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# Thermal Maturation and Subsidence History Studies in Some Parts of the Eastern Niger Delta Basin, Southern Nigeria Using Well-logs

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***Authors' contributions***

*This work was carried out in collaboration between all authors. Authors EDU and MAA designed the study performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author IT managed the analyses of the study. Author AOO managed the literature searches. All authors read and approved the final manuscript.*

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## ABSTRACT

Subsidence history and hydrocarbon maturation studies was analysed using well log data from four adjacent fields from the eastern part of Niger Delta basin. Three major tectonic phases of the basin evolution were identified as, firstly, a phase of subsidence from the mid to early Miocene, a second phase of uplift from the early Miocene to the mid Pliocene then lastly a period of subsidence from the mid Pliocene to the early Pliestocene. Results from Vitrinite Reflectance models of the wells showed sediments of Belema, Inda and Idama wells were thermally immature for hydrocarbon generation with values less than 6.5%$R_o$, whereas Robertkiri-14 well showed sediments were thermally mature source rock sediments with a modelled %Ro value of 6.5, this showed the well and by extension the field had great mature hydrocarbon potential.

*Keywords: Subsidence history; hydrocarbon maturation; petromod; well-logs.*

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## 1. INTRODUCTION

Sedimentary basins are regions of massive depression on the earth formed by subsidence where thick deposits of sediments accumulates [1]. They are sometimes referred to as regions of prolonged subsidence where a gradual or sudden sinking of the earth's surface due to subsurface geologic processes occurred [2]. Mechanisms that can cause subsidence sufficient enough to create a basin include crustal thinning, mantle-lithosphere thickening, sedimentary and tectonic loading, asthenospheric flow and crustal densification [3].

Subsidence in sedimentary basins causes thermal maturation in progressively buried sedimentary layers, if the sediments are rich in organic matter it could lead to development of hydrocarbons [4]. From 1970's analysing the sedimentary basins evolution which included understanding the subsidence phases history and basin uplift to determine the relative importance and implications of various basin subsidence mechanisms became a very significant aspect of hydrocarbon exploration. The ability to reconstruct or model the subsidence history of a sedimentary basin not only aids in assessing its hydrocarbon potential, it also reveals the tectonic regimes the basin had undergone, its hydrodynamics and geological evolution [5-8]. The underlying concept demonstrated by several models of basin formation by early researchers was that the crust expanded when subjected to extreme temperatures by passive upwelling of the upper mantle material, which then led to the thinning of the crust [9-11]. The thermal anomaly created by the replacement at depth of a lighter shallow crustal material by the denser asthenospheric material, decayed by conductive cooling which caused a thickening and subsequently subsidence of the lithosphere ,thus, forming a basin, this mechanism is similar to that proposed for the formation of the oceanic lithosphere by [12]. The isostatic subsidence which is as a result of the cooling of the thermal anomaly is proportional to an exponential function of time, as such, thermal subsidence can be estimated by extending the cooling model of the oceanic lithosphere to sedimentary basins [7,8].

Improvements in dating of stratigraphic units and estimates of paleobathymetry information, largely driven by advances in micropaleontology gave rise a technique termed geohistory analysis by [13]. Geohistory analysis aim to produce a curve for subsidence and sediment accumulation rates through time. Quantitative computational techniques to undo depositional processes of sedimentary basins, providing a time-lapse insight to their sedimentation process came into play afterwards. The Niger Delta sedimentary basin has undergone several tectonic regimes. This research makes use of information from well logs to model the subsidence history of the eastern Niger Delta basin.

## 2. MATERIALS AND METHODS

### 2.1 Geology of Study Area

The study area is located within latitudes $6^0$ 15'' E and $7^0$ 15'' E and longitudes $4^0$ 15'' N and $4^0$ 40'' N in Rivers State onshore of the Eastern Niger Delta basin (Fig. 1). The area has a low lying topography and it is drained by tributaries of the River Niger. It falls within the Niger Delta petroleum system [14]. Sedimentary history and geomorphological studies of the modern Niger Delta identified the three major lithostratigraphic units in the subsurface of the Niger Delta [15,16], these are the Akata, Agbada and Benin Formations which decrease in age basinward with the Benin Formation as the youngest, reflecting the overall regression of depositional environments within the Niger Delta clastic wedge. The Akata, Agbada and Benin formations reflect a gross coarsening-upward sediments deposited in marine, deltaic, and fluvial environments respectively.

### 2.2 Study Design

This study makes use of 22 deep well logs from 4 adjacent fields in the eastern Niger Delta basin, Petrel and Petromod software's are used for analysis. Subsidence analysis using Petromod software required information of stratigraphy, lithology and Petroleum Systems Elements and also geochemical parameters like Total Organic Carbon (TOC), Hydrogen Index (HI) and Petroleum Kinetics (Fig 2). The first set of parameters required for modelling which included stratigraphy, lithology and Petroleum Systems Elements were obtained by lithostratigraphic analysis of well logs using Petrel from the area with biostratigraphic information as constrain, while geochemical parameters (TOC and HI) used in modelling were obtained from available research literature in public domain.

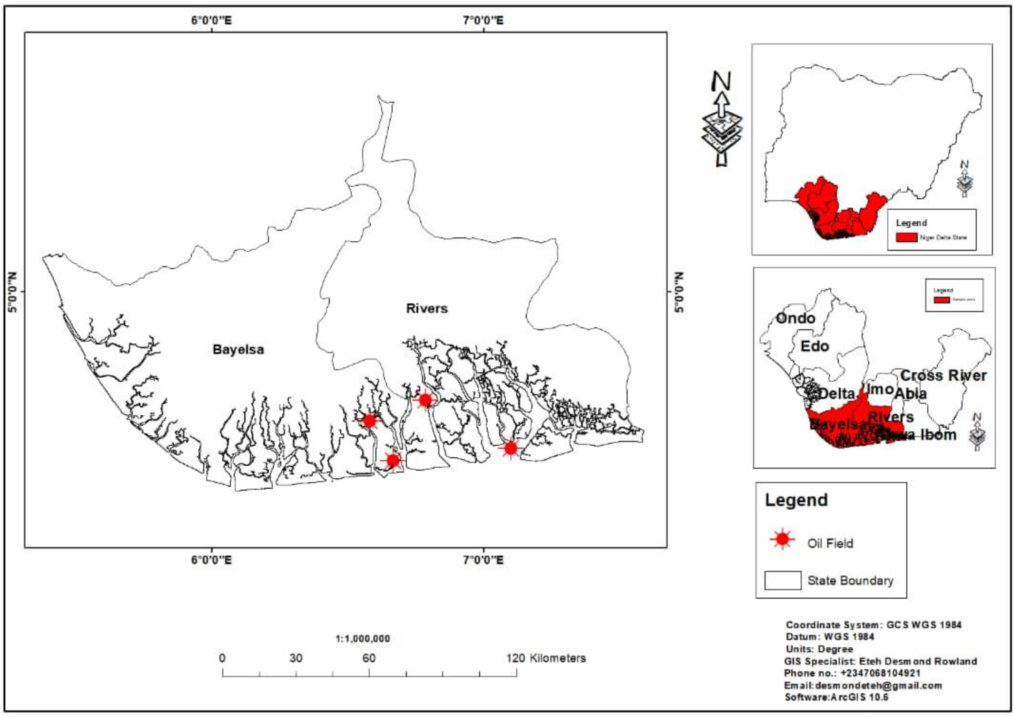


**Fig.1. Map of the Niger Delta showing study area**

Results from lithostratigraphic analysis (Fig 3–6) were used to populate modelling charts (Table 1). Boundary conditions like Basal Heat Flow (BHT), Paleowater Depth (PWD) and Sediment Water Interface Temperature (SWIT) were also obtained from literature in the area. [17] kinetic model was used for this study, it correlates the oil window for mixed types II/III kerogen, the model also uses a broad distribution of the Arhenius rate constants to compute thermal maturation which it correlates with reflectance of Vitrinite. The thermal maturation indicator (Table 2) used in this study is Vitrinite Reflectance [18].

## WORKFLOW

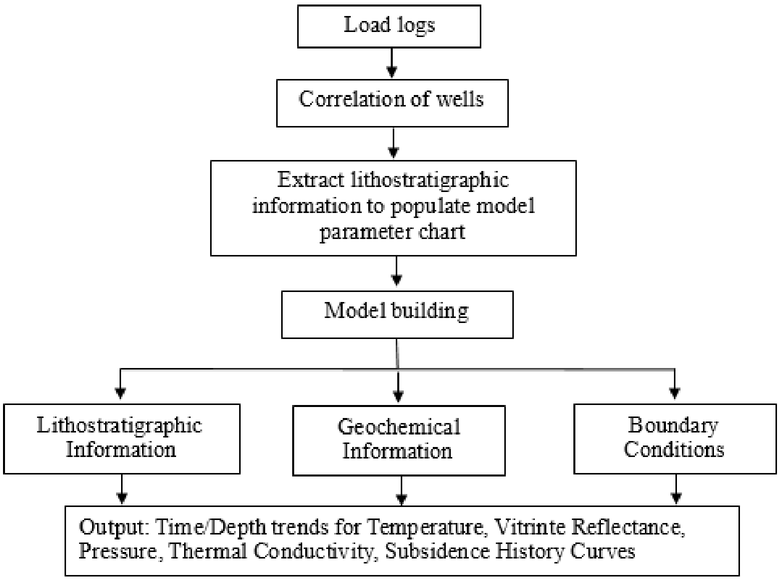


**Fig. 2. Workflow for subsidence modelling**

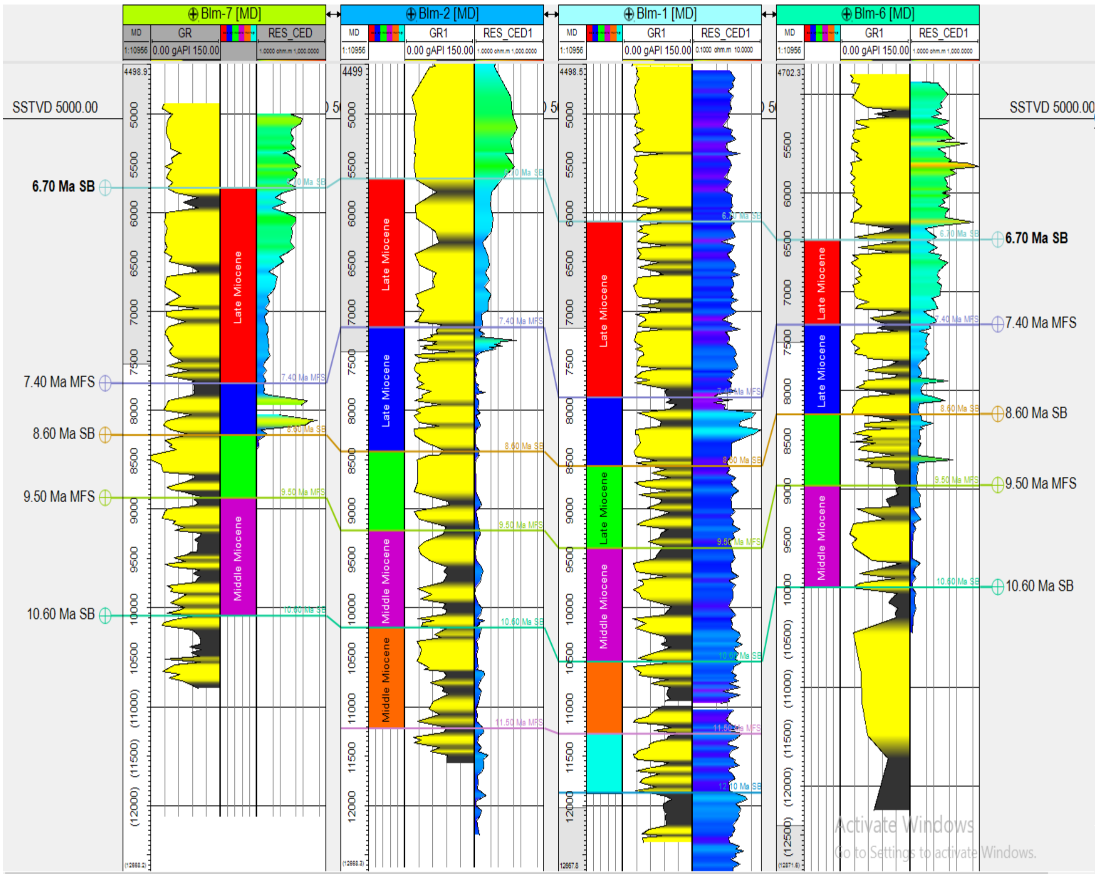


Fig. 3. Lithostratigraphic analysis on Belema wells

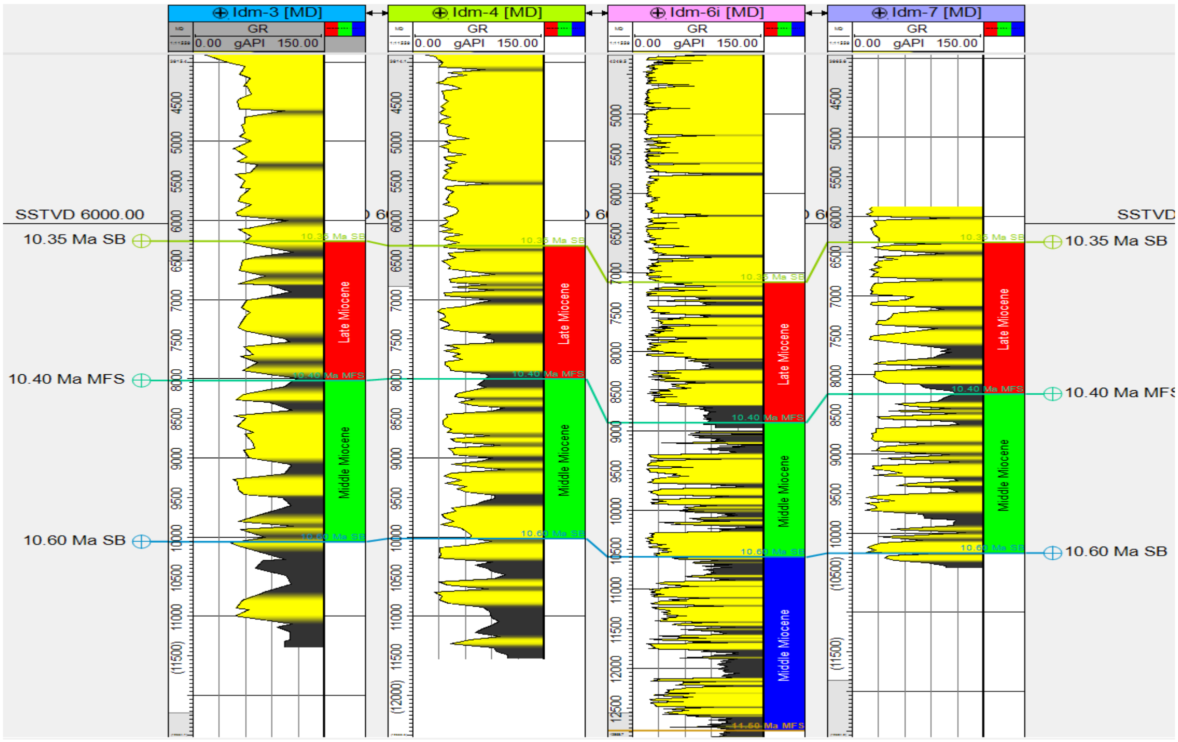


Fig. 4. Lithostratigraphic analysis on Idama wells

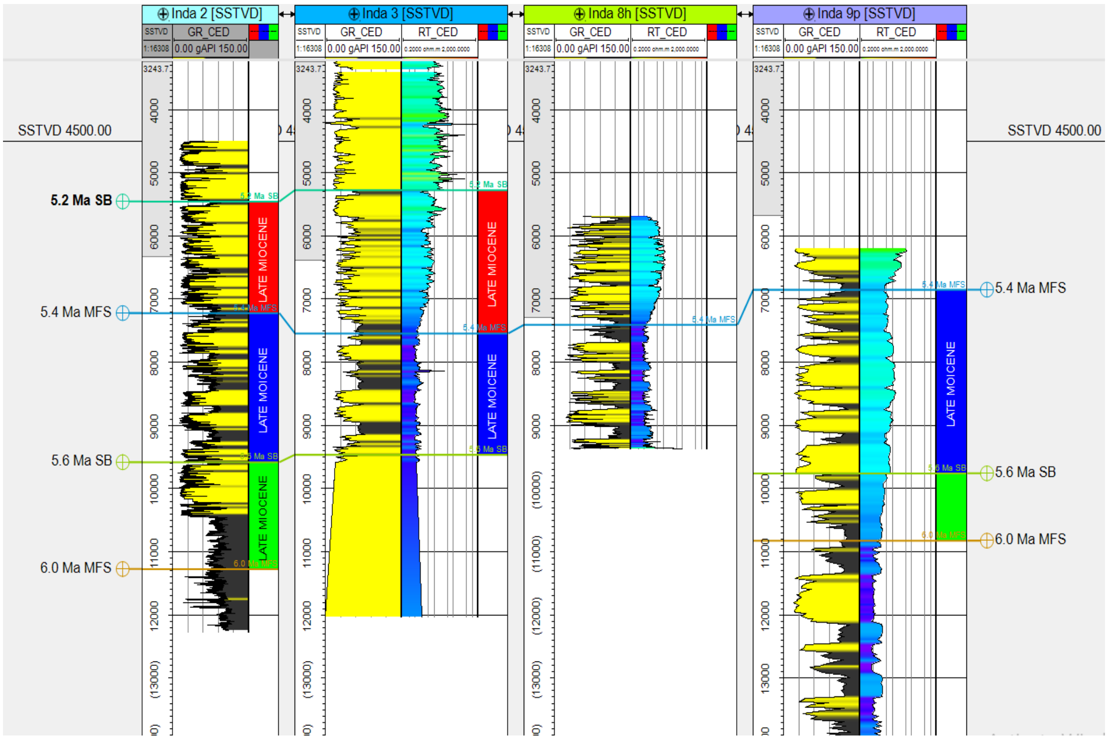


Fig. 5. Lithostratigraphic analysis on Inda wells

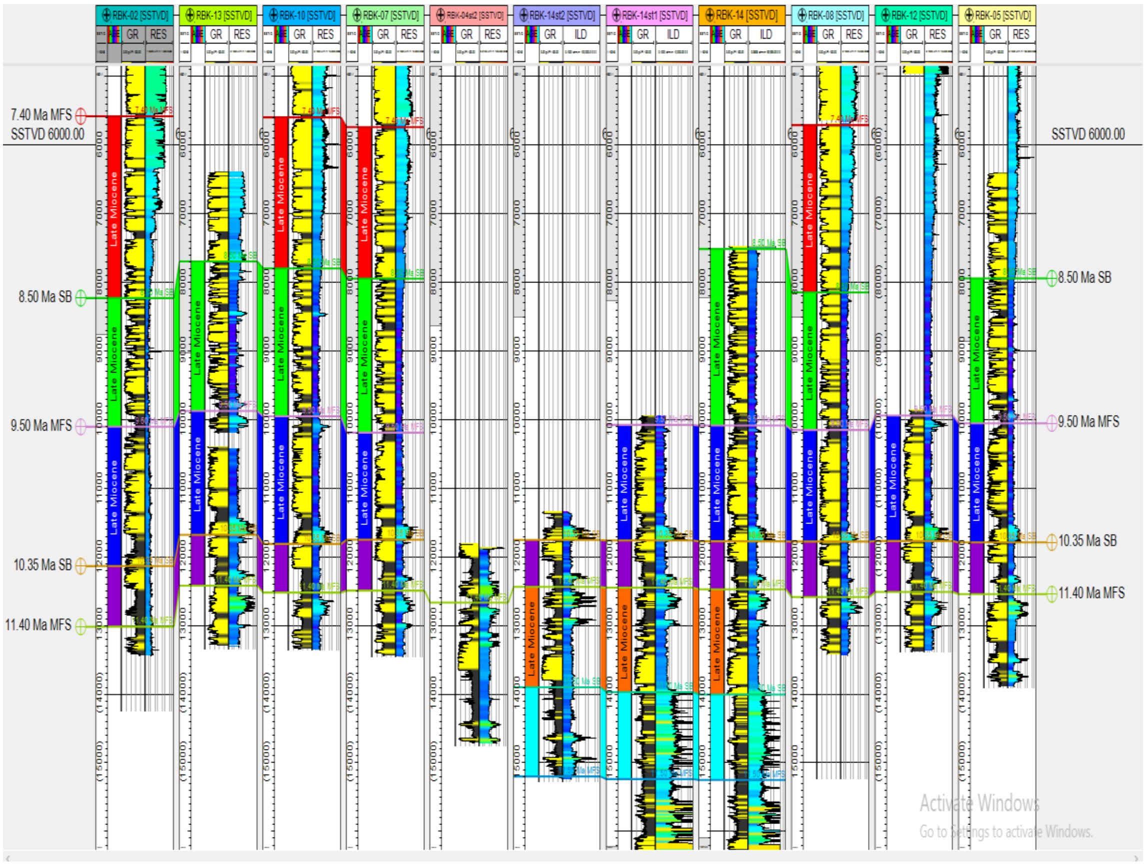


Fig. 6. Lithostratigraphic analysis on Robertkiri wells

**Table 1. Model parameters for some wells obtained by lithostratigrapic analysis**

**BLM - 1**

| Layer | Top | Base | Thick | Depo. From | Depo. To | Lithology | PSE | TOC | Kinetics | HI |
|---|---|---|---|---|---|---|---|---|---|---|
| Late Miocene | 6088 | 7873 | 1785 | 7.4 | 6.7 | SANDSTONE | Reservoir Rock | 0.82 | Burnham(1989)_TIII | 58 |
| Late Miocene | 7873 | 8563 | 690 | 8.6 | 7.4 | SHALE | Source Rock | 0.82 | Burnham(1989)_TIII | 58 |
| Late Miocene | 8563 | 9391 | 828 | 9.5 | 8.6 | SANDSTONE | Reservoir Rock | 0.82 | Burnham(1989)_TIII | 58 |
| Late Miocene | 9391 | 10540 | 1149 | 10.6 | 9.5 | SHALE | Source Rock | 0.82 | Burnham(1989)_TIII | 58 |
| Late Miocene | 10540 | 11270 | 730 | 11.5 | 10.6 | SANDSTONE | Reservoir Rock | 0.82 | Burnham(1989)_TIII | 58 |
| Late Miocene | 11270 | 11867 | 597 | 12.1 | 11.5 | SHALE | Source Rock | 0.82 | Burnham(1989)_TIII | 58 |
| Middle Miocene | 11867 | 12360 | 493 | 12.8 | 12.1 | SANDSTONE | Reservoir Rock | 1.2 | Burnham(1989)_TIII | 72 |
|  |  |  |  |  | 12.8 |  |  |  |  |  |

**BLM - 2**

| Layer | Top | Base | Thick | Depo. From | Depo. To | Lithology | PSE | TOC | Kinetics | HI |
|---|---|---|---|---|---|---|---|---|---|---|
| Late Miocene | 5649 | 7163 | 1514 | 7.4 | 6.7 | SANDSTONE | Reservoir Rock | 0.83 | Burnham(1989)_TIII | 57 |
| Late Miocene | 7163 | 8416 | 1253 | 8.6 | 7.4 | SHALE | Source Rock | 0.83 | Burnham(1989)_TIII | 57 |
| Late Miocene | 8416 | 9214 | 798 | 9.5 | 8.6 | SANDSTONE | Reservoir Rock | 0.83 | Burnham(1989)_TIII | 57 |
| Late Miocene | 9214 | 10196 | 982 | 10.6 | 9.5 | SHALE | Source Rock | 0.83 | Burnham(1989)_TIII | 57 |
| Late Miocene | 10196 | 11216 | 1020 | 11.5 | 10.6 | SANDSTONE | Reservoir Rock | 0.83 | Burnham(1989)_TIII | 57 |
| Late Miocene | 11216 | 12271 | 1055 | 12.1 | 11.5 | SHALE | Source Rock | 0.83 | Burnham(1989)_TIII | 57 |
|  |  |  |  |  | 12.1 |  |  |  |  |  |

**IDM - 3**

| Layer | Top | Base | Thick | Depo. From | Depo. To | Lithology | PSE | TOC | Kinetics | HI |
|---|---|---|---|---|---|---|---|---|---|---|
| Late Miocene | 6254 | 8022 | 1768 | 10.4 | 10.35 | SANDSTONE | Reservoir Rock | 0.82 | Burnham(1989)_TIII | 57 |
| Middle Miocene | 8022 | 10000 | 1978 | 10.6 | 10.4 | SHALE | Source Rock | 1.3 | Burnham(1989)_TIII | 70 |
| Middle Miocene | 10000 | 11386 | 1386 | 11.5 | 10.6 | SANDSTONE | Reservoir Rock | 1.3 | Burnham(1989)_TIII | 70 |
|  |  |  |  |  | 11.5 |  |  |  |  |  |

**IDM - 4**

| Layer | Top | Base | Thick | Depo. From | Depo. To | Lithology | PSE | TOC | Kinetics | HI |
|---|---|---|---|---|---|---|---|---|---|---|
| Late Miocene | 6312 | 8001 | 1689 | 10.4 | 10.35 | SANDSTONE | Reservoir Rock | 0.82 | Burnham(1989)_TII | 58 |
| Middle Miocene | 8001 | 10018 | 2017 | 10.6 | 10.4 | SHALE | Source Rock | 1.2 | Burnham(1989)_TII | 75 |
| Middle Miocene | 10018 | 11529 | 1511 | 11.5 | 10.6 | SANDSTONE | Reservoir Rock | 1.2 | Burnham(1989)_TII | 75 |
|  |  |  |  |  | 11.5 |  |  |  |  |  |

**INDA - 2**

| Layer | Top | Base | Thick | Depo. From | Depo. To | Lithology | PSE | TOC | Kinetics | HI |
|---|---|---|---|---|---|---|---|---|---|---|
| Late Miocene | 5455 | 7225 | 1770 | 5.4 | 5.2 | SANDSTONE | Reservoir Rock | 0.82 | Burnham(1989)_TIII | 58 |
| Late Miocene | 7225 | 9577 | 2352 | 5.6 | 5.4 | SHALE | Source Rock | 0.82 | Burnham(1989)_TIII | 58 |
| Late Miocene | 9577 | 11277 | 1700 | 6 | 5.6 | SANDSTONE | Reservoir Rock | 0.82 | Burnham(1989)_TIII | 58 |
| Late Miocene | 11277 | 12229 | 952 | 6.7 | 6 | SHALE | Source Rock | 0.82 | Burnham(1989)_TIII | 58 |
|  |  |  |  |  | 6.7 |  |  |  |  |  |

**INDA - 3**

| Layer | Top | Base | Thick | Depo. From | Depo. To | Lithology | PSE | TOC | Kinetics | HI |
|---|---|---|---|---|---|---|---|---|---|---|
| Late Miocene | 5265 | 7542 | 2277 | 5.4 | 5.2 | SANDSTONE | Reservoir Rock | 0.83 | Burnham(1989)_TIII | 59 |
| Late Miocene | 7542 | 9458 | 1916 | 5.6 | 5.4 | SHALE | Source Rock | 0.83 | Burnham(1989)_TIII | 59 |
| Late Miocene | 9458 | 12013 | 2555 | 6 | 5.6 | SANDSTONE | Reservoir Rock | 0.83 | Burnham(1989)_TIII | 59 |
|  |  |  |  |  | 6 |  |  |  |  |  |

**RBK - 7**

| Layer | Top | Base | Thick | Depo. From | Depo. To | Lithology | PSE | TOC | Kinetics | HI |
|---|---|---|---|---|---|---|---|---|---|---|
| Late Miocene | 5736 | 7945 | 2209 | 8.5 | 7.4 | SHALE | Source Rock | 0.8 | Burnham(1989)_TII | 57 |
| Late Miocene | 7945 | 10186 | 2241 | 9.5 | 8.5 | SANDSTONE | Reservoir Rock | 0.8 | Burnham(1989)_TII | 57 |
| Late Miocene | 10186 | 11746 | 1560 | 10.35 | 9.5 | SHALE | Source Rock | 0.8 | Burnham(1989)_TII | 57 |
| Late Miocene | 11746 | 12943 | 1197 | 10.4 | 10.35 | SANDSTONE | Reservoir Rock | 0.8 | Burnham(1989)_TII | 57 |
| Late Miocene | 12943 | 13435 | 492 | 10.5 | 10.4 | SHALE | Source Rock | 0.8 | Burnham(1989)_TII | 57 |
|  |  |  |  |  | 10.5 |  |  |  |  |  |

**RBK - 8**

| Layer | Top | Base | Thick | Depo. From | Depo. To | Lithology | PSE | TOC | Kinetics | HI |
|---|---|---|---|---|---|---|---|---|---|---|
| Late Miocene | 5712 | 8144 | 2432 | 8.5 | 7.4 | SHALE | Source Rock | 8.2 | Burnham(1989)_TIII | 59 |
| Late Miocene | 8144 | 10147 | 2003 | 9.5 | 8.5 | SANDSTONE | Reservoir Rock | 8.2 | Burnham(1989)_TIII | 59 |
| Late Miocene | 10147 | 11778 | 1631 | 10.35 | 9.5 | SHALE | Source Rock | 8.2 | Burnham(1989)_TIII | 59 |
| Late Miocene | 11778 | 12587 | 809 | 10.4 | 10.35 | SANDSTONE | Reservoir Rock | 8.2 | Burnham(1989)_TIII | 59 |
| Late Miocene | 12587 | 13400 | 813 | 10.5 | 10.4 | SHALE | Source Rock | 8.2 | Burnham(1989)_TIII | 59 |
| | | | | | 10.5 | | | | | |

**Table 2. Relationship between vitrinite reflectance and organic maturity [18]**

| $R_o$ Value | Organic Maturity |
|---|---|
| $R_o < 0.65$ | Immature |
| $0.65 < R_o < 0.80$ | Oil and gas generation |
| $0.80 < R_o < 1.0$ | Cracking of oil and gas |
| $1.0 < R_o < 2.5$ | Gas condensate zone |

## 3. RESULTS AND DISCUSSION

### 3.1 Belema Wells

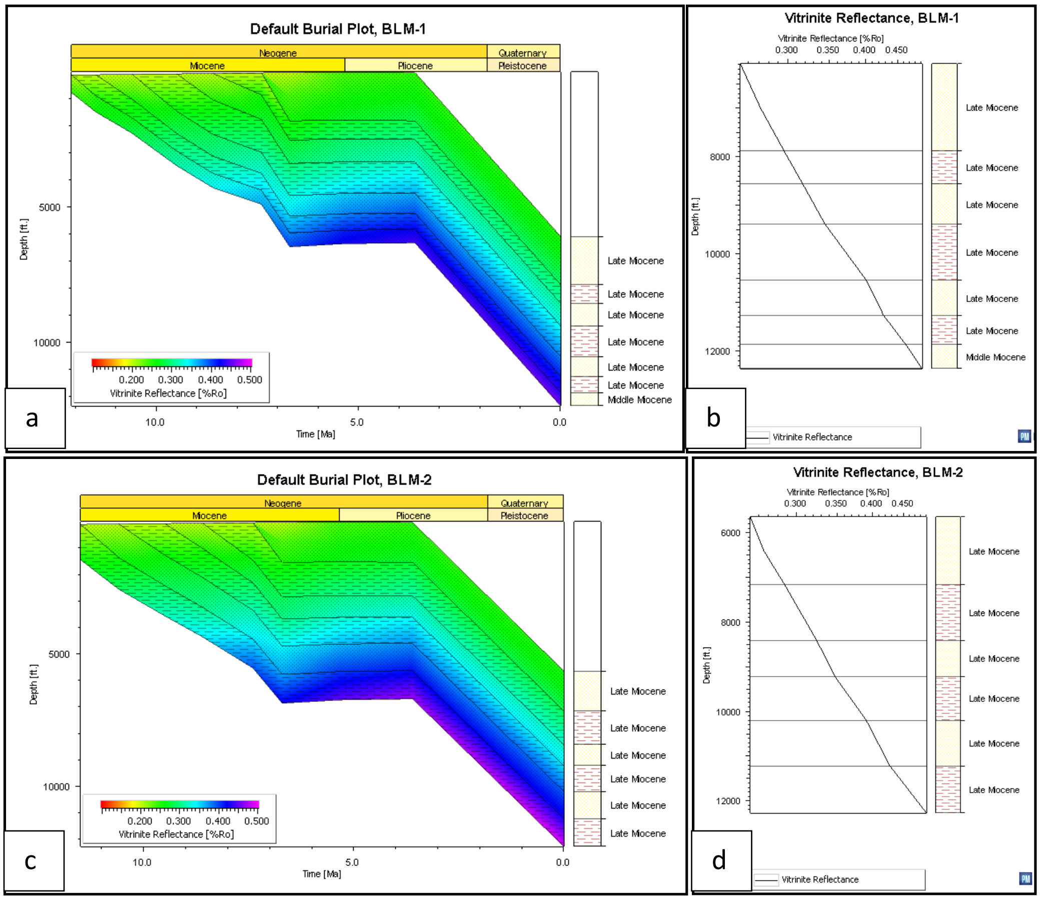


Fig. 7. **(a) Subsidence history curve for BLM-1 (b) VR trend with depth for BLM-1 (c) Subsidence history curve for BLM-2 (d) VR trend with depth for BLM-1**

The burial history curve for wells BLM-1(Fig. 7a) and BLM-2 (Fig. 7c) showed an episode of high constant subsidence from the early Miocene between 7.5 Ma to middle Miocene 12 Ma, this created room for the deposition of sediments 5 000 ft thick, after this period there was a very rapid rate of subsidence from the middle Miocene between 7 Ma to 7.5 Ma, this allowed for the deposition of 2, 000 ft of sediments. A period of uplift then followed between the middle Pliocene at 4.5 Ma to the middle Miocene at 7 Ma, this was a period when erosion of the surface sediments occurred. A final phase of constant high subsidence then followed between the middle Pliestocene to the middle Pliocene at 4.5 Ma creating accommodation for the deposition of over 5, 500 ft of sediments. The Vitrinite Reflectance models showed a general trend of increase in values with depth. BLM-1 (Fig. 7b) and BLM-2 (Fig. 7d) showed a range of $\%R_0$ values of 0.25$\%R_0$ from depths of about 6, 000 ft to 0.5$\%R_0$ at depths over 12, 000 ft. The range $\%R_0$ values observed are associated with immature source rock sediments.

### 3.2 Idama Wells

The subsidence history curve for wells IDM-3 (Fig. 8a), IDM-4 (Fig. 8c) showed very similar tectonic episodes. Firstly, there was a period of very rapid subsidence in the late Miocene from 10 Ma to 10.5 Ma which created accommodation for the deposition of sediments 5, 000 ft thick, this period was followed by an extended period uplift between 3.5 Ma in the middle Pliocene to 10 Ma in the early Miocene, eroding surface sediments over 500 ft thick. After the uplift came another episode of rapid subsidence from the early Pliestocene to the middle Pliocene at 3.5 Ma, this period created room for sediments over

5, 500 ft thick to be deposited in the basin. The Vitrinite Reflectance models of IDM-3 (Fig. 8b) and IDM-4 (Fig. 8d) showed an increase in %Ro with depth for all wells. The maximum %Ro values for wells IDM-3 and IDM-4 was 4.2%Ro showing that the source rock sediments were immature for hydrocarbon generation.

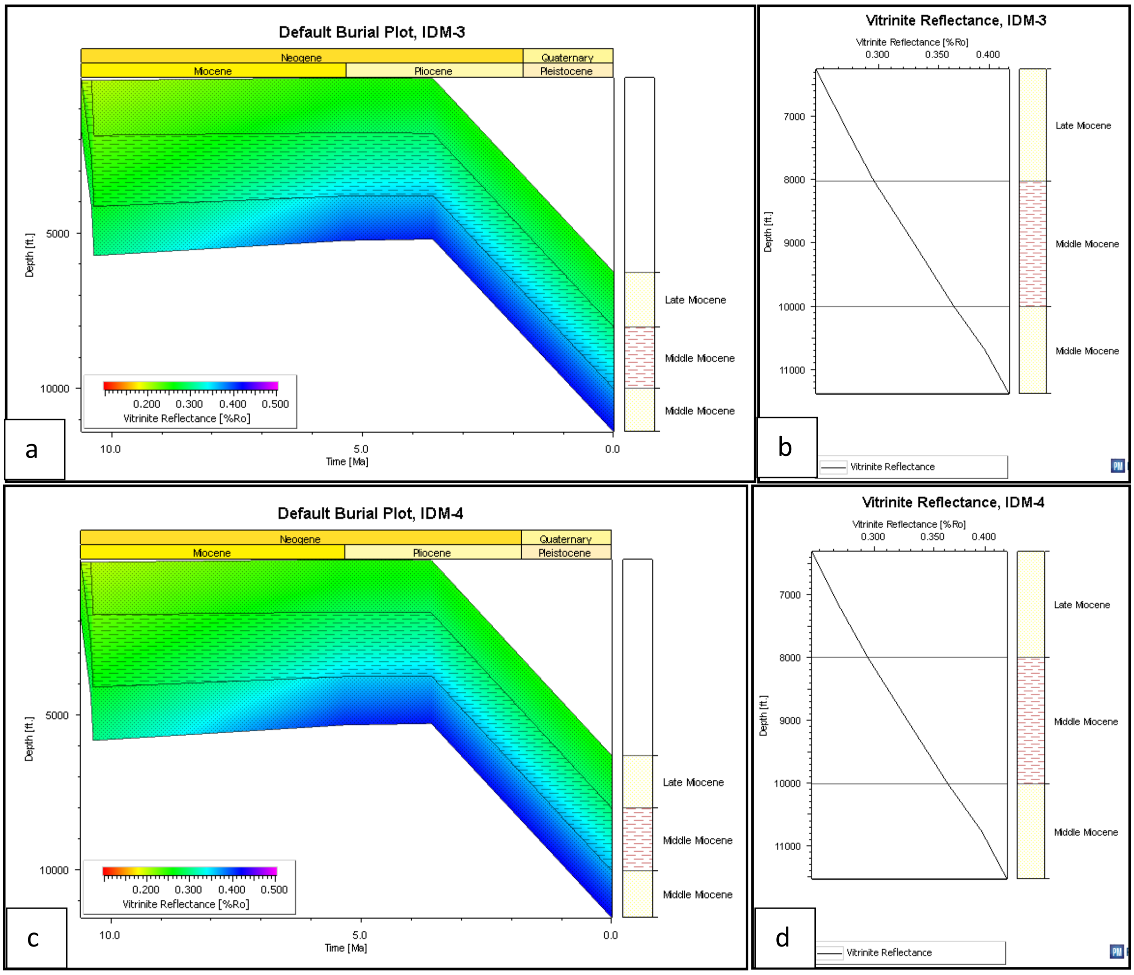
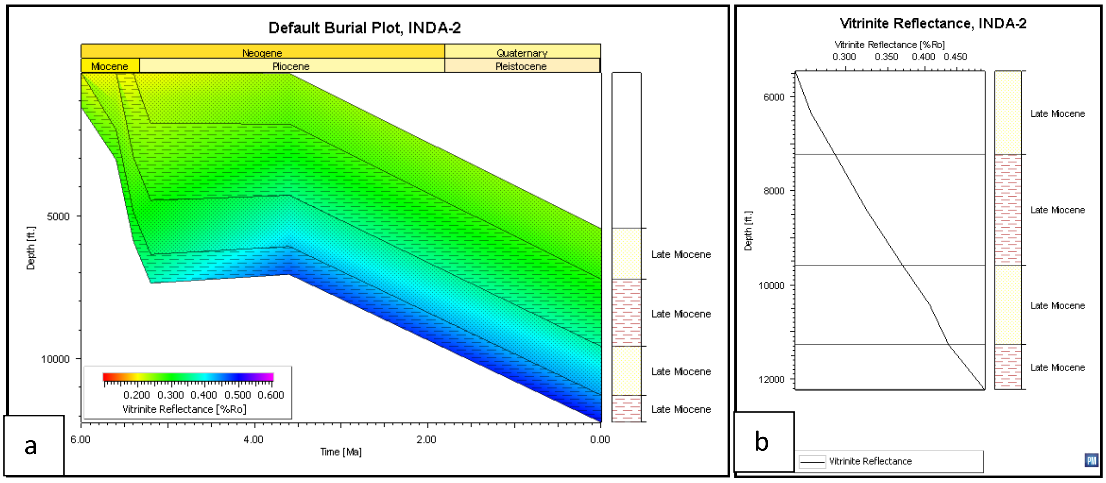


**Fig. 8. (a) Subsidence history curve for IDM-3 (b) VR trend with depth for IDM-3 (c) Subsidence history curve for IDM-4 (d) VR trend with depth for IDM-4**

### 3.3 Inda Wells



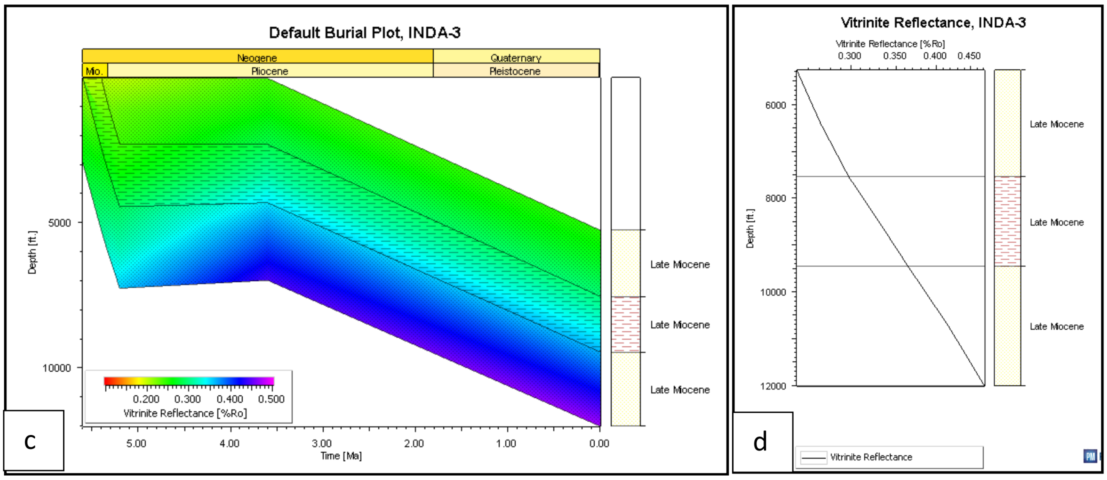


**Fig. 9.** (a) Subsidence history curve for INDA-2 (b) VR trend with depth for INDA-2 (c) Subsidence history curve for INDA-3 (d) VR trend with depth for INDA-3

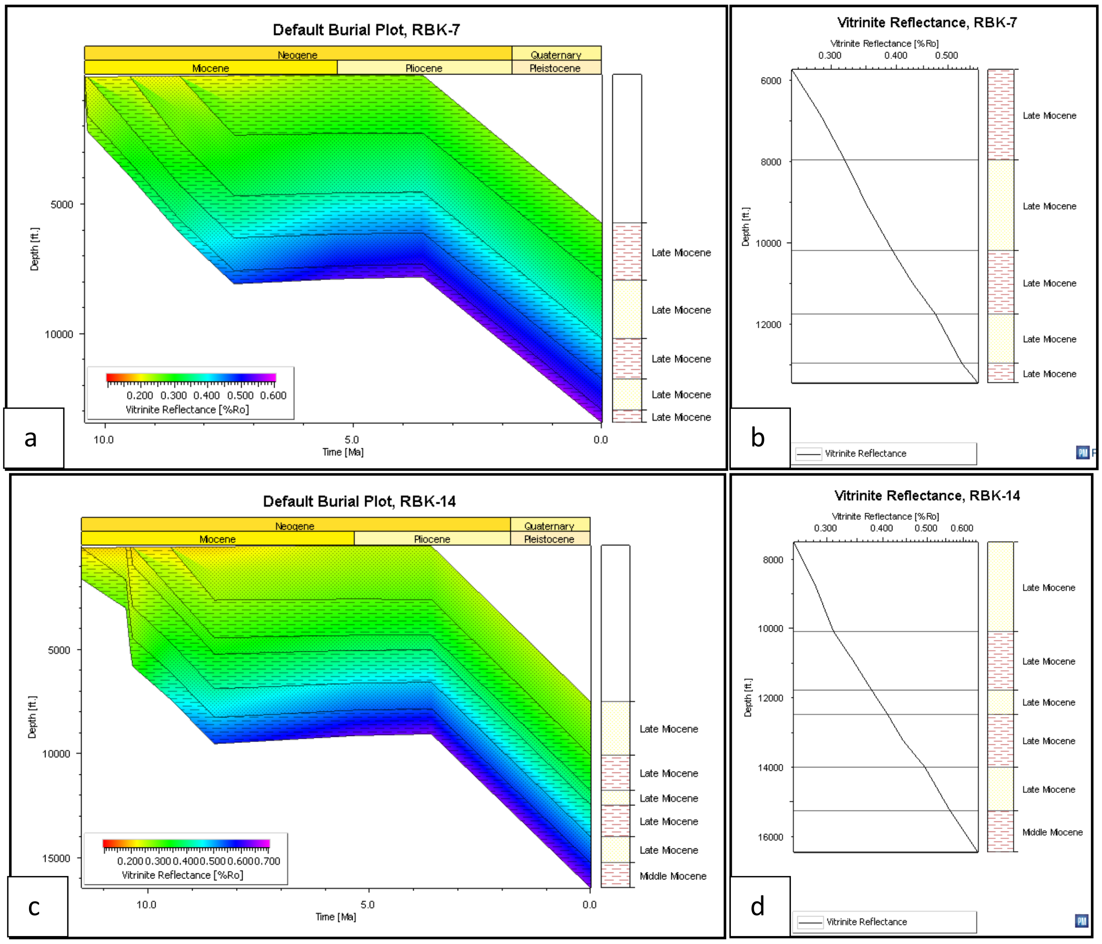


**Fig. 10.** (a) Subsidence history curve for RBK-7 (b) VR trend with depth for RBK-7 (c) Subsidence history curve for RBK-14 (d) VR trend with depth for RBK-14

Subsidence curve for well Idm-2 (Fig. 9a) showed there was a high rate of subsidence in the early Miocene between 5.5 Ma to 6 ma, this created room for the deposition of an average 2, 000 ft of sediments, after this episode there was a period of more rapid subsidence between 5.2

Ma and 5.5 Ma marking the early Miocene, this created accommodation for the deposition of sediments 4, 500 ft thick. An episode of uplift then occurred between 3.5 Ma in the middle Pliocene to 5.5 Ma in the late Pliocene/early Miocene, after the erosional episode created by the uplift, a high rate of subsidence was then observed from the early Pliestocene to 3.5 Ma in the middle Miocene which accounted for the deposition of sediments of thickness of 4, 500 ft in the basin. Well Inda-3 (Fig. 9c), on the other hand showed a period of rapid subsidence from the late Pliocene at 5 Ma to the early Miocene at 6 Ma, creating room for the deposition of sediments 4, 000 ft thick. This was followed by an episode uplift which lasted till the middle Pliocene between 3.5 Ma and 5 Ma. A high rate of subsidence then occurred between the early Pliestocene, this created accommodation for the deposition of sediments with an average thickness of 4, 000 ft in the basin.

Vitrinite Reflectance model profile for wells Inda-2 (Fig. 9b) and 3 (Fig. 9d) showed increasing values with depth. Values ranged from 0.2%Ro for average depths of 5, 500 ft to 0.5%Ro for average depth of 12, 000 ft for both Inda-2 and Inda-3 well depicting the source rock was immature for hydrocarbon generation.

The subsidence curve for Rbk-7 (Fig. 10a) showed a high rate of subsidence from the mid to early Miocene between 6.5 Ma and 10 Ma which created accommodation for the deposition of sediments 5, 000 ft thick, this was followed by a period of gradual uplift from the early Miocene to Middle Pliocene between 3.5 Ma and 6.5 Ma. Lastly, another high episode of subsidence was observed between the middle Pliocene at 3.5 Ma and the early Pliestocene, creating room for the deposition of over 6, 000 ft thick sediments. Subsidence curve for Rbk-14 (Fig. 10c) showed a first episode of high rate of subsidence in the late Miocene at 10.6 Ma, this created accommodation for deposition of sediments 2, 000 ft thick. A rapid episode of subsidence occurred after this in the early Miocene from 10.5 Ma to 10.6 Ma, creating room for the deposition of 3,000 ft of sediments. A less rapid subsidence followed which lasted till the middle Miocene between 8 Ma and 10.5 ma creating accommodation for sediments 4, 000 ft thick. An episode of uplift and erosion followed till the middle Pliocene between 3.5 Ma and 8 Ma, after this a high rate of subsidence occurred which lasted till the early Pliestocene making room for the deposition of sediments with an average thickness of 6, 500 ft in the basin.

The Vitrinite Reflectance models showed an increasing trend with depth, wells Rbk-7 (Fig. 10b) showed a maximum %Ro value less than 0.65, Rbk-14 (Fig. 10d) had a value of exactly 0.65%Ro, what this implies is that sediments from Rbk-14 well are thermally mature source rock sediments, as such, they have a potential for hydrocarbon generation.

## 4. CONCLUSION

Subsidence history and basin maturation analysis of the Eastern Niger Delta showed the sedimentation rates and thermal maturation of hydrocarbon source rock in the basin. This research was able to establish that three major tectonic phases occurred during the evolution of the Basin. Firstly, a phase of subsidence from the mid to early Miocene, a second phase of uplift from the early Miocene to the mid Pliocene and lastly a period of subsidence from the mid Pliocene to the early Pliestocene. The thick sediments presently observed in the basin was deposited during the phases of subsidence where accommodation in the basin was created for sediment accumulation. Vitrinite Reflectance models of the wells showed sediments of Belema, Inda and Idama wells were thermally immature for hydrocarbon generation with values less than 6.5%$R_0$, whereas the model for Robertkiri-14 well showed sediments of the well were thermally mature source rock sediments with a modelled %Ro value of 6.5, this showed the well and by extension the field had great mature hydrocarbon potential.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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