Basement Structure Offshore Dahomey Basin, Nigeria: New Insights from Aeromagnetic and 3D Seismic Interpretation

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Abstract

The basement structure offshore Dahomey Basin Nigeria was investigated in this study using geophysical attributes interpreted from high-resolution aeromagnetic (HRAM) and 3D seismic data. Edge detection filtering including first vertical derivative (FVD), tilt derivative (TDR) and total horizontal derivative of upward continuation (THDR_UC) to 10km was applied to the HRAM data to locate the contacts of geological features. Depth to magnetic sources and sedimentary thickness was determined using the source parameter imaging (SPI) method. Volumetric attributes analysis enabled mapping of the basement surface and basement faults from the 3D seismic volume. From the data interpretation results, we propose a new structural model of the offshore Dahomey Basin. The study area is characterized by conjugate wrench systems dominated by rotated and tilted fault blocks and horst-graben features. Arising from this, there is a better understanding of the dominant influence that oceanic transform faults and the basement architecture play on the development and petroleum geology of the basin. Major trends of the faults are in the NNE-SSW, NE-SW, NW-SE, and WNW-ESE directions. The regional tilt of the basement is both to the south and east, resulting in a series of half-graben sub-basins trending in the ENE-WSW and NW-SE directions. Basement depth and sedimentary thickness within these sub-basins range between 4.5 – 6.3km. The sub-basins present potential prospective zones where further exploration efforts should be intensified. The overall implications of the regional tectonic trends and stress-field direction on petroleum systems development, trap styles, and hydrocarbon prospectivity in the basin are discussed.

Introduction

The Dahomey Basin (Figure 1) is an inland and offshore basin that covers the western coast of Nigeria where it is delimited by the west edge of the Niger Delta (Brownfield and Charpentier, 2006). The basin has become a prime target for hydrocarbon exploration following recent exploration successes in neighboring countries including Ghana, Senegal and Benin. However, the tectono-stratigraphic framework of the offshore Dahomey Basin Nigeria remains poorly understood largely due to paucity of subsurface data and few well penetrations available in the public domain for detailed studies. Poor exploration outputs from the onshore and shallow shelf portions of the basin necessitates that exploration focus be shifted towards the grossly underexplored but highly prospective offshore areas.

Aeromagnetic and seismic surveys are viable geophysical techniques which have found successful application in frontier basin studies where they are deployed to map subsurface geological structures, basin morphology, basement depth and extent of the sedimentary basin (Saibi et al., 2016). Characterizing the structural configuration of the basement is critical for successful hydrocarbon exploration program in a frontier basin (Oladele and Ayolabi, 2014). Knowledge of the basement architecture remains key to unlocking the unrealized hydrocarbon potentials especially in the Lower Cretaceous syn-rift plays offshore Dahomey Basin (Babangida, 2021; Okoro et al., 2021). The basement faults and fracture networks may exert control on the overlying sediments, affecting subsurface fluid flow and hydrocarbon trap styles. Since they are products of the tectono-stress regimes responsible for the basin development, the basement structures generally control the basin architecture and influence the distribution of petroleum systems elements, subsurface heat flow patterns and thermal maturation pattern of the sediments at depths (Saibi et al., 2016; Ali et al., 2017; Okoro et al., 2021). The present study combines HRAM and 3D seismic interpretation for regional investigation of the basement morphotectonic features and architecture of the offshore Dahomey Basin to identify half-graben sub-basins where thicker sedimentary packages have accumulated for further exploration targeting.

Data Analysis and Interpretation Techniques

The HRAM data was subjected to structural enhancement filtering including first vertical derivative (FVD), tilt derivative (TDR) and total horizontal derivative of upward continuation (THDR_UC) to 10km to locate the edges and contacts of shallow and deep-seated linear features. Rosette plots of the extracted lineaments were analyzed to infer the dominant structural trends in the basin. Depth to magnetic sources and sedimentary thickness were determined using the source parameter imaging (SPI) method, while the basement block pattern and architecture were modeled along a selected profile (e.g., Thompson, 1982; Roest et al., 1992; Blakely, 1995; Philips, 2000; Thurston et al., 2002; Nabighian et al., 2005; Reeves, 2005).

Volumetric attributes were extracted from the 3D seismic cube to enhance the interpretation of down-to-basement faults and the basement surface. The faults were manually picked across the area covered by the seismic cube and modeled to understand the fault surface geometry. 1D thermal maturation modeling of a nearby oil well performed by Adeoye et al. (2020) was used to evaluate the sediment thermal maturity and timing of hydrocarbon generation and expulsion from the source rocks. The 1D model was needed to assess the burial and thermal history of the sediments and to establish the presence of Cretaceous petroleum systems in the offshore Dahomey Basin.

Results

The FVD, TDR and THDR_UC (10km) maps (Figure 2a-c) of the study area detected the edges of shallow and deep-seated anomalies of varying magnetic intensities. The anomalies showed different orientations in the NW-SE, NE-SW, NNE-SSW and WNW-ESE directions and follow major lineaments trends in the basin. The SPI depth map (Figure 3) imaged the rugged basement topography and revealed variations in sedimentary thickness across the basin. Two sub-basins identified simply as Graben-1 and Graben-2, were mapped in the offshore Dahomey Basin. Sedimentary thickness in the sub-basins vary between 4.5 to 6.3km. 2D forward model of a profile drawn across the sub-basins revealed the rugose geometry of basement block pattern (Figure 4a and 4c). The horst-graben architecture of the basement was confirmed from the interpreted NE-SW trending seismic line within Graben-1 (Figure 4b).

On the seismic section, the basement was recognized by a high amplitude reflection at its top and its chaotic seismic pattern (Figure 4b). The basement rocks are characterized by tilted (rotated) fault blocks and half-graben structures which are deeply buried beneath thick sedimentary successions. The structures influenced the deposition of syn-rift (divergent seismic reflection character) and post-rift (sub-parallel to parallel seismic reflection character) sequences in the half-graben sub-basins created during the Late Jurassic opening of the Gulf of Guinea (Omatsola and Adegoke, 1981). The faults cut across each other, forming half-graben structural basins trending in the ENE-WSW and NW-SE directions (Figure 5). Depth structure map of the basement surface depicted a rugged morphology characterized by amalgamation of horsts and half-graben structures (Figure 6a). The interpreted 3D seismic volume covered a portion of Graben-1 sub-basin from our SPI depth map (Figure 3). As such, the four half-graben sub-basins identified on the seismic structure map of the basement were all observable on the 3D display of the SPI depth map (Figure 6b).

1D burial history model of a nearby offshore oil well (Figure 7) was used to illustrate the tectonic controls on burial and thermal events in the basin. Orogenic episodes marked by uplifts and erosions were defined by major unconformities including the Albian-Cenomanian, Santonian, Eocene-Oligocene and Miocene unconformities (MacGregor et al., 2003; Brownfield and Charpentier, 2006; Adeoye et al., 2020). The modeled vitrinite reflectance enabled the calibration of different past and present heat flow scenarios and eroded sediment thicknesses in the basin. The Early Cretaceous subsidence initiated by rock fragmentation, block faulting and sagging marked the beginning of sedimentation of continental deposits including conglomeratic sandstones, claystones and shales of varying thicknesses across the study area. About 3000m of sediments accumulated in the offshore well during the Berriasian to Aptian times. As the rifting climaxed in Albian times, the basin development was dominated by transform faulting, wrench tectonism and rapid basement subsidence which creating accommodation for the deposition of siliciclastic sediments during the first marine incursion in the basin.

The final separation of Africa from South America connected the North and South Atlantic Oceans resulting to a full marine transgression in the Dahomey Basin and other adjacent basins like the Benue Trough. This maximum flooding event led to the deposition of thick Cenomanian and Turonian organic rich shale across Dahomey Basin and Southern Benue Trough (Adeoye et al., 2020).

Discussion

The aeromagnetic expressions of the offshore Dahomey Basin show a close relationship with the major geological features in the basin. Four lineaments set trending in the NE-SW, NNE-SSW, NW-SE and WNW-ESE were mapped from the filtered aeromagnetic maps (Figure 2). The conjugate nature of the lineaments is an indication that they are products of the transform tectonics that controlled the development of the Gulf of Guinea in the Early Cretaceous (Fairhead et al., 2013; Gaina et al., 2013). The structures resulted from basement re-organizations in response to the multi-phase rifting processes that heralded the opening of the Equatorial Atlantic margin (Mustapha et al., 2019). These morphotectonic features influenced the development of horst and graben features and affected the distribution of sub-basins, trapping mechanisms and the overall petroleum geology of the offshore Dahomey Basin (Okoro et al., 2021; Babangida, 2021).

The NNE-SSW and NE-SW trending lineaments follow the orientation of pre-existing zones of crustal weakness which were reactivated by the Late Jurassic extensional and transtensional forces that acted on the oceanic transform faults and created deep structural basins within the Gulf of Guinea (Ajakaiye et al., 1986; Akpan and Yakubu, 2010; Davison et al., 2015). These lineament sets pre-dates the NW-SE and WNW-ESE trending lineaments whose origin were associated with inter-/intra-cratonic stress-related changes of the African Plate (Olagoke et al., 2020) including the Late Albian-Cenomanian compressional event (Benkhelil, 1989), the Santonian orogeny (Benkhelil et al., 1998) and the far-field stresses resulting from African – Euro-Asian Plate interactions (Teasdale, 2001; Eze et al., 2001; Fairhead et al., 2013).

The identified basement depressions (sub-basins) on the SPI depth map were actually confirmed to be an amalgamation of smaller half-graben sub-basins from the 3D seismic interpretation (Figure 6). The horst block separating the two larger grabens (sub-basins), together with the smaller horst blocks, faults and lineaments make-up the main structural elements that controlled the trap styles in the basin by enhancing the development of anticlinal closures and structural traps (Etobro, 2017; Babangida, 2021). 2D forward model of the selected profile drawn across the sub-basins showed that the basement block pattern depicts a horst-graben architecture, controlled by block faulting, block tilting and rotation. Hence, a new structural model for the basement offshore Dahomey Basin, consisting of half-grabens within a larger graben structure flanked by horst blocks, is proposed in this study (Figure 6).

The trend of the syn-rift down-to-basement faults are typically in the ENE-WSW direction (blue faults in Figure 5), indicating the E - W separation of the African and South American Continents. The conjugate NW-SE wrench faults (yellow faults in Figure 5) interpreted from the seismic developed as a result of the clockwise rotation of the two Atlantic margins (dashed circle in Figure 5). This suggests evidence of strike-slip movements in the underlying basement. Structural orientation of the major faults bounding the ENE-WSW grabens are in alignment with the trend of the Romanche and Chain Fracture Zones.

Two of the secondary transform faults were observed to intersect the basement at the location of the 3D seismic data (Figure 5 inset map at the top left). The Santonian – Campanian compressional event which affected the entire West African Rift System (WARS) including the Dahomey Basin, the Benue Trough and the Chad Basin in the northeast was responsible for the horizontal movements along the NW-SE trending faults, resulting in lateral shearing with limited vertical displacement of the faults (Benkhellil, 1989). This affected the sealing capability of the faults, creating excellent fault-dependent closures like those encountered in the Upper Cretaceous discovery offshore southwestern Nigeria (Babangida, 2021). However, no evidence of compression was identified from the interpretation of the Lower Cretaceous structural framework in this study.

The burial history plot (Figure 7) revealed rapid burial rates for the Cenomanian, Turonian and Coniacian source rocks in the study area. The source rocks attained the early maturity stage following their exposure to peak temperatures. This was indicated by the estimated vitrinite reflectance of 0.62%VRo, suggesting that the source rocks reached about 10% of their generation potential at 87 Ma (Coniacian). Hence, the Coniacian times marked the early oil generation window in the offshore Dahomey Basin. The onset of source rock transformation and the amount of organic matter transformed in a source rock depends on the kerogen type, time and burial controlled temperature increase.

The Santonian orogeny triggered further burial of the Cenomanian and Turonian source rocks, making them to reached their maximum temperature and realize 50% of their transformation potential at 87 and 86 Ma (Santonian) respectively. Whereas the Cenomanian and

Turonian source rocks attained transformation ratios of 83% and 69% at 54 Ma (Early Eocene) and 50 Ma (Late Eocene) respectively, the Coniacian source rocks were yet to reach sufficient maturity to generate hydrocarbons. The transformation ratio plot (Figure 8) revealed that the Cenomanian and Turonian source rocks have been subjected to temperatures almost sufficient for total kerogen conversion, while the Coniacian source rocks were at the early maturation stages, having significant potentials to generation hydrocarbons if subjected to higher temperatures.

Conclusions

The interpretation of aeromagnetic and 3D seismic dataset used in this study has enabled a better understanding of the structural controls on the basement architecture and its influence on the tectonic development and petroleum geology of the Nigerian sector of the offshore Dahomey Basin. Structurally, the study area is characterized by conjugate wrench faults, reflecting the imprints of transform tectonism which controlled the development of the horst-graben architecture of the basement. Major trends of the faults are in the NNE-SSW, NE-SW, NW-SE, and WNW-ESE directions. Regional tilt of the basement is both to the south and east, resulting in several half-graben sub-basins trending in the ENE-WSW and NW-SE directions. Aeromagnetic basement topography mapping revealed adequate sedimentary thicknesses in these half-grabens which forms part of a larger graben structure flanked by horst blocks. Hence, a new structural model comprising of half-grabens within a larger graben feature is proposed for the basement structure of the offshore Dahomey Basin. The key elements of a petroleum system have been identified from 1D thermal maturation studies of a nearby offshore oil well, which suggests the possible existence of a petroleum play in the syn-rift sequence contained within the identified half-graben features. It is therefore necessary that future exploration campaigns in the Nigerian sector of the offshore Dahomey Basin be targeted towards these highly prospective half-graben sub-basins to test the potentials of the syn-rift plays.

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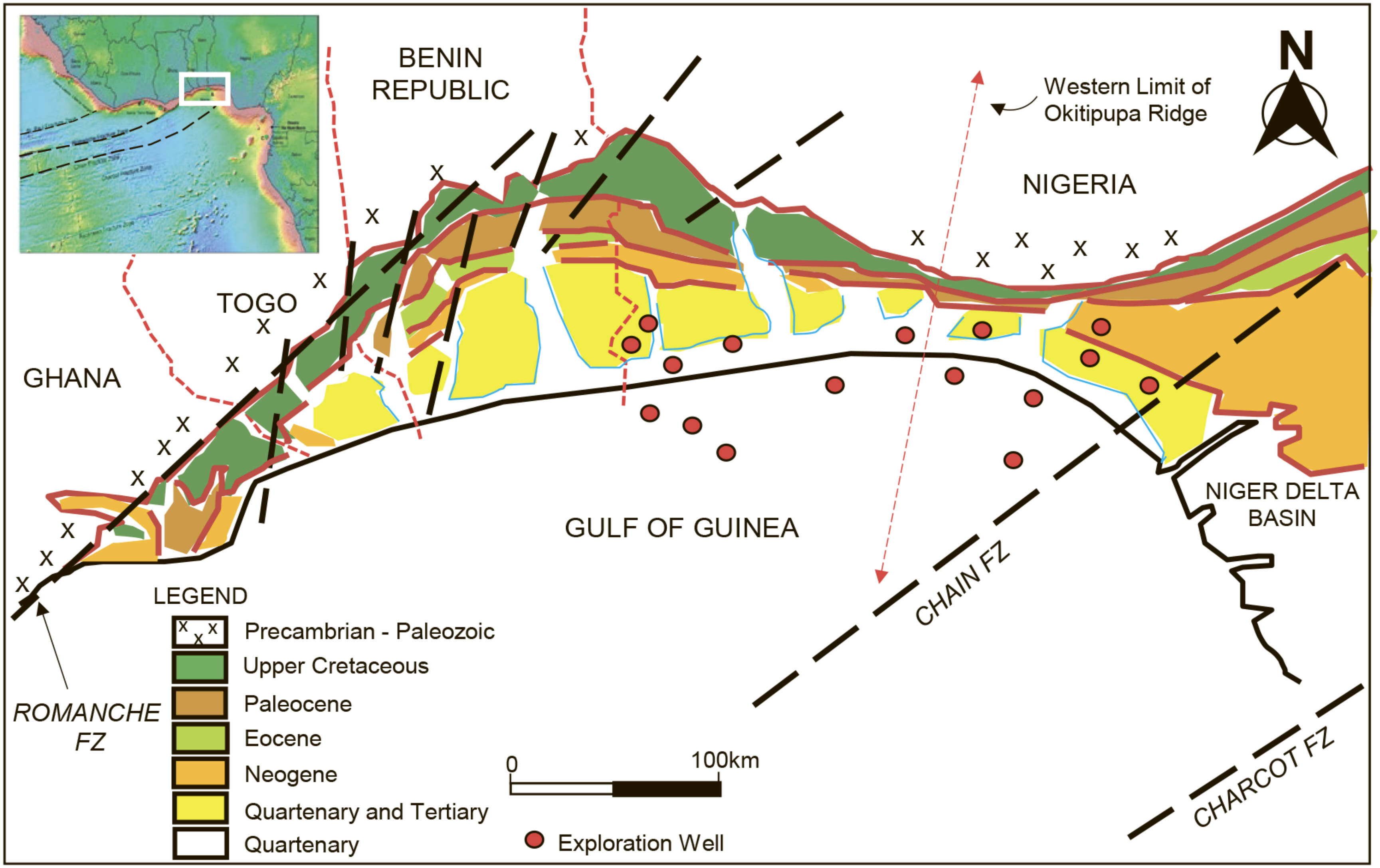

Figure 1. Geological framework of the Dahomey Basin (modified after Billman, 1992).

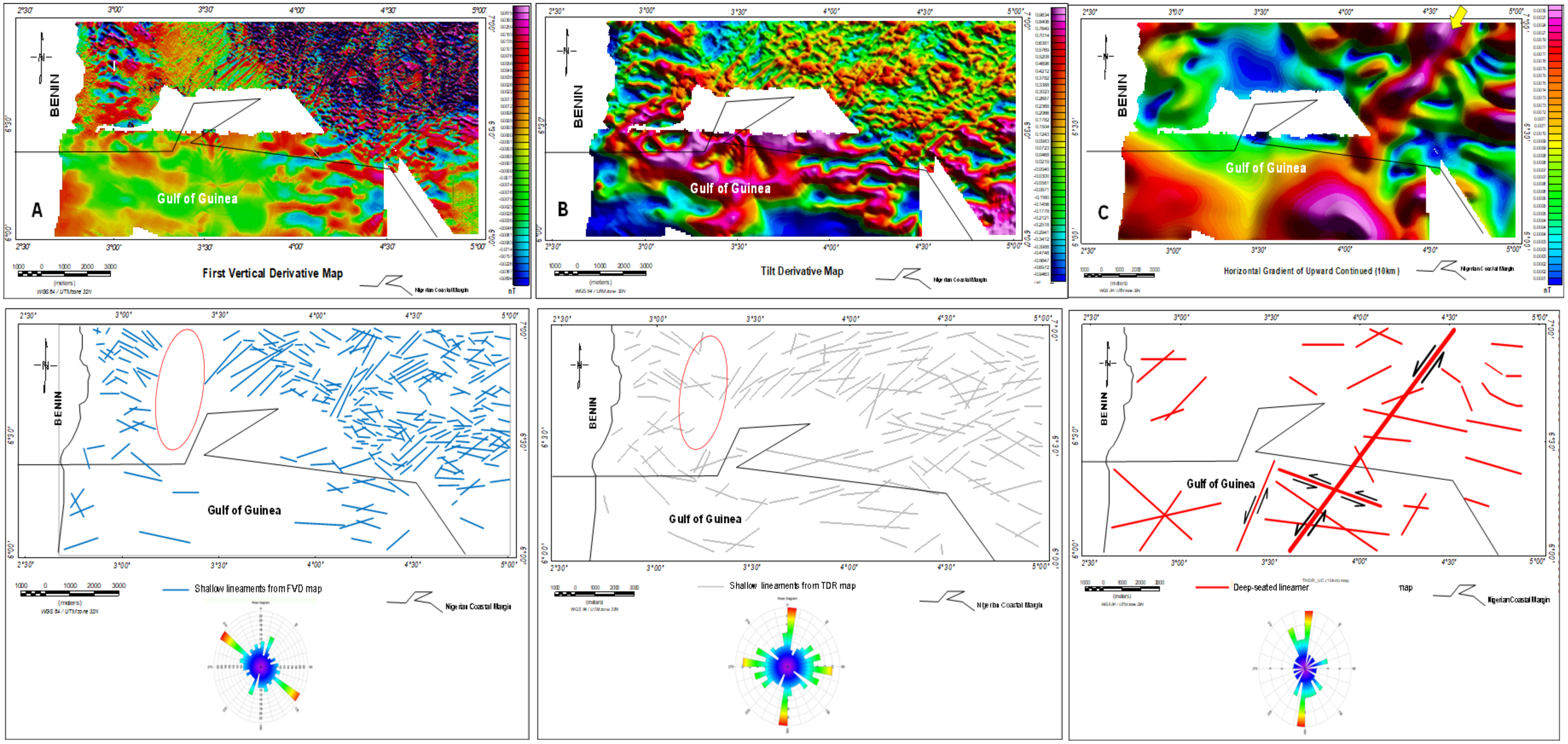

Figure 2. FVD, TDR and THDR_UC (10km) maps of the study area, with the extracted lineaments and rosette plots.

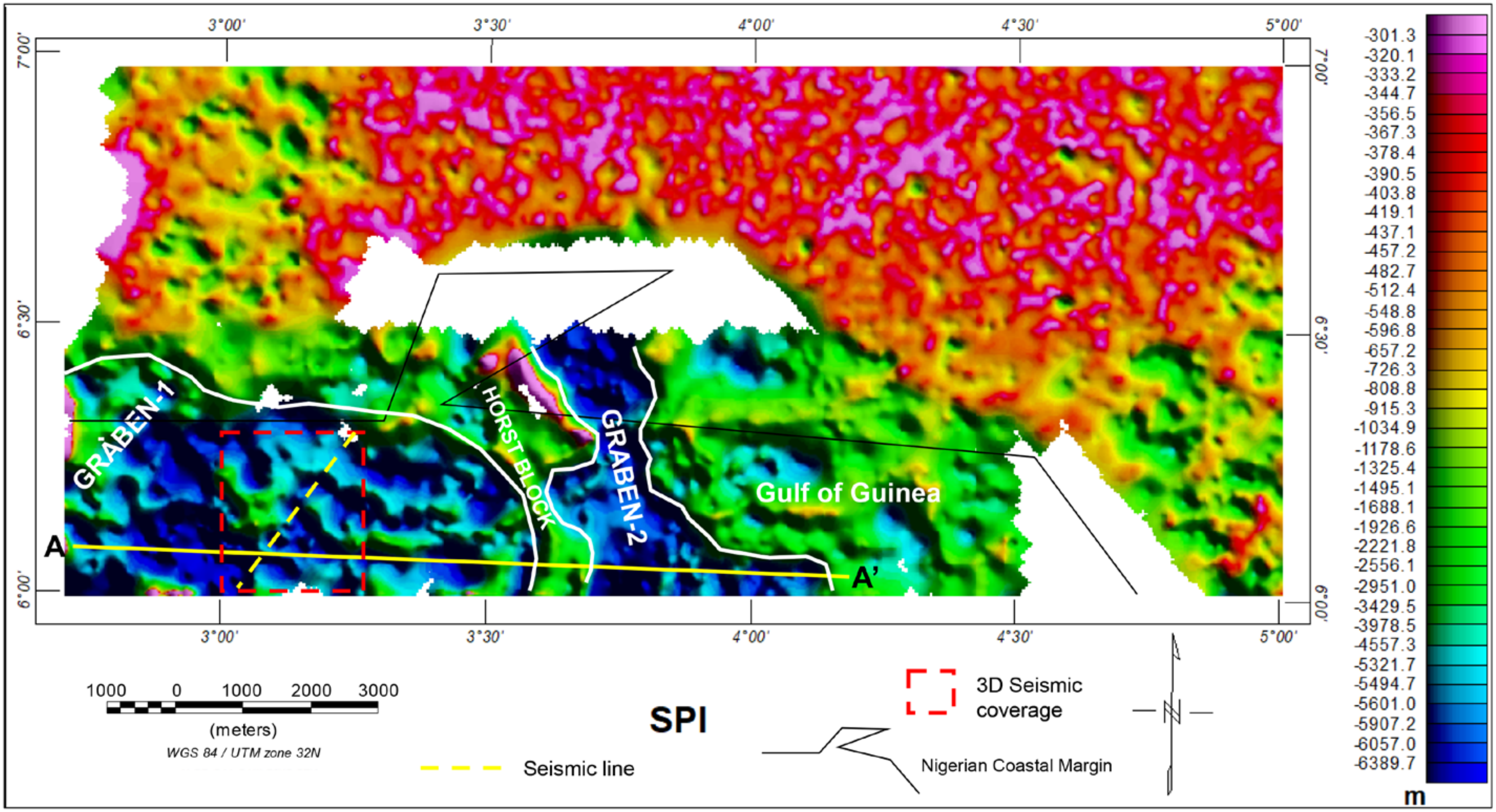

Figure 3. SPI depth map of the study area showing the mapped sub-basins. The yellow line is the modeled 2D profile in Figure 4c, while the yellow broken line is the interpreted seismic section presented in Figure 4b.

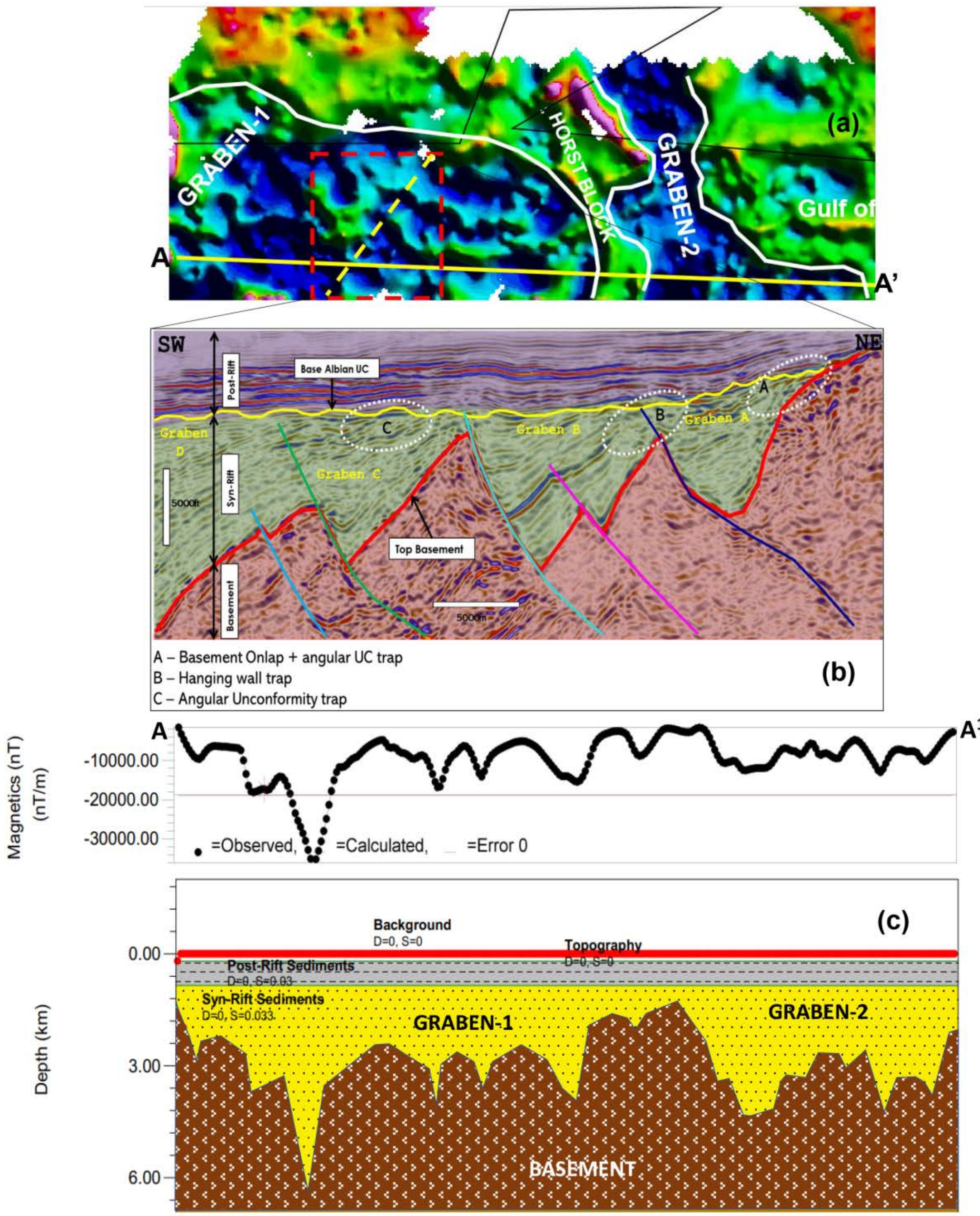

Figure 4. (a) SPI depth map showing the sub-basins (b) NE-SW seismic profile showing the fault framework, sedimentary fill pattern and trapping types in the Lower Cretaceous syn-rift (c) 2D forward model of profile A-A' showing the basement block pattern in the study area.

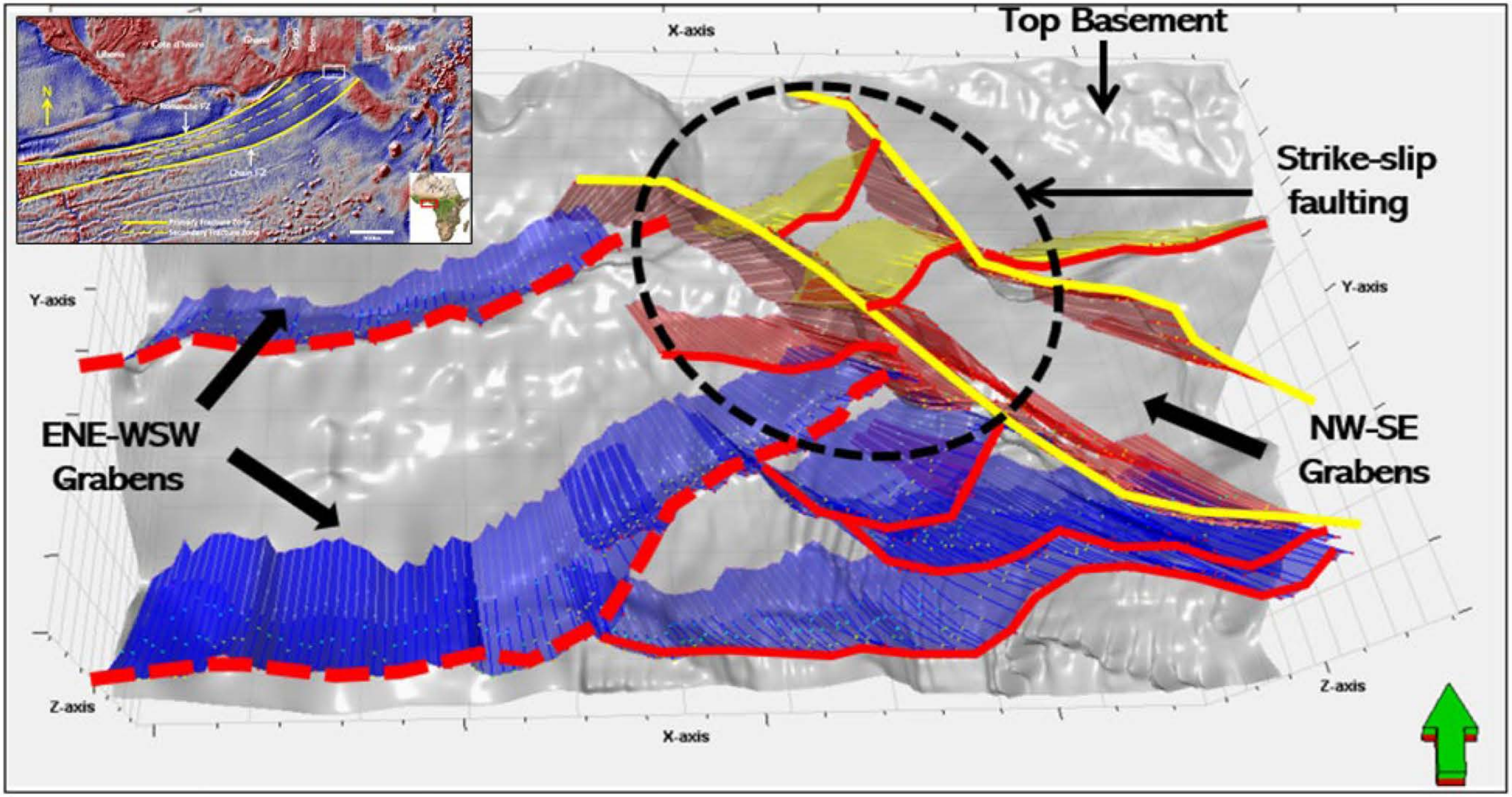

Figure 5. Fault framework in the Lower Cretaceous syn-rift half-graben depocenters offshore Dahomey Basin. The white surface in the background is the map of the top of the basement. Inset is a gravity map showing regional structural trend in the WATM.

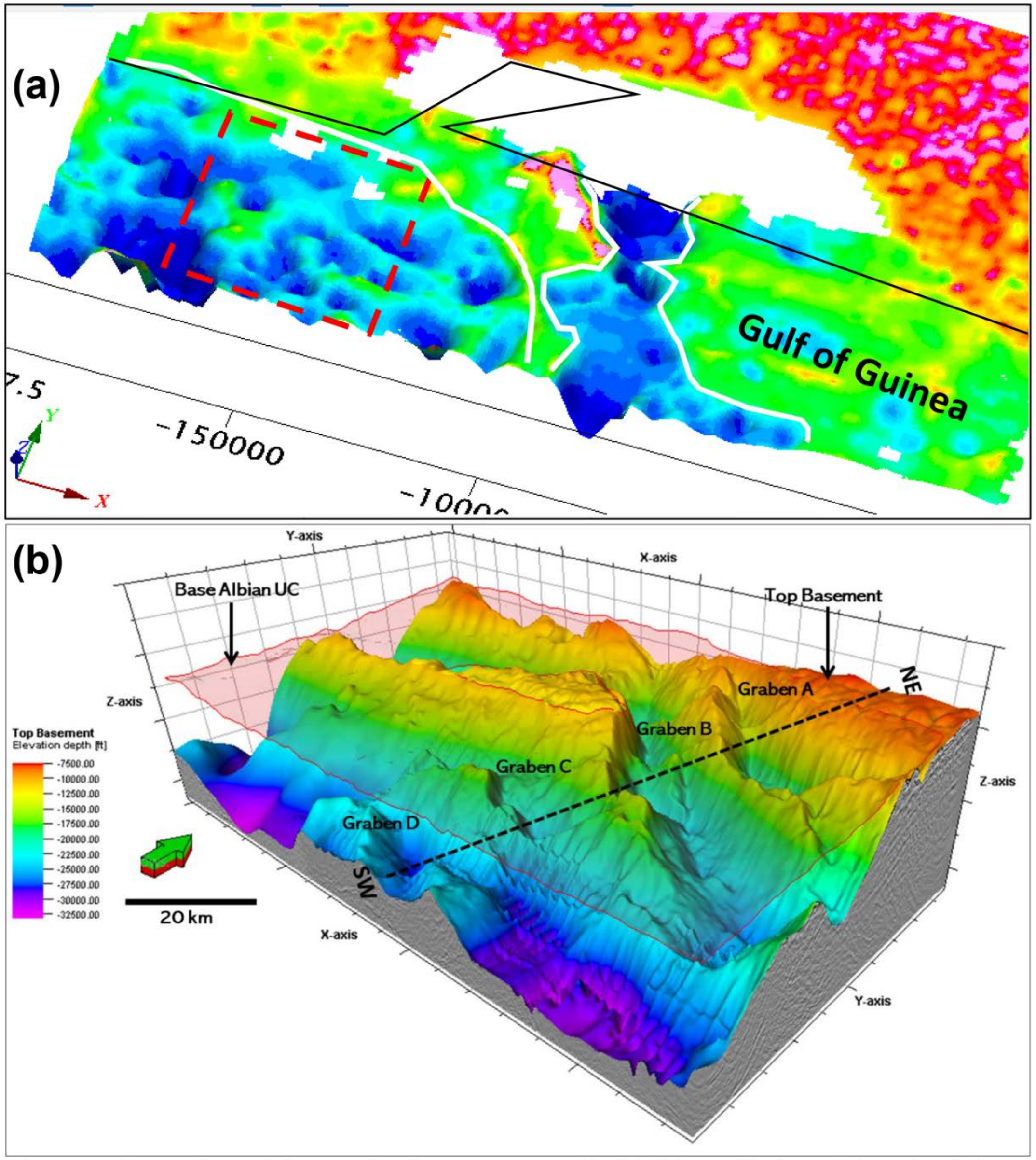

Figure 6. (a) 3D view of the SPI depth map compared with (b) 3D display of the seismic interpreted depth structure map of the basement surface. Syn-rift half graben sub-basins from the seismic depth structure map are part of a larger graben feature (Graben-1) in our SPI depth map (broken red square box).

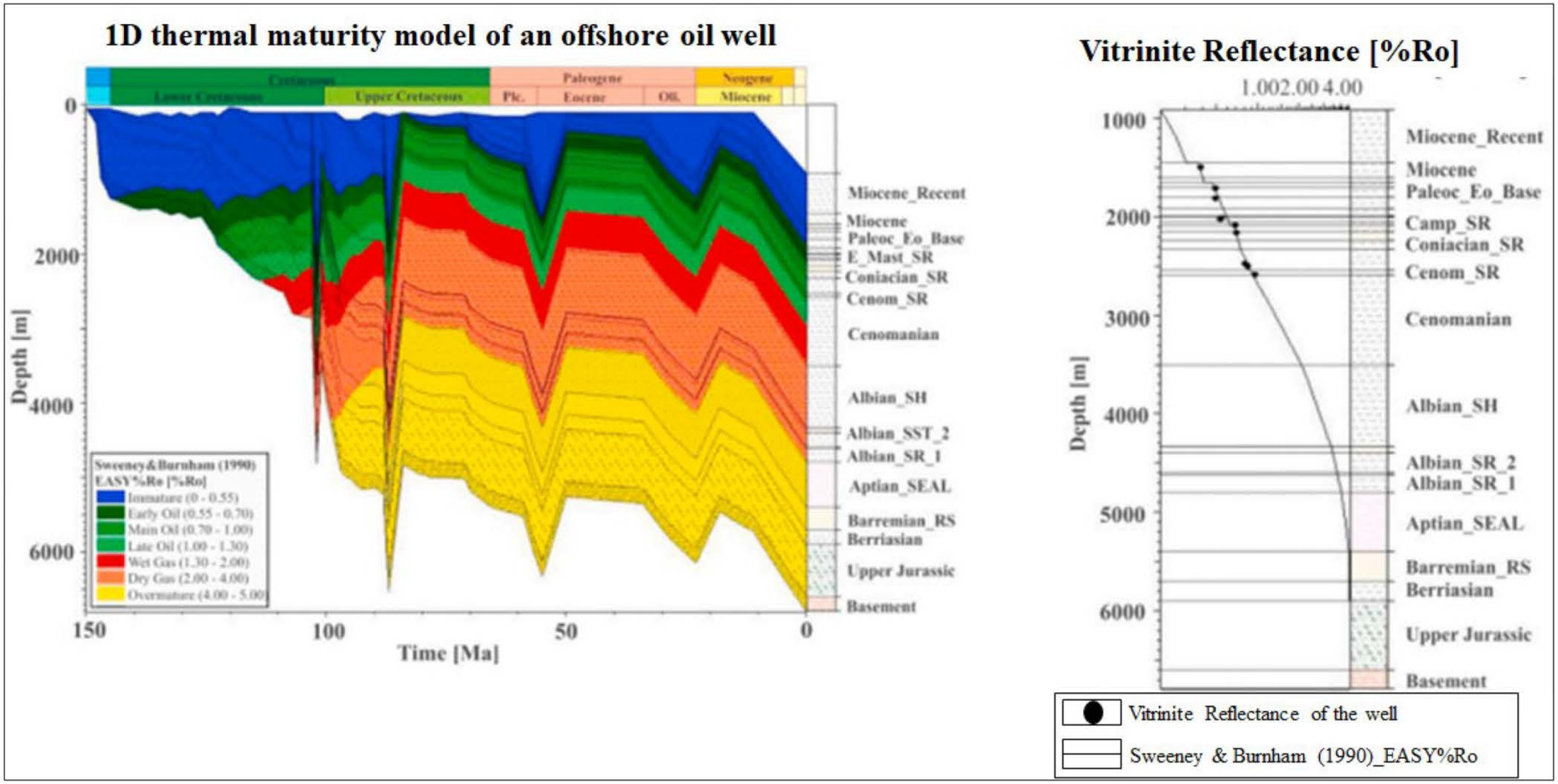

Figure 7. Burial history model of a nearby offshore well with resulting vitrinite reflectance overlay (Sweeney and Burnham, 1990). The two oldest rapid burial and erosion events were the most significant periods of the source rock transformation. A best fit between calculated (black line) and measured vitrinite reflectance (black dots) is observed in the well (modified after Adeoye et al., 2020).

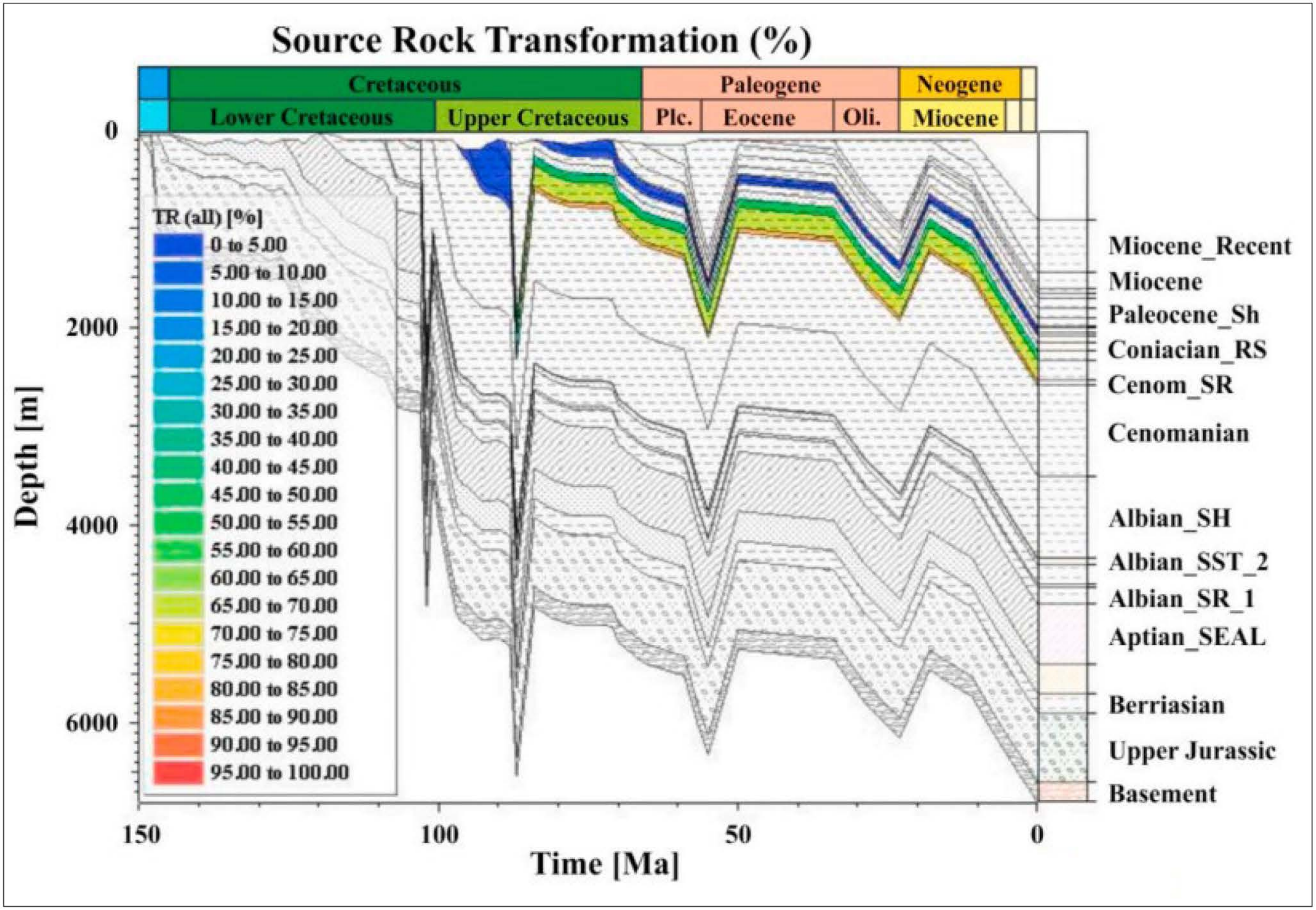

Figure 8. Transformation ratio plot of Cenomanian, Turonian and Coniacian source rocks in the nearby offshore well showing generation of hydrocarbon above 80% in the older Cenomanian source beds after Upper Cretaceous burial and erosion event (modified after Adeoye et al., 2020).