3D Basin Architecture Using Gravity and Magnetic Data Closes a Structural Gap in Petroleum Systems Modeling

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ABSTRACT

Depth to basement in most parts of the Niger Delta is beyond the reach of wells drilled for exploitation of oil resources. As a consequence, investigation of the architecture of the basin cannot be done with seismic data and well information alone. To build a basin architecture that serves a strong solution input to a basin model, other forms of data capable of investigating deeper into the subsurface are needed. Potential field data (magnetic and gravity) can serve this purpose. They can reveal large and small-scale features in the basement lithology and morphology, as well as determine the facies distribution within sedimentary units. Potential field data provides an invaluable source of basin information, which can complement seismic and well data. Basin modeling is a major requirement needed to carry out a petroleum systems analysis. To build a basin model, knowledge of the basement architecture and the sedimentary facies distribution are essential. This can be achieved using potential field data constrained by well and seismic information. In the Niger Delta basin, the possibility of deeper opportunities is becoming recognized. In order to test the viability of these opportunities, a petroleum systems analysis is vital. An exploration study carried out by EMR required a basin model for the petroleum systems analysis of some deeper prospects. These prospects were mapped on seismic, but the seismic data and wells did not penetrate deep enough to the Akata formation and basement complex. As a consequence, a basin model could not be built using seismic data and well information alone. To bridge this gap, potential field data had to be sought and analyzed to determine the basement architecture and stratigraphy of the overlying sediments in the study area. In this study, Airborne gravity and magnetic data were purchased from the Nigerian Geological Survey Agency (NGSA). A litho-constrained inversion of the gravity data was done to create a 3D model of the basement morphology and structural maps of the major formations of the Niger Delta. The inversion was also done to determine the density distribution within the major stratigraphic units. The density distribution was used to characterize the stratigraphic units in terms of sand and shale potential. An inversion of the magnetic data was carried out to determine the susceptibility distribution of the newly modelled basement complex. This distribution was used to determine the mafic and felsic composition of the basement, which was useful in heat flow calculations. By integrating the gravity and magnetic methods with seismic and well data, a 3D basin architecture that fed into the 3D basin model was created. The basin architecture was found to be consistent with known geology of the area. When fed into the petroleum system analysis, deeper prospects were successfully identified.

Keywords: Basement, Basin Architecture, Modelling Structural, Morphology

INTRODUCTION

In a prospectivity study, a 3D basin architecture was required for the petroleum system analysis of some deeper prospects found offshore in the Niger delta basin (Figure 1). Knowledge of the basement morphology and sedimentary facies distribution within the basin is required to construct a 3D model of the basin architecture. Unfortunately, seismic data and wells in the Niger delta do not go deep enough into the Akata formation and basement complex. As a result, building a 3D basin architecture of the Niger Delta cannot be achieved using seismic and well data alone.

Other types of data capable of probing deeper into the subsurface are required to close the gap between the reach of these data types and the top of the Akata formation and the underlying basement. This can be accomplished using potential field data (magnetic and gravity). They can disclose large and small-scale lithologic and morphologic features of the basement, as well as constrain lithological distribution within sedimentary units. The potential field data is a valuable source of information that can be used in

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conjunction with seismic, well data, and outcrop information to build a 3D model of the basin architecture.

By integrating potential field data with seismic and well data, a surface to basement model can be built using a litho-constrained inversion of gravity and magnetic data and refined for input to the petroleum system analysis of deep prospects.

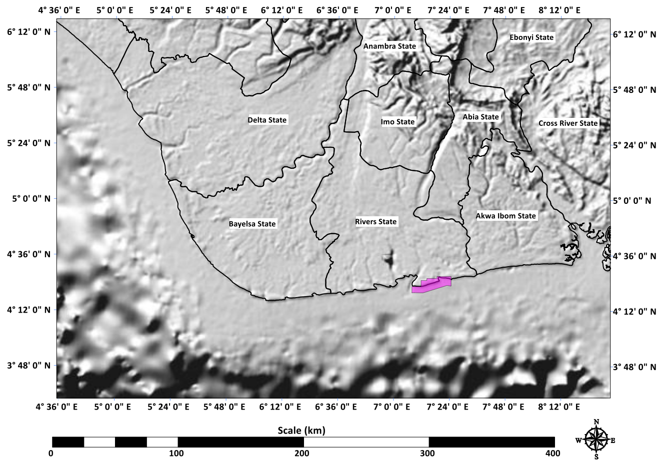

Figure 1: Map of the Niger delta basin showing location of prospect.

Geologic setting

In the Niger Delta, three primary formations, the Benin, Agbada, and Akata formations have been identified. The three formations represent sedimentary deposition in three different environments: continental, transitional, and marine (Short & Stauble, 1967). Onshore, south of the Imo Shale, the Benin formation forms extensive outcrops (Figure 2).. The Agbada formation outcrops as abandoned beach ridges a few kilometers inland from the present-day shore. The Akata formation outcrops subsea on the seafloor of the delta slope and open continental shelf. The Imo Shale is thought to be the onshore equivalent of the Akata formation (Whiteman, 1982).

The Benin Formation is over 90% sand, with a few zones of shaly intercalations (Figure 3). In general, only a small portion of the formation constitutes shale. To date, not a lot of oil has been found in the Benin formation. The formation is fresh water bearing, and the age is given as Oligocene to Recent.

The Agbada formation comprises alternations of sand and shales (Figure 4). The sandy portions make up the main hydrocarbon reservoirs and the shales make up the seals. The Agbada formation is divided into an upper unit comprising sand-shale alternations and a lower unit in which shales dominate. The sand percentage is approximately 75% in the upper unit and 50% in the lower unit (Whiteman, 1982) .

The Akata formation comprises marine dark gray shales

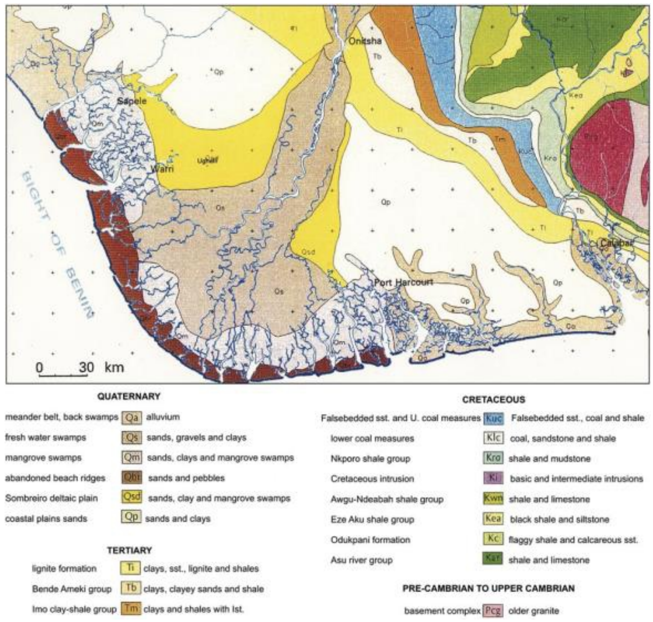

Figure 2: Geological map of the Niger Delta basin (Reijers, 2011).

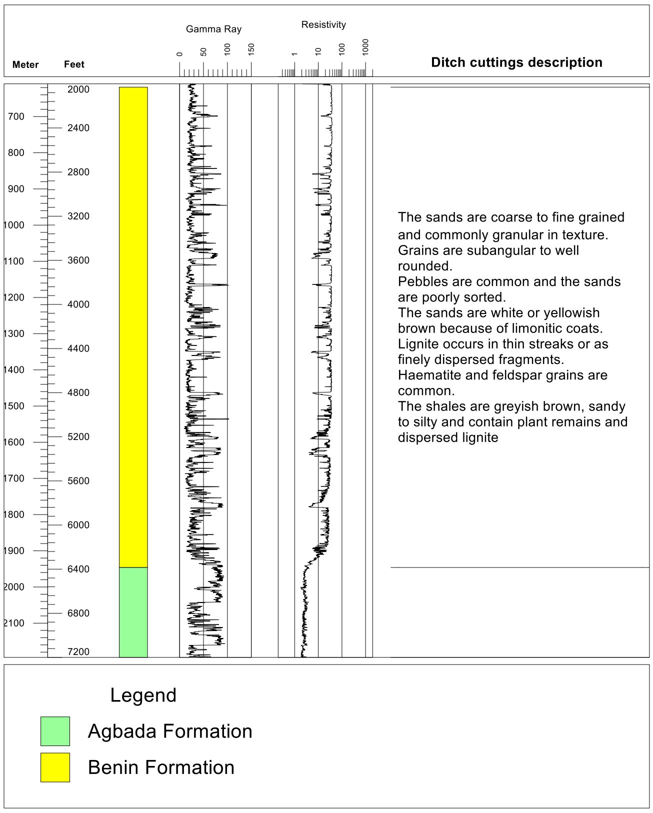

Figure 3: GR and Resistivity logs showing petrophysical characteristics of the Benin Formation.

(Figure 5). It has sandy or silty inter-beds in the upper part of the formation where it grades into the Agbada Formation. The Akata formation is thought to be the main source rock for the Niger delta basin. The formation probably underlies the whole of the Niger Delta and outcrops as the Imo shale, which is considered an up-dip equivalent of the Akata facies (Whiteman, 1982).

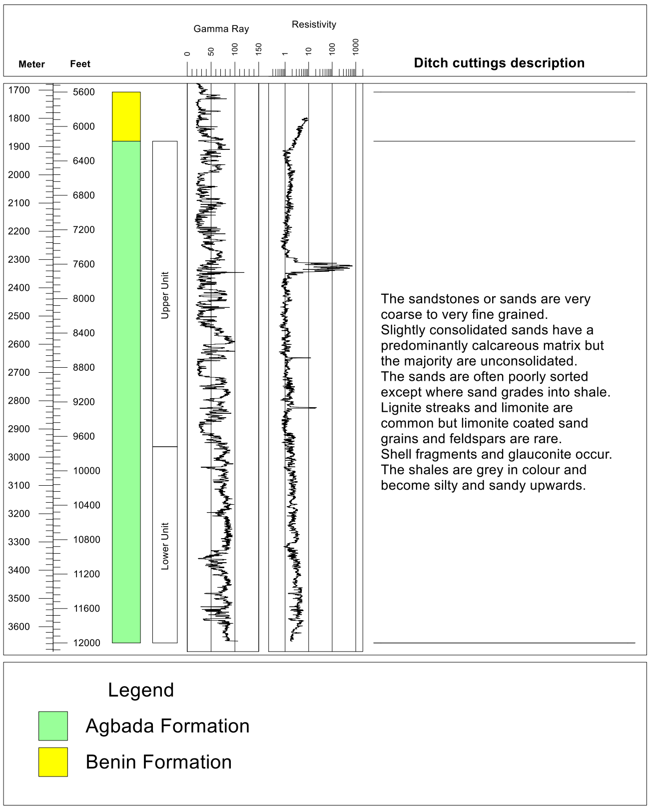

Figure 4: GR and Resistivity logs showing petrophysical characteristics of the Agbada Formation.

Overview of the data input to the development of basin architecture

Geologic and Structural Data

A depth to basement map of the Niger Delta developed by Kaplan, Lusser, & Norton, (1994) using worldwide earthquake seismology provided the input for the basement morphology. Structural maps of the Benin, Agbada, and Akata formations created using information from wells and seismic data (Avbovbo, 1978) were sought out for infilling. These maps were digitized and geo-referenced (Figures 6 – 9) to prepare them for use in the basin architectural modeling process.

Preprocessing of gravity Data

To obtain the residual gravity anomaly map, a regional-

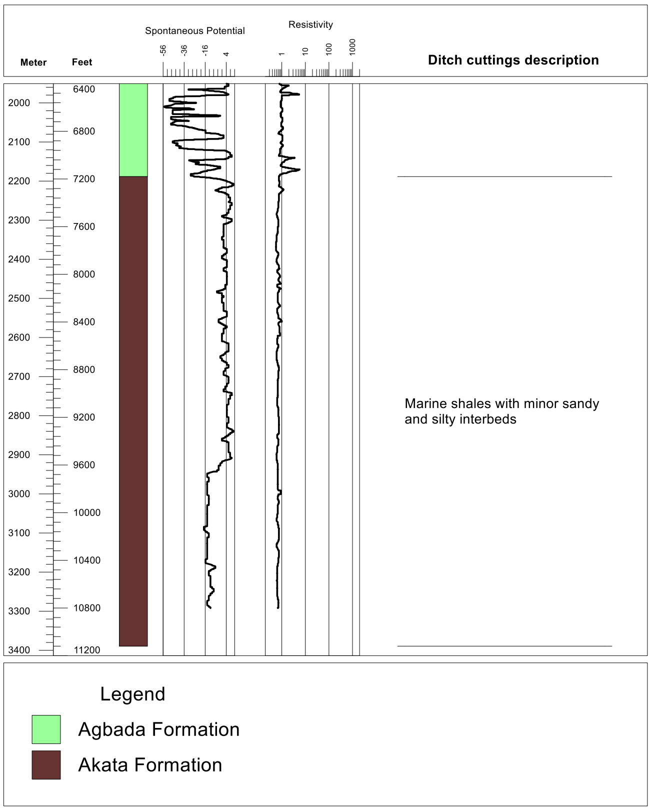

Figure 5: SP and Resistivity logs showing petrophysical characteristics of the Akata Formation.

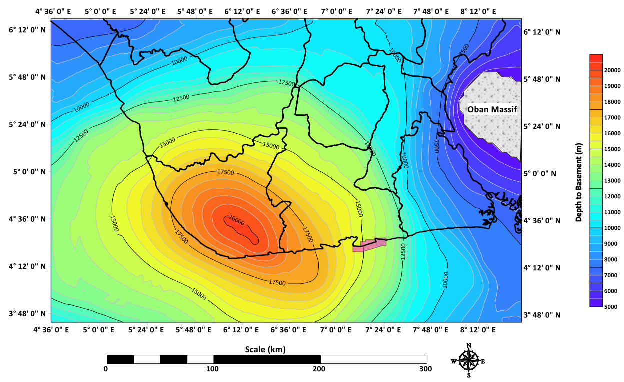

Figure 6: Depth to basement map modified after Kaplan, Lusser, & Norton, (1994).

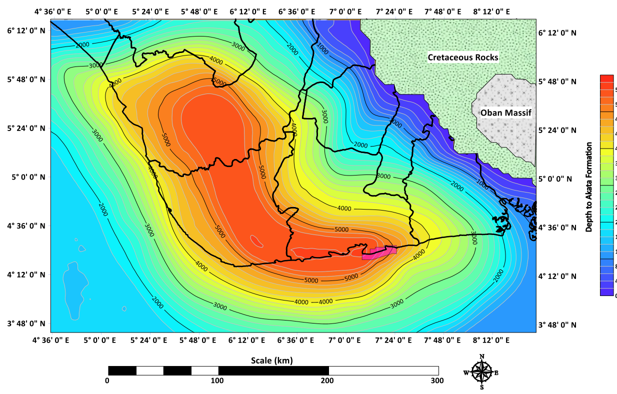

Figure 7: Structural map of top of Akata formation modified after Avbovbo (1978).

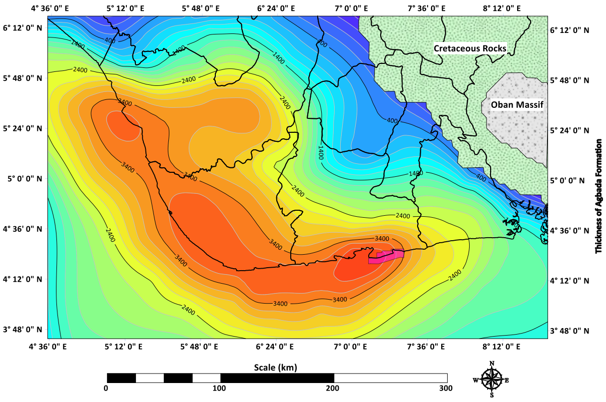

Figure 8: Thickness (Isopach) map of Benin Formation modified after Avbovbo (1978).

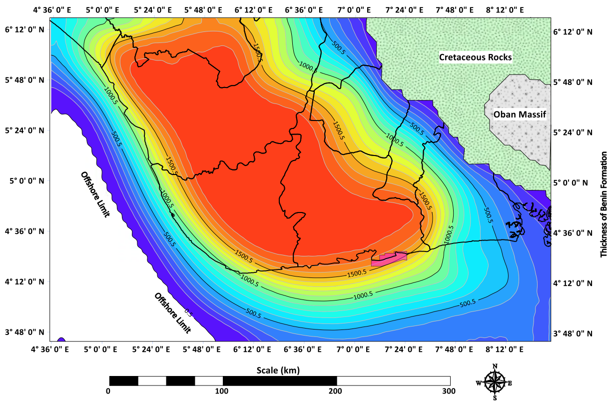

Figure 9: Thickness (Isopach) map of Benin Formation modified after (Avbovbo, 1978).

residual separation operation was carried out to isolate near surface anomalies from deep-seated ones. Five major anomalous zones (I to V) were identifed on the residual map (Figure 10). The map was then superimposed on the Palaeo-drainage trend and advancing coastline map of the Niger Delta (Reijers, 2011) to enable interpretation of the observed anomalies (Figure 11).

Based on Figure 11, the central swamp, coastal swamp, greater Ughelli, and northern depobelts which are low gravity anomalous regions are included in Anomaly I. The low gravity anomalies of the regions result from the depobelts being overlain by thick, unconsolidated, high porosity sands of the Benin formation. The thickness map of the Benin formation (Figure 9) supports this.

Anomaly II correlates with the offshore depobelt in terms of location. This is a region of high gravity anomaly. The high gravity anomaly is caused by the shale diapers that characterize this zone as confirmed by a SW-NE 2D seismic cross section taken across the zone (Figure 12).

The region of the Qua Ibo collapse correlates with Anomaly III. This is a region of low gravity anomaly (Figure 11). The gravity anomaly is low because the region of collapse has, through time, been in-filled with high porosity, poorly compacted sediments.

The Oban Massif and the Abakaliki high, respectively, correspond to anomalies IV and V, which are zones of high anomaly (Figure 11). The high gravity anomaly in these zones is caused by the shallow depth of the basement in the regions.

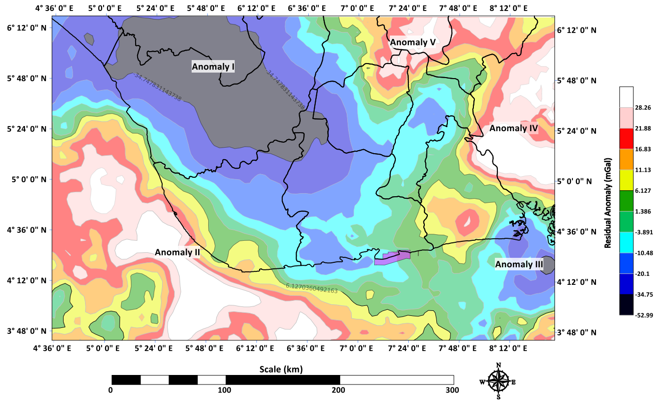

Figure 10: Residual gravity anomaly map showing anomalous zones.

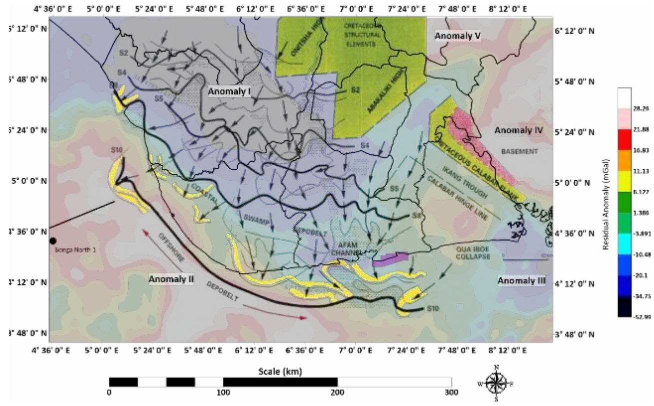

Figure 11: Palaeo-drainage trend and advancing coastline map of the Niger Delta superimposed on the residual gravity anomaly map.

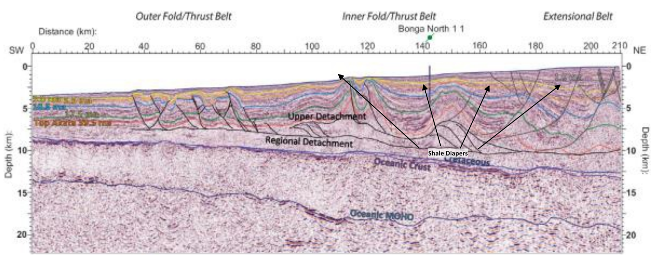

Figure 12: 2D seismic section showing location of shale diapers (Bellingham, Connors, Haworth, Radovich, & Danforth).

Preprocessing of Magnetic Data

Processing of the magnetic data was done using the apparent susceptibility filter. The susceptibility filter is a compound filter that performs a reduction to the pole of the acquired magnetic data and effects a geometric correction to produce an apparent susceptibility map. The apparent susceptibility filter assumes that the magnetic response is caused by a collection of vertical prisms that are of infinite depth in extent. This is an idealized approximation, hence the descriptor apparent.

The apparent susceptibility map reveals four NNE trending anomalous zones (Figure 13). The Okitipupa Ridge and the Charcot fracture zone, respectively, are responsible for anomalies I and II. The Oban massif is associated with Anomaly III, and the Abakaliki structural high is associated with Anomaly IV.

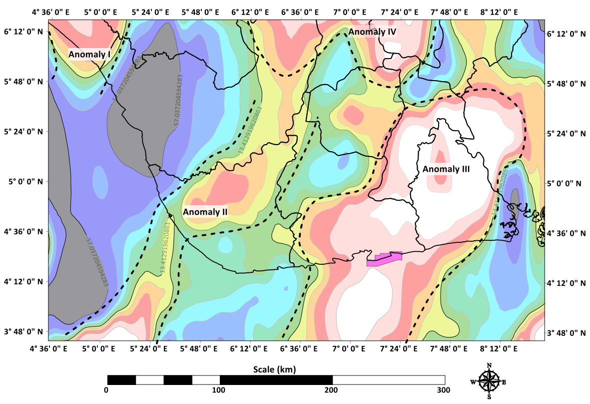

Figure 13: Apparent susceptibility map showing anomalous zones.

METHODOLOGY

Potential field data is used as an aid to subsurface modeling because there are generally insufficient observations from seismic, well and outcrops to construct a realistic 3D model that describes the basin at depth. The 3D distribution of physical properties (density and susceptibility) is related to variations in potential field response. If these physical properties can sensibly be related to geologic units, then potential field data can provide additional insight to basin geology.

In this study, Airborne gravity and magnetic data were purchased from the Nigerian Geological Survey Agency (NGSA). An initial model of the basin was built using a present day geological map of the Niger Delta and structural maps of Niger Delta formations gotten from literature. These maps were digitized and georeferenced before being used in the model. The average densities of the individual formations were then estimated from available well logs. These formations were assigned their average densities to populate the model with this property. With the formations and their property in place, the initial model was ready. The model was discretized and, via a forward modelling process, the gravity response of the discretized model was calculated.

This calculated gravity response was then compared with actual airborne gravity data. An output root mean square (RMS) error from the system represents how close the calculated gravity is to actual gravity data. This error is expressed as a percentage of the actual gravity data. A limit of 1% was set for allowable models. A Litho-constrained, stochastic gravity inversion process was carried out to iteratively refine the model and output progressively better gravity response and model realizations. With each iteration, the inversion slightly adjusts one cell of the discretized model, either in terms of structure or property. Following the slight alteration, gravity response is recalculated and again compared with actual gravity data. The model is preserved if the misfit is better than the previous iteration. The model is rejected if the misfit is worse. Because of the non-deterministic nature of the inversion process, iteration does not stop when the predefined low limit is reached. The process is repeated as many times as the user specifies.

A statistical distribution of all models that met the cut-off criteria was done and the most probable realization chosen as the final model.

The most probable geologic model derived from the gravity inversion process was used as the initial model for the magnetic inversion. The average magnetic susceptibility of the Niger Delta formations was obtained from literature. The susceptibility of the sedimentary units was set at 0 SI because sedimentary rocks are not magnetic. For the basement, a susceptibility of 0.0004 SI, which is the average susceptibility of gneiss, was assigned. As with the gravity inversion process, the model was discretized and via a forward modelling process, the magnetic response of the discretized model was calculated.

This calculated magnetic response was then compared with actual airborne magnetic data. A limit of 5% was set for allowable models. A magnetic inversion process was carried out to iteratively refine the model and output progressively better magnetic response and model realizations. A statistical distribution of all models that met the cut-off criteria was done and the most probable realization chosen as the final model.

RESULTS AND DISCUSSIONS

3D architectural model of the basin

Figure 14 shows the finished 3D basin architectural model of the Niger delta. After 1,200,000 iterations, the inversion produced a general misfit of 0.3 mGal about 1% RMS error between calculated and acquired gravity response (Figure 15). The large misfit surrounding the Oban massif is likely due to the model's failure to account for the heterogeneity in the rock composition.

Figure 16 depicts the volumetric proportion of the various geological strata that make up the delta. The delta is underlain by Cretaceous rocks, which account for 13.2% of its volume onshore and thin out as you go offshore (Figure 17). The Akata formation is the most extensive geologic formation. It covers 31.5% of the basinal volume and sits regionally beneath the Agbada formation. The Agbada formation on the other hand covers about 14.9% of the basinal volume and occurs almost Delta wide below the Benin formation.

The Benin formation sits mainly onshore and extends marginally at depth to the shallow marine environment. It accounts for 7.4% of the basinal volume. The Agbada and Akata formations have outcropped on the northeastern side of the Niger Delta Complex because of regional subsidence and warping, which resulted in the exposure and erosion of the older parts of the delta complex. The Ameki formation is the outcrop of the Agbada formation, according to Whiteman (1982), while the Imo shale is the outcrop of the Akata formation.

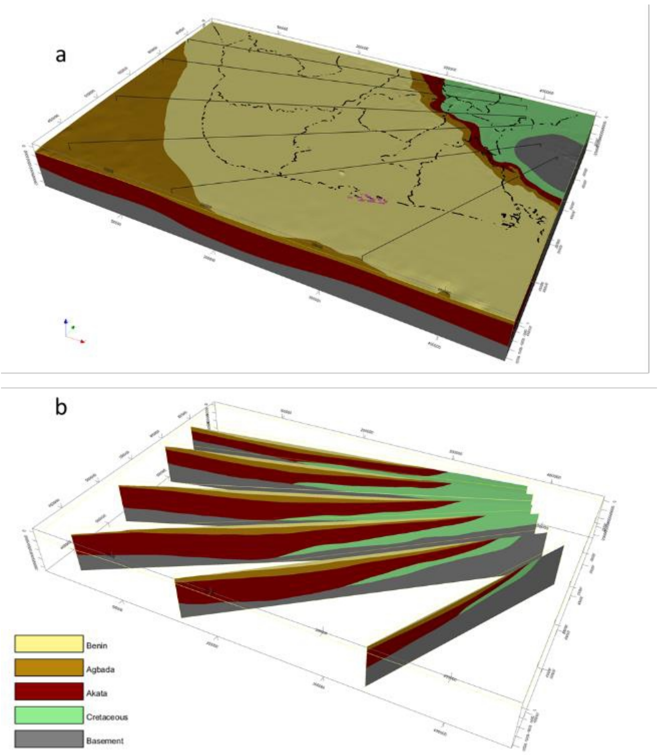

Figure 14: a) 3D view of the geological units with 6 control sections perpendicular to the sedimentation strike. b) Distribution of the geological units in the control sections.

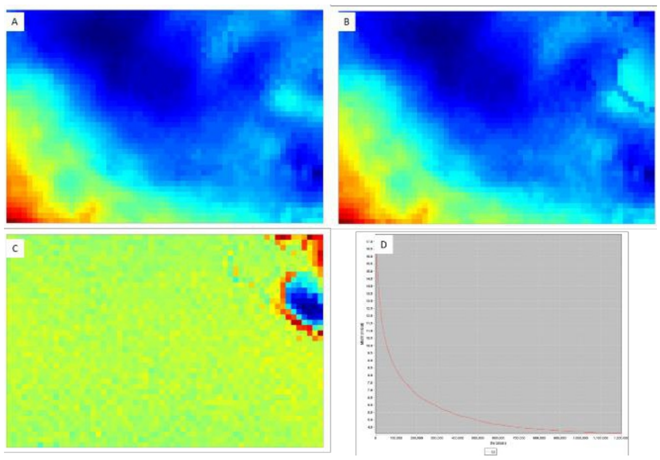

Figure 15: (a) observed gravity anomaly (b) calculated gravity anomaly (c) Misfit between the observed and the model-computed Bouguer Anomaly. (d) RMS misfit of the whole gravity grid.

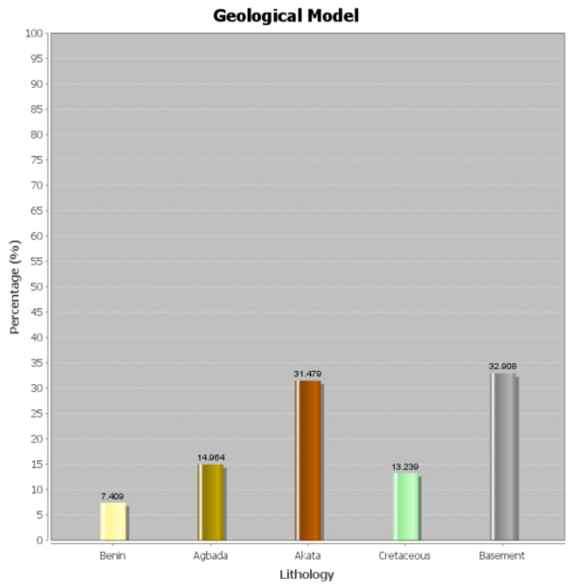

Figure 16: Bar chart of the volume proportions of geological formations.

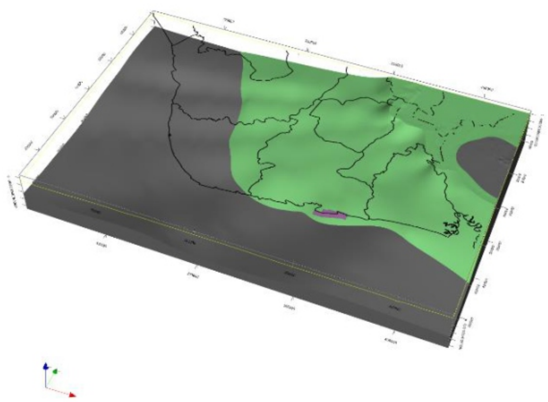

Figure 17: 3D geological model showing extent of Cretaceous sediments.

Density Volume

The distribution of density within the major formations resulted from gravity inversion. The sand/shale content of the individual formation is a function of density. The higher the density, the more likely the shale content will be higher and the lower the density, the more likely the sand content will be higher. The Benin, Agbada, and Akata formations have average densities of 2.09 g/cc, 2.28 g/cc, and 2.42 g/cc, respectively. The Cretaceous sediments have a density of 2.52 on the average.

The total porosities of the Benin, Agbada, Akata formations and the Cretaceous sediments were calculated using the density volume (Figure 19). The Benin formation has an average porosity of 0.34, reflecting the formation's unconsolidated and shale-free features. The Agbada formation has an average porosity of 0.22. The porosity distribution of this formation is bimodal, which corresponds to the formation's sand and shale composition (Figure 20).

The average porosity of the Akata formation is 0.11. You would expect that in the offshore region where the Akata formation is at its deepest (Figure 19), that the porosity will drop, but it doesn't. This indicates under-compaction. The development of shale diaper offshore was caused by this under-compaction phenomenon. The Cretaceous strata has an average porosity of 0.07, which indicates that the formation has a high level of compaction and cementation.

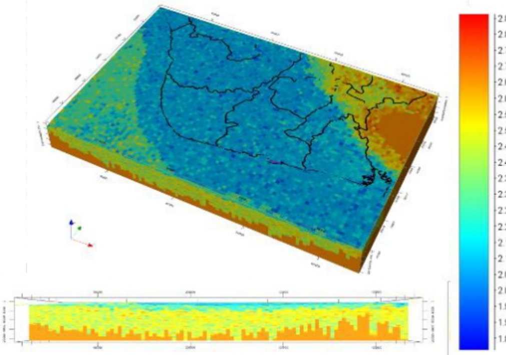

Figure 18: 3D density distribution model of the Niger delta.

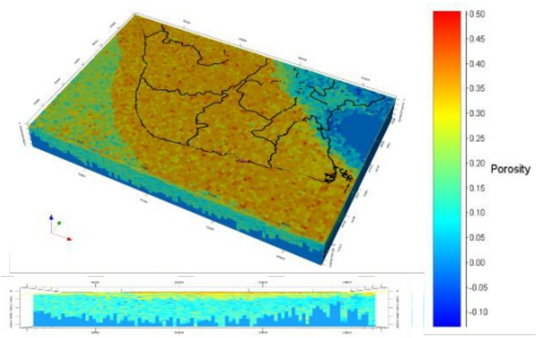

Figure 19: 3D porosity distribution model of the Niger delta.

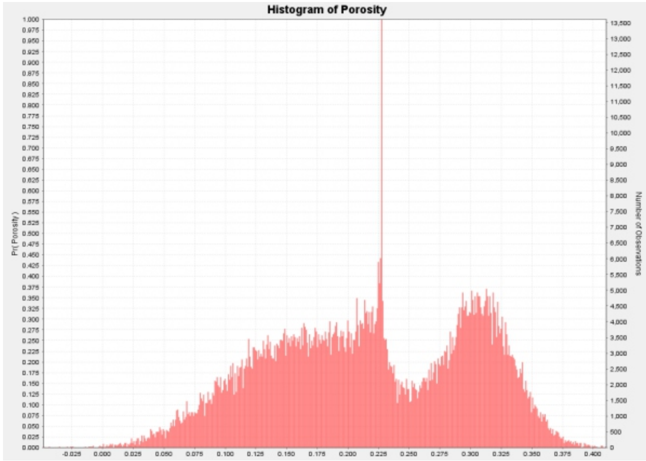

Figure 20: Histogram of porosity in the Agbada formation.

Susceptibility Volume

The inversion of the magnetic data was carried out to determine the susceptibility distribution of the basement complex (Figure 21). On the average, mafic rocks have a higher susceptibility than felsic rocks. Thus, the 3D susceptibility distribution shows the mafic and felsic composition of the basement complex. Figure 22 shows Okitipupa high, Onitsha high, Abakaliki high, Oban massif and Charcot fracture zone. These components of the basement complex have a high susceptibility because of their mafic composition. Mafic rocks have a higher iron content than felsic rocks.

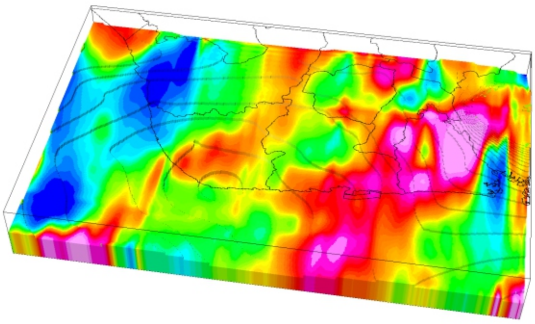

Figure 21: 3D susceptibility distribution within the basement of the Niger delta.

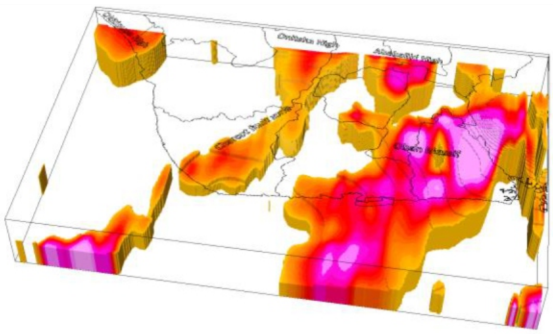

Figure 22: 3D susceptibility distribution showing basement components.

CONCLUSIONS

- A 3D basin architectural model of the Niger delta was to be created to serve as an input to a basin model for a petroleum system study of the deeper prospects. The model was to be able to provide a depth to basement map, Isopach map of akata formation, the base map of the agbada formation and provide an idea of the basement lithology. It was also to be able to depict the distribution and variation of facies within the formations.
- Using a litho-constrained inversion of gravity and magnetic data, the architectural model was created. The model was confirmed to be realistic as it conforms to known geologic features of the basin.
- With gravity inversion, density information was re-distributed in the major formations. The higher the density, the higher the shale content. The lower the density, the higher the sand content. As a consequence, the model depicts the distribution and variation of facies within the formations.
- The model was able to output a depth to basement map, Isopach map of akata formation, the base map of the agbada formation and provide an idea of the basement lithology.
- The relatively high porosity at the deeper end of the Akata formation, as evidenced in the density volume, indicates under-compaction. The existence of shale diaper in the zone confirms this inversion result.
- The magnetic inversion was able to help image the basement complexes and expose regions of high iron content and consequent high heat flow that needs to be taken into consideration when building the basin model.
- With the 3D basin architectural model, the ambiguity concerning the extent of the cretaceous sediments was resolved. Some authors omit the cretaceous sediments while some opine that the sediment spread is basin wide. The 3D basin architectural model shows that the cretaceous sediments occur onshore but thins out and becomes absent as you go offshore.
- The resulting porosity volume from the inversion process can serve as a useful input in pore pressure prediction.
- The objectives of creating an architectural model of the basin was met. When the model was fed into the petroleum system analysis, deeper prospects were identified.

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