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EVOLUTION AND SUBSIDENCE OFTHE BIDA BASIN

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ABSTRACT
Basement subsidence and geological formations' burial history are reconstructed for Bida Basin, using hypothetical well-site stratigraphy extrapolated from geological formations' thickness data obtained from outcrops. Lateral development of the basin is also reconstructed and the hydrocarbon generation status of its argillaceous sediments is evaluated from estimated time- temperature index (TTI) and vitrinite reflectance (Ro) values. The basement subsidence curve is identical with the burial curve for oceanic crust and continental rift basins, thereby linking the basin's genesis and evolution with plate tectonics. The basin evolved from a rift that was created as Abakaliki -Benue Fold Belt developed in response to the tectonic pulse arising from the collision between West African Plate and Central African Plate between 85 Ma and 80 Ma. The sea transgressed from the Gulf of Guinea into the basin in Upper Maestrichian to deposit Enagi and Agbaja Formations. The transgression terminated in the central portion of the basin. The estimated maximum temperature attained by the source rock is 26°C. Estimated cumulative time- temperature index is 0.225 and its corresponding vitrinite reflectance is 0.3 % RI. The source rocks have not experienced catagenesis.

Keywords: **Time-temperature index, Vitrinite reflectance, Tectonic pulse, Catagenesis**

LOCATION EXTENT AND GEOLOGICAL SYNOPSIS OF BIDA BASIN

Bida basin is one of the inland basins in Nigeria, and it is located within 8°00'N and 10°30'N and longitudes 4°30'E and 7°00'E (Fig.1).

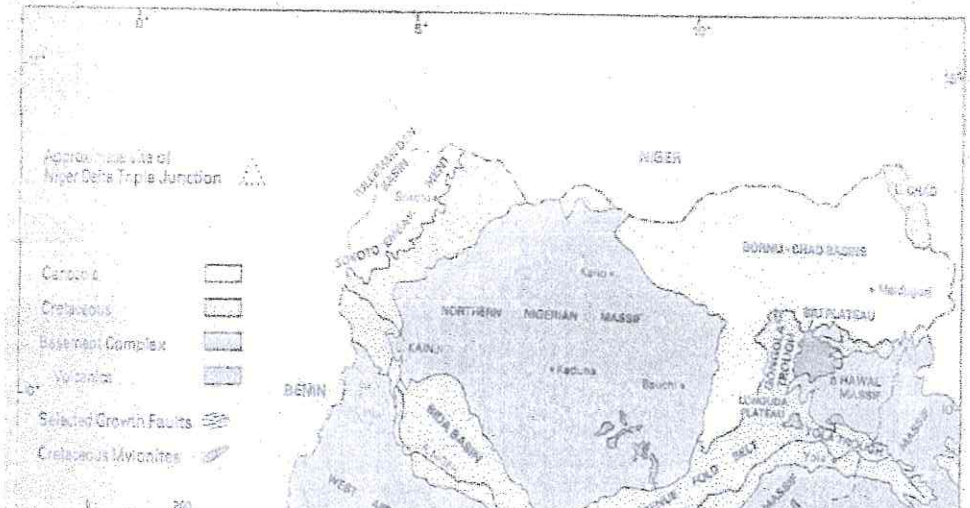


Fig1: Generalised geological Map of Nigeria, showing Bida Basin and other main sedimentary Basins (Whiteman ,1982).

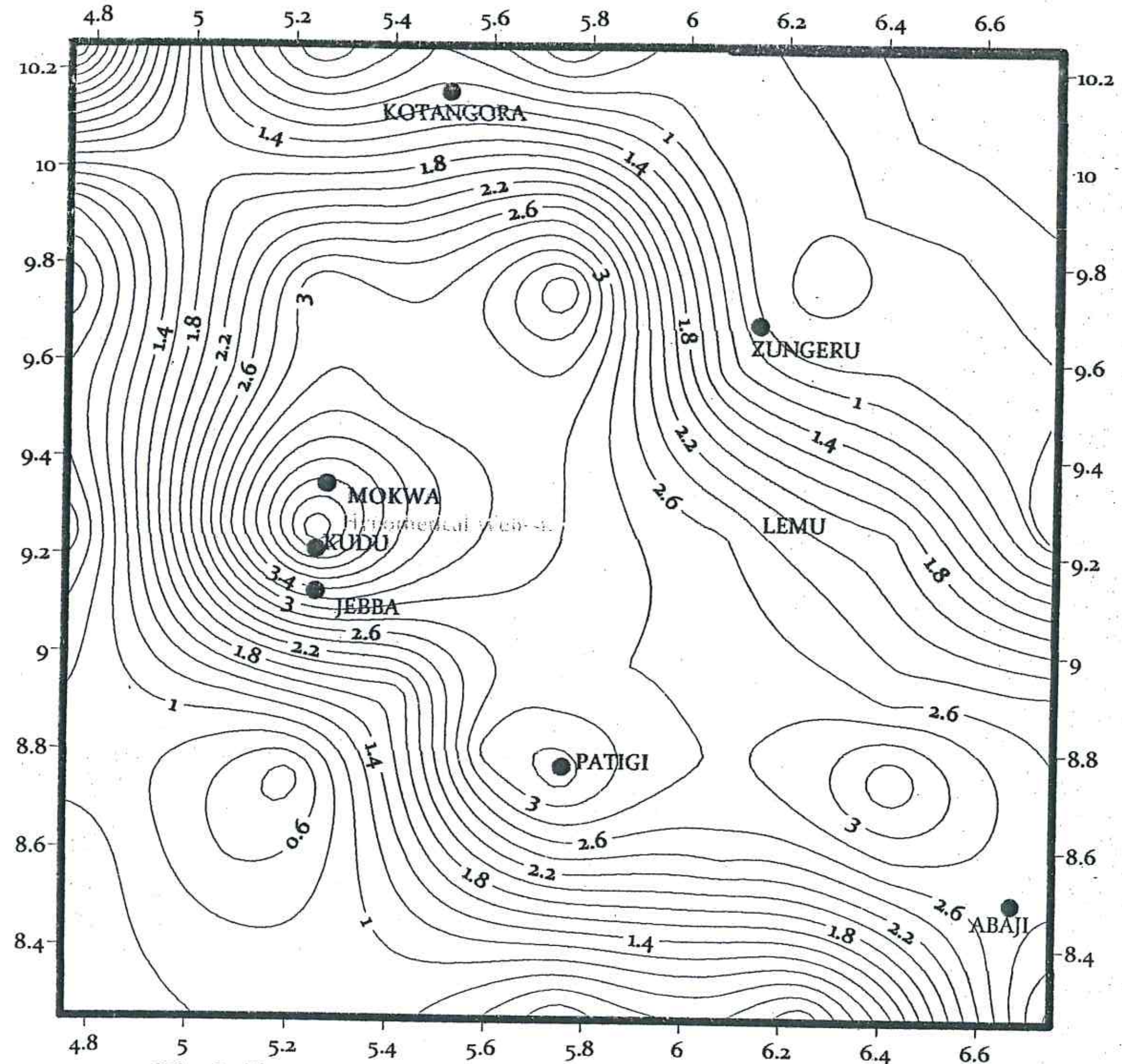
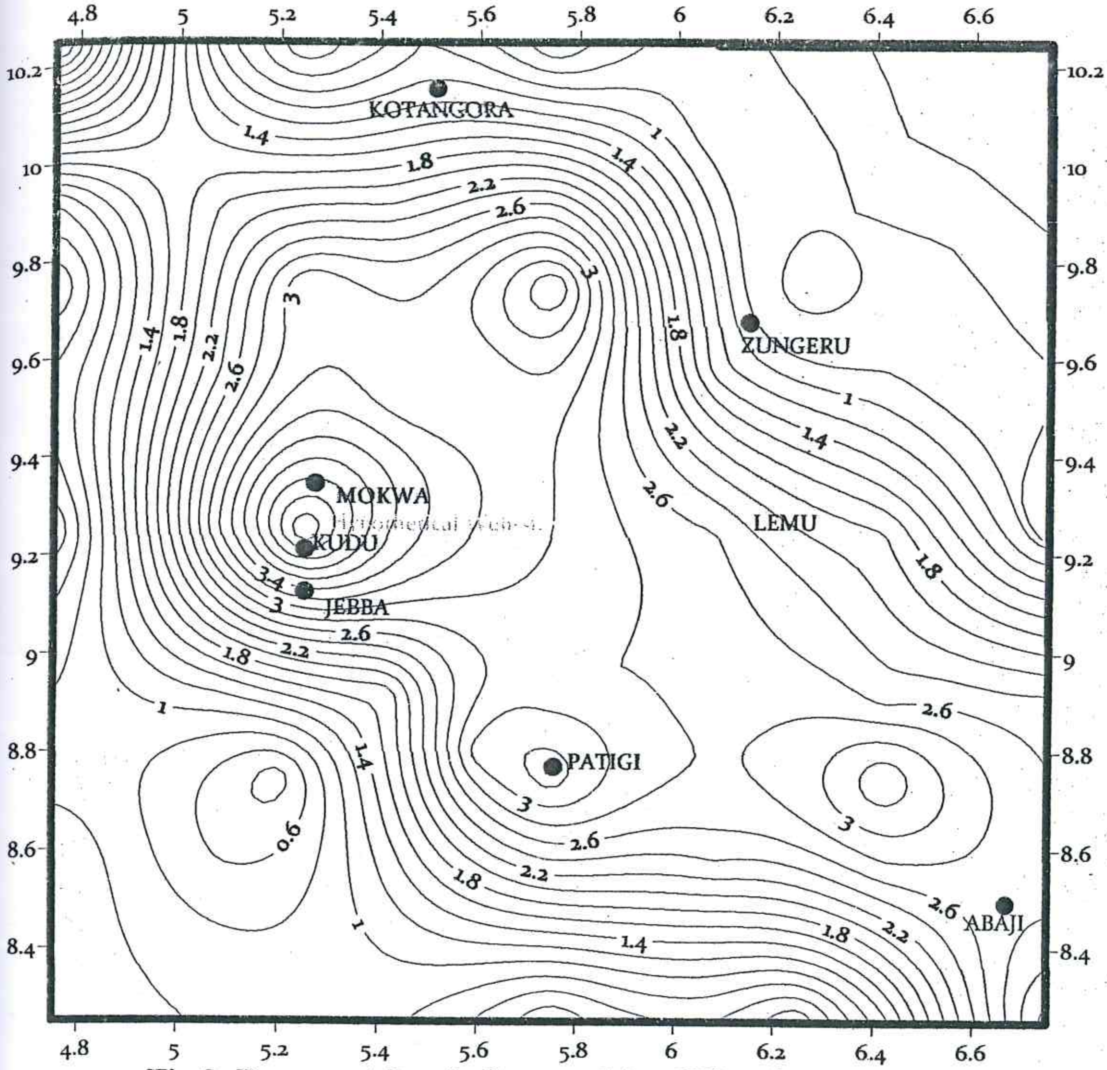


Fig 3: Basement Depth Contour Map (Udensi and Osasuwa, 2004)

The sediments unconformably overlie the Precambrian to probably Paleozoic basement complex. Unlike the pre-Santonian Cretaceous sediments, the entire sedimentary content of the Bida Basin is unfolded, unmetamorphosed and lack lead-zinc mineralization. Adeleye (1989) reports the occurrence of Campanian - Maestrichtian sporomorphae in some of the sediments around Mokwa. He also reports freshwater to shallow marine biota in the sediments. Olugbemiro and Nwajide (1997) report that grain size distribution and particle morphogenesis study reveals that sediments of Bida Basin were deposited in fluvial to transitional marine environments. Ojo and Akande (2006) report that lithofacies association in the southeastern portion of the basin indicates deposition in freshwater to near shore marine environment. They also report the occurrence of marine Maestrichtian dinoflagellate cysts. The Bida Basin can thus be succinctly described as a post - Santonian basin containing Campanian - Maestrichtian fluvial to marginal marine sediments. On the basis of lithostratigraphy the Bida Basin can be divided into northern and southern portions. According to Jones (1958) the southern Bida Basin contains Campanian to Maestrichtian Lokoja and Patti Formations. The Patti Formation is succeeded by Agbaja Formation (Adeleye and Dessauvagie, 1972). In the northern portion of the basin are Bida Formation, Sakpe Formation, Enagi formation and Batati Formation. The sediment



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Age	**NORTHERN BIDA BASIN**		**SOUTHERN BIDA BASIN**
Tertiary and recent	Superficial deposits (Laterite, Superficial deposits (laterite, sands		
Maastrichian	Batati Formation Enagi Formation Sakpe Formation		Agbaja Formation Patti Formation
Campanian	Bida Formation	Jima member Doko member	Lokoja Formation
Precambrian to lower Paleozoic	Basement complex		

Fig4: Stratigraphic successions in Bida Basin(Adeleye,1976)

The Bida Formation consists of para - conglomerates (conglomerates set in mudstone matrix), sandstones, siltstones and mudstones in a fining upward sequence. The formation is subdivided into Jima Member and Doko Member. The Doko Member contains widespread cross - stratification and ripple marks. These internal bedding features rarely occur in Jima Member. Sections of ferruginised mudstones occur in the formation. Between Zungeru and Wushishi are outcrops of the Bida Formation directly overlying the basement. Its lateral equivalent (the lokoja Formation) nonconformably overlies the basement around Lokoja, between Felele and Koton-Karifi. Its lithologic composition is basal conglomerate, fine to pebbly sandstone, siltstone to mudstone - in upward fining sequence.The Bida Formation is succeeded by oolitic – pisolitic ironstones called the Sakpe Formation, while the Lokoja Formation is succeeded by Patti Formation.

Patti Formation consists of fine to medium, grey and white sandstones; carbonaceous silts and shales, thin coal seams and oolitic ironstones. Overlying Sakpe Formation is Enagi Formation, which contains yellow to purple units of sandstones, siltstones and mudstones. Coal seams have been encountered in shallow bore-holes at Enagi. Patti Formation is overlain by Agbaja formation. The Agbaja Formation shows very rapid facies changes characteristic of shallow marine origin (Ehinola et al, 2006). The Enagi Formation is overlain by Batati Formation, comprising ferruginised sandstones and claystones, oolitic ironstones.

FOCUS, SCOPE AND FRAMEWORK OF STUDY

Whiteman (1982) reports that the mode of formation of Bida Basin and its date of inception are uncertain. Onuoha (1986) remarks that the sedimentary basins in Nigeria have their origin linked to extensional activities during the Mesozoic. Obaje et al (2004) reports that the inland basins of Nigeria constitute one set of Cretaceous and later rift basins in Central and West Africa, whose origin is related to the opening of the South Atlantic. Both Onuoha (1986) and Obaje et al (2004) imply that models developed for the evolution and subsidence of continental margins and continental rift basins should be applicable to the Nigerian basins as well. To verify this implication for Bida Basin, its basement subsisdence history and geologic formations' burial history are reconstructed. In addition, the lateral development of the basin is reconstructed and the hydrocarbon generation status of its argillaceous sediments is evaluated. The study of tectonic and stratigraphic evolution has considerable relevance to hydrocarbon exploration (Mckenzie, 1978). Whiteman (1982) remarks that deep dry gas prospects might exist within the Bida Basin if structures are present in depth and if coal is present beneath the topmost cover in the basin - in analogy to neighbouring contemporary petroliferous Anambra Basin. This was probably the thinking of Great Basin Petroleum Company when they leased and promoted the area. The company neither performed seismic studies nor drilled deep wells before relinquishing the acreage. The omission and repetition of some lithologic units encountered in the area might be due to faulting or mere cyclic deposition.

Carbonaceous shales, mudstones and coal seams in outcrops of Enagi and Patti Formations, Agbaja Formation and those encountered in water bore holes (in Kudu, Enagi and Badeggi) constitute source rocks. Thus Bida basin meets the most fundamental requirement for petroleum prospectivity assessment, employing integrated tectonic evolution, subsidence and geo-history study.

METHODOLOGY

Extrapolated data from extensive field geological observations and published data were used because a deep well has neither been drilled nor seismic data acquired in Bida Basin. From the ratio of thickness of geological formations exposed at outcrops, a lithostratigraphic section was inferred for an hypothetical well-site located at Kudu(Fig1). Outcrop pattern of observed geological formations indicates that any well drilled at Kudu would penetrate the complete geologic section in the basin. This is based on Walther's Law of Facies Association, which states that vertical lithofacies is a stacking of observed lateral lithofacies. The sediment thickness at the hypothetical well-site is obtained from buried magnetic rock depth contour map published for Bida Basin (Udensi and Osazuwa 2004).

Using total sediment thickness and inferred lithostratigraphic section for hypothetical well-site at kudu as fundamental inputs, basement subsidence history with overlying geological formations' burial history is was reconstructed.

During reconstruction, compaction effects were corrected with the decomposition technique employed by Sclater and Christie (1980).

The technique employs a mathematical model which determines the thickness (hs) of a geologic formation from depth to its present top (Z_1) and bottom (Z_2) and employs this thickness to determine the depth to the top (z_3) and bottom (Z_4) of the geologic formation at earlier geological times (Fig. 5).

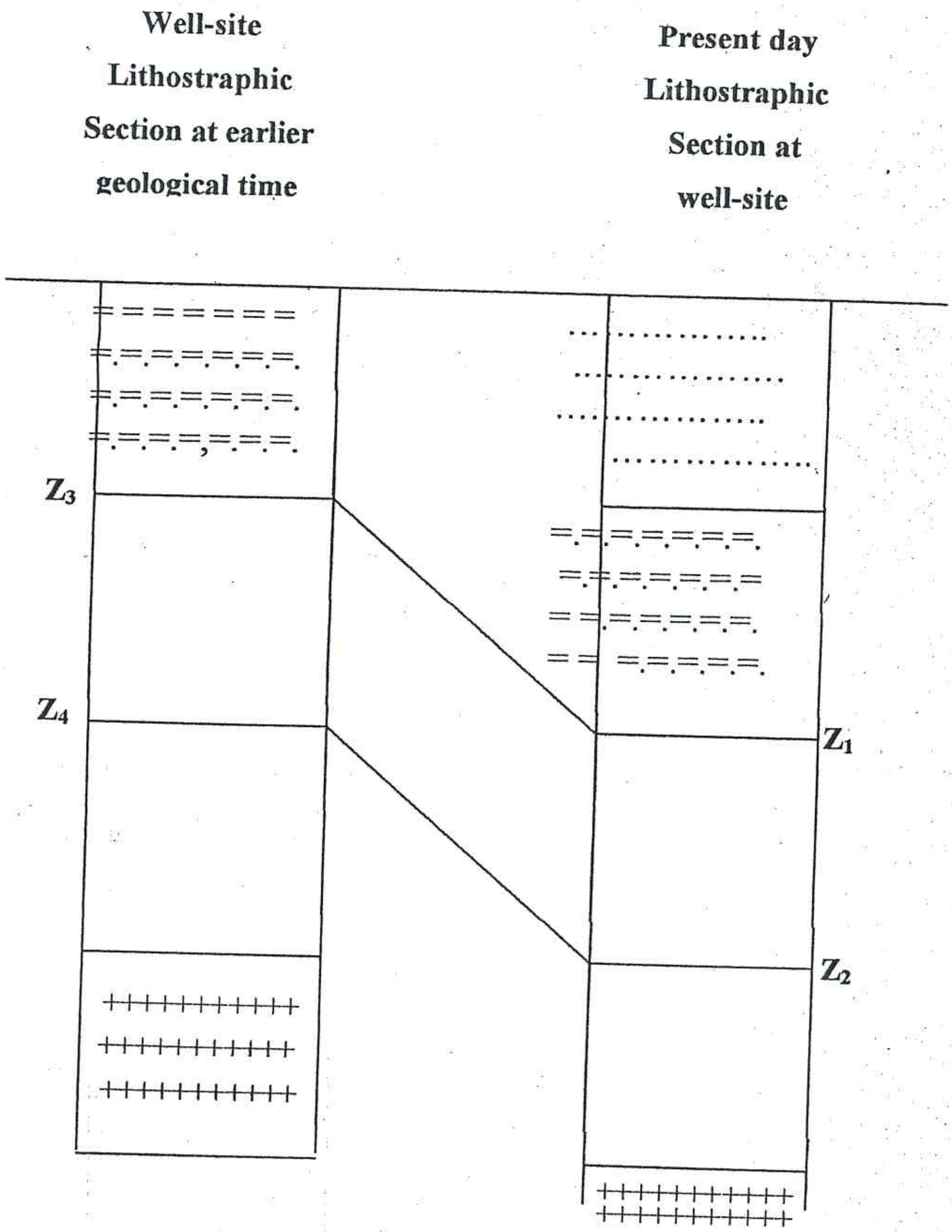

Fig. 5: Diagrammatic Illustration of Mathematical Model for Formation Thickness Determination through Geological Time.

Falvey and Middleton (1981) states that if the present depth to top and bottom of a sedimentary unit are Z_1 and Z_2 respectively, depth to top of the unit Z_3 and bottom of the unit Z_4 at an earlier time is given by:

$$Z_4 - {}^1/C \ln [1+\phi_o \, CZ_4] = h_s + Z_3 - {}^1/C \ln [1+ \phi_o \, CZ_3] \qquad (1)$$

Where $hs = \int_{Z_1}^{Z_2} \left[1 - \phi_{(Z)}\right] dz \qquad (2)$

$\phi_{(z)}$ represents porosity at depth z. Because Bida Basin is a clastic basin, porosity varies exponentially with depth as follows:

$$\phi_{(z)} = \phi_0 e^{-cz} \quad (3)$$

$$h_s = \int_{Z_1}^{Z_2} \left[1-\phi_o e^{-CZ}\right] dz \quad (4)$$

$$h_s = \int_{Z_1}^{Z_2}(1)\, dz - \int_{z_1}^{z_2}\phi_o e^{-CZ} dz \quad (5)$$

$$h_s = [Z]_{Z_1}^{Z_2} - \left[-\frac{\phi_O}{C}e^{-CZ}\right]_{Z_1}^{Z_2} \quad (6)$$

$$h_s = (Z_2 - Z_1) - \left[-\frac{\phi_o}{C}e^{-CZ_2} - \left(-\frac{\phi_O}{C}e^{-CZ_1}\right)\right] \quad (7)$$

$$h_s = (Z_2 - Z_1) - \left[-\frac{\phi_O}{C}e^{-CZ_2} + \frac{\phi_O}{C}e^{CZ_1}\right] \quad (8)$$

$$h_s = (Z_2 - Z_1) + \frac{\phi_O}{C}e^{-CZ_1} - \frac{\phi_O}{C}e^{-CZ_1} \quad (9)$$

$$h_s = (Z_2 - Z_1) + \frac{\phi_O}{C}\left(e^{-CZ_2} - e^{-CZ_1}\right) \quad (10)$$

ϕ_0 is surface porosity of sedimentary unit.

ϕ_0 was assumed to be 0.55, since ϕ_0 generally varies between 0.4 and 0.7 (Middletion, 1984). C is assumed to be 0.00045, following Magara (1986). The subsidence curve for top of basement and burial curves for overlying geological formations were plotted. The plotted curves were compared with subsidence curve of oceanic crust in order to ascertain the origin of the basin. Following Onuoha and Ofoegbu (1988) and Durand (2003), paleo temperatures were estimated using the following mathematical model:

$T_{(z)} = T_0 + g_{(z)} Z_{(t)}$,

where $T_{(z)}$ is formation temperature at depth (z), g(z) is geothermal gradient at depth(z), Z(t) is depth at geological time (t) and T_o is surface (soil) temperature. 30°C/km was assumed value for geothermal gradient, being the average value of geothermal gradients for sedimentary basins (Taylor et al, 1998). Surface temperature was taken to be 20°C, which is typical of tropical - equatorial regions.

The maturity status of Enagi Formation (being the formation with shales rich in organic matter) was estimated following the technique of Lopatin (1971) and Vvaples (1980). In the technique the maturity status is estimated using time- temperature index (TTI) as follows:

$$TTI = \sum_{n\min}^{n\max} \Delta t_n t^n ,$$

where Δt_n is the length of geological time spent by the formation in the nth temperature interval, τ^n is the temperature factor of the interval, n-max and n-min are the n-values of the highest and lowest temperature intervals encountered. The list of temperature intervals, index values (n) and temperature factors (τ^n) for calculating TTI (Table1)is as follows:

Table1 : Values of parameters for estimating TTI (Magara,1986).

Temperature	Index Value, n	Temperature factors, τ^n
20 - 30	-8	2^{-8}
30 - 40	-7	2^{-7}
40 - 50	-6	2^{-6}
50 - 60	-5	2^{-5}
60 - 70	-4	2^{-4}
70-80	-3	2^{-3}
80-90	-2	2^{-2}
90-100	-1	2^{-1}
100-110	0	2°
110-120	1	2^{1}

Vitrinite reflectance value is estimated from TTI - Vitrinite reflectance chart (Fig.6) Waples (1980).

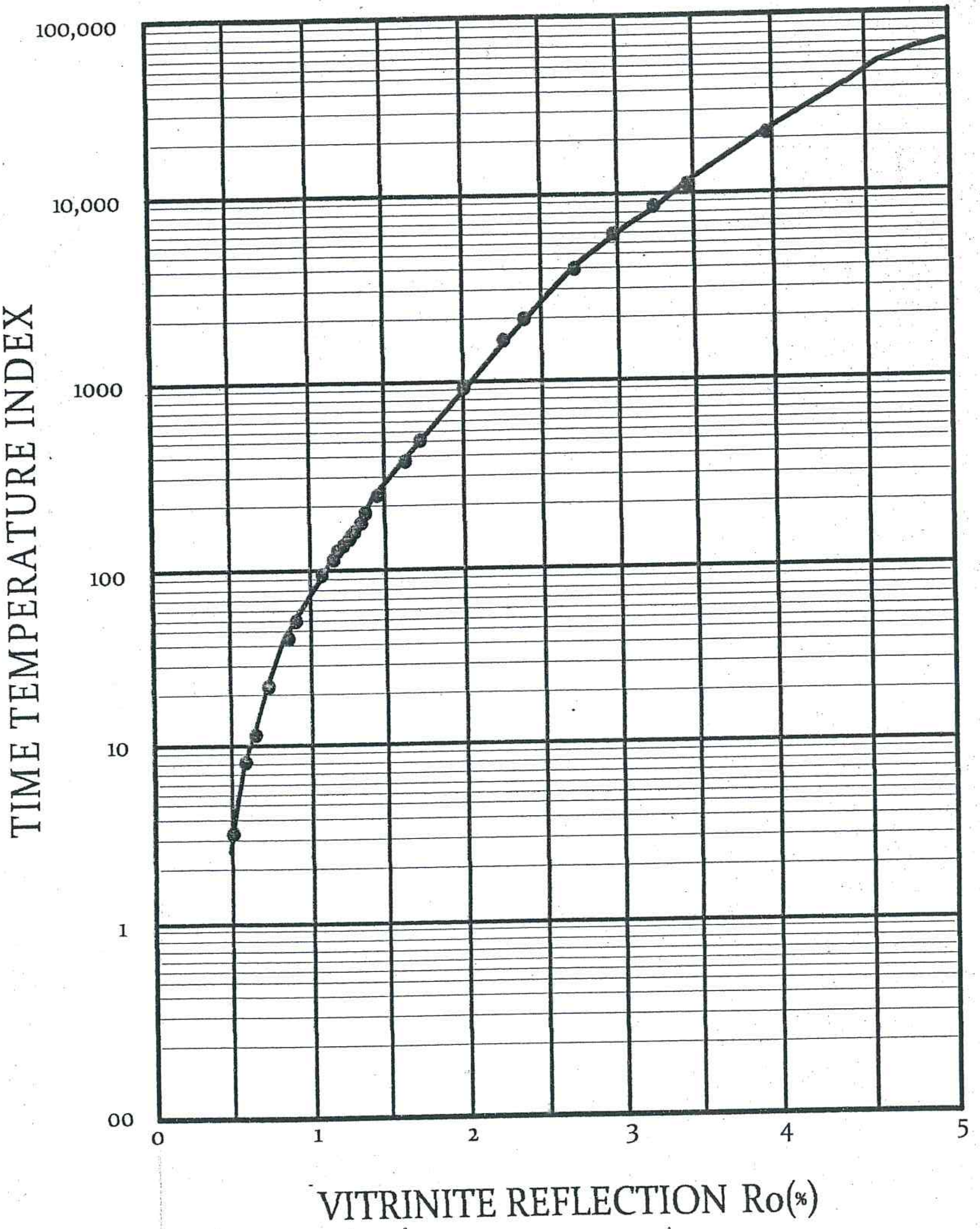

Fig. 6: TTI - Vitrinite reflectance Chart Waples, 1980)

Following Tissot and Welte (1978) and Waples (1980), the maturity status and oil generation stage for the Enagi Formation (hence for the Bida Basin) was deduced.

DISCUSSION

A histogram of successive basement and formation burial depth through geological time is presented in Fig 7.

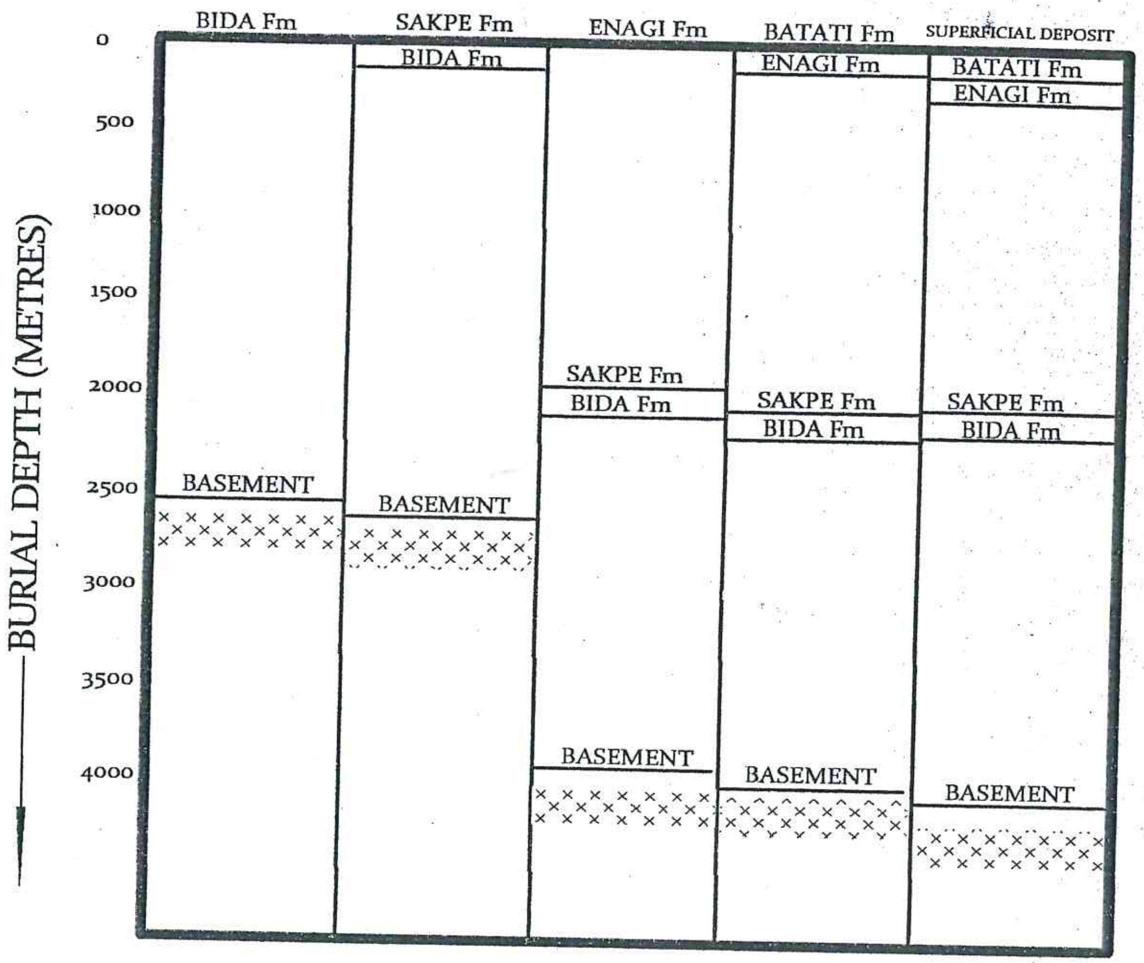

Fig .7: Histogram of successive change of basement and formation burial depth

The subsidence curve for the basement surface and burial curves for the geological formations (Fig 8) approximate the negative exponential curve that approaches the horizontal axis asymptotically.

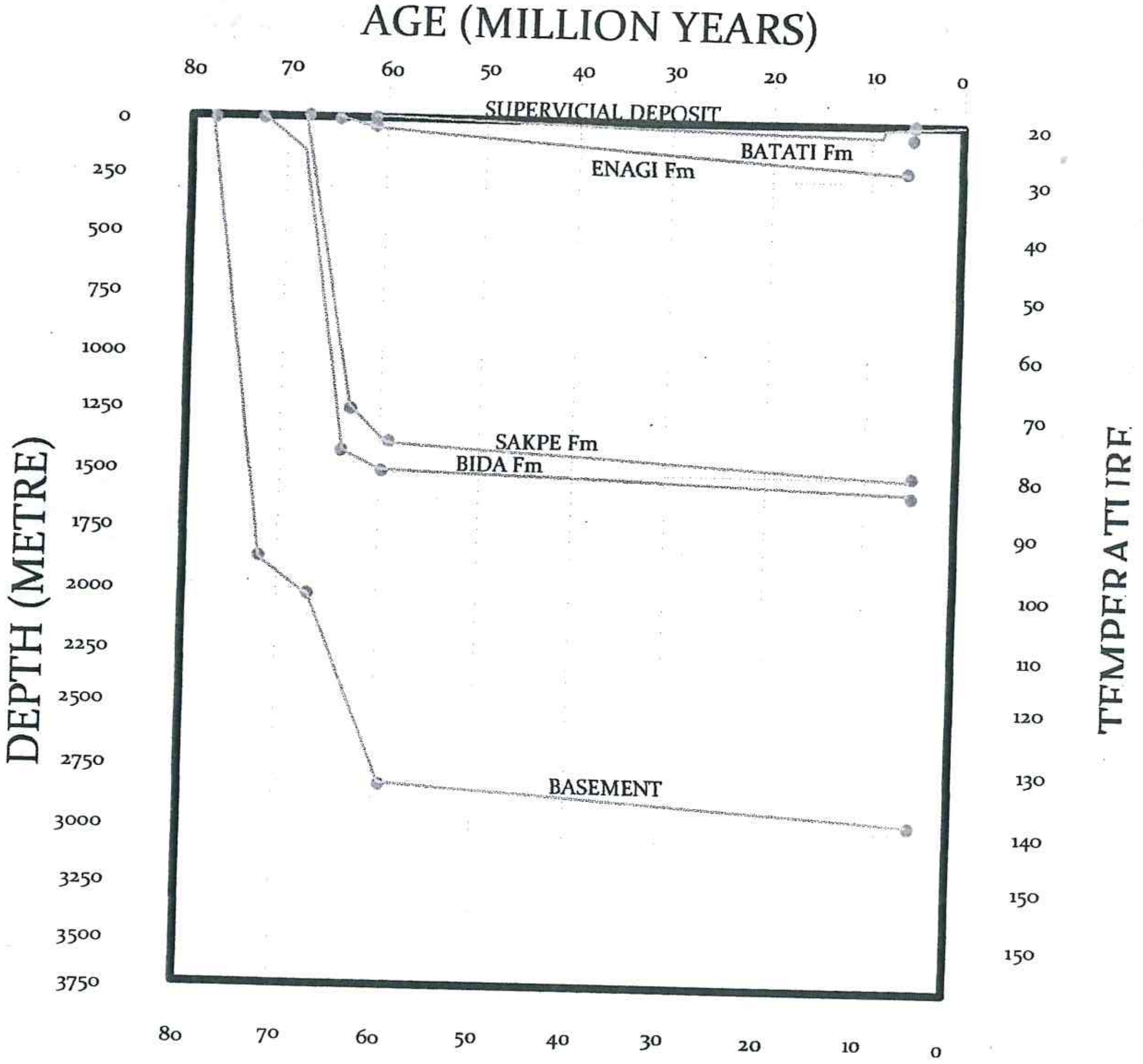

Fig 8: Curves for burial of basement surface and formation top, and formation temperature at burial depth

The shape of these curves is analogous to the burial curve for oceanic crust and continental rift basins. This indicates that the genesis and evolution of the Bida Basin is directly linked with plate tectonics. The flooring of the basin with non marine sediments in form of basal paraconglomerates, is in conformity with floor constituents of grabens resulting from continental rifting. The basal conglomerates represent the stage when the basin floor was still above sea and fluvial system dominated the depositional regime.

The presence of basal conglomerates on the basin floor and the negative exponential subsidence of the basin floor, in response to thermal cooling and contraction, constitutes an incontrovertible evidence that the Bida Basin originated from rifting. The rift that developed into the Bida Basin is a consequence of the tectonic pulse generated from convergent interaction between the West African Plate and Central African Plate from 85 Ma to 80 Ma, when the Benue - Abakaliki Fold

Belt was created by tectonic inversion. Burke et al (1971) and Nwachukwu (1972) proffer that the Benue - Abakaliki Fold Belt evolved from disruptive and convergent plate interactions. Senghor (1976), Keary and Vine (2003) state that in distal regions of zone of convergent plate interactions, grabens called impactogens may develop in response to tensional forces associated with the collision. According to them, such impactogens trend perpendicularly to the tectonic inversion structure. This is in conformity with the perpendicular relationship between NE - SW trend of the Bida Basin and NW - SW trend of the Benue - Abakaliki Fold Belt (Fig. 1). During the Campanion around 74 Ma (6 Ma after the Santonian tectonic pusle) alluvial fan and braided fluvial deposits (constituting the Bida Formation) were Laid down around Kontagora, Wushishi, Bida and Agaie by river networks flowing southeastwards from Northern Nigeria massif on the northwest(Fig.9).

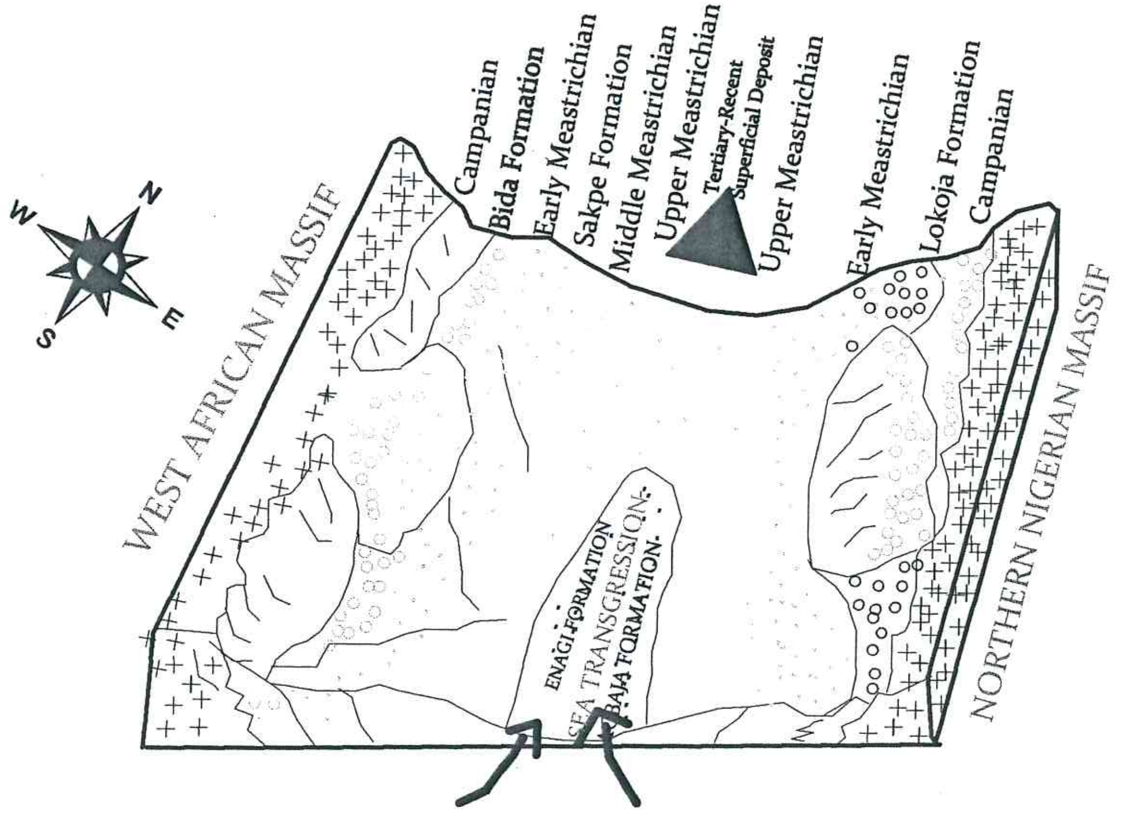

Fig. 9: Lateral development of Bida Basin

Coeval with this event was the laying of contemporary similar deposits (constituting the Lokoja Formation) at Lokoja, Mokwa, Auna and Doko by river networks flowing northwestwards from the West African Massif on the southeast (Fig.9). The braided Campanian river networks became meandering in early Maestrichtian, depositing Patti Formation around Abaji and Ahoko. During the early part of Upper Maestrichtian the river networks interfaced with the sea that was transgressing inland from the Gulf of Guinea. This resulted in the deposition of marginal marine sediments (Agbaja, Sakpe and Enagi Formations) around Dekina, Ahoko, Koton Karifi, Gerinya, Tawari, Enagi and Kudu in the southeastern and central portions of the basin (fig 9). The vertical lithofacies sequence and lateral lithofacies sequence in the northwestern portion of the basin indicate that the sea did not transgress up to this part of the Bida basin. As the Upper Maestrichtian was signing out, the sea began to regress and the river systems became domineering, depositing the fluvial Batati Formation.

The maximum temperature attained by Enagi Formation (the source rock formation) is 26°C. The shales never attained the threshold temperature for oil birth, implying they did not enter the catagenesis stage of kerogen alternation (Fig. 10).

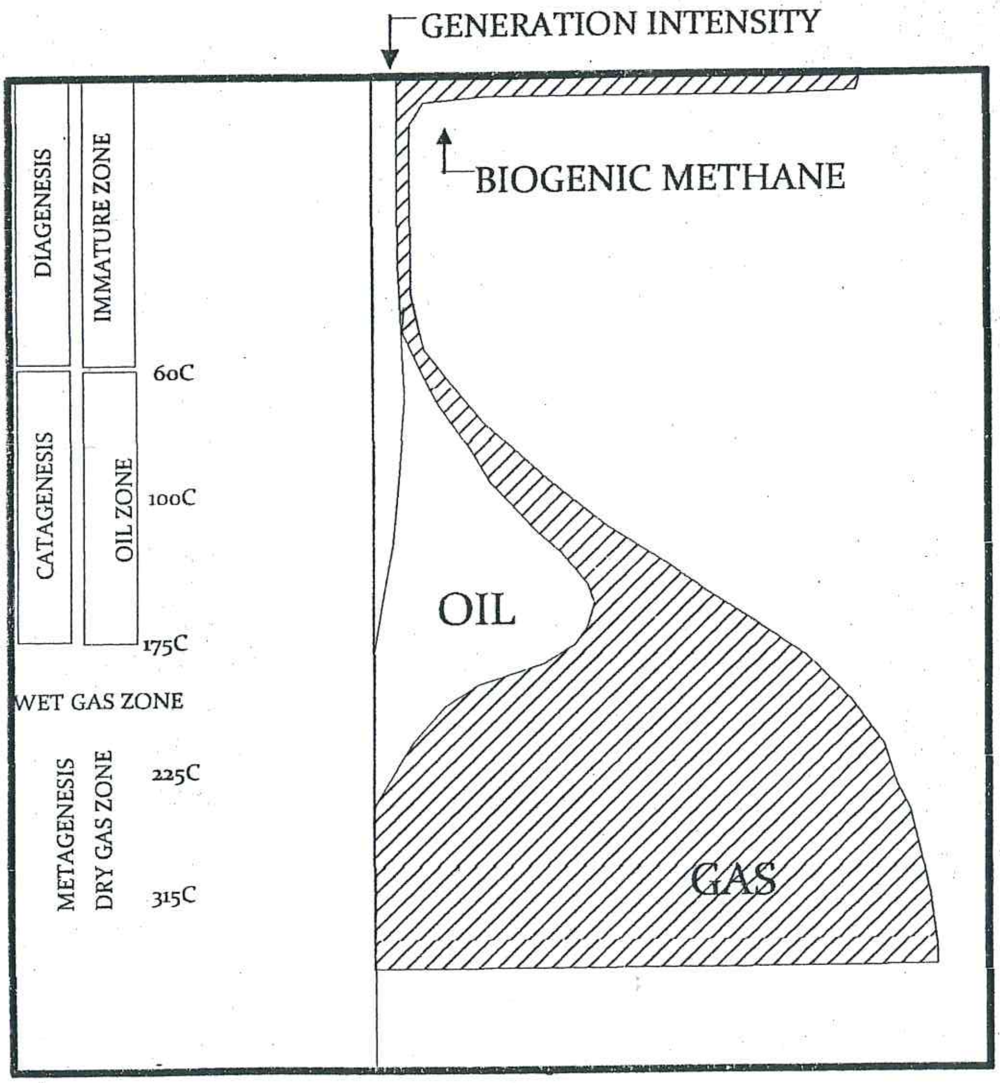

Fig 10:Petroleum Generation in relation to temperature and depth (Adapted from Tissot and Welte, 1978).

Estimated $\sum$ TTI (cummulative time-temperature index) is 0.225, corresponding to vitinite reflectance of about 0.3% R_0. The estimated vitrinite reflectance value and attained maximum temperature of 26°C indicate that the Enagi Formation is an immature source rock (Fig.10 and Table 2) .

Table 2: Correlation of $\sum$ TTI with several important stages of oil generation (Waples, 1980)

STAGES	TTI	%Ro
Onset of oil Generation	15	0.68
End of oil Generation	75	1.00
End of oil generation	160	1.30
Upper TTI limit for occurrence of wet gas	6500	3.50

This is in agreement with the findings of Ehinola et al (2006) that shales from Bida Basin have measured vitrinite values between 0.24 and 0.58, indicating thermal immaturity. They confirmed the shale's thermal immaturity status by thermal maturity parameters computed from terpanes and sterane distribution. However stratigraphic petroleum pool might exist in stratigraphic traps constituted by lateral facies change in southeastern portion of Bida Basin, where it coalesces with the petroliferous Anambra Basin. Possibility for such petroleum pools could be created if petroleum generated by mature source rocks in Anambra Basin are arrested by lateral facies changes when migrating northwestwards.

CONCLUSION

The Bida Basin contains freshwater to marginal marine Campanian-Maestrichtian sediments. The pattern of underlying basement subsidence curve and sediments' burial curve links the genesis and evolution of the basin with plate tectonics. The basin evolved from a rift that formed when Benue-Abakaliki fold Belt was created in response to the tectonic pulse arising from collision between Central African Plate and West African Plate between 85Ma and 80Ma. The vertical lithofacies sequence and lateral lithofacies sequence indicate that the sea transgressed only from the Gulf of Guinea in the south, and the transgression terminated in the central portion of the basin. The maximum temperature attained by the source rock, their estimated TTI and Ro Values show that the source rocks in the basin are immature. Possible northwestwards migrating oil and gas from neighbouring Anambra basin could be

stratigraphically entrapped in the zone where the Bida merges with the Anambra Basin.

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