures of magnetic anomalies are grouped into high (57.9–89.1 nT), intermediate (38.2–57.9 nT), and low (4.0–38.2 nT) magnetic intensities, which are associated with contracting basement rocks features. The obtained lineaments from the THD reveal areas of various deformations such as brittle, which is associated with faults/fractures, and ductile

deformation, which is associated with folds of geological features. The faults, as depicted by the UC map, reveal different depth ranges of 500–2250 m at the western side and 1,500–1,250 m at the northwestern area of the study. Since it has been on record that September 11, 2009, earth tremor of magnitude 4.4, with the epicenter at Allada, Bennis Republic, 128 km west of Lagos, Nigeria occurred within the study area, it can be inferred that the established geologic fault architecture could be responsible for the hazard and be part or synthetic to the Ifewara-Zungeru fault in Nigeria.

**Keywords:** magnetic intensity, tectonic deformation, fault architecture, tremor, aeromagnetic data

## 1 Introduction

Fault occurs when there is a mechanical break or generic discontinuity within the rock volume. It could also be termed as the displacement in a rock volume by fracturing along a planar interface. A fault initiates or propagates when there is equity between the stress and strength of a rock. Some of the mechanisms that produce high stress within the crust include fluid pressure; lithostatic; geothermal occurrence; tectonic forces as regard to lithospheric plates' movement; geologic processes such as volcanic activities, folding as well as salt intrusion; and other forces by extraterrestrial bodies [1]. The fault architecture is related to the fault size, orientation, shape, and its interconnectivity [2]. It could also be termed as the overall distribution of fault's displacement into subfaults.

Any event that occurs suddenly in nature could be termed as natural disaster. Such events are wildfire, solar flare, sinkhole, cyclone, drought, thunderstorm, tornado, flood, volcanic eruption, landslide, hurricane, tsunami, and earthquake. Of all these events, earthquake has been regarded as the greatest disaster [3]. It comes swiftly, without giving uncertainty room for its occurrence [4]. This phenomenon is so scary as a result of its destructiveness to lives, properties, and economy. Generally, earthquake is

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believed to occur within tectonic margins, but record has showed that it could also occur outside the tectonic margins, as in the case of Nigeria [5].

Nigeria is situated on a seismic inactive plate, but the rate at which tremors are being recorded (via instrumental and/or historical platforms) from 1933 across the country till the recent one that occurred in Federal Capital Territory, Abuja, in 2018 had proved that Nigeria is no longer safe from earthquake occurrence(s), which requires further investigations. Nigeria resides on the eastward of the Atlantic Ocean, which is attached to the passive margins (Figure 1) toward the south and southwestern regions of the country. Geologically, there have been consistent openings or movement in the Atlantic margins since the Jurassic (201.3 – 145 Mya) to present [6]. Unlike the active margins (such as the Pacific), which is associated with devastating earthquake occurrences as a result of subduction tectonics, passive margins (such as Atlantic) are believed to be stable and quiet; and due to this, little awareness and preparation have been made for earthquake occurrences along the passive margins, especially Nigeria and other countries in the coastal region of West Africa.

For about 85 years of seismic activities in Nigeria, there was no record of loss of life nor damage of properties, but of recent, damage to properties were observed. The geological

structures and some human activities have aided the mechanisms that are responsible for the seismic events in Nigeria [3]. The years of occurrence of these events are 1933, 1939, 1964, 1984, 1985, 1987, 1990, 1994, 1997, 2000, 2006, 2009, 2016, and 2018 [7,8]. In recent time, these events have begun to produce a scary outcome, which could be likened to a detonation of a small fission bomb as reported by [9]. If this event is not properly monitored, seismic activities with greater magnitude than those recorded earlier (magnitude of up to 4.5) could be triggered in the region [10]. According to the literature, some locations that have been affected by tremors so far include Saki, Igbogene, Kwoi, Sambang Dagi, Dan Gulbi, Kano, Kombani Yaya, Lupma, Abuja, Yola, Gembu, Abeokuta, Oyo, Ibadan, Ogbomoso, Akure, Shagamu, Ijebu-Ode, Lagos, Okitipupa, Warri, Ile-Ife, Ijebu-Remo, Ohafia, Kundunu, Obi, Akko, Kurba, Jerre, Benin, Edo, Jushi-Kwari, Akure, and Abomey-Calavi [3,6,11,12]. Their studies had shown that more than half of the seismic events in Nigeria occurred in southwest ([SW]; Figure 2). This shows that southwestern region of Nigeria is more vulnerable to tremor occurrence compared to other zones. However, the epicenters of these earthquakes with their locations are presented in Table 1.

Critical review of the previous works has revealed that tremor occurrence in Nigeria could be attributed to regional

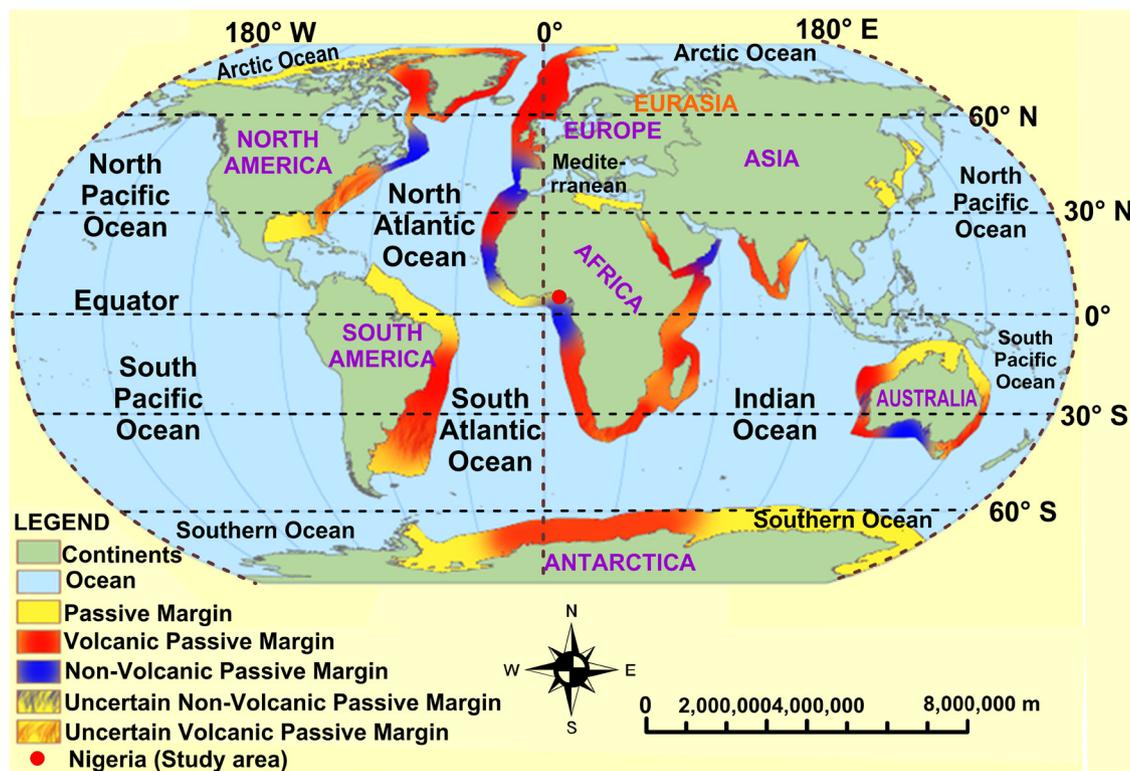


Figure 1: Global distribution of passive margins (Modified after [33]).

stress, presence of weakened zones in the crust, and transfer of stress from plate boundaries [3,6–8,11–25]. The West African Craton and Congo Craton bounded the Nigerian Basement Complex in the west-northwest and east-south-east directions, respectively. This could have deduced the stress acting in this orientation, because records of tremors in Nigeria have been along this orientation [26,27]. Regional stress could cause intraplate earthquakes on preexisting faults within the crust that are of low strength. When the intrusive rock (magma) strength is weaker than the host, this could generate a localized stress within the body of rock. Rock intrusions in the sedimentary terrains of Nigeria could have resulted to sufficient stress capable of causing tremors. As reported by Short and Stauble [28], stress generated as a result of upwelling magma deforms the crust, which leads to faults. Over (geologic) years, these faults are covered by sediments that have formed the midplate structures, which are subjected to tectonic compressional stress [28]. As the stress continues, a failure will occur at the spot of initially fractured zone within the pristine rock, which could result in intraplate tremors [29]. All the aforementioned factors can create fault in the crust which could be a reason for the occurrence of tremors in Nigeria. This has necessitated this study to map the crustal fault architecture along Lagos–Ore axis, SW Nigeria using the high-resolution aeromagnetic data (HRAD). The HRAD is a highly efficient geophysical tool that delineates geostructural features such as shears, faults, and dyke [30]. Among the researchers who have demonstrated the effectiveness of HRAD in delineation and mapping of faults in Nigerian shore include Oladejo *et al.* [27], Awoyemi *et al.* [30,31], and Awoyemi *et al.* [32]. The outcome of this study will enable the masses to know the routes/channels of these seismic energies whenever it is released.

## 2 Geology and brief tectonic activity of the study area

The study area falls within the latitude 6° 05' 00" to 7° 25' 00" N and longitude 2° 43' 00" to 4° 31' 00" E, with elevation ranges between 85 and 375 m. The geology of Nigeria is of the reorganized Basement rocks in western part of Africa [9,35,36], which dissociates West Africa from Congo Cratons [3,9,37–39]. These rocks are composed of the geological features from African igneous and meta-sedimentary rocks [40]. The two obvious geological settings in Nigeria are the Sedimentary Basins and the Basement Complex [3,40–43]. These two geological settings are well

represented in the study area. Lagos lies on Dahomey (Benin) basin – one of the Nigerian sedimentary terrains, while Ore is situated on the Basement complex of SW Nigeria (Figure 3a).

Dahomey basin is located in the SW Nigeria covering Ondo, Ogun, and Lagos states. Dahomey Basin encapsulates the onshore and offshore zones of this region. The onshore includes the region where the Tertiary and Cretaceous sedimentary rocks are revealed along the quarries and roadcuts [44]. This basin is bounded at the west of Niger–Delta basin and the Basement rocks to the north. Both basins are of course low lying, as expected of a basin. The Dahomey basin extends beyond Nigeria and, like the Niger Delta, seems to have some oil deposits, although the former is far less explored than the latter. The Continental basin of the former is not as extensive, and the seabed slopes away relatively steeply from shore; while in the central Niger–Delta, the seabed slopes away gently, making for a wider area continental shelf. Lagos state as a whole is littoral, low-lying, and swampy, except for some areas inland, the Ogun, Osun, Opara, Yewa, and Weme rivers among others drain into the various lagoons and creeks that wind their way through the terrain, such as the Lagos and Lekki lagoons or the Badagry creek. The geology of Dahomey basin is mainly composed of shale and sand, with some intercalations of limestone. The limestone thickens toward the west of the basin as well as down dip of the coast and its environs. As reported by these researchers [39,44–53], the lithostratigraphic formations of this basin from Cretaceous to Tertiary are grouped as Abeokuta Group (Cretaceous), Ewekoro (Paleocene)/Akinbo Formations (Late Paleocene – Early Eocene), Oshosun Formation (Eocene), Ilaro Formation (Eocene), Coastal Plain Sands/Benin Formation (Oligocene to Recent), and Alluvium (Recent age; Figure 3b).

Ore is one of the major towns in Ondo state, which is constituted by the Pre-Cambrian Basement rocks of SW Nigeria (Figure 3a and b) [35,54], though some parts of the state are constituted by the formations of Dahomey basin. The Basement Complex of SW Nigeria is chiefly composed of metamorphic and crystalline rocks of over 550 million years old [55,56]. The crystalline Basement rocks of SW are grouped into Migmatite-Gneiss, metasedimentary and meta-volcanic rocks (which is also referred to as Schist Belt), and Pan-African Older Granite [57,58]. The predominant rock in Ore is granite. This rock is massively distributed, which can contribute to the state economy if properly mined. Further readings about the Basement Complex of SW Nigeria have been discussed by [30,41] and [45].

The seismic events mechanism in Nigeria can be explained in terms of the fractures within the Basement

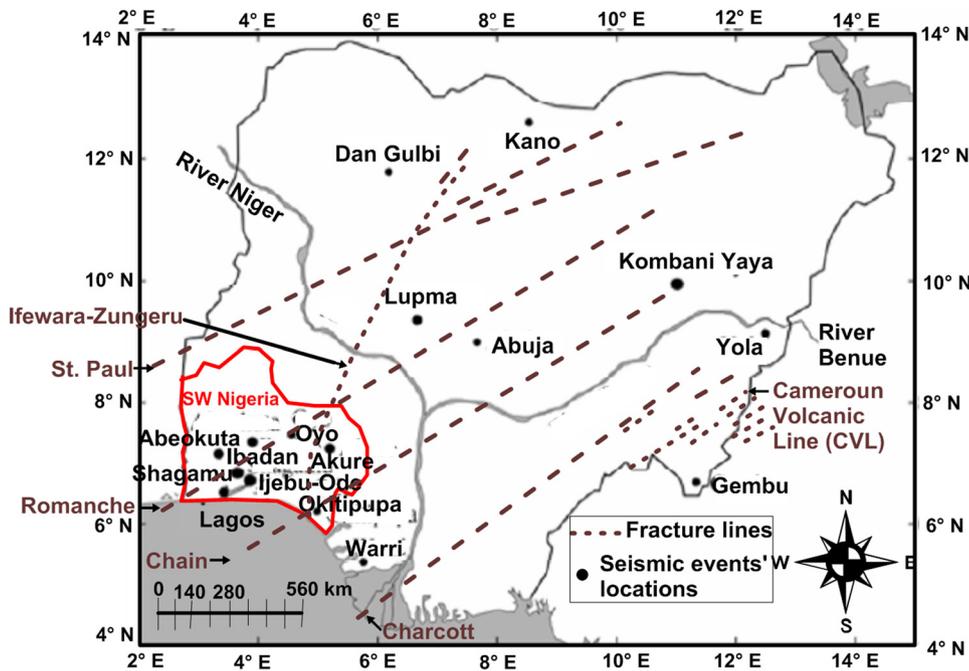


Figure 2: Map of Nigeria revealing some locations where seismic events had occurred (adapted from [6] and [34]).

rock and extension of these faults in sedimentary terrain to the Atlantic Ocean [6]. The Nigerian coastal zone lies between the African and South American plates. Some of the recorded tremors around Nigeria, especially in SW Nigeria where these events are highly concentrated, could have been initiated through the built-up stresses around plate boundaries. When these stresses propagate to the center of the plate, it can trigger a phenomenon known as intraplate tremor, especially on already established faults [42]. Some of the important fault systems in Nigeria that have resulted from transcurrent movement include Anka, Kalangai, Ifewara-Zungeru faults [59]. Of all these fault systems, Ifewara-Zungeru fault is the longest already established linear feature in the Basement Complex of Nigeria. This fault is about 250 km long that bisects the Romanche and Chain fracture lines (extending from the Atlantic Ocean to the northeast [NE] part of Nigeria) in the SW and cuts across the St. Paul's fracture line in the northwest (NW) region of Nigeria [26,34,60] (Figure 2). It took its origin from SW Nigeria and stretched to the NW region of the country, with a north-northeast (NNE)–south-southwest orientation [6] (Figure 3a). As reported by Akpan and Yakubu [6], the epicenters of the earthquakes in SW Nigeria fall between the Romanche and Chain Fracture zones (Figure 2).

### 3 Materials and methods

Many geophysical methods are available for studying the litho-structure of the subsurface at regional dimension.

Among the methods are gravity, magnetic, electromagnetic, electrical resistivity, and radiospectrometry; however, magnetic method was employed in this study. Magnetic data can be acquired on ground, in air, and in marine; however, the regional study requires aeromagnetic data. Aeromagnetic data is an essential tool in delineation of Basement rocks and estimation of depth to magnetic sources, even in sedimentary terrain without being disturbed by obstacles [61–64].

The aeromagnetic data of Lagos–Ore were collected from the Nigerian Geological Survey Agency (NGSA). It composes sheet numbers 278, 279, 280, 281, 278A, 279A, 280A, and 281A; southern part of 259, 260, 261, 262, and 263; as well as western part of 282 and 296 [65]. The data sheets cut across parts of Ogun, Ondo, Oyo, and Osun states as well as the entire Lagos state (Figure 3a and b). The data sets were acquired by the Fugro Airborne Survey Limited for the NGSA in the year 2003–2009 [66]. The survey was conducted in drape mode using the real-time differential GPS at a sensor mean terrain clearance of 75 m. The spacings of both the traverse and the tie lines are 500 and 2,000 m, with the orientation of the flight and tie lines in NW-southeast (SE) and NE-SW, respectively [66]. The data sets were de-cultured, leveled, corrected for International Geomagnetic Reference Field, gridded at an appropriate cell size that amplifies the information contained in the anomaly, and suppresses the latitudinal effect and unwanted signal (noise) [67,68].

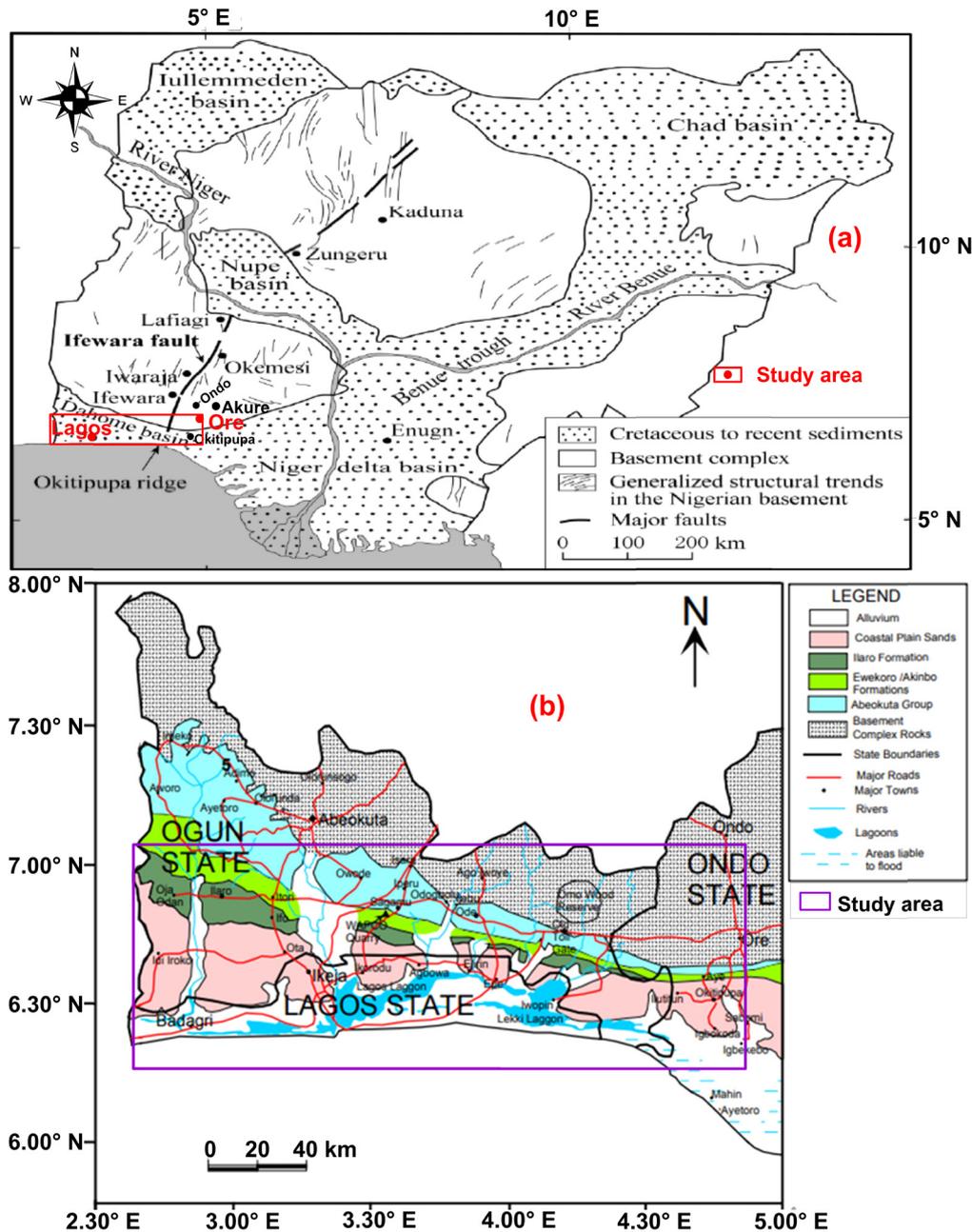
**Table 1:** Historical seismic events in Nigeria (adapted from [3])

Date of event	Felt area	Probable epicenter	Intensity/magnitude
1933	Warri	—	
June 22, 1939	Lagos, Ibadan, Ile-Ife	Akwapin fault in Ghana	6.5 ML
July 28, 1948	Ibadan	Close to Ibadan	
July 2, 1961	Ohafia	Close to Ijebu-Ode	
December 21, 1963	Ijebu-Ode	Close to Ijebu-Ode	V
April 23, 1981	Kundunu	At Kundunu village	III
October 16, 1982	Jalingo, Gembu	Close to Cameroun Volcanic Line	III
July 28, 1984	Ijebu-Ode, Ibadan, Shagamu, Abeokuta	Close to Ijebu-Ode	VI
July 12, 1984	Ijebu Remo	Close to Ijebu-Ode	IV
August 2, 1984	Ijebu-Ode, Ibadan, Shagamu, Abeokuta	Close to Ijebu-Ode	V
December 12, 1984	Yola	Close to Cameroun Volcanic Line	III
June 18, 1985	Kombani Yaya	Kombani Yaya	IV
July 15, 1986	Obi	Close to Obi town	III
January 27, 1987	Gembu	Close to Cameroun Volcanic Line	V
March 19, 1987	Akko	Close to Akko	IV
May 24, 1987	Kurba	Close to Kurba village	III
May 14, 1988	Lagos	Close to Lagos	V
June 27, 1990	Ibadan	Close to Ijebu-Ode	3.7 ML
April 5, 1990	Jerre	Close to Jerre village	V
November 7, 1994	Ijebu-Ode	Dan Gulbi	4.2 ML
1997	Okitipupa	Close to Okitipupa Ridge	IV
2000	Edo	Siluko, Edo	4.5 ML
August 15, 2000	Jushi-Kwari	Close to Jushi Kwari village	III
March 13, 2000	Benin	55 km from Benin City	IV
March 7, 2000	Ibadan, Akure, Abeokuta, Ijebu-Ode, Oyo	Close to Okitipupa	4.7 ML
May 7, 2000	Akure	Close to Okitipupa	IV
May 19, 2001	Lagos	Close to Lagos City	IV
August 8, 2002	Lagos	Lagos City	IV
March, 2005	Yola	Close to Cameroun Volcanic Line	III
March 25, 2006	Lupma	Close to Ifewara	III
September 11, 2009	Abomey-Calavi	Close to Benin	II
November 5, 2011	Abeokuta	Close to Abeokuta	4.4
July 10, 2016	Saki	Oyo State	IV
August 10, 2016	Igbogene	Bayelsa	III
September 11, 2016	Kwoi	Kaduna State	III
September 12, 2016	Sambang Dagi	Kaduna	III
September 7, 2018	Abuja	Mpape	3.0

The field data (i.e., total magnetic intensity [TMI]) were generated in  $x$ ,  $y$ , and  $z$  format (where  $x$ ,  $y$ , and  $z$  represent longitude, latitude, and TMI, respectively) on Microsoft Office Excel, so as to export it to Oasis Montaj™ 6.4.2 package [95]. Rockware™ 15 software was used to convert the Universal Transverse Mercator values for  $x$  and  $y$  to geographic coordinates, in order to juxtapose the resultant maps with the geological map of the study area. In order to enhance the local subsurface features, the residual magnetic intensity (RMI) was generated by removing the regional magnetic field intensity from the data.

In this study, the reduction-to-equator (RTE) filter (on Geosoft Oasis Montaj) was used to enhance the features on RMI data, because the study area falls within the low

magnetic latitude zone. RTE makes Earth's magnetic field and magnetization of the magnetic sources to appear horizontal, centers the peaks of magnetic anomalies over their sources, and removes the magnetic latitudinal influences on RMI [69]. The RTE was performed using two-dimensional fast Fourier transform (2D-FFT) method, with the mean inclination and declination values of  $-11.10$  and  $-4.90$ , respectively. Oladunjoye et al. [68] stated that applying 2D-FFT on potential field data simplifies the complex information that is embedded in the original data. It also improves the quality of data being processed for effective geological deductions. One of such simplifications is to derive maps on which the amplitude of the displayed function is directly or simply related to a physical property of the underlying rocks as well as inherent



**Figure 3:** Geological maps. (a) Nigerian map revealing the most prolonged linear feature, some structural trends and study area (modified after [22]). (b) Dahomey Basin and part of SW Basement Complex rocks showing Lagos–Ore axis (adapted from [44]).

structural features and other desired parameters. The RTE-RMI data were further subjected to total horizontal derivative (THD) and depth continuation (upward and downward) enhancement techniques using Geosoft Oasis Montaj workstation as applied by [30–32, 68–73].

The THD was applied due to its ability to enhance lineaments, which are structural deformations associated with faults (fractures with displacement) or any other linear features [73]. The mathematical expression for THD [74] is

presented in equation (1). The algorithm used for THD has been presented by Gunn [75], while further mathematical explanation to this enhancement has been discussed by Blakely [76]. The THD map produced from RTE residual map is as shown in Figures 8 and 10.

$$THD = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2} \tag{1}$$

where  $T$  is the magnitude of the potential field data.

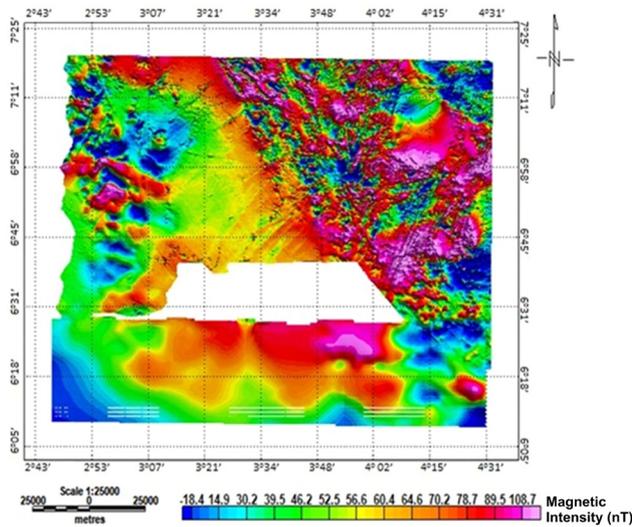


Figure 4: TMI relief image map of Lagos-Ore axis.

Continuation technique enhances transformed observed anomalous potential field to higher or lower elevations, which are known as upward and downward continuations. It also smoothens the residual data by alternating high-frequency or short wavelength anomalies relative to their opposite signatures [68,77]. This technique can be adopted in place of low-pass and high-pass filters [78]. The advantages of continuation technique over low pass and high pass include the following: prominent reduction and separation of near surface (shallow) effects over the deeper ones [68]; its use in the estimation of depth to magnetic

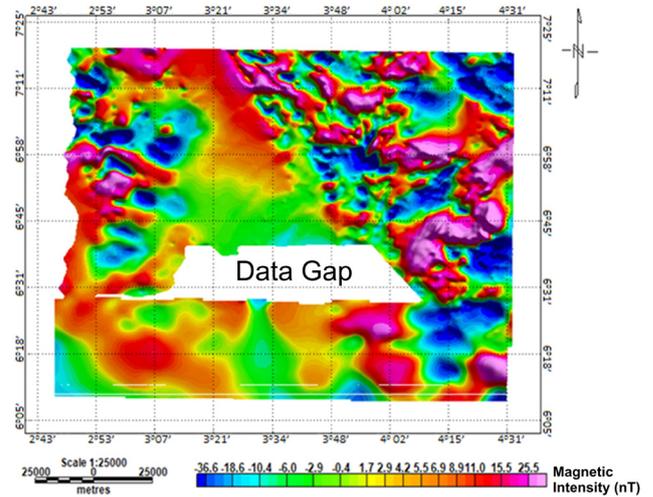


Figure 6: Residual magnetic field map of Lagos-Ore axis.

sources; and it retains the signatures of the geopotential field anomaly, provided that the continuation does not intrude into the top of the magnetic body [79]. The amplitude of potential over a magnetic body changes with elevation as an exponential function of wavelength [69]. In downward continuation, the magnetic sources are enhanced at certain depth, such that the measurement's plane is brought near the source. As reported by [80], downward continuation maps the components with high wave numbers, enhances the resolution of anomalous bodies, and enables perfect estimation of vertical and lateral extent of magnetic sources. The main shortcoming of downward continuation is that its computation is unstable and deviates from the true features of potential field data due to noise [81]. However, the computation of upward continuation (UC) is stable at higher heights, which accounts for contributions from various sources. The stability of UC and horizontal derivative has

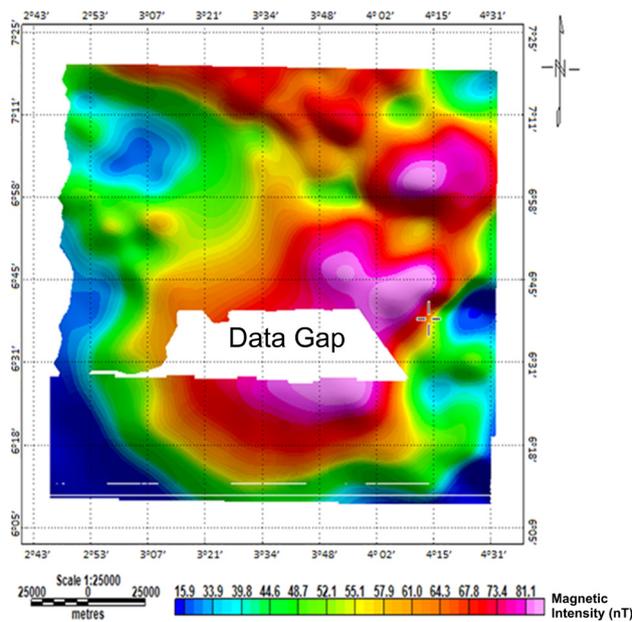


Figure 5: Regional magnetic field of Lagos-Ore axis.

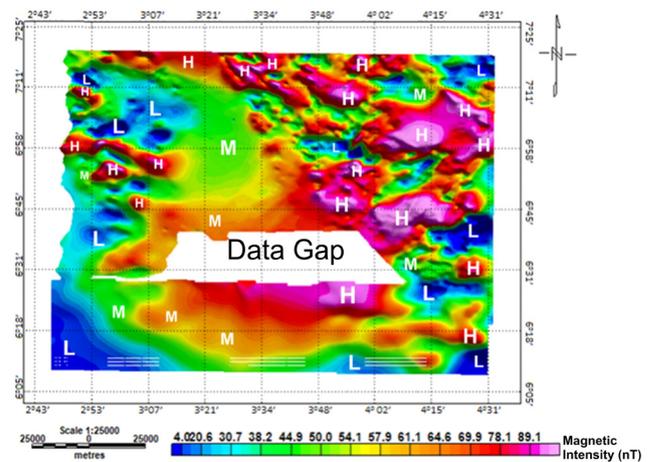


Figure 7: RTE-RMI map of Lagos-Ore axis.

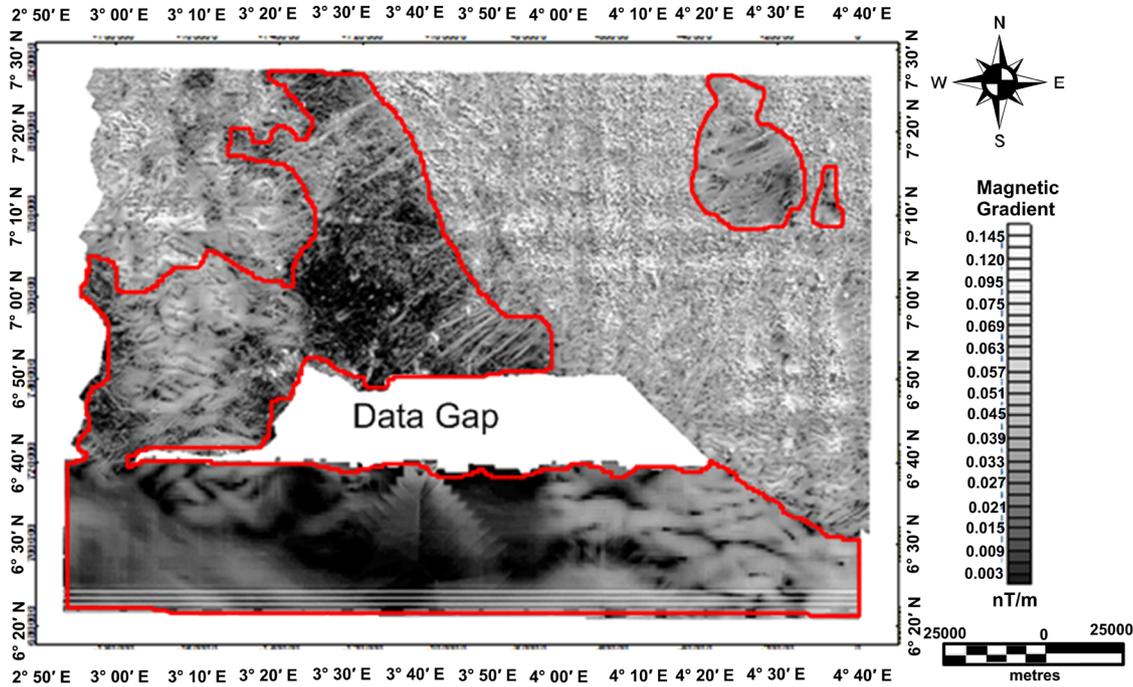


Figure 8: Gray-shaded THD map of Lagos–Ore axis.

made them to be included in computation of downward continuation model [78] using the Taylor’s series as presented in equation (2).

$$T(x, y, h) = T(x, y, 0) + \frac{\partial T}{\partial z}h + \frac{1}{2!} \frac{\partial^2 T}{\partial z^2}h^2 + \dots + \frac{1}{m!} \frac{\partial^m T}{\partial z^m}h^m \tag{2}$$

where  $T(x, y, h)$  = potential field at the level of  $h$ ,  $T(x, y, 0)$  = original potential field data,  $m$  =  $m$ th-order vertical derivative of the potential field, and  $h$  = continuation height.

However, computation of UC from Taylor’s series can be expresses as:

$$T(x, y, -h) = T(x, y, 0) - \frac{\partial T}{\partial z}h + \frac{1}{2!} \frac{\partial^2 T}{\partial z^2}h^2 + \dots + \frac{1}{m!} \frac{\partial^m T}{\partial z^m}(-h^m) \tag{3}$$

where  $T(x, y, -h)$  = potential field at the level of  $-h$ .

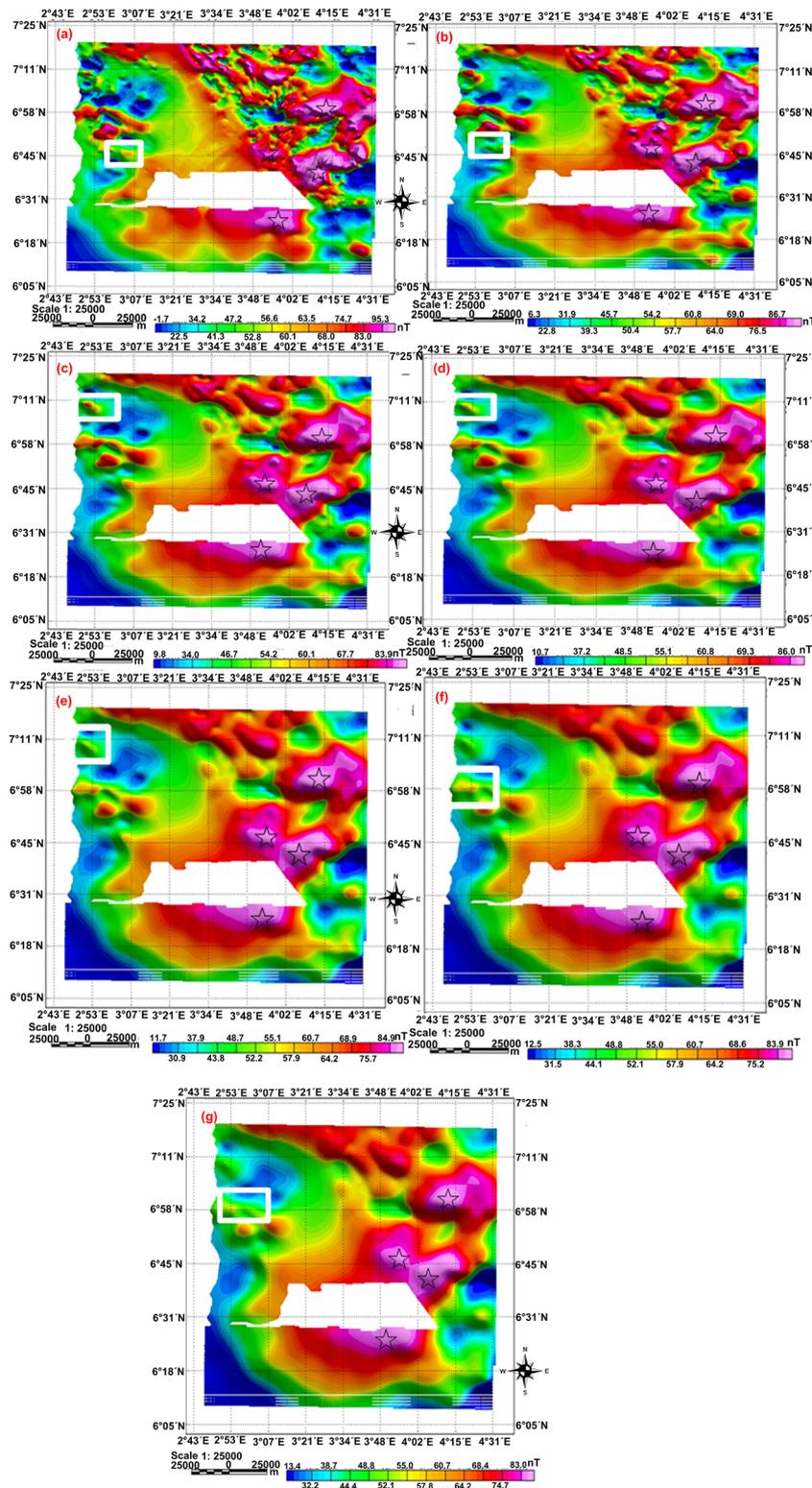
The two continuations require  $m$ th-order vertical derivatives of the potential field. At higher order, the vertical derivatives become unstable, which can influence the noise effects [82]. Therefore, the Taylor’s series, especially equation (3) is limited to order 3 [78]. The algorithm used in the two continuations (upward and downward) has been presented by [75]. The resulting maps (Figure 9a–g) revealed the individual depth to magnetic sources (either shallow or deep sources) based

on the level of continuation. The magnetic derivatives and other output maps obtained from processing and filtering were then superimposed on the geological map and RTE aeromagnetic RMI map of Lagos–Ore axis using ArcGIS 10.3 and Surfer 11.0 in order to produce the fault map of the study area.

## 4 Results and discussion

### 4.1 Aeromagnetic maps

The TMI map of the study area is presented in Figure 4. Figures 5 and 6 are the regional magnetic intensity and RMI maps, respectively. After the removal of the regional effect from the TMI data, most of the unpronounced features on TMI data (Figure 4) become enhanced on the residual map (Figure 6). The magnetic zone apportionment is based on the shape, pattern, and the magnetic intensity on the residual map. Magnetic highs are located toward the northeastern, eastern and northwestern zones of the study area. These signatures could be interpreted as near surface magnetic minerals, with shallow overburdens [57,83,84]. Magnetic lows that trend in NW-SE orientation intruded into the magnetic highs of the study area. These intrusions are also noticed around the southern and northwestern zones of the



**Figure 9:** Fault detection maps obtained from UC process of RTE-RMI map of Lagos–Ore axis. (a) At depth 500 m, (b) at depth 750 m, (c) at depth 1,250 m, (d) at depth 1,500 m, (e) at depth 1,750 m, (f) at depth 2,000 m, and (g) at depth 2,250 m.

study area. This could be associated with the depletion of magnetites or network of lineaments, which could be fractured/weak zones or regions with thick overburden [69,85–87].

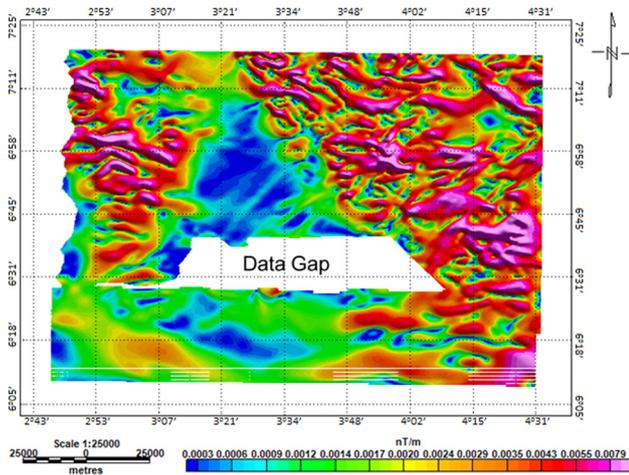


Figure 10: THD map of the study area.

## 4.2 The RTE-RMI map

Figure 7 displays slight shift in the positions of magnetic anomalies to the NW of the initial positions on the total magnetic anomaly. The RTE filter was applied to the RMI in order to locate the observed magnetic anomalies directly over the magnetic source bodies that caused the anomaly as well as to remove the influence of magnetic latitude on the residual anomalies as shown in RTE-RMI map of Lagos–Ore axis (Figure 7). The RTE filter enables one to determine the gradient along the direction of the greatest rate of change and trend. For RTE, the gradient to the east

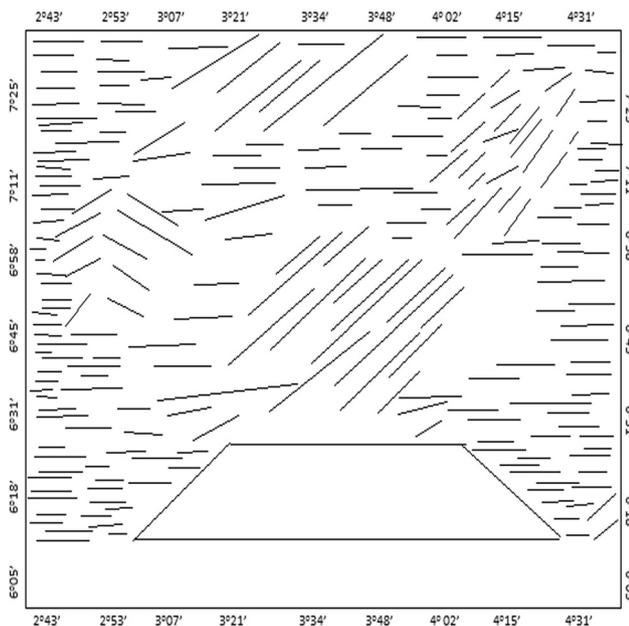


Figure 11: Magnetic lineaments map of Lagos–Ore axis as extracted from the THD.

and north are  $dx$  and  $dy$ , since the angle of the output grid equals zero at the equator. The color-shaded RTE-RMI map of Lagos–Ore axis is characterized by high ( $H$ , depicted by red and pink colors on the legend), medium ( $M$ , depicted by green color on the legend), and low ( $L$ , depicted by color blue on the legend) magnitude magnetic anomalies. In Figure 7, the high-magnitude magnetic anomaly signatures have magnetic field intensity ranging from 57.9 to 89.1 nT, which are most dominant at the northeastern half and sparingly at northwestern part, and these are the areas of shallow depth to the magnetic sources. The intermediate magnetic anomalies varied in magnetic intensity from 38.2 to 57.9 nT; and they are most prevalent in a convex arc form about northeastern half, these portions are of average depth to the magnetic anomalies. The low magnetic anomalies ranged between 4.02 and 38.2 nT; these are scattered over the study area but abound mostly at the edges, viz., NW, SW, SE, and NE of the area they represent deep depth to the magnetic sources.

## 4.3 Basement mapping and structural framework

Basement mapping involves delineation of the deep and shallow magnetic sources. These are as exemplified by the RTE-RMI map in Figure 7. The zones of high magnetic intensity indicated by  $H$  on Figure 7 are regions of shallow magnetic sources (shallow basement); while those of low magnetic intensity indicated by  $L$  are regions of deep magnetic sources (deep basement). The regions indicated by intermediate magnetic intensity ( $M$ ) lie between the deep and shallow basements. The THD map as revealed in Figure 8 could only distinguish between areas of deep and shallow basement as exemplified by areas of rarity of lineaments [68]. These are as demarcated and or delineated by red lines on the map.

Furthermore, regions of consistent high amplitude on the upward depth continued maps of the study area are regions of deep depth to magnetic sources. However, sharp changes from high-amplitude to low-amplitude anomalies delineated by white rectangles on the maps (Figure 9a–g) are areas of fault zones. Consequently, the faults revealed by UC maps represented by white rectangles are at different depths in the subsurface; there are faults at the western sides of the depth range of 500–2,250 m (Figure 9a,b,f and g) and northwestern sides at the depth range of 1,500–1,250 m parts (Figure 9c–e).

Conversely, regions of increased amplitude denoted by black stars in Figure 9 are regions of shallow depth to top of

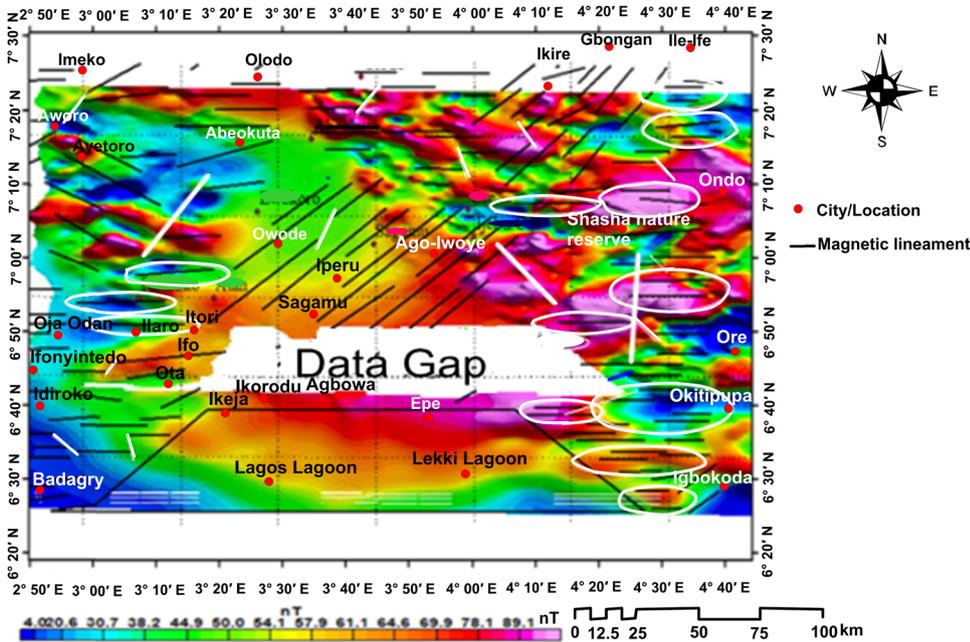


Figure 12: Combined lineaments map of Lagos–Ore with its RTE-RMI map.

magnetic sources. The structural framework was based on normalized magnetic derivatives by virtue of its suitability for structural mapping [68,88–91]. Based thereon, the magnetic lineaments extracted from THD map (Figure 10) have been overlain on RTE-RMI map (Figure 11) using Arc-GIS 10.3 software to obtain the map in Figure 12. Points or regions where the magnetic lineaments are in concordance with the anomalies (represented by white oval shapes) are geologically characterized as ductile deformation zones; while regions where the magnetic lineaments are in discordance with the anomalies are geologically characterized as brittle deformation zones. The associated geological features are either folds for ductile deformation zones or fractures/faults for brittle deformation zones. Brittle deformation zones commonly contain water (especially in shallow bedrock at the depth less than 100 m) and thus allow different chemical and physical weathering processes to take place within the zone, resulting in the decomposition of magnetite to hematite and pyrrhotite to goethite and elemental sulfur [92].

Most of the E-W lineaments on the overlain map (Figure 12) are associated with ductile deformation zones around Idiroko, Iwopin, Okitipupa, Igbokoda, Ore, northeast of Ijebu-Ode, the southeastern part (Ondo State axis), and the northeastern (Osun State axis) edges. However, the NE-SW lineaments are more associated with brittle deformation zones crisscrossing through the central portion around Atan, Ewekoro, Sagamu, Ijebu-Ode, and toward the NNE zone of the study area. The NW-SE lineaments as observed in the northern part as well as some of the E-W lineaments around Abeokuta also exhibit brittle deformation characteristics.

The results of this study are in agreement with the works of [93] and [94] who reported that the maximum depth to the aquiferous units within Atan–Ota axis, a brittle deformation zone, varied from 80 to 130 m.

## 5 Conclusion

The HRAD of the Lagos–Ore axis have been processed and interpreted. The magnetic anomalies observed had revealed a high magnetic intensity of 57.9–89.1 nT, intermediate magnetic intensity of 38.2–57.9 nT, and low magnetic intensity of 4.0–38.2 nT, which are associated with contracting basement rock features. The lineaments obtained from the THD map revealed areas of various deformations: brittle (associated with faults/fractures) and ductile deformation (associated with folds). The faults revealed by UC are at different depth ranges of 500–2,250 m at the western side and 1,500–1,250 m at the northwestern side of the study area.

Based on the fault architecture of the study area, it could be concluded that the established linear features could be synthetic to the established major Ifewara-Zungeru fault, which could cause a devastating effect when tectonically active. Furthermore, the faults established both at the deep and at shallow depths in the study area could serve as conduits for the passage of seismic energy whenever it is released. Also, reoccurrences of pockets of tremors along Badagry–Idiroko axis

are possible, since Allada (latitude 6°39'0"N, longitude 2°9'0"E), which experienced an earthquake of magnitude 4.4 on September 11, 2009, is 128 km away from Lagos. It is therefore recommended that the Nigerian government should pay more attention to earthquake monitoring in the SW part of Nigeria, so that there would be pre-warning to subsequent seismic events. Finally, the established zones of linear features should be considered as the forbidden zones for the nuclear power generation (NPG) in case the Nigerian government intends to explore NPG as an alternative source to hydroelectric power generation in the future.

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