Structural interpretation of the south-western flank of the Anambra Basin (Nigeria) using satellite-derived WGM 2012 gravity data

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Highlights

- New insights on subsurface structures and sedimentary thickness at the western margin of the Anambra Basin.
- The Anambra Basin is a petroliferous province within southern Nigeria.
- The upward continuation technique was used for calculating the Bouguer anomaly.
- Lineaments were determined from total horizontal derivative technique.
- 2.5D forward gravity modelling reveals a depth sufficient for hydrocarbon accumulation.

Abstract

The Anambra Basin in the west of the lower Benue Trough is one of Nigeria's most petroliferous provinces. The subsurface structure has been extensively studied using various geophysical methods except for the mapping of structural lineaments. For the present study, the satellite-derived World Gravity Map 2012 (WGM 2012) global gravity model was utilized to study structural features located at different depths. Upward continuation at the height of 30 km was used to extract the regional anomaly from the Bouguer anomaly. The residual anomaly was determined after the deduction of the regional gravity anomaly from the Bouguer anomaly. The total horizontal derivative (THD) of the complete Bouguer, regional, and residual anomalies was used to map the lineaments. The Bouguer gravity anomaly ranges from −58 to more than +28 mGal and presents two generic trends in the E-W and NNE-SSW directions. The regional Bouguer anomaly reveals a Moho depth of 38.0 km from the CRUST1.0 model. The amplitude pattern of the residual gravity anomaly was used to distinguish seven high residual anomalies (HR1-HR7) and four low residual anomalies (HL1-HL4). The residual anomalies of HR1-HR7 are inferred to be hypabyssal igneous rocks. The low residual anomalies of HL1-HL4 are interpreted to be Paleogene and Cretaceous deposits of the Niger Delta complex, and the Bende-Ameki, Imo, Nsukka, Ajali, Mamu, and Nkporo formations. Based on THD analysis, the major structural trends are found to be in NE-SW and NW-SE directions. In addition, 2.5-dimensional forward modelling using the residual Bouguer anomaly along profile CD was performed, providing a variation of the basement depth between 3.5 km and 6.5 km. Therefore, the sedimentary thickness is adequate for the recommended minimum depth for source rock formation and petroleum accumulation with respect to the other petroleum system elements.

Keywords: Gravity anomaly; Gravity modelling; Structural lineaments; Total horizontal derivative; Benue trough

1. Introduction

The gravity method is a useful geophysical technique for identifying and mapping subsurface geological structures (Abtout et al., 2014; Altinoğlu et al., 2015; Khazri and Gabtni, 2018; Bba et al., 2019; Dilalos et al., 2019) and is commonly used to demarcate lineaments (Hu et al., 2015; Zhang et al., 2015; Mauri et al., 2018; Chouhan, 2020; Chouhan et al., 2020a). The demarcation of lineaments, e.g. faults, folds, fractures, joints, geological contacts etc., is a very important step in studying the tectonic framework and the hydrocarbon trapping mechanisms of sedimentary basins (Isyaku, 2018).

The Anambra Basin, situated west of the lower Benue Trough in the southern part of Nigeria, is an inland sedimentary basin and one of Nigeria's most promising hydrocarbon producing fields (Fig. 1a, Obaje, 2009). During the last few decades, due to its high potential for hydrocarbon exploration, the basin has attracted a variety of studies that used a wide range of geological and geophysical methods (Agagu and Adighije, 1983; Cratchley et al., 1984; Benkhelil, 1989; Onwuemesi, 1997; Abbass and Mallam, 2013; Adetona and Abu, 2013; Obiora et al., 2015; Abdullahi and Singh, 2018; Ekwueme et al., 2018; Obasi et al., 2018; Okorie et al., 2019; Oguama et al., 2020). A first power spectrum analysis of magnetic data showed varying thicknesses of sedimentary deposits within the basin between 0.9 and 5.6 km (Onwuemesi, 1997). In contrast, more recent geophysical studies, using an integrated analysis of spectrum analysis and source parameter imaging in the upper part of the basin, corrected the range of sedimentary thickness to a spectrum between 0.08 and 9.85 km (Adetona and Abu, 2013). Adetona and Abu (2013) also revealed a N-E and NE-SW-oriented structural trend in the upper part of the Anambra Basin. Furthermore, calculations from source parameter imaging provided information on the existence of a magnetic anomaly in the Nsukka region (Fig. 1) with depths varying between 0.15 and 3 km (Obiora et al., 2015). The Euler deconvolution of the Nsukka area's magnetic data revealed depths of shallow magnetic sources that vary between 8 and 129 m (Obiora et al., 2015). The magnetic anomalies in the Nsukka area mainly originate from iron-rich minerals, such as limonite, pyrite, hematite, and pyrrhotite. Ekwueme et al. (2018) carried out a study in the region of Idah and Angba that depicts a magnetic source depth between 2.2 km and 6.8 km. The Ubiaja and Illushi regions have a NE-SW structural trend of magnetic anomalies with depths varying between 3 and 5.5 km (Okorie et al., 2019). Most recently, Oguama et al. (2020) used magnetic data to study the structural lineaments at the eastern margin of the Anambra Basin. The majority of these lineaments are oriented in a NE-SW direction. Similar to Oguama et al. (2020), previous studies on the Anambra Basin's lineaments mostly used the delineation magnetic method. In contrast, very few gravity studies are available on the basin (Agagu and Adighije, 1983; Obasi et al., 2018). Therefore, there is a need to determine structural lineaments based on gravity studies to improve the understanding of the subsurface lithologies and determine the sedimentary thickness. Both magnetic and gravity analyses, naturally, cannot replace seismic studies that exhibit much higher resolutions (Fairhead, 2012). Nevertheless, in developing countries and remote areas, gravity surveys, recorded from an aircraft or satellite, can provide a very cost-efficient alternative that may provide very reliable data on very large areas (Downey, 2004; Ennen and Hall, 2011; Fairhead, 2012). The resulting information can play a key role in hydrocarbon exploration in these areas. Available data indicates that the Anambra Basin could be as rich as the Niger Delta Basin regarding its hydrocarbon potential. In addition to coal, the basin holds an estimated gas reserve of ca. 30 trillion cubic feet and 1 billion barrels of oil (Dublin-Green and Agha, 1999).

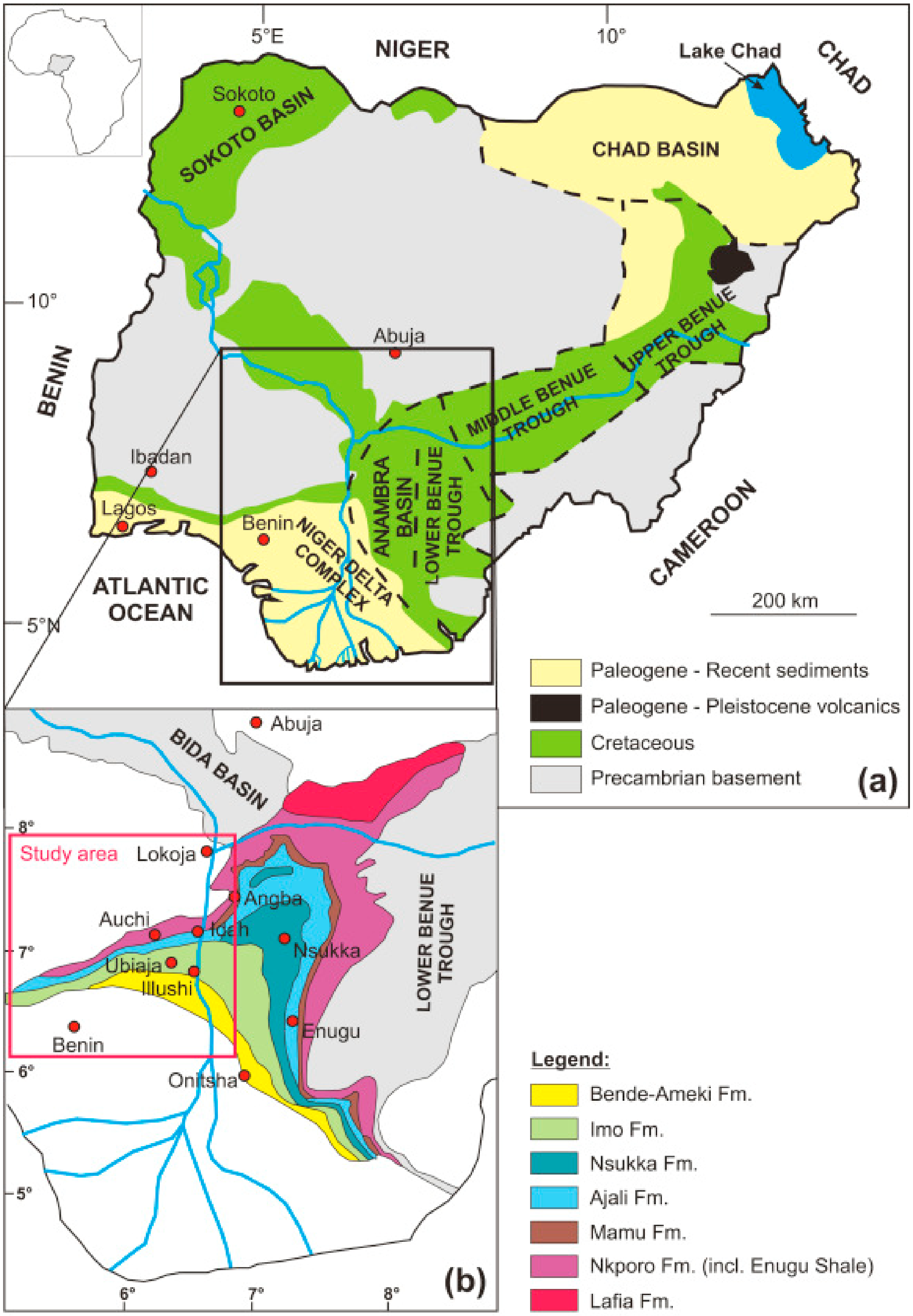

Fig. 1. (a) Geological map of Nigeria showing the Anambra Basin (Obaje, 2009) [Inset: Map of Africa showing the location of Nigeria]. (b) Geological map of the Anambra Basin showing the location of the study area (Nwajide, 1990).

Both magnetic and gravity surveys are well suited for detecting lateral variations, faults, etc. In contrast, seismic surveys are more suited for analysing vertical variations in rocks and the boundaries between layers in a sequence of rocks. The gravity method may be more straightforward than the magnetic method because the magnetic anomalies can be affected by small variations in the occurrence and distribution of magnetic minerals such as titano-magnetites, which may have little relation to the overall lithology (Fairhead, 2012). However, the gravity method does not have such a drawback. A gravity survey is a non-destructive remote sensing geophysical method that measures variations of the rock density from the geological subsurface. The Bouguer anomaly is the measured gravity that is corrected for the known gravity effects (Karcol et al., 2017), indicating the response of the entire density fluctuation below the surface. Therefore, it is an aggregate of the regional and residual gravity anomalies within a given area (Petit et al., 2002). The Bouguer anomaly technique has been used internationally in the interpretation of subsurface structures, trends and sedimentary basin infills (Flinders et al., 2010; Fairhead, 2012; de Castro et al., 2014; Zhang et al., 2015; Alrefaee, 2017; Chouhan, 2020; Chouhan et al., 2020a; Njeudjang et al., 2020; Wang et al., 2021).

In the past, the Shell-BP Petroleum Development Company and the Nigerian Geological Survey Agency carried out a gravity survey to study the basin architecture of the Benue Trough and part of the Anambra Basin (Agagu and Adighije, 1983). However, due to the difficult terrain, the gravity survey could not be completed for the whole basin. For this reason, satellite-derived gravity data are needed for these areas to provide a complete picture of the basin architecture at the south-western flank of the basin. This area had previously been neglected in former studies (Fig. 1b). There are many global gravity models such as EIGEN6C4 (Förste et al., 2014), EGM 2008 (Pavlis et al., 2012) and XGM 2019 (Zingerle et al., 2020), which have spatial resolutions in the order of 10 × 10 km. All of these models have been used for a variety of gravity studies, often with the purpose of extracting lineaments (Kumar et al., 2019; Sahoo and Pal, 2019; Chouhan et al., 2020a), tectonic features (Kumar et al., 2020; Sahoo and Pal, 2021), mineral exploration (Rani et al., 2019) and density modelling (Chouhan, 2020; Chouhan et al., 2020b). However, the WGM 2012 is the first set of global gravity anomaly maps that takes a realistic earth model into account, and considers the contribution of most surface masses such as atmosphere, land, oceans, inland seas, ice caps, and ice shelves (Kahveci et al., 2019). This gravity model is suitable for mapping lineaments, Moho depth and sedimentary thickness (Alemu et al., 2018). As the WGM 2012 has already been successfully used by several research projects to study rift basins (Titi and Minarto, 2017; Alemu et al., 2018; Guo and Gao, 2018; Chouhan, 2020), we decided to use the same model for this study. The present study is the first to use satellite-derived WGM 2012 gravity data and provide this much needed information for the Anambra Basin. The purpose of this study is to provide new information on the lineaments of the Anambra Basin, related to residual and regional gravity anomalies, and thereby shedding new light on both shallow and deep seated structures within the basin.

2. Geological setting

The Anambra Basin is a NE-SW-trending syncline that is part of the Cretaceous-Paleogene rift evolution of the West African Rift Systems (WARS) (Binks and Fairhead, 1992). It was formed as a response to subsidence and stretching of the major plates during the breakup phase of Gondwana (Genik, 1992). Gravity interpretations deduced that the combined thickness of the Cretaceous-Paleogene sediments on the southern limit of the Anambra Basin could rise to more than 12 km into the Niger Delta Basin (Agagu and Adighije, 1983). The

Anambra Basin is hypothesized to be a subsidiary of the Benue Trough (Abubakar, 2014). The basin was formed due to the western extension of the trough during the middle Santonian tectonic episode, typified by faulting, volcanic and intrusive activity, and uplift and folding of older sediments (Ofoegbu, 1985; Obaje, 2009). The basin, therefore, represents the post-rift stage of the Benue Trough and covers an area of ca. 40,000 km^2 (Ogala, 2011; Edegbai et al., 2019a).

Sedimentation in the Anambra Basin commenced after the Santonian episode (Obi et al., 2001; Edegbai et al., 2019b). The Late Campanian-Early Maastrichtian fill consists of the Nkporo Formation, the Owelli Sandstone, and the Enugu Shale (Fig. 2), comprising mainly marine dark grey shales, sandy shales, sandstones and ironstones (Nwachukwu, 1972; Nwajide, 1990; Oboh-Ikuenobe et al., 2005; Edegbai et al., 2019b). The Maastrichtian fill includes the Mamu Formation, which was initially referred to as the Lower Coal Measure (Simpson, 1954). This formation consists of estuarine to marine sediments, deposited in marsh, central basin, barrier beach washover, bay, fluvial-tidal, channel-floodplain, shoreface, tidal flat, and open shelf-environments (Edegbai et al., 2019b; Dim et al., 2019). This formation was followed by the shallow marine, subtidal, and fluvial Ajali Formation (Tijani et al., 2010; Nwajide, 2013). The Nsukka Formation conformably overlies the Ajali Formation, marking the termination of Maastrichtian deposition and the onset of Paleocene sedimentation in the basin. The Nsukka Formation represents fluvio-deltaic deposits that accumulated during a regressive phase (Obi et al., 2001). The Paleocene depositional episode resulted in the deposition of the Imo Formation. This was followed by the deposition of the Bende-Ameki Formation during the Late Eocene, signifying the onset of the Niger Delta progradation (Nwajide, 1980).

Age (Ma)		Formation	Environs
PALEOGENE	EOCENE	Bende-Ameki Fm.	Deltaic/ Continental
	PALEOCENE	Imo Fm.	Shallow marine shelf
		Nsukka Fm.	Fluvio-deltaic/ marginal marine
UPPER CRETACEOUS	MAAS-TRICHTIAN	Ajali Fm.	
	CAMPANIAN	Mamu Fm.	
		Nkporo Fm./ Owelli Sandstone/ Enugu Shale	Marine/ shelf/ continental
	CONIACIAN	Anambra platform unit (Awgu Shale)	

Fig. 2. Stratigraphy of the Anambra Basin (Tijani et al., 2010).

3. Material and methods

3.1. Gravity data

The data used for this contribution was gathered from the International Gravimetric Bureau (BGI) gravity database (http://bgi.obs-mip.fr). The World Gravity Model 2012 (WGM 2012) is a joint gravity data set, which includes satellite data based on Challenging Minisatellite Payload (CHAMP), Gravity Recovery and Climate Experiment (GRACE), Earth Gravity Model 2008 (EGM 2008), Gravity Field and Steady-State Ocean Circulation Explorer (GOCE), Technical University of Denmark 10 (DTU 10) global gravity field, elevation data of the Global Topography 30 arc-second (GTOPO30), and in-situ gravity data. All data sets mentioned above are conjoint through the iterative least-squares method and have a maximum spherical harmonic coefficient of up to 2190° and order 2159° (Andersen et al., 2010; Balmino et al., 2012; Pavlis et al., 2012). The WGM 2012 gravity data have a spatial coverage with a highresolution of 9 × 9 km (Balmino et al., 2012; Pavlis et al., 2012) and are provided in electronic form for educational and research applications (Balmino et al., 2012).

3.2. Data processing and modelling

Topographic corrections, i.e. Bouguer plate and terrain corrections, were performed to process a free-air anomaly map (electronic supplementary material 1). Once the corrections were applied, the complete Bouguer anomaly was computed using a density of 2670 kg/m^3 for the Bouguer slab and the digital elevation model ETOPO1 for topographical heights. The calculated Bouguer anomalies contain both the anomalies related to shallow (high-frequency anomalies) and deep-seated (low-frequency anomalies) sources (Blakely, 1995; Lowrie, 2007). For detailed interpretations and better delineation of the subsurface structures, a separation of anomalies related to shallow (residual) and deeper (regional) parts is necessary, a process called regional-residual separation (Lowrie, 2007). This is performed by various techniques such as wavelength filtering, polynomial fitting, and continuation of the Bouguer anomaly (Lowrie, 2007). For the present study, the upward continuation technique was adopted. The upward continuation is a classic technique used to calculate the Bouguer anomalies on to a surface, which is higher than that of the surface of observation. It is based on the principle of equivalent stratum (Blakely, 1995). The shorter wavelength anomalies (belonging to shallower features) are attenuated more rapidly than long-wavelength anomalies (belonging to deeper features) during the upward continuation. Thus, the anomaly calculated after the upward continuation and having a longer wavelength anomaly can be considered to be a regional Bouguer anomaly (Lowrie, 2007). Choosing an optimal height for upward continuation is an inherent problem in this method. To resolve this ambiguity, Jacobsen (1987) proposed a method to choose an optimal height. Thus, the regional field, determined by the upward continuation of a gravity anomaly at height x, is connected to sources situated at half the height of upward continuation, i.e. x/2 (Jacobsen, 1987). This idea was used to select an optimal height and extract the regional anomaly from the Bouguer anomaly.

To determine the structural lineaments, the total horizontal derivative (THD) of the Bouguer anomaly was calculated. In theory, several other gradient techniques than the THD can be used for this purpose such as tilt-derivative, analytical signal, theta derivative, and balanced horizontal derivative. However, the greatest advantage of THD over the other techniques is that this method is least susceptible to noise in the data because it only requires the calculations of the two first-order horizontal derivatives of the field (Blakely, 1995;

Pilkington and Keating, 2004). The THD method is widely used as the edge detection using the Bouguer anomaly, and it is reliable in locating the edges of density variation from the gravity data (Blakely, 1995). THD measures the lateral change in density and does not require any prior information about the anomaly sources. The total horizontal derivative was calculated using the following expression:

$$THD = [(\delta p/\delta x)^2 + (\delta p/\delta y)^2]^{1/2} \quad (1)$$

Here, $\delta p/\delta x$ and $\delta p/\delta y$ represent the horizontal derivatives of the Bouguer anomaly p in the x and y directions, respectively. The computed THD was least affected by noise in the data since it is estimated by the two first-order horizontal derivatives of the gravity field (Cordell and Grauch, 1985; Saibi et al., 2019). The THD maximal crest value is noticed straight over the edges of the source body (i.e. geologic contacts, faults, fractures). Nevertheless, when the source body is not almost vertical or many anomalies are near, at that point, an offset may be noticed in the highest range value of THD (Blakely, 1995; Grauch and Cordell, 1987). Chouhan (2020) has tested the efficiency of the THD technique through theoretical models and found that the maximum values lie straight above the edges of the source body. In the current study, the peak value of the THD was used to demarcate the structural lineament.

In this study, the 2.5 dimensional (2.5D) forward gravity modelling of the residual Bouguer anomaly was done using the GM-SYS software. This software is based on the algorithm of Talwani et al. (1959) and Talwani and Heirtzler (1964), which computes the gravity reaction of numerous polygonal-structured shapes of finite strike range (Chouhan, 2020). Gravity models along two profiles were created. The accuracy of the model was tested by comparing the model's gravity response to observed measurements and minimizing the rms error. Details of the rms error calculation can be found in the GMSYS manual (Oasis Montaj GMSYS manual; pages.geo.wvu.edu/~wilson/gmsys_49.pdf). The models were generated by taking the regional geology of the study area into account.

The interpretation of gravity surveys can be done qualitatively or quantitatively. The qualitative interpretation includes the anomalous geophysical information that is extracted from the regional and residual anomalous maps and their correlation with the geology of the basin. In contrast, the quantitative interpretation involves 2.5D modelling to estimate the depth and dimensions of the sedimentary cover (Hope and Eaton, 2002; Kamguia et al., 2005).

4. Results

As shown in Fig. 3, the Bouguer gravity anomaly ranges from −58 to +30 mGal. To extract the regional anomaly from the Bouguer anomaly, upward continuation of the Bouguer anomaly was used at the height of 30 km (Fig. 4a), corresponding to an anomaly depth of 15 km (cf., Jacobsen, 1987). Thus, the regional Bouguer anomaly in this study provides information below the depth of 15 km. The residual anomaly was calculated after subtracting the regional anomaly from the Bouguer anomaly (Fig. 4b). The anomalous regional map (Fig. 4a) and the anomalous residual map (Fig. 4b) display gravity values ranging from −38.9 to 6.2 mGal, and −6.8 to 7.6 mGal, respectively. An application of the total horizontal derivative of the Bouguer anomaly was calculated for the residual and regional Bouguer anomalies and was used to detect the lineaments. The total horizontal derivative of the Bouguer anomaly is shown in Fig. 5a. The THD map derived by using the residual Bouguer anomaly is presented in Fig. 6a. The calculated THD map, using the regional Bouguer anomaly, is shown in Fig. 7a. The lineaments were determined using the peak values of THD anomalies. The identified lineaments are oriented in NE-SW, NW-SE, N-W, E-W directions. In addition, an overlay map of the lineaments established by past studies and the present study was generated. The overlay lineament is shown in Fig. 7c. Furthermore, 2.5-dimensional models were produced to determine the thickness of the sedimentary rocks and the depth to the basement in the study area.

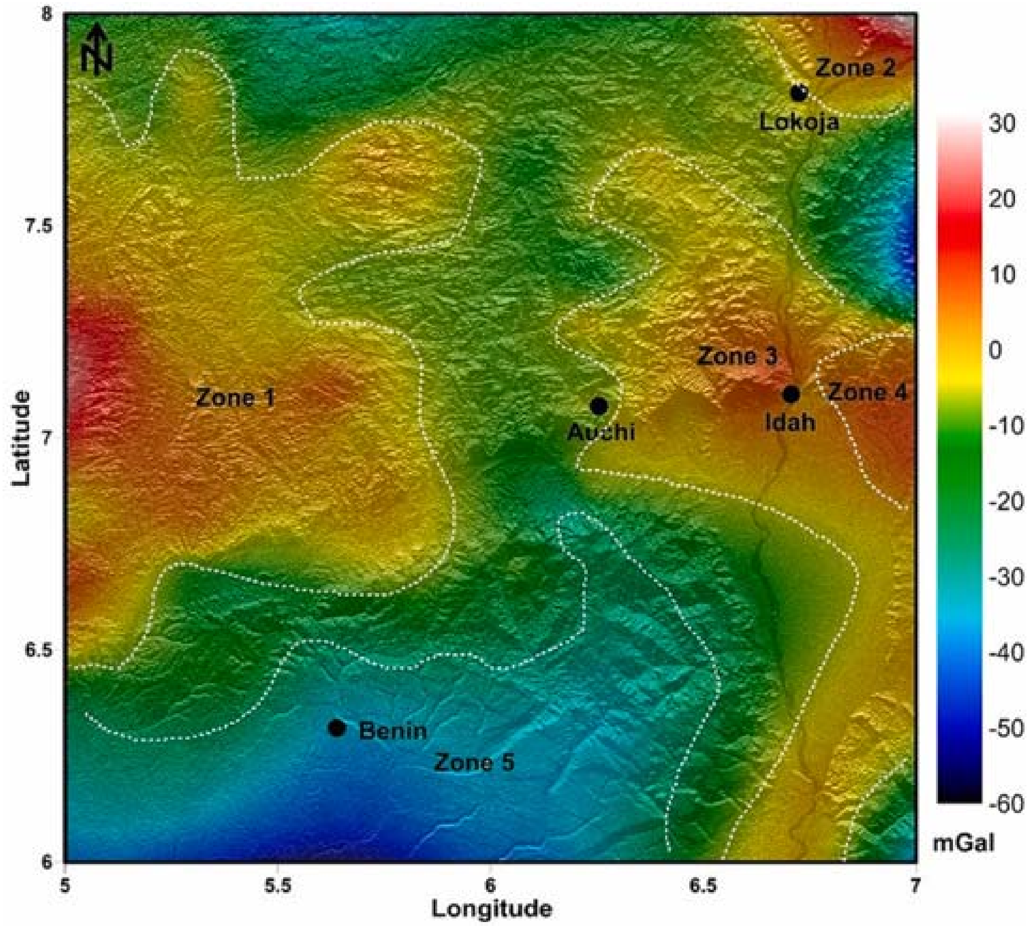

Fig. 3. The Bouguer anomaly map of the Anambra Basin draped over a digital elevation model (DEM). Based on the anomaly pattern, the whole study area is divided into five zones (Zones 1, 2, 3, 4 and 5) and their boundaries are represented by white dashed lines. Black dots represent the major locations in the study area.

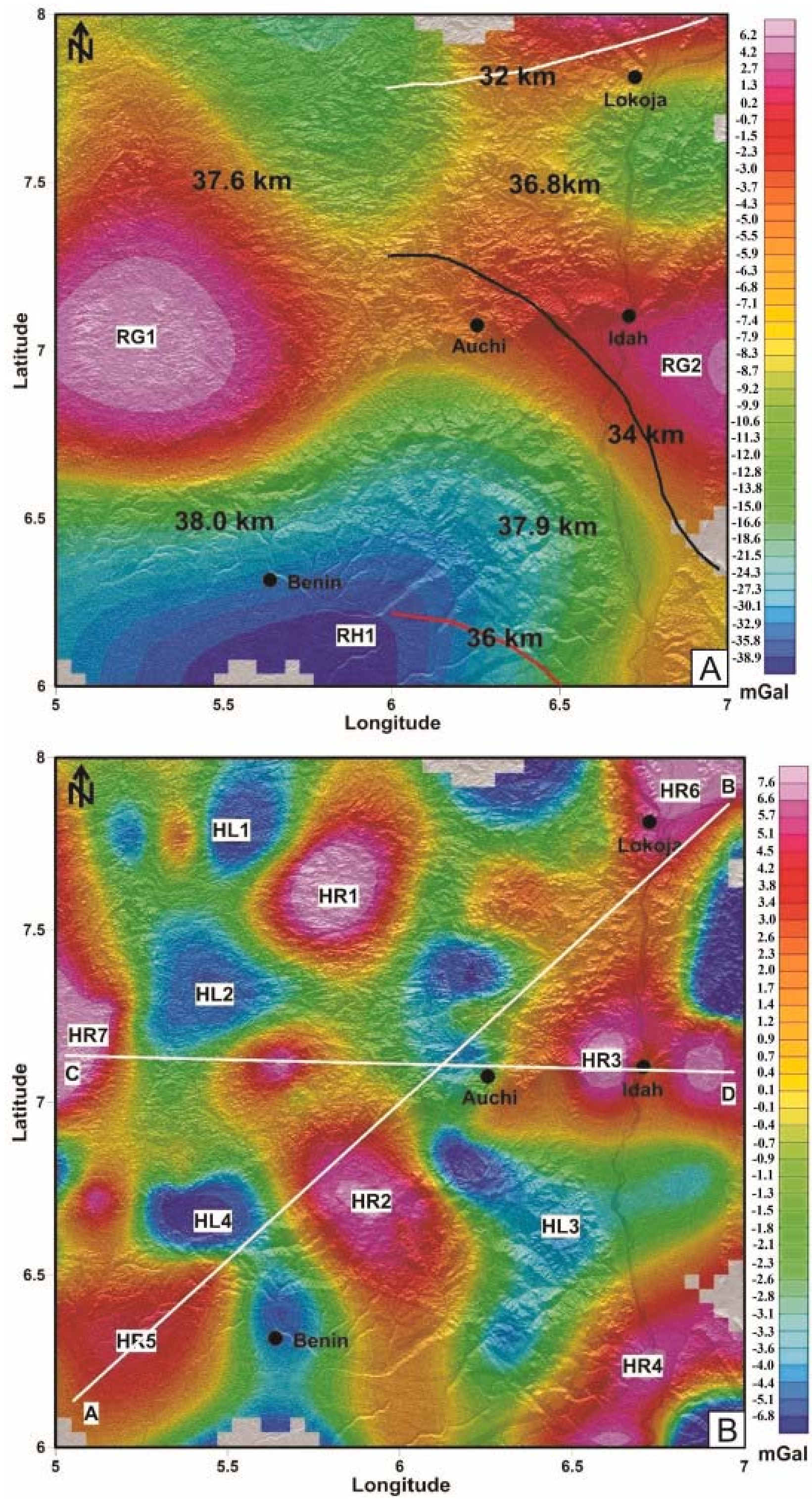

Fig. 4. (a) Regional gravity anomaly map of the Anambra Basin, calculated by upward continuation at a height of 15 km, draped over a DEM. Black dots represent the major locations in the study area. White, black and red contour lines represent the 32, 34 and 36 km Moho depths, respectively (Djomani et al., 1995). Digits represent the Moho depths from the CRUST 1.0 model. RG1, RG2 and RH1 show the high and low regional Bouguer anomalies.(b) Residual gravity anomaly map of the Anambra Basin draped over a DEM. HR1-HR7 and HL1-HL4 define the identified conspicuous gravity highs and lows in the study area.

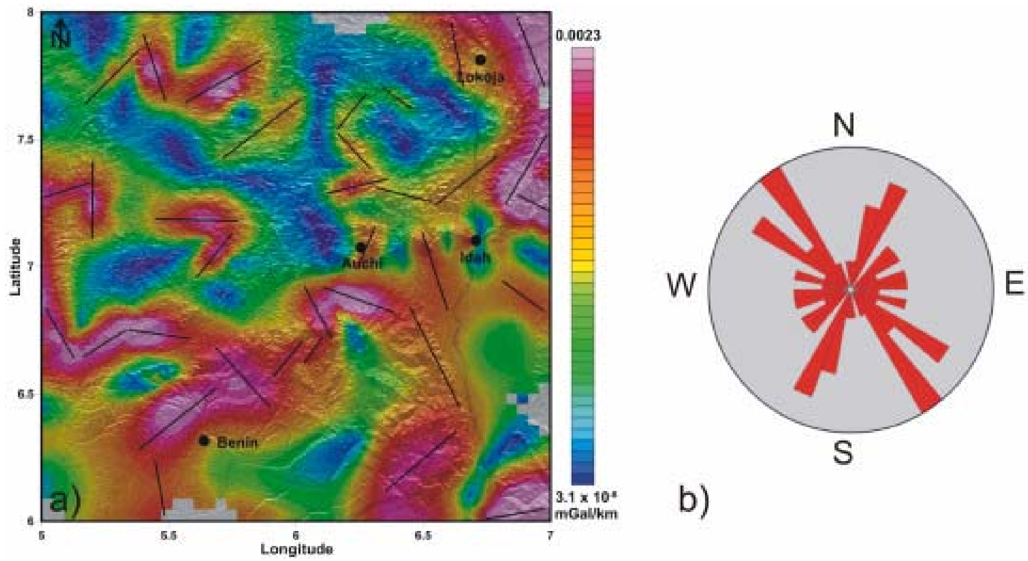

Fig. 5. (a) Total horizontal derivative (THD) of the Bouguer anomaly over the Anambra Basin draped over a DEM. Black dots represent the major locations in the study area. Black lines represent the lineaments. (b) Rose diagram of the lineaments using THD of the Bouguer anomaly.

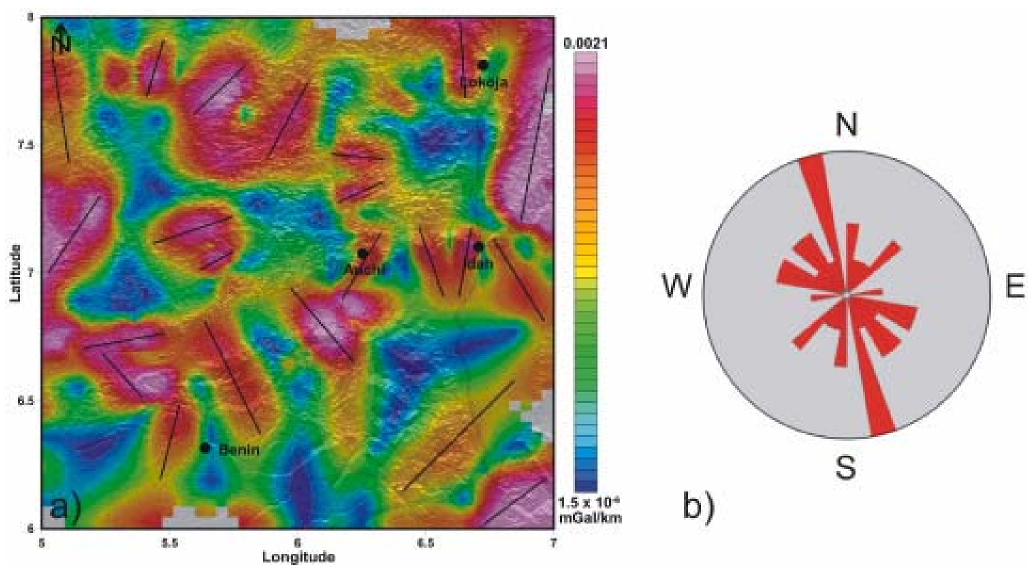

Fig. 6. (a) Total horizontal derivative (THD) of the residual Bouguer anomaly over the Anambra Basin draped over a DEM. Black lines represent the lineaments. (b) Rose diagram of the lineaments using THD of the residual Bouguer anomaly.

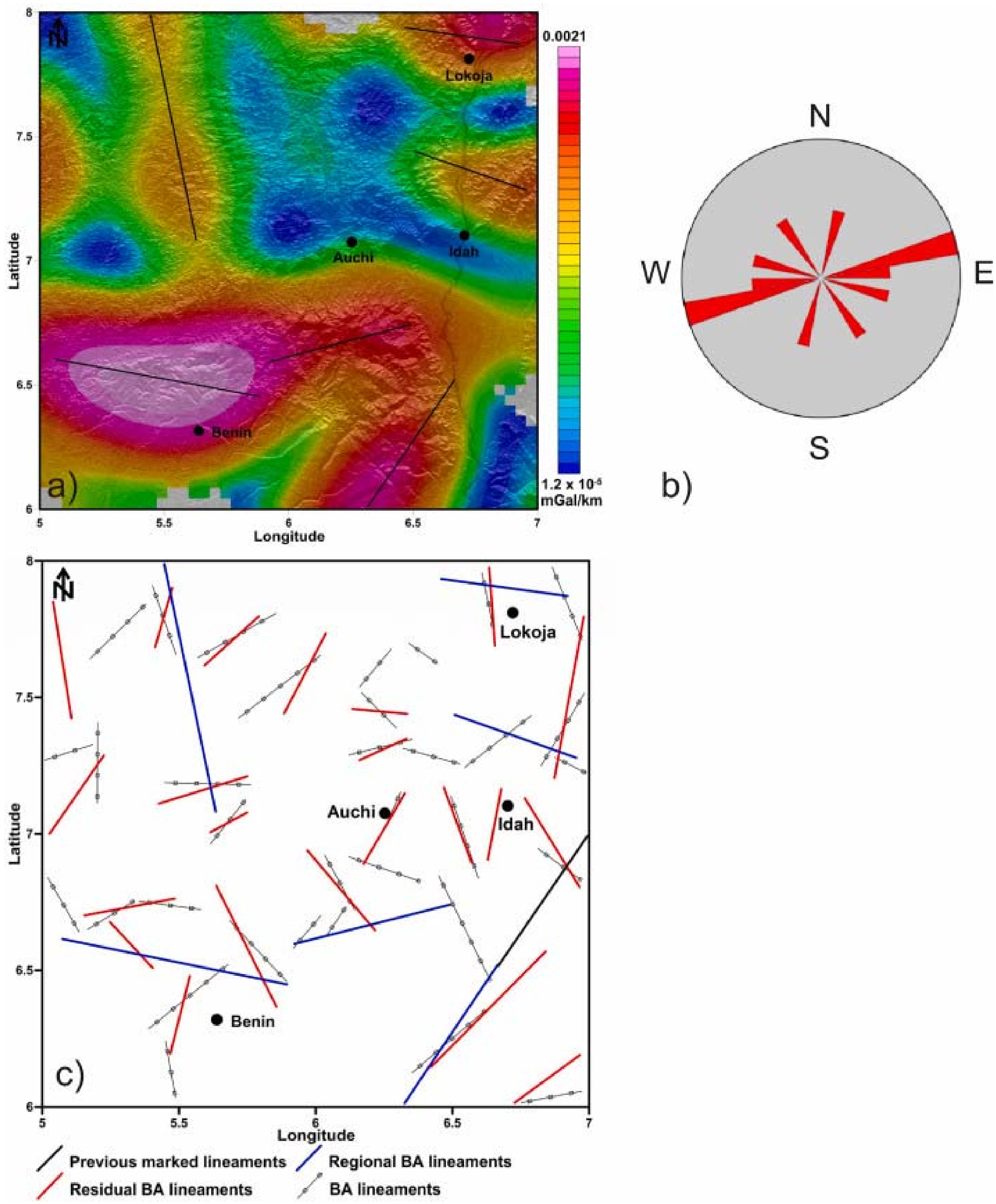

Fig. 7. (a) Total horizontal derivative (THD) of the regional Bouguer anomaly over the Anambra Basin draped over a DEM. Black lines represent the lineaments. (b) Rose diagram of the lineaments using THD of the regional Bouguer anomaly. (c) Revised map showing the recorded lineaments in the study area.

4.1. Gravity modelling of profile lines

The residual Bouguer anomaly was used for the 2.5-dimensional gravity modelling along the profiles AB and CD (Fig. 4b). The profiles for modelling were chosen to make sure that they cross the majority of the prominent anomalies (Fig. 4b). During the gravity modelling, two layers, the basement and the overlying sedimentary cover, were considered. Opted densities of the sedimentary and basement layers were 2400 kg/m^3 and 2700 kg/m^3, respectively (cf., Obasi et al., 2018).

4.1.1. Gravity modelling along profile AB

The NE-SW oriented gravity model along profile AB (Fig. 4) has a profile length of 300 km and is shown in Fig. 8a. During the modelling along profile AB, the root mean square error was kept below 0.16. The variation of basement depth along the profile AB is between 4 and 6 km.

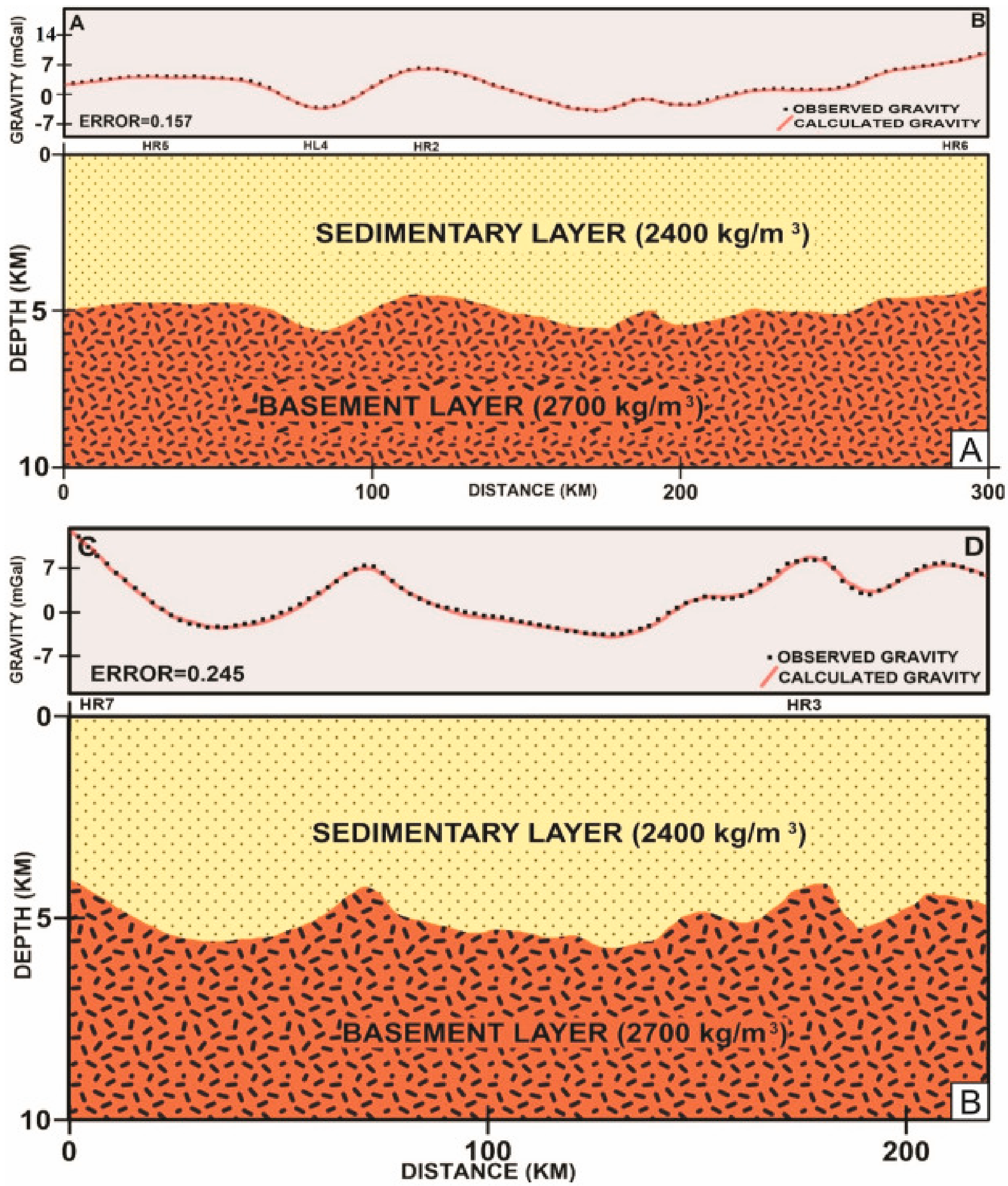

Fig. 8. The results of the gravity modelling along (a) the AB profile, and (b) the CD profile (Fig. 4b).

4.1.2. Gravity modelling along profile CD

Profile CD has a profile length of 220 km and is oriented in an E-W direction (Fig. 4, Fig. 8b). The root mean square error was kept below 0.25 during the modelling along the profile. The forward modelling results show that the basement depth along the profile CD varies between 3.5 and 6.5 km (Fig. 8b).

5. Discussion

The Bouguer gravity anomaly is a combination of the regional and residual gravity anomalies within the study area (Blakely, 1995; Petit et al., 2002; Lowrie, 2007). The southern part of the map's anomalous gravity values gradually increase from −58 to more than +20 mGal towards the study area's western and eastern parts (Fig. 3). The Bouguer anomaly pattern of the study area exhibits two general trends in E-W and NNE-SSW directions (Fig. 3), and the Bouguer anomaly values over the Anambra Basin and its surroundings consist of negative (-ve) and positive (+ve) anomalies. Negative anomalies are generally attributed to materials that are less dense than the surrounding basement. Positive gravity anomalies correspond to denser materials than the surrounding basement (Eyike et al., 2010). Density differentiation between rocks forming the earth's crust gave rise to the various anomalies of low and high amplitudes in the gravity field (Riad, 1977). Based on the amplitude pattern, five zones can be distinguished within the study area (Fig. 3). Zone 1 is located in the western part of the study area, where high anomaly values can be observed. The exposure of the basement complex in Zone 1 might be a possible explanation for this high Bouguer anomaly. A similar interpretation can be given for the high anomaly values of Zone 2. A shallow depth of the basement rocks can be observed throughout the Idah region (Abbass and Mallam, 2013), and the high Bouguer anomaly of Zone 3 is probably associated with this. Zone 4 lies directly over the Nsukka Formation (Fig. 1b), and a shallow basement is a possible explanation for that. Finally, Zone 5 is located in the southern part of the studied area and on top of the Niger Delta complex (Fig. 1b). This zone shows the lowest values within the studied area. This may be attributed to a thick succession of sedimentary rocks. Similar deductions have been made earlier for the eastern margin of the basin (Obasi et al., 2018), where the Bouguer gravity values range from −22.1 to 33.5mGal, which could be credited to the existence of igneous rocks, lower to middle Cretaceous sediments, upper Cretaceous to Paleogene deposits, and alluvium (Obasi et al., 2018).

The regional Bouguer anomaly from the CRUST1.0 model reveals a Moho depth of 38.0 km, dipping in SW direction (Fig. 4a). This is consistent with the SW-trend of the negative anomalous gravity. The prominent high gravity values in E-W directions are characterized as RG1 and RG2. In contrast, the low gravity value in south-western direction is regarded as RH1. The present regional Bouguer anomaly shows the lower values in the southern part of the study area. Therefore, the low value of the regional anomaly RH1 is associated with the deeper Moho (Fig. 4a) (cf., Agagu and Adighije, 1983). The eastern part of the regional Bouguer map is consistent with the calculated Moho depth of Djomani et al. (1995) (contour maps are presented in Fig. 4a), which shows a southward dipping Moho. The circular gravity highs RG1 and RG2 are present at the western and eastern margins of the study area, possibly reflecting the presence of one or more intrusive bodies at a lower crustal level (cf., Adighije, 1981; Ekwueme et al., 2018). Similar deductions of the Moho depth were made by Adighije (1978) for the Lower Benue Trough, where a Moho depth ranging from 20 to 30 km was postulated. A crustal thickness of 22–30 km below the Niger Delta was recognized from gravity data (Benkhelil et al., 1988), which is consistent with our model. The generated residual gravity anomalies signify a distinct gravity variance in the study area, which serves as a pointer to categorize anomalous geological sources' effects. Based on amplitude values, seven high residual anomalies HR1-HR7 and four low anomalies HL1-HL4 have been identified (Fig. 4b). Onwuemesi's (1997) magnetic modelling revealed that the basement depth in zone HR4 is shallow due to an elevated basement floor. A deeper basement floor was observed in zone HL3, which promoted the deposition of a thick sedimentary succession on top of the basement floor. The power spectrum analysis and source parameter imaging of magnetic data depicts the basement depths in the region of Idah and Lokoja, varying between 5 and 5.5 km, i.e. they are shallower than in many other parts of the study area (Abbass and Mallam, 2013). This may also be the possible explanation for the gravity highs HR3 and HR6. The basement depth is shallow over HR1, explaining the gravity high (Ekwueme et al., 2018). The residual anomalous gravity at the basin's western margin is characterized by distinct elliptical, annular and elongated anomalies dispersed throughout the map and determines the subsurface structural orientation within the study area. This is denoted by the identified high (HR1-HR7) and low (HL1-HL4) amplitudes. The high residual gravity anomalies are interpreted as hypabyssal igneous rocks such as granites, granodiorites and andesites, forming a shallow basement (Adighije, 1981; Cratchley et al., 1984; Benkhelil, 1989; Abdullahi and Singh, 2018). In contrast, the low negative anomalies are attributed to Paleogene and Cretaceous sediments of the Niger Delta complex, and the Bende-Amaki, Imo, Nsukka, Ajali, Mamu and Nkporo formations (Obasi et al., 2018; Ekwueme et al., 2018).

The THD of the Bouguer anomaly (Fig. 5a) indicates that most determined lineaments in the southern part of the study area are oriented in NE-SW and NW-SE directions. In contrast, the lineaments in the northern part exhibit NE-SW and N-W trends (Fig. 5a). The rose diagram of the lineaments shows the two orientations in NW-SE and NE-SW directions (Fig. 5b).

To determine the deeper and shallow seated structural features at the western margin, the THD was calculated by using both the regional and residual Bouguer anomalies. As a result, the structural features can be found in depths of up to 15 km. The northern part of the THD of the residual map shows NE-SW and E-W trending structural features. The lineaments in the southern part have NE-SW and NW-SE trending directions (Fig. 6a), respectively. The rose diagram of the lineaments shows the three orientations in NNW-SSE, NE-SW and NW-SE directions (Fig. 6b).

The calculated THD map (Fig. 7a) of the regional Bouguer anomaly shows the trends of the determined lineaments that exist in depths below 15 km. The northern part of the regional THD map shows NW-SE trending structural features, the lineaments in the southern part have a NE-SW trend. The rose diagram of the lineaments shows orientations in ENE-WSW, NNE-SSW and NW-SE directions (Fig. 7b). Based on the present analysis, a revised map of the existing lineaments within the study area is provided in Fig. 7c.

The faults that run across the western, eastern, northern and southern margins of the study area formed major and minor fractures with displacement (Benkhelil, 1982; Onuoha, 1999). The main structural systems that controlled the formation and the evolution of the basin affected all Cretaceous and Paleogene formations. The predominant trends of the lineaments in the Cretaceous and Paleogene sediments are NW-SE and NE-SW, consistent with Onuoha's (1999) trends for major faults in the Benue Trough and Anambra Basin. Other trends observed in the area such as NNE-SSW, ENE-WSW, NNW-SSE, E-W are of a lesser significance. In the lower Benue Trough, normal faults are found to cut across folds in the post-Santonian deposits (Benkhelil, 1982). They have been reported in outcrop sections within the Anambra Basin (Obi and Okogbue, 2004). Benkhelil et al. (1988) reported NNE-SSW and NE-SW directions as the main active structural trends in regions around Nsukka and Onitsha, which constitute the eastern margin of the basin. The Chain Fracture zone and Romanque Fracture zone characterize the lower Benue Trough and the Anambra Basin associated with the identified lineaments (Benkhelil, 1982; Onuoha, 1999).

The structural framework of the western Anambra Basin indicates the potential for a structural trapping framework for hydrocarbon accumulation in the Anambra Basin. The tectonic elements in the Anambra Basin can be attributed to the Santonian tectonic episode that affected the Cretaceous deposition (Burke et al., 1972; Agagu and Adighije, 1983) and is inferred to be a possible explanation for the structural trends in the study area.

Gravity modelling of profile AB reveals that the basement depth in the Lokoja region varies between 4 and 5 km. The power spectrum analysis and source parameter imaging of magnetic data shows that the basement depth in the region of Lokoja is approximately 5 km (Abbass and Mallam, 2013), which is consistent with the results of this contribution. The gravity profile AB passes through the vicinity of the residual high Bouguer anomaly HR2, HR5 and HR6 (Fig. 4b). Basement depth values are 5 km, 4 km and 4 km over the zone of HR2, HR5 and HR6, respectively (Fig. 8a). The profile also passes through the zone of the low Bouguer anomaly HL4, where the basement depth is 6 km (Fig. 8a).

Gravity modelling along profile CD passes through the high residual Bouguer anomalies HR3 and HR7, where basement depths of 3.5 and 4 km could be identified (Fig. 5b). In the region of Idah, the basement depth ranges between 4 and 5 km, which is consistent with the results of Abbass and Mallam (2013). The basin's central and south eastern parts were reported to contain varying thicknesses, ranging from 0.4 to 6 km, with the basin's central part attaining the highest thickness (Obasi et al., 2018). In addition, Agagu and Adighije (1983) estimated sediment thicknesses of 5–10 km in the Onitsha Basin at the eastern margin of the Anambra Basin.

The thickness of 5 km, calculated in this study, indicates that the basin was active during the Campanian to Maastrichtian (Obi and Okogbue, 2004). This is shown by the thick Cretaceous deposits in the western segment and overlying Paleogene sediments towards the southern Niger Delta complex. This study has shown that the sedimentary overburden is sufficient for the required minimum depth of 1 km for hydrocarbon accumulation with respect to the other elements of a petroleum system (Hunt, 1996). However, due to high geothermal gradients (20–35°°C/km; 25–54°C/km) that limit liquid hydrocarbon (oil) generation, the basin is gas prone (Whiteman, 1982; Onwuemesi, 1997; Onuoha and Ekine, 1999; Obaje et al., 2004; Bello et al., 2017; Yakubu et al., 2020) and exploration should be focused on gas within the matured sections of the basin with good organic richness, potential reservoir beds and a well-known structural framework. We can deduce that the subsidence and sedimentation rates in the Cretaceous and Paleogene evolution of the Anambra Basin and Niger Delta complex can be hypothesized to have been influenced by the delineated faults and fractures (cf., Onuoha, 1999).

6. Conclusions

Analysis of high-resolution gravity data over the southwestern margin of the Anambra Basin of southern Nigeria and the interpretation of profiles reveal the following:

1. The Bouguer anomalies trend in E-W and NNE-SSW directions and five zones could be identified within the study area, arising from their characteristic amplitude patterns. The high gravity anomalies are associated with granites, granodiorites and andesites. The intermediate gravity values represent Middle to Upper Cretaceous sediments. Finally, the low gravity values, occurring at the southern margin, are interpreted as Paleogene sedimentary rocks.
2. The new information on the regional Bouguer anomaly reveals that the Moho depths range between 36.8 and 38.0 km in the study area, corresponding to the low gravity anomaly that was recorded in the southern part of the area.
3. The residual Bouguer anomaly reveals seven high anomalies HR1-HR7 and four low residual anomalies HL1-HL4.
4. Interpretation of the geophysical data indicated that two main structural trends control the Anambra Basin; NE-SW and NW-SE. The NW-SE, NE-SW lineaments may serve as possible migratory pathways for fluids (hydrocarbon and hydrothermal).
5. This study shows that the sedimentary accumulation, reaching 5 km, is sufficiently thick and may serve as a good indication for a high hydrocarbon potential in the western segment. We recommend integrating geochemical methods, well logs, and seismic data to validate these findings.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The International Gravimetric Bureau (BGI) and the International Gravity Field Service (IGFS) are acknowledged for assembling the data, making them available in digital form for this research work, and granting permission to publish the findings. E.J.O. and N.L. thank the University of Pretoria for their financial support. Furthermore, N.L. thanks the National Research Foundation of South Africa (NRF) for financial support (Grant number 127060). A.K.C. is thankful to his Director General (ISR) for his permission to carry out this work. R.Y. appreciates the financial support from the China-ASEAN Maritime Cooperation Fund Project [grant No.12120100500017001] and the National Natural Science Foundation of China (grant No. 41972146). The authors are grateful to the editor and the two anonymous reviewers for providing thoughtful insights, which have significantly improved the manuscript.

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