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Insights into the Tectonic Framework of the Benin Basin from Satellite Gravity Data Interpretation

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Abstract
Satellite gravity data were interpreted to characterise the basement morphotectonic features and architecture beneath the Benin Basin of Nigeria. The Bouguer anomaly data was processed using the high-pass filter to generate the residual anomaly grid, which formed the basis for other edge enhancement techniques like the first vertical derivative (1VD), and tilt angle derivative (TDR) in order to map linear geological features of interest. The interpreted lineaments showed major trends in the NNE-SSW, ENE-WSW, NNW-SSE, N-S, and E-W directions. 2D forward modeling of the basement architecture revealed structural mini basins located offshore of the study region. The mini basins may have accommodated over 4 km thick sedimentary packages, indicating that they have great potentials for hydrocarbon prospectivity if the right conditions for the existence of all the petroleum systems elements are met. It is recommended that future exploration efforts be concentrated on the identified mini basins to ascertain their potential through well test drilling and prospect generation in the Benin Basin of Nigeria.

Keywords: Tectonic framework, Architecture, Satellite gravity data, Benin Basin

Introduction

The Benin Basin (Fig. 1) lies within the Gulf of Guinea. The areal coverage encloses Nigeria's western coast where it is bounded the Cenozoic Niger Delta's west fringe (Brownfield & Charpentier, 2006). Recent discoveries in Upper Cretaceous deep-water plays in the neighboring Benin, Ghana, and Senegal, has triggered growing interests to explore for conventional hydrocarbon deposits in the Nigeria's part of the basin. Despite the successes recorded in Aje and Ogo oilfields offshore Lagos, significant yet untapped potentials remain hidden at deeper intervals of the Lower Cretaceous syn-rift sequences which are grossly under-explored (Babangida, 2021; Okoro et al., 2021). Characterizing the basement architecture and morphotectonic features is critical to unlocking the unrealized potentials in the basin. Hence, an understanding of the basement structuration will be key to proper identification of mini-basins where thicker sedimentary successions have accumulated. Such areas will show greater promises for finding new oil and gas pools (Okoro & Onuoha, 2019).

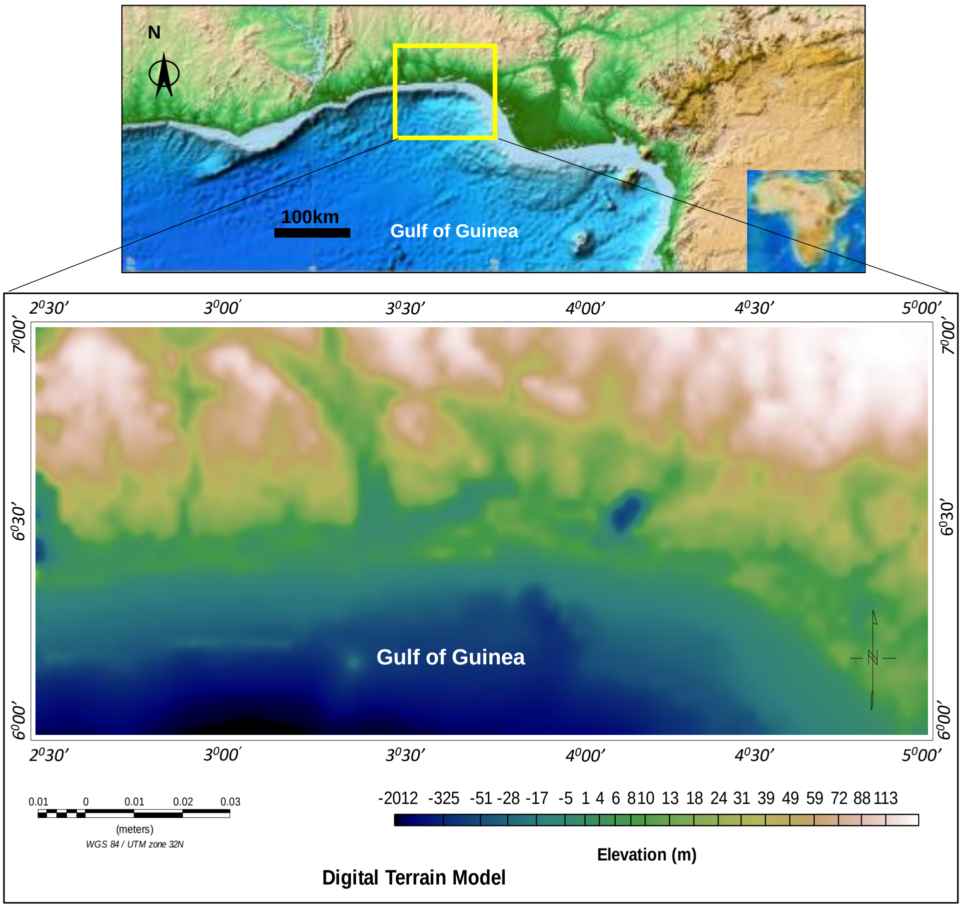

Fig. 1. Digital Terrain Model of the Benin Basin (Image courtesy of NOAA and BGI). Yellow box shows the basin location within the Equatorial margin.

Satellite gravity data are low-cost geophysical tools used in mapping regional tectonic features, basin geometry, depth to basement estimation, and extent of the sedimentary basin (Li & Morozov, 2006; Saibi et al., 2016). Several workers have tried to characterize the geologic elements in the Benin Basin of Nigeria using different geophysical approaches (Opara et al., 2012; Osinowo & Olayinka, 2013; Oladele et al., 2016). However, only little have been done to understand the major role played by the underlying basement morphotectonic features in controlling the regional arrangement of mini-basins, the source-reservoir-seal facies setup, and the overall influence on basal heat-flow variations and sediment thermal maturity patterns at different depths. The present study aims at utilizing satellite gravity data to characterize the morphotectonic features and basement architecture of the Benin Basin. The specific objectives are to: (i) map lineaments and analyze their tectonic trends, (ii) model the basement geometry, and (iii) identify mini-basins and isolate favorable areas for hydrocarbon exploration in the study area.

Geologic setting

The transform-dominated Benin Basin is a rift type basin located within Nigeria's Western Transform Margin (Fig. 2). It is covered by latitudes 6^0 00'N and 7^0 00'N and longitudes 2^0 30'E and 5^0 00'E. The basin is bounded to the east and west by the Ghana Ridge (Romanche Fracture Zone) and Okitipupa Ridge (Chain Fracture Zone) (Omatsola and Adegoke, 1981; Onuoha & Ofoegbu, 1988; Burke et al., 2003; Brownfield & Charpentier, 2006). The Benin Basin of Nigeria extends from onshore through shallow shelf into the deep-water, with bathymetry ranging from 50 to 5000 ft (Babangida, 2021). Tectonic development of the basin involved transcurrent motions along oceanic transform faults, basement faulting, fragmentation and block rotation (Omatsola & Adegoke, 1981; Akande et al., 2012). Evolutionary history of the Gulf of Guinea comprises of the Precambrian to Late Jurassic pre-rift stage, the Lower Cretaceous syn-rift stage, and the Upper Cretaceous to Tertiary post-rift stage, which allow the stratigraphic succession to be divided into three megasequences separated by major unconformities that marked the end of each stage (Billman, 1992; Mascle et al., 1988; Brownfield & Charpentier, 2006; Kaki et al., 2013). Detailed description of the stratigraphic sequence in the Benin Basin have been provided in scholarly articles (Omatsola & Adegoke, 1981; Balmino et al., 2011; Akande et al., 2012; Bonvalot et al., 2012; Falebita et al., 2020). The reported lithostratigraphic units are the Abeokuta Group (Cretaceous); the Ewekoro Formation

(Paleocene); the Akinbo Formation (Late Paleocene to early Eocene); the Oshosun and Ilaro Formations (Eocene), and the Benin Formation (Pleistocene to Recent) (Fig. 3).

Data and methods

Satellite gravity data

The study utilized satellite gravity (WGM2012) data. This gravity model is a high-resolution 2'x2' regional grids evolved from Earth Spherical Model with spatial resolution of ~9km (Nabighian et al., 2005; Whitehead and Musselman, 2008). It is made available for free by the Bureau Gravimetric International (BGI) through their website (https://bgi.obs-mip.fr). The WGM2012 is a combination of gravity results from marine, airborne, and land surveys, together with the Gravity Recovery and Climate Experiment (GRACE) satellite data, Challenging Minisatellite Payload (CHAMP), Earth Gravity Model 2008 (EGM2008), Technical University of Denmark 10 (DTU10) global gravity, Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) models (Falebita et al., 2020).

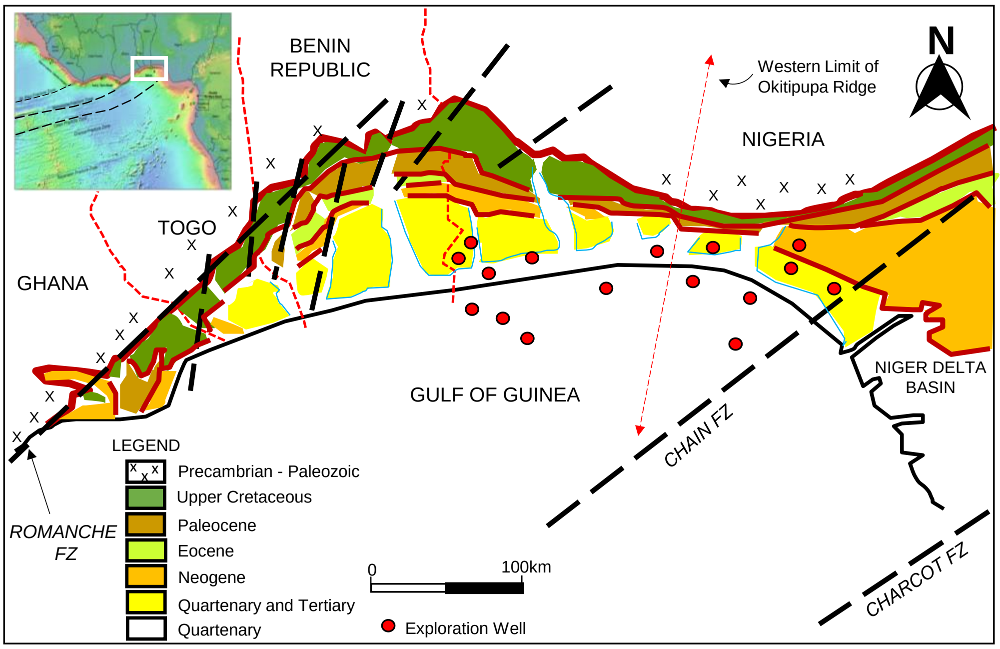

Fig. 2. Regional geologic setup of the Benin Basin (Billman, 1992).

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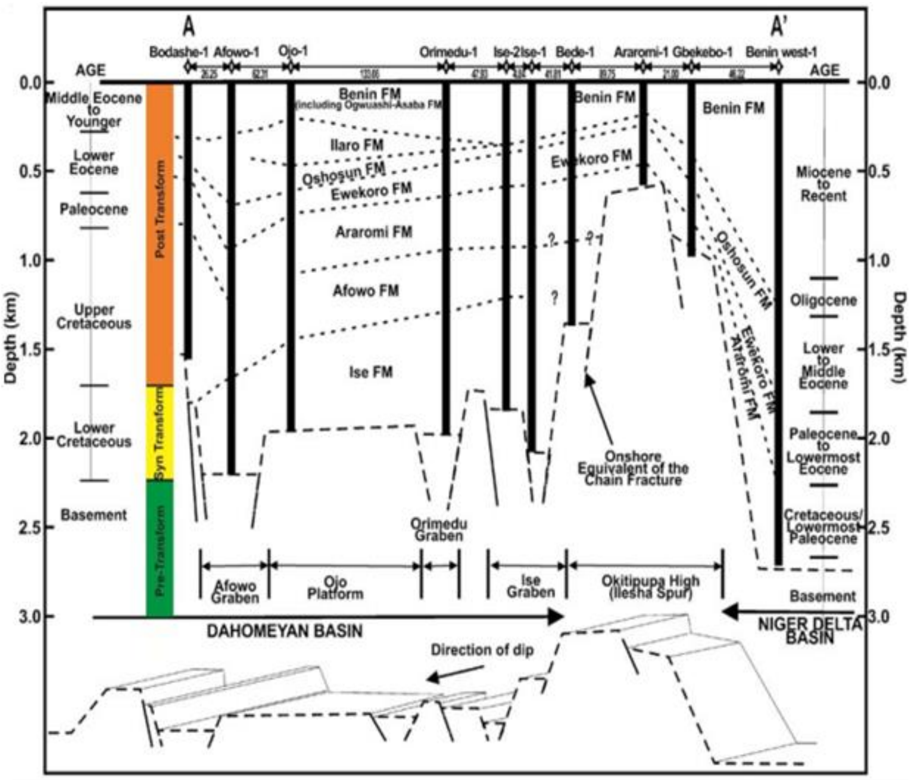

Fig. 3. Regional stratigraphic disposition of the Benin Basin and Niger Delta Basin (Brownfield and Charpentier, 2006).

The Bureau Gravimetrique International (BGI) compiled these data, supported by the United Nations Educational Scientific and Cultural Organization (UNESCO) in conjunction with the International Gravity Field Services (IFGS). The Bouguer gravity grids have been determined at global scale utilizing spherical harmonic approach, with 2.7g/cm^3 as the reduction density (Nabighian et al., 2005; Whitehead & Musselman, 2008).

Data processing and interpretation techniques

The Bouguer gravity anomaly grid was processed using the high-pass filter, applying a 1000 km wavelength cut-off to eliminate deep mantle source effects (Reeves, 2005) and obtain the map of residual Bouguer gravity anomaly of the region. First vertical derivative (1VD) and tilt angle derivative (TDR) filters were then applied to the residual gravity anomaly grid to detect and map contacts of deep-seated features of regional extent in the basin. Structural trend of the lineaments was determined by analyzing their rose diagram plots. Theoretical basis of the above methods has been provided in classical literatures (Cordell & Grauch, 1985; Blakely, 1995; Verduzco et al., 2004; Osinowo & Olayinka, 2013).

Results

Geophysical expressions of region

The residual Bouguer gravity anomaly map showed alternations in low (blue), intermediate (green), and high (red) anomalies that are strongly oriented in the WNW-ESE, NW-SE, E-W, and NE-SW directions (Fig. 4). The anomalies showed contrasting density values ranging from -25.9 to over 13.5 mGal. The central and southwestern portions of the study area are dominated by high anomalies (red), while low anomalies (blue) characterize the southeastern and western parts of the region. Intermediate anomalies (green) drape almost every part of the study area, with major concentration in the northwestern portion of the basin.

Morphotectonic features of the Benin Basin

The filtered gravity maps (1VD and TDR) and the interpreted lineaments are presented in figures 5, 6, 7, and 8. It can be observed that the region is characterized by near-surface and deeper lying linear geological features, with major trends in the ENE-WSW, N-S, NNE-SSW, E-W, and NNW-SSE directions.

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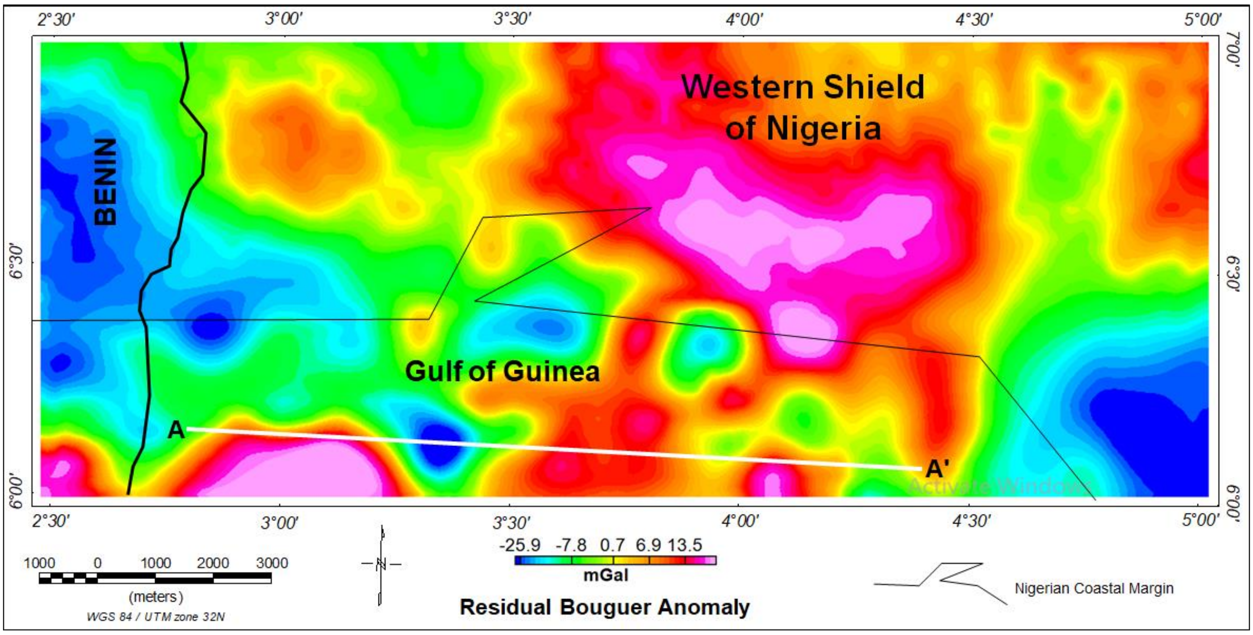

Fig. 4. Residual Bouguer gravity anomaly map of the basin. Line A – A' is the modeled profile in figure 9.

The lineaments cut across each other, typical of wrench-related faults that fragmented the basement complex rocks to different blocks having varying density contrasts (Onuoha & Ofoegbu, 1988; Akande et al., 2012; Falebita et al., 2020). The conjugate character of the lineaments indicates that their origin is connected with the Late Jurassic transtensional and transpressional block movements that led to the opening of the Equatorial margin. These linear features also controlled the development and arrangement of half-graben structural basins, source-reservoir-seal facies setup, and hydrocarbon trapping systems, and also provided the pathways for the early migration of generated petroleum in the basin (Okoro et al., 2021). Deep-seated linear features inferred from the filtered gravity maps were interpreted in this study to represent deep-seated crustal weakness zones that influenced the South Atlantic tectonic development in the Early Cretaceous times (Benkhelil et al., 1998; Fairhead et al., 2013; Ajama et al., 2017).

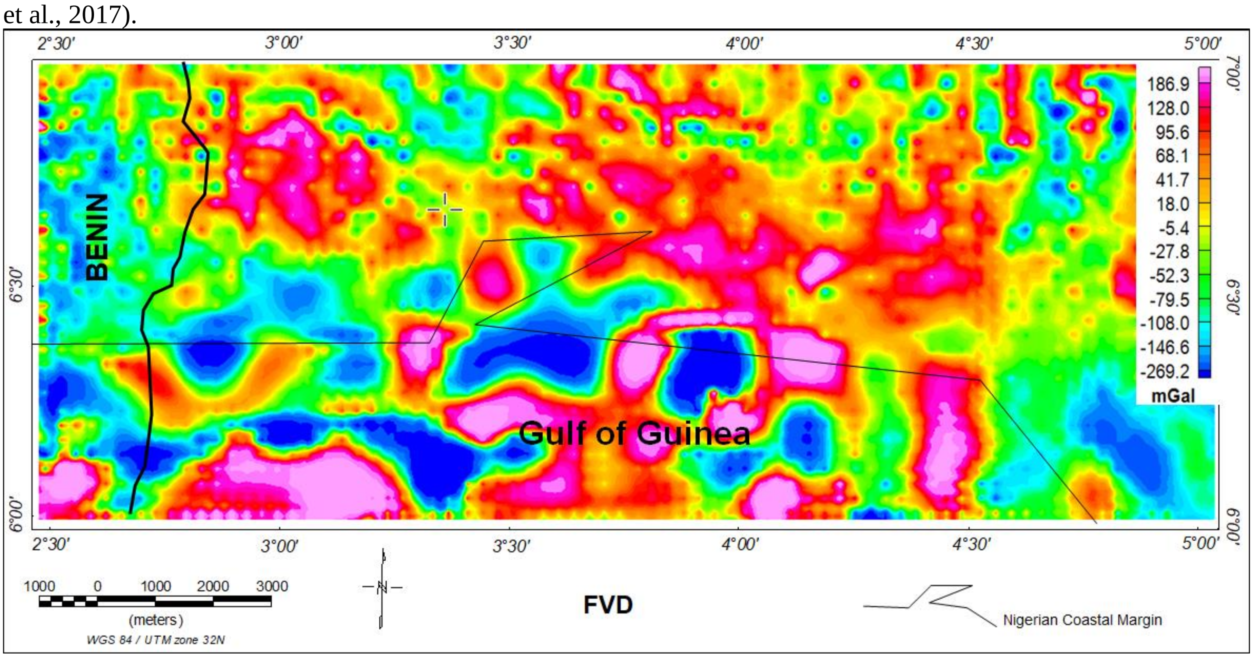

Fig. 5. 1VD map of the region.

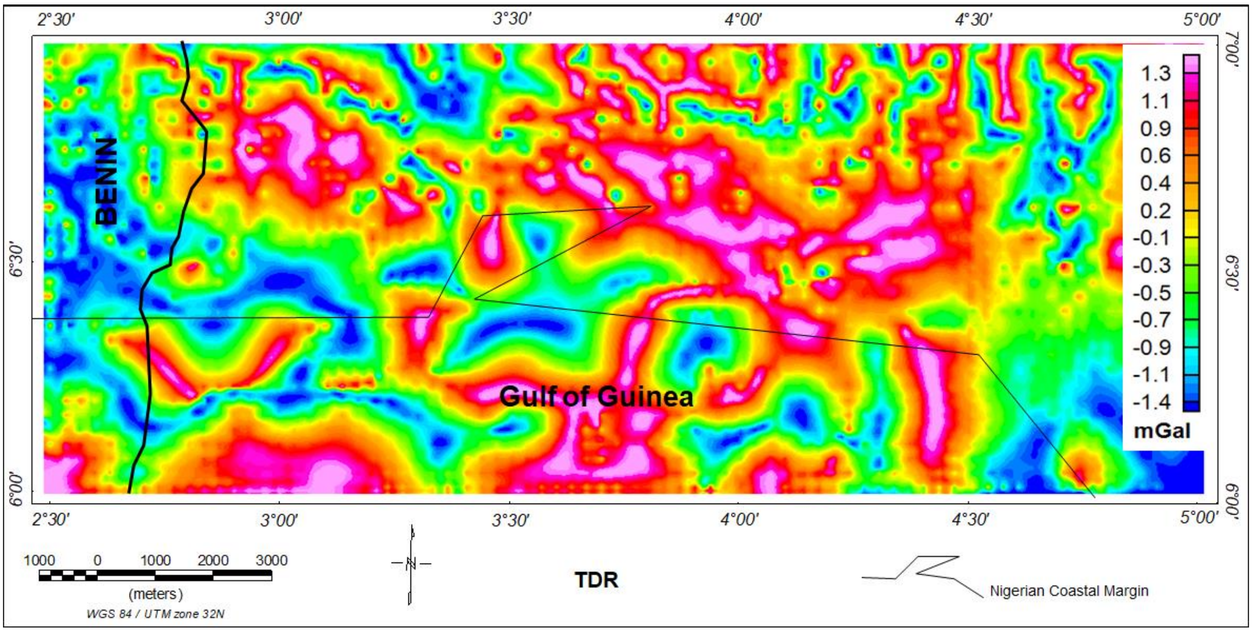

Fig. 6. Tilt angle vertical derivative map of the region.

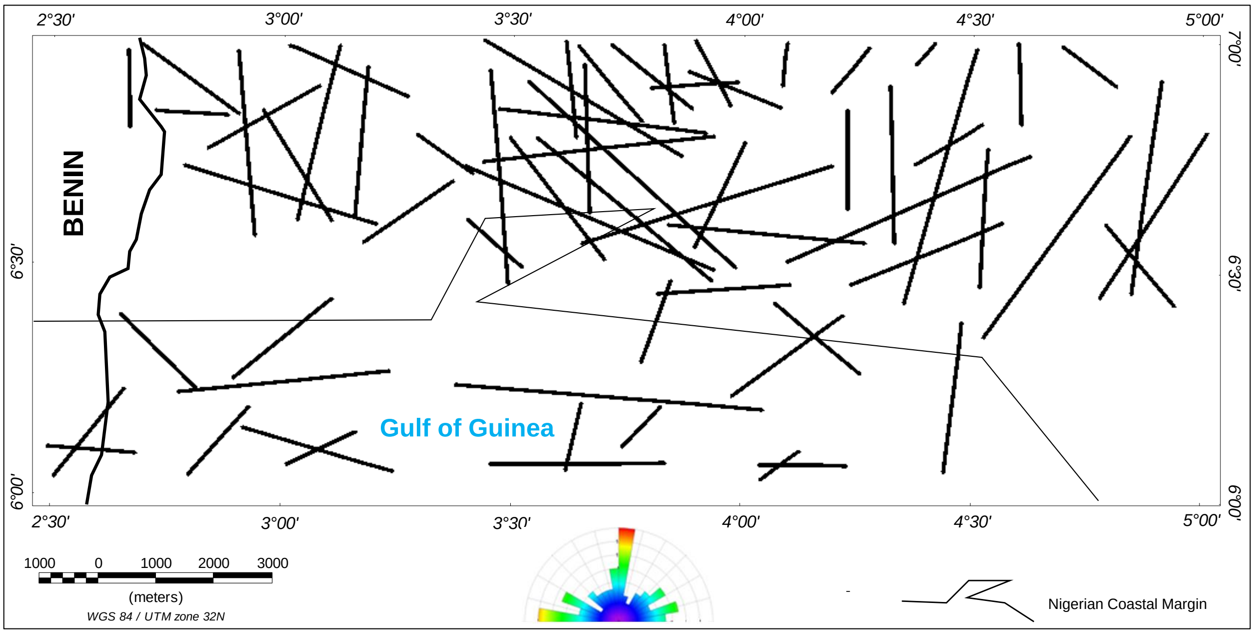

Fig. 7. Lineaments interpreted from the 1VD map, with rosette plot indicating the major geological trend.

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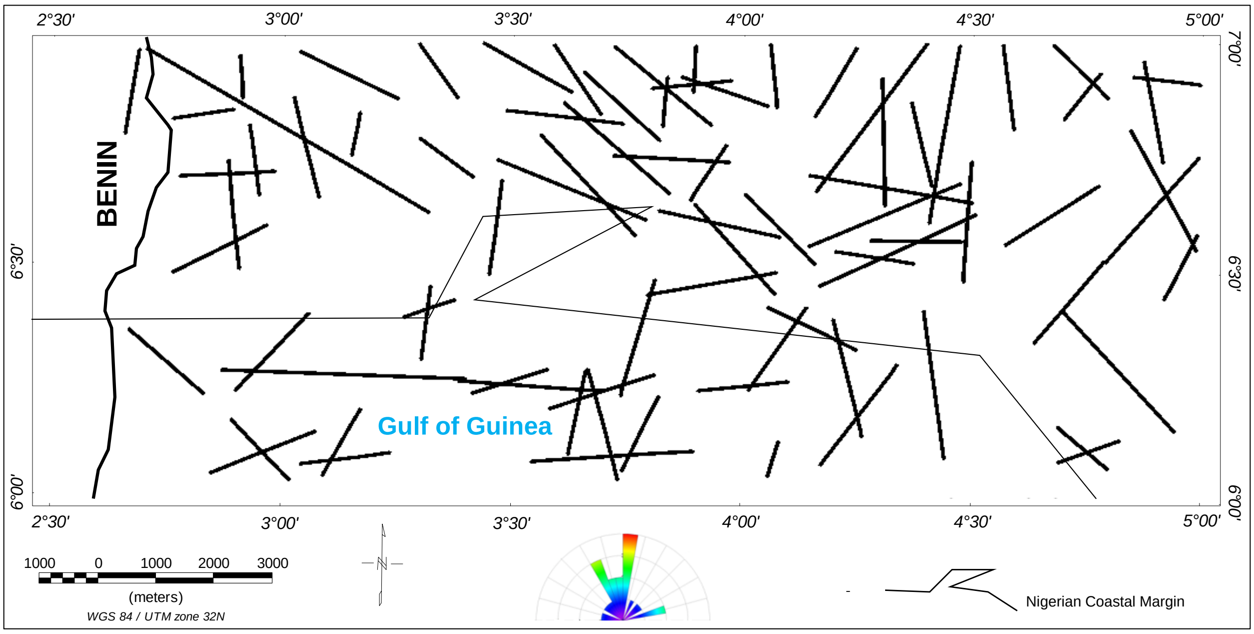

Fig. 8. The interpreted lineaments of the TDR map, with rosette plot indicating the main geological trend.

2D forward modeling and basement morphology

Geophysical signatures of the region showed gravity anomaly variations which indicates that the basement is characterized by rugose block pattern, typical of a horst-graben topography. The alternations in high, low and intermediate anomalies reflect variations in the arrangement of rocks of varying densities, the geomorphology of the basement, and boundaries of conspicuous geologic structures. The rugged topography of the basement was established on the modeled 2D profile (Fig. 9) drawn across the offshore part of the basin. The model showed that the basement is made up of horst and graben features which largely influenced sediment deposition, trapping mechanism and distribution of hydrocarbon play elements in the Benin Basin.

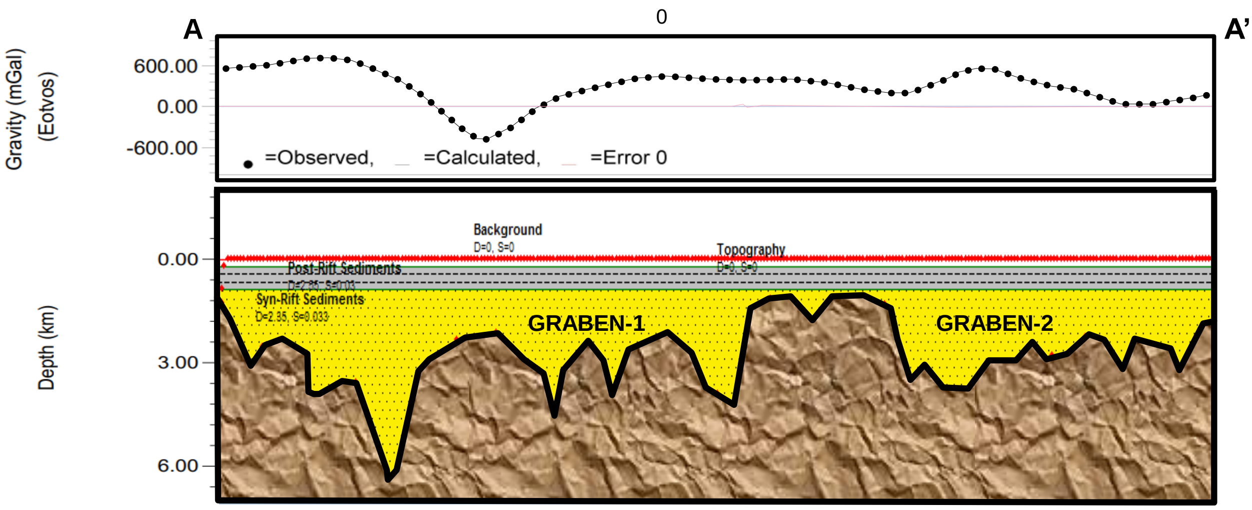

Fig. 9. Profile A – A' showing the basement geometry.

Discussion

The residual Bouguer anomaly expressions of the study area reflect variations in density contrasts of the basement and other geological features in the basin. For instance, the northeastern and central portions of the region exhibit marked variations of high gravity signatures which reflects the varying densities of the highly metamorphosed Western Nigeria's basement complex. The southwestern and southern parts that showed high gravity signatures indicate graben features characterized by high density ultramafic (basaltic) oceanic basement rocks. The trend of these anomalies suggests effects of near-surface and deeper tectonic features of the basement which controlled sedimentary deposition in the study area.

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The morphotectonic features interpreted in this study reflect re-arrangement of the basement due to various tectonic events associated with the evolution of the basin (Oluyide, 1988; Benkhelil et al., 1998; Oladele & Ayolabi, 2014). Five lineament sets oriented in the NNE-SSW, N-S, ENE-WSW NNW-SSE, and E-W directions were observed from the rosette plots. The NNE-SSW, E-W, and ENE-WSW lineaments relates to the pre-existing basement fractures and lines of weaknesses connected to the oceanic megastructures that controlled the breaking of the Gondwana Supercontinent (Semere & Woldai, 2006; Nemčok et al., 2012; Kaki et al., 2013; Davison et al., 2015; Oladele et al., 2016). The NNW-SSE and N-S lineaments which formed at a later stage of the basin development (Nemčok et al., 2012; Oladele et al., 2016) are products of the Late Albian-Cenomanian and the Santonian-Campanian events (Benkhelil et al., 1998) that impacted most part of the West African Rift System (WARS). There are also contributions from the far-field stresses arising from the tectonic interactions between the African and Euro-Asian Plate boundaries (Benkhelil et al., 1998; Fairhead et al., 2013; Mustapha et al., 2019).

The two basement depressions delineated from the 2D basement geometry model (Graben 1 and Graben 2) may have accommodated up to 4 km thick sedimentary successions, indicating that these parts of the basin possess great potentials for hydrocarbon prospectivity. This assertion is consistent with the findings of Okoro et al. (2021) who estimated a depth range of 4.5 to 6.3 km for the sub-basins mapped within the offshore part of the study area using aeromagnetic data. The basement structure exerts a major influence on the overall basin petroleum geology, controlling the arrangement of petroleum systems elements and trapping geometry by enhancing formation of anticlinal traps and fault-dependent closures. Larger portions of the mini-basins remain untested by the drill bit. It is therefore recommended that future exploration activities should be targeted towards the offshore part of Nigeria's Benin Basin.

Conclusions

The interpretation of satellite gravity data enabled characterization of the morphotectonic features, basement geometry, and sediment thickness within the Nigerian sector of the Benin Basin. Geophysical signatures of the region revealed alternating high, low, and intermediate anomalies suggesting differences in density contrasts of the subsurface rocks. The filtered gravity maps showed deeper lying lineaments. These morphotectonic structures showed conjugate relationships, with major trends in the ENE-WSW, N-S, NNE-SSW, E-W, and NNW-SSE directions, indicating that their origin is associated with the transform-dominated processes that created the Equatorial margin. 2D forward modelling of the basement architecture revealed horst and graben features, reflecting the rugous topography of the basement beneath the Benin Basin. The grabens may have accommodated up to 4 km thick sediments, and hence possess great potentials for hydrocarbon exploration. Block rotation, faulting, and tilting largely influenced the observed architecture of basement.

Recommendation

Future exploration activities should be concentrated on the offshore part of the Benin Basin owing to the identified mini-basins with thicker sediment accumulation.

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