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Preliminary Integrated Hydrocarbon Prospectivity Evaluation of the Bida Basin in North Central Nigeria

By

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Abstract

The Bida Basin is a NW-SE trending intracratonic structure extending from slightly south of Kontagora in Niger State in the north to the area slightly beyond Lokoja (Kogi State) in the south. All geological maps available on the Bida Basin had lumped the sediments in the basin as one undifferentiated Nupe Sandstone, making it impossible to infer the prospectivity of the basin for hydrocarbon exploration. The delineation of inferred boundaries between the formations in the basin is a significant initial criterion in evaluating the hydrocarbon prospectivity. The formations deposited in the Bida Basin comprise the Bida Sandstone at the base, followed successively upward by the Sakpe, Enagi and Batati Formations in the Northern/Central Bida Basin while the Lokoja, Patti and Agbaja Formations constitute lateral equivalents in the Southern Bida Basin. An institutional research project of the Ibrahim Badamasi Babangida University Lapai (IBBUL), supported by the Niger State Government, has carried out preliminary geological mapping and completed a prospectivity map for the Bida Basin. Geochemical analysis of samples from drilled shallow wells (at Agaie and Kudu) and outcrops was also undertaken along with interpretation of geophysical aeromagnetic data. From the preliminary geological map prepared, prospective areas, ranked as Less Prospective, Prospective and More Prospective are discernable. Geochemical data show that mainly gas and some oil would have been generated within the Prospective and More Prospective sections in the basin. The data also show that the Kudu Shale Member within the Enagi Formation and Ahoko Shale Member within the Patti Formation constitute the source rocks for hydrocarbon generation in the Northern and Southern Bida Basin, respectively. Geophysical aeromagnetic data evaluation indicates depths of more than 2,000m (> 2 Km) within the identified prospective areas. The combined geological and aeromagnetic maps provide the basis for detailed further prospectivity evaluation by the University (IBBUL), NNPC, DPR and local and international investors in the search for oil and gas in the Bida Basin. The prepared geological map is the first complete geological map to be produced on the Bida Basin.

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1.0. Introduction

Petroleum (oil and gas) accounts for up to 95% of Nigeria's foreign earning and has remained the major supporter of its economy since it was first discovered in commercial volume in 1956. Globally, petroleum as energy source will continue to dominate other primary energy sources and is expected to account for up to 60% of the world energy demand by the year 2030. Therefore the more oil and gas Nigeria has as recoverable reserves, the better it will be for her national economy and development. However, petroleum unfortunately is an exhaustible resource and dwindles on reserve with time. Therefore as a country, it is imperative on Nigeria to continue the search for more oil and gas to add to her reserves, if and only if, the country is to maintain the lead as a major oil producer and meet up with her vision 20:2020.[1]

In addition to the Niger Delta Basin from which all of the country's current production of petroleum is derived, Nigeria is blessed with numerous other sedimentary basins comprising the Anambra, Bida, Sokoto, Bornu (Chad), and Dahomey Basins, as well as, the Benue Trough made up of the Lower, Middle and Upper Benue Troughs. These basins have structural and stratigraphical similarities with contiguous intracratonic rifted basins of Niger Republic, Chad Republic and Sudan where commercial oil accumulations have been discovered.

The Bida Basin, also known as the Mid-Niger or Nupe Basin, is located in north-central Nigeria while the Sokoto Basin, sometime referred to as the SE Iullemmeden Basin is located in north-western Nigeria (Fig. 1). The two basins constitute two paleographically related sets (Fig. 2) of Nigeria's inland basins (mentioned above). These basins constitute another set of a series of Cretaceous and later rift basins in Central and West Africa whose origin is related to the opening of the South Atlantic (Fig. 3). Commercial hydrocarbon accumulations have recently been discovered in Chad, Niger and Sudan within this rift trend. In SW Chad, development of the Doba discovery (with estimated reserves of about 1 billion barrels) resulted in the construction of a 1070 km long pipeline to the Atlantic coast. In the Sudan, "giant" fields (including Unity 1 and 2, Kaikang and Heglig) have been discovered in the Muglad Basin *(1)*. The present study has been carried to shed more light on the hydrocarbon prospectivity of the Bida Basin which shall form the basis for evaluating the reserves and identifying prospects of commercial values and drillable sites in the basin.

[1]Vision 20:2020 is Nigeria's strategic plan to ensure that by the year 2020, the country will be one of the world's 20 largest economies, able to consolidate its leadership role in the continent of Africa and establish itself as a significant player in the global economic and political arena.

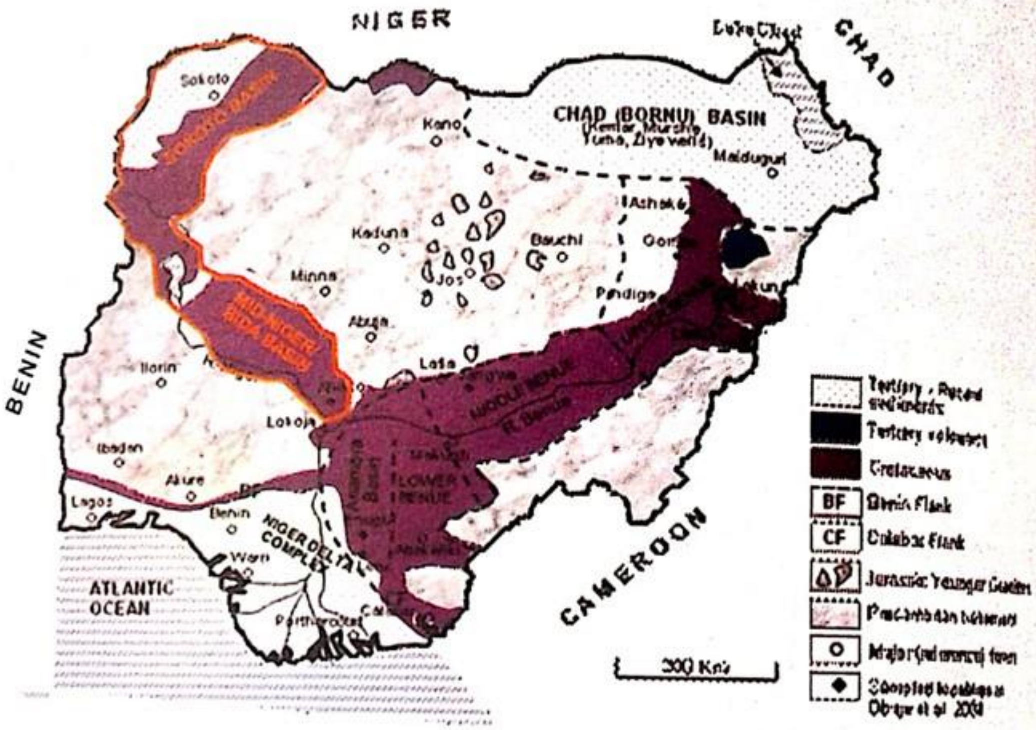

Fig. 1. Generalized geological map of Nigeria showing the location of the Bida and Sokoto Basins

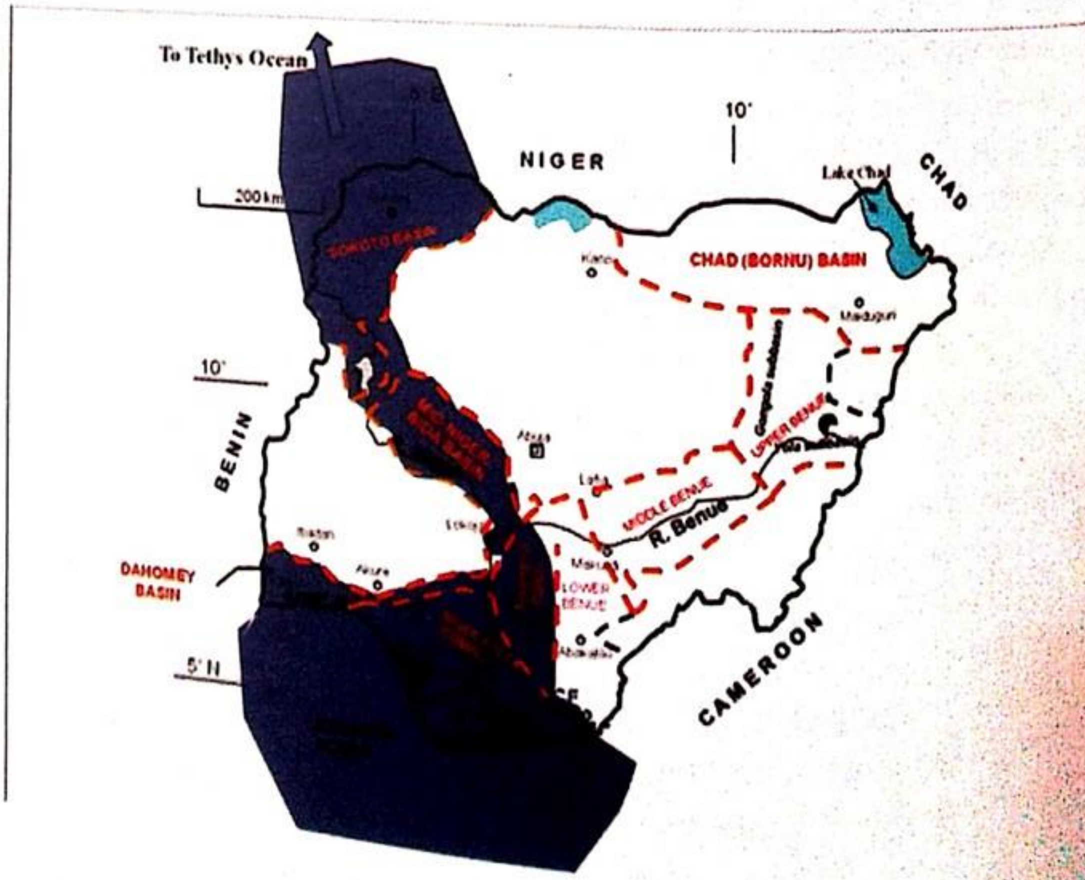

Fig. 2. Maastrichtian paleogeography of Nigeria: the sea passed through the Bida and Sokoto Basins to connect to the Tethys

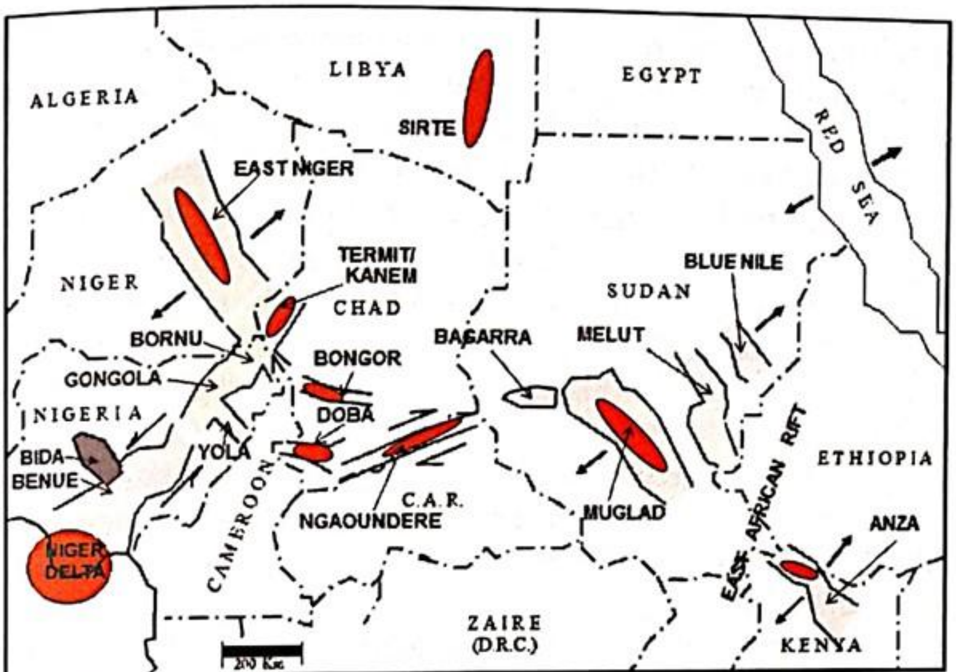

Fig. 3. Regional section map of western and central African rifted basins showing the relationship of the Maglad, Doha and East Niger Basins to the Benue Trought/Gongola Basin. Locations of regional shear zones (marked with half arrow) and major zones extension (complete arrow) are shown. (Adapted from schull, 1988).

Major oil and/or gas discovery

2.0. Literature Review and Knowledge Gap

Literature on the Bida and Sokoto Basins is very scanty unlike on the other inland basins which are widely documented. The stratigraphy and sedimentation of Upper Cretaceous succession of the Bida Basin were documented by Adeleye and Dessauvagie[2] in the central parts of the basin around Bida. The study defined and established the mappable litho-stratigraphic units that are currently being used for the Bida Basin. Interpretations of Landsat imageries and borehole logs, as well as geophysical data by Ojo[3] suggested that the basin is bounded by a system of linear faults trending NW-SE while the gravity studies of Ojo and Ajakaiye[4] point to a series of central positive anomalies flanked by negative anomalies, similar to the adjacent Benue Trough and typical of rift structures.

[2]Adeleye, D. R. and Dessauvagie, T. F. J. 1972. Stratigraphy of the Mid-Niger Emabyment near Bida, Nigeria. In: Dessauvagie, T. J. F. and Whiteman, A. J. (Eds), Proceedings of the Conference on African Geology, Ibadan University Press, Ibadan, pp181-186.

[3]Ojo, S. B. 1984. Middle Niger Basin revisited: magnetic constraints on gravity interpretations. Abstract, 20th Conference of the Nigeria Mining and Geosciences Society, Nsukka, pp52–53.

[4]Ojo, S. B. and Ajakaiye, D. E. 1989. Preliminary interpretation of gravity measurements in the Mid-Niger Basin area, Nigeria. In: Kogbe, C.A. (Ed.), Geology of Nigeria, 2nd edition, Elizabethan Publishers, Lagos, pp347–358

University-based research works on aero- and ground-magnetic and gravimetric geophysical surveys are available on parts of the Bida Basin[5]. These works generally corroborate the interpretations of Ojo[6] and Ojo and Ajakaiye[7] that outlined the basin as being bounded by a system of linear faults. In addition to the preliminary stratigraphic investigations carried out by Adeleye and Dessauvagie[8], further stratigraphic analyses were undertaken by Adeleye[9] in which the type localities and type sections for the geologic formations in the Bida Basin were located and described. Braide[10] attempted some sedimentological interpretations of sections in parts of the Southern Bida Basin. In that study, fluvial depositional models were ascribed to the Lokoja Formation and parts of the Patti Formation indicating some relatively good quality reservoir rocks in portions of these formations. Obaje et al.[11] and Akande et al.[12] presented some source rock geochemical results on a few samples from the Patti Formation in the Southern Bida Basin. Both studies indicated that based on the few samples analyzed, sedimentary organic matter in the basin were in the early stages of oil generation and postulated also that the organic matter are more gas-prone than oil-prone.

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[5]Udensi, E. E. and Osazuwa, I. B. 2004. Spectral determination of depths to magnetic rocks under the Nupe Basin, Nigeria. Nigerian Association of Petroleum Explorationists (NAPE) Bulletin 17, 22–27.

[6]Op.Cit

[7]Op. Cit

[8]Op. Cit

[9]Adeleye, D. R. 1974. Sedimentology of the fluvial Bida Sandstones (Cretaceous), Nigeria. Sedimentary Geology 12, 1-24.; Adeleye, D. R. 1975. Nigerian Late Cretaceous stratigraphy and paleogeography. AAPG Bulletin 59, 2302-2313.;Adeleye, D. R. 1989. The Geology of the Mid-Niger Basin. In: Kogbe, C. A. (Ed.), Geology of Nigeria, 2nd ed. Elizabethan Publishing Co., Lagos, pp283–287.

[10]Braide, S. P. 1992a. Geologic development, origin and energy mineral resource potential of the Lokoja Formation in the southern Bida Basin. Journal of Mining and Geology 28, 33–44.; Braide, S. P. 1992b. Syntectonic fluvial sedimentation in the central Bida Basin. Journal of Mining and Geology 28, 55–64.; Braide, S. P. 1992c. Alluvial fan depositional model in the northern Bida Basin. Journal of Mining and Geology 28, 65–73.

[11]Obaje, N. G., Wehner, H., Scheeder, G., Abubakar, M. B. and Jauro, A. 2004. Hydrocarbon prospectivity of Nigeria's inland basins: from the viewpoint of organic geochemistry and organic petrology. AAPG Bulletin 87, 325–353.

[12]Akande, S. O, Ojo, O. J., Erdtmann, B. D. and Hetenyi, M. 2005. Paleoenvironments, organic petrology and Rock-Eval studies on source rock facies of the Lower Maastrichtian Patti Formation, southern Bida Basin, Nigeria. Journal of African Earth Sciences 41, 394-406.

Kogbe[13] and Petters[14] carried out some biostratigraphical investigations in parts of the Sokoto Basin. Fossil occurrences in the different formations were collected and analyzed in that study, which allowed the interpretation of the depositional environments and construction of Maastrichtian paleogeographical maps for the Sokoto Basin.

All the previous works in the Bida and Sokoto Basins are preliminary in nature. Nowhere were their implications on the hydrocarbon prospectivity of the basins evaluated. This is because the data were scanty and did not include detailed geological map interpretations nor organic geochemical, high-resolution biostratigraphical, petrographical and petrophysical inputs. The interpretations of Obaje et al.[15] and Akande et al.[16] were based on only a limited (indeed very few) samples. The work of Kogbe[17] and that of Petters[18] did not cover many parts of the Sokoto Basin and no correlations panels were established. No organic geochemical results of any type on any parts or successions in the Sokoto Basin had ever been presented such that the hydrocarbon prospectivity of the basin had never been assessed in any detail.

3.0. The Bida Basin

While the overall focus of the study is on the Bida and Sokoto Basins, the present preliminary / pilot study focuses only on the Bida Basin. The Bida Basin is a NW-SE trending intracratonic structure extending from Kontagora in Niger State in the north to the area slightly beyond Lokoja in the south (Fig. 4). It is delimited in the NE and SW by the basement complex and merges with the Anambra and Sokoto Basins to the SE and NW respectively. Its sedimentary fill comprises post-orogenic molasse and thin unfolded marine sediments. The basin is a gently down-warped trough whose origin is closely connected with Santonian orogenic movements in SE Nigeria and the Benue valley. The basin trends perpendicular to the main axis of the Benue Trough and the Niger Delta Basin and is regarded as the NW extension of the Anambra Basin, both of which were major depocentres during the third major transgressive cycle in the Late Cretaceous.

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[13]Kogbe, C. A. 1979. Geology of the South-eastern (Sokoto) Sector of the lullemmeden Basin. *Dept. of Geology, Ahmadu Bello. University Zaria Bulletin* 32, 142pp; Kogbe, C. A. 1981a. "Continental terminal" in the Upper Benue Basin of north-eastern Nigeria. *Earth Evolution Series, Special Issue 1*, 149-153.; Kogbe, C. A. 1981b. Cretaceous and Tertiary of the Iullemmeden Basin of Nigeria (West Africa). Cretaceous Research 2, 129-186.

[14]Petters. S. W. 1982. Central West African Cretaceous-Tertiary benthic foraminifera and stratigraphy. Palaeontographica Abt. A 179, 1-104.

[15]Op. Cit

[16]Op.Cit

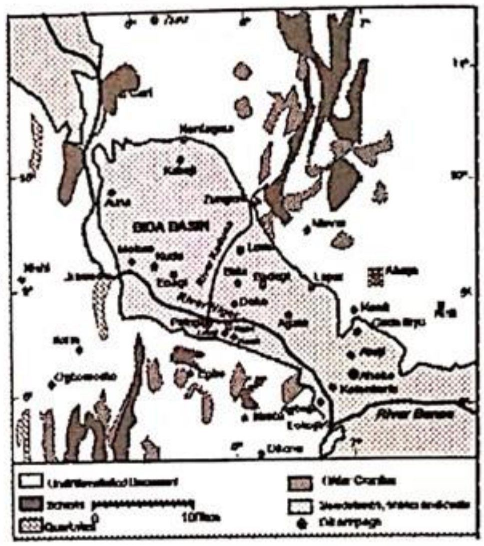
[17]Op. Cit. 13

[18]Op. Cit.

Fig. 4. Extent of Bida Basin.

Available geological maps of the Bida Basin have lumped the sedimentary formations into one undifferentiated Nupe Sandstone.

In this way it is not possible to infer prospectivity



The Bida Basin is generally subdivided into two portions, namely the Northern Bida Basin and the Southern Bida Basin. No concrete line of subdivision can be drawn but the boundary approximates the subdivision shown in Figure 5. In the Northern Bida Basin, four mappable lithostratigraphic units are recognized, namely, the **Bida Sandstone** (divided into the **Doko Member** and the **Jima Member**), the **Sakpe Ironstone**, the **Enagi Siltstone**, and the **Batati Formation**. These are correlatable with the stratigraphic units in the Southern Bida Basin (Fig. 6).

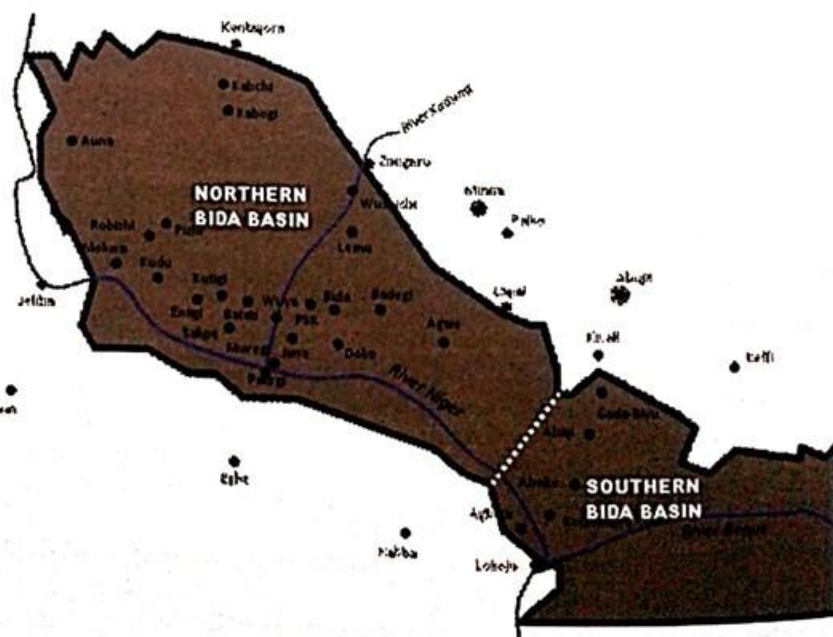


Fig. 5. Approximate boundary indication between the Northern Bida Basin and the Southern Bida Basin

In the Southern Bida Basin (which has been studied in more detail, e.g. Ladipo et al.[19]; Akande et al.,[20] exposures of sandstones and conglomerates of the **Lokoja Formation** directly overly the Pre-Cambrian to Lower Paleozoic basement gneisses and schists. This is overlain by the alternating shales, siltstones, claystones and sandstones of the **Patti Formation** (ca. 70–100 m thick in the Koton-Karfi and Abaji axis). The Patti Formation is succeeded by the claystones, concretionary siltstones and ironstones of the **Agbaja Formation**.

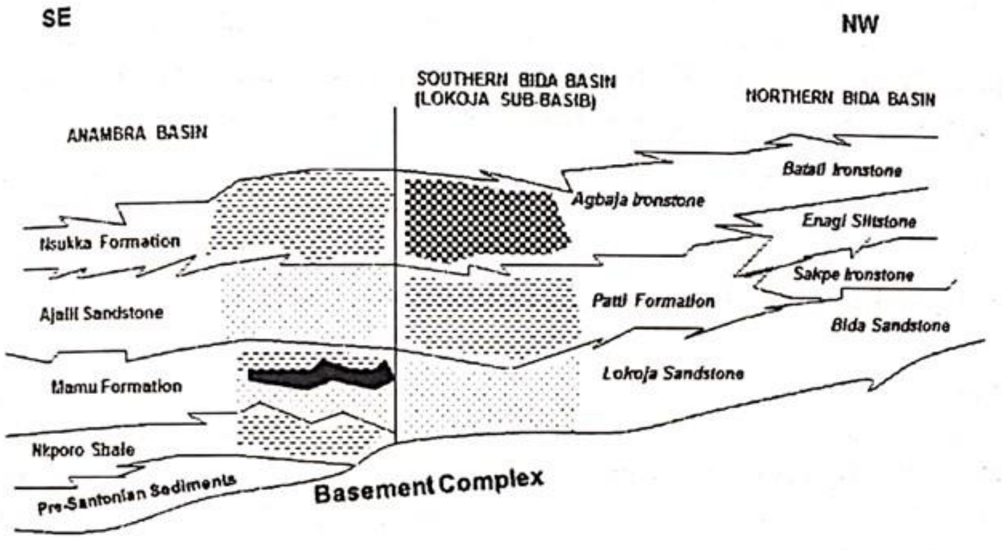


Fig. 6. The formations in the Nothern and Southern Bida Basin are correlatable with those in the Anambra Basin in the south-east.

4.0. Scope of Work and Methodologies Adopted

The scope of the preliminary work comprises geological mapping, sample collection, sample processing, data generation and data analyses. The methodologies adopted comprise:

- Fieldwork and stratigraphical sample collection.
- Preparation of a geological / prospectivity map.
- Petroleum geochemistry of some outcrop and shallow well samples.
- Geophysical aeromagnetic data acquisition and processing.

Apart from departmental laboratories at the Ibrahim Badamasi Babangida University, Lapai, laboratory facilities available at the Nasarawa State University, Keffi; Getamme Lab, Portharcourt; Geo-Forschung Research Centre, Potsdam, Germany; and at the Federal Institute for Geosciences and Natural Resources,

[19] Ladipo, K. O., Akande S. O. and Mucke, A. 1994. Genesis of ironstones from the Mid-Niger sedimentary basin: evidence from sedimentological, ore microscopic and geochemical studies. Journal of Mining and Geology 30, 161-168.
[20] Op. Cit

Hannover, Germany as well as facilities procured in the course of this project were used for this preliminary study. Funding for the project was provided overwhelmingly by the Niger State Government through the Gubernatorial Committee on Bida Basin Development (GCBBD).

Fieldwork and stratigraphical sample collection

Geological fieldwork and sample collection were carried out throughout the entire Bida Basin to produce a comprehensive geological map and to obtain good quality samples for analytical studies. Fresh outcrop samples and samples from drilled shallow wells at Agaie and Kudu were collected. Macrofossil assemblages as they occur on the field were used to validate the correlations of the rock units. Structural analyses were undertaken on the field. Anticlinorial cores were particularly targeted as they afforded opportunities to sample rock units that have been thrusted to the surface by tectonic processes and for which their equivalent units generally lie very deep down below the surface. The resultant geological map is used to construct subsurface cross-sections with the objective of delineating areas with thicker sediment piles.

The sampling design covered as much of the area as possible using road cuts and other exposed outcrops to collect stratigraphic samples. Rock types, bed thicknesses, textural features, sedimentary structures, structural features and depositional environments were recorded at every outcrop. The field study lasted 20 days, divided into transects of 10 days each in the months of December 2011 and February 2012.

Petroleum geochemistry

Organic geochemical analyses were carried out on selected outcrop and shallow well samples to provide information on organic richness, kerogen type and maturity of potential source rocks. The details include the followings:

Total Organic Carbon (TOC) analysis to determine the level of organic matter richness (quantity): have they met the minimum limit for hydrocarbon generation?

Rock Eval pyrolysis for the determination of the Hydrogen Indices (HI), Oxygen Indices (OI), Production Indices (PI) and Tmax as a measure of the organic matter quality: If quantity has met the minimum limit, what type of hydrocarbon would be generated? Oil or gas? The Tmax is the measure of the organic matter maturity: Where does the maturity fall with relative to oil generation window? Immature for oil generation, mature for oil generation or overcooked for oil generation?

The geochemical analyses were undertaken at Getamme Geochemistry Laboratory in Port-Harcourt.

Geophysical aeromagnetic data acquisition and processing

Aeromagnetic maps of sheets covering the Bida Basin were acquired from the Nigerian Geological Survey Agency. The maps were processed to determine probable depths to basement, basement topography and buried magnetic materials. The field magnetic data were processed using mathematical operations of the 'Fast Fourier transform' (FFT) algorithm, which is a precursor of spectral analysis. Further processing of the aeromagnetic data / maps was undertaken using the GEOSOFT software to convert the aeromagnetic raw data to depths to basement on a colour index scale.

5. 0. Results and Interpretations

Geological Mapping and Preparation of Prospectivity Map

The preliminary geological mapping undertaken reveals some details of the composition and aerial extent as well as the inferred boundaries of the formations in the Bida Basin. All previous geological maps available on the Bida Basin have lumped the sediments in the basin as one undifferentiated Nupe Sandstone, making it impossible to infer the prospectivity of the basin for hydrocarbon exploration and acreage assessment. The delineation of inferred boundaries between the formations in the basin is a significant initial criterion in evaluating the hydrocarbon prospectivity. The geological mapping exercises have identified the four lithostratigraphic formations in the Northern Bida Basin and the three in the Southern Bida Basin as discussed and interpreted bellow.

Northern Bida Basin

The Bida Sandstone

The Bida Sandstone is divisible into two members, namely the Doko Member and the Jika Member. The Doko Member is the basal unit and consists mainly of very poorly sorted pebbly arkoses, sub-arkoses and quartzose sandstones. These are thought to have been deposited in a braided alluvial fan setting[21]. The Doko Member underlies the Jima Member, and the two rock units show gradational relationships. They both contain sandstones, breccias and argillaceous rocks in varying proportions. The sandstones of the Doko Member are arkosic to quartzose, generally poorly sorted, with angular to sub-angular grains. Massive appearance is common. Wave ripples (ripple marks) and large scale cross beddings are very prominent in the Doko Member

[21] Braide, S. P. 1992a. Geologic development, origin and energy mineral resource potential of the Lokoja Formation in the southern Bida Basin. Journal of Mining and Geology 28, 33–44.

at Doko village (Fig. 7). Bioturbution structures consisting mainly of *Thallasinoides* and *Ophiomorpha* burrows exist within the Doko Member indicating some occasional marine inundations into the generally braided fluvial channel deposits of the Doko Member. Thick to very thick flat-bedding and localised cross-stratifications are also present. Many of the coarser quartz grains commonly show smooth, flat surfaces giving the impression of vein quartz. The quartz and feldspar grains are irregular, rod-like or roughly tabular. The arkosic sandstones are the basal units exposed. They are commonly medium to very coarse and pebbly. The sorting is fair to poor. The arkoses are often mottled: brown, yellow, grey and pink. They are interbedded with finer-grained lithic feldspathic and feldspathic sandstones. Very poorly sorted, very coarse to fine argillaceous and pebbly quartzose sandstones and subsidiary subgreywacke, however, dominate the subfacies. They succeed and grade into the basal arkoses. Some are friable, medium to very coarse and pebbly, whereas others are hard, medium to very fine, argillaceous and poorly sorted. Several paleo-channels exist in the Doko Sandstone subfacies. The channel-filling contrasts with the underlying beds. Some spherical to sub-spherical masses of coarse argillaceous sandstones with occasional quartz pebbles in the outer areas occur locally. Siltstone and mudstone pebbles, and some thin, indurated, ferruginized, dark-brown sandstone bands are present in several localities.

Fig. 7. Mapping and logging of the Bida Sandstone (Doko Member) at Doko village near Bida

The Jima Member is dominated by cross-stratified quartzose sandstones, siltstones and claystones. Trace fossils comprising mainly *Ophiomorpha* burrows and *Thallasinoides* occur abundantly in the Jima Member (Fig. 8) suggesting a possible shallow marine subtidal to intertidal influence during sedimentation. The Jima Sandstone Member is considered as the more distal equivalent of the upper part of the Lokoja Sandstone, where similar features also occur. Planar and tabular cross-beddings occur in many horizons of the Jima Member.

Sediments of the Bida Sandstone occupy the flanks of the basin (Fig. 18) and they were mapped in detail at Bida, Doko, Jima and Baro. Areas covered by the Bida Sandstone are assumed to be the shallowest in terms of sediment thickness and constitute the "highs" or horst structures and are presumably the least prospective.

Fig. 8. Highly bioturbated coarse grained sandstones of the Bida formation (Jima Member) exposed at Jima. The bioturbation burrows are very significance to increasing reservoir porosity and permeability.

The Sakpe Formation

The Sakpe Formation comprises mainly oolitic and pisolitic ironstones (Fig. 9) with sandy claystones locally, at the base, followed by dominantly oolitic ironstone which exhibits rapid facies changes across the basin, at the top. Exposures of the Sakpe

Formation are rarely encountered in the basin; however, prominent outcrops and exposures of the Sakpe Formation occur in the village of Sakpe. The Sakpe Formation is the least geologically exposed as can be seen from the geological map in Figure 18.

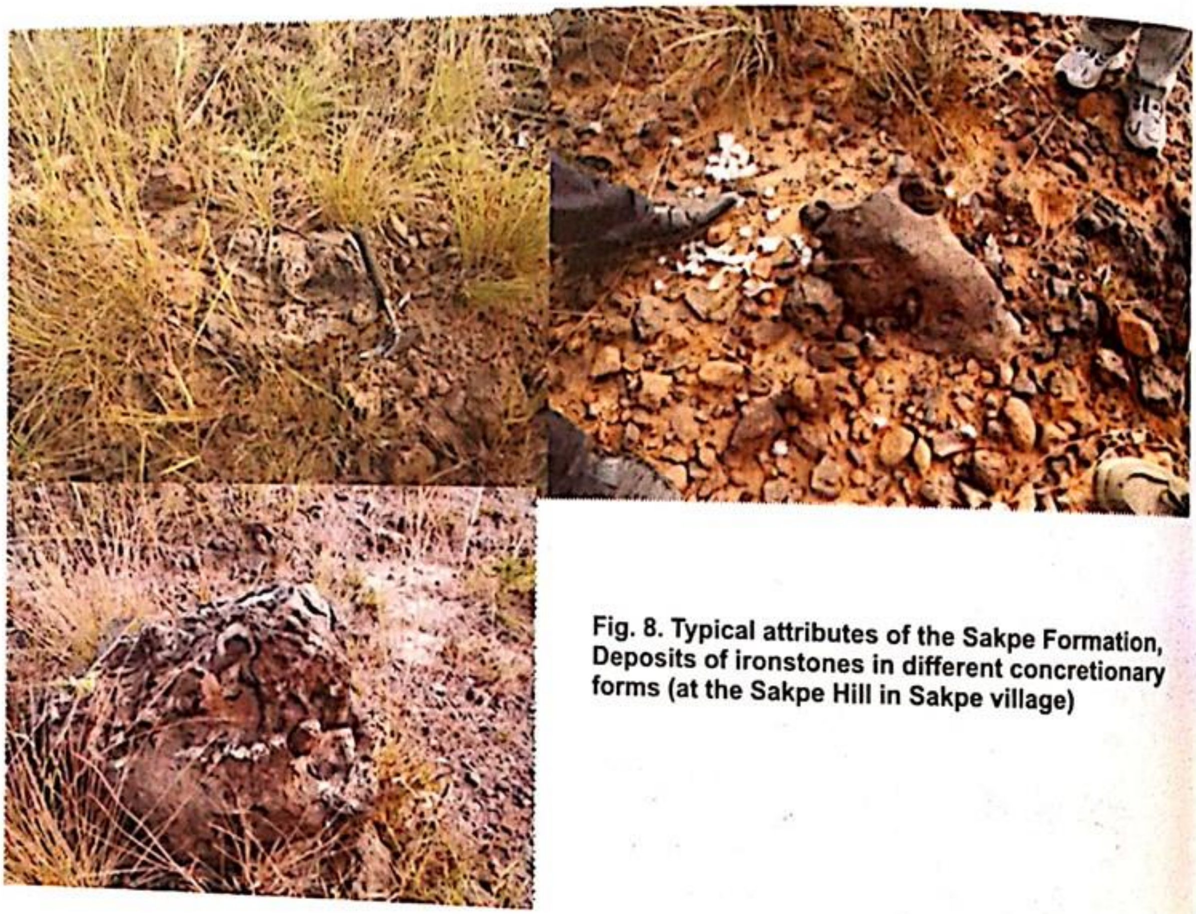


Fig. 8. Typical attributes of the Sakpe Formation, Deposits of ironstones in different concretionary forms (at the Sakpe Hill in Sakpe village)

The Enagi Siltstone

The Enagi Siltstone consists mainly of siltstones and correlates with the Patti Formation in the Southern Bida Basin. The siltstones are generally whitish to grey-white in colour and well-sorted, typified by those occurring within and around the town of Batati (Fig. 10). Other subsidiary lithologies include sandstone-siltstone admixture and in some places with abundant massive claystones. Fossil leaf impressions and rootlets occur occasionally within the formation. The formation ranges in thickness of between 30m and 60m. Mineral assemblage consists mainly of quartz, feldspars and clay minerals.

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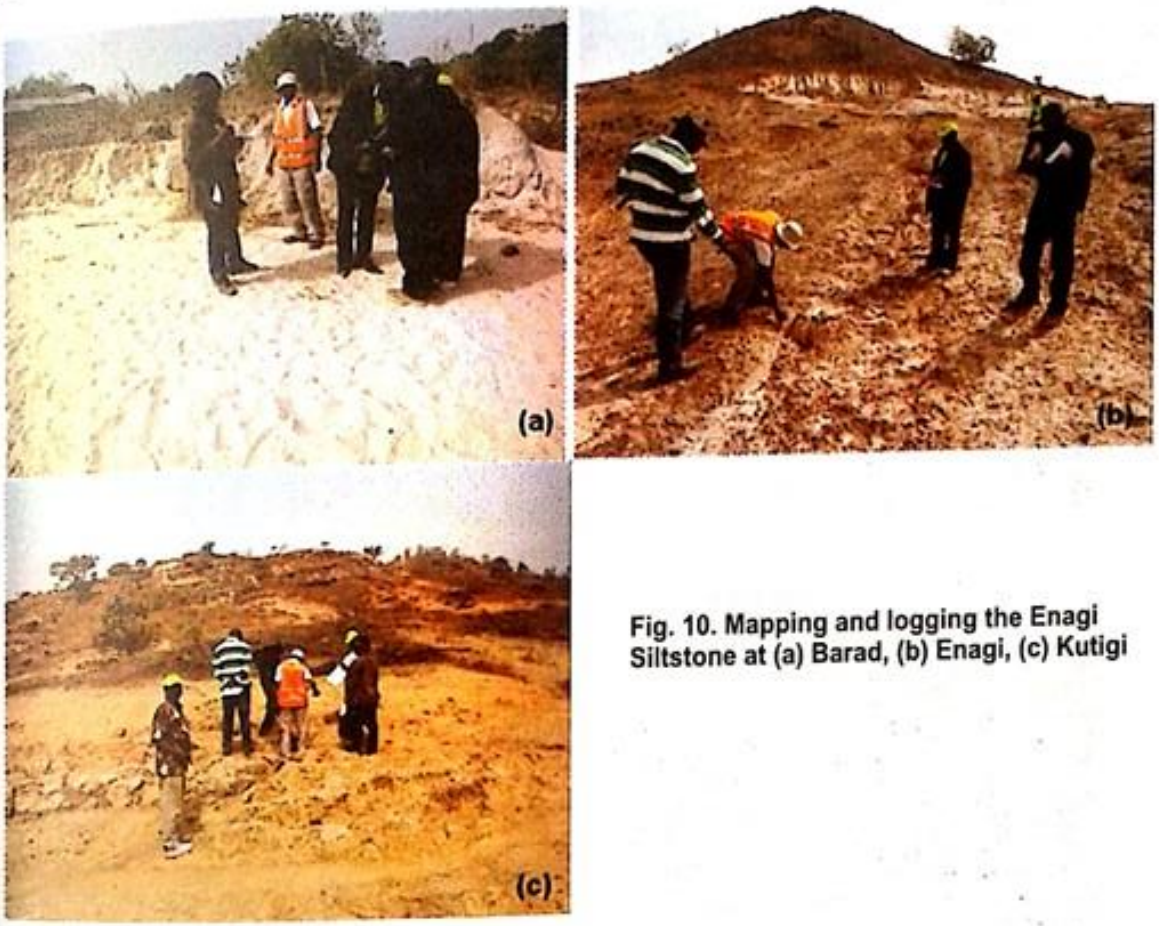

Fig. 10. Mapping and logging the Enagi Siltstone at (a) Barad, (b) Enagi, (c) Kutigi

Bioturbation structures are rarely encountered within the Enagi Formation but foraminiferal recovery indicates that the Enagi Formation is of shallow marine environments in most parts. The Enagi Formation correlates with the Patti Formation in the Southern Bida Basin. The Enagi Formation encompasses the Kudu Shale (Kudu Shale Member), a dark-grey, black shale unit (Fig. 11) envisaged to be the potential source rock for hydrocarbons that might have been generated in the Bida Basin. The Kudu Shale on the other hand correlates with the Ahoko Shale in the Southern Bida Basin. The Kudu Shale occurs generally in the sub-surface in the Northern Bida Basin. A shallow well drilled to a depth of 70m at Kudu village for the purpose of sample collection encountered the Kudu shales at a depth of 30m and continued up to the 70m end-depth (Fig. 11). A similar well drilled at Agaie indicates that the Kudu Shale occur at a depth below 70m as it was not encountered throughout the 70m depth (Fig. 12).

The Enagi Formation covers more than 70% of the surface area of the Bida Basin (see geological map) and most parts covered by the formation are expected to be prospective, at least more prospective than the areas covered by the Bida Sandstone and less prospective than the "sink" areas covered by the Batati Formation (see geological/prospectivity maps and cross-sections). In this study, the Enagi Formation was mapped and logged in detail at Agaie, Batati, Enagi, Kutigi, Mushegu, Kandi and Enwan.

Fig. 11. Dark-black carbonaceotis shales (Kudu Shale Member) from shallow well drilled at Kudu

Fig. 12. The shallow well drilled at Agale did not encounter the Kudu shales

The Batati Formation

This Batati Formation constitutes the uppermost units in the sedimentary sequence of the Northern Bida Basin. The Batati Formation consists of argillaceous, oolitic and goethitic ironstones (Fig. 13) with ferruginous claystone and siltstone intercalations and shaley beds occurring in minor proportions, some of which have yielded nearshore shallow marine to fresh water fauna[22]. The sporadic occurrences of surface exposures of the Batati Formation and its tight contoural relationship to the Enagi and Bida Formations wherever it occurs show that the Batati Formation occupies "rifted

[22] Adeleye, D. R. 1974. Sedimentology of the fluvial Bida Sandstones (Cretaceous), Nigeria. Sedimentary Geology 12, 1-24.

sinks" (grabens). These areas present the thickest sediment piles and consequently the most prospective for hydrocarbons in term of sediment thickness in the Bida Basin. Although these areas may be interpreted as synforms, they are actually rifted structures, where the Batati Formation remains deposited in the grabens and eroded on the horsts.

The Batati Formation was mapped and logged in detail at Pattishabakolo and Edozighi (near Bida) and at Kandi and Enwan (near Gulu).

Fig. 13. Sections of the Barad Formation exposed on the road from Bida to Pattishabakolo (a, b); and at Kandi near Gulu (c).

Southern Bida Basin

The Lokoja Formation

Lithologic units in this formation range from conglomerates, coarse to fine grained sandstones, siltstones and claystones in the Lokoja area (Fig. 14). Subangular to subrounded cobbles, pebbles and granule sized quartz grains in the units are frequently distributed in a clay matrix. Both grain-supported and matrix-supported conglomerates form recognizable beds at the base of distinct cycles at outcrops. The sandstone units are frequently cross-stratified, generally poorly sorted and composed mainly of quartz and feldspar and are thus texturally and mineralogically immature. The general characteristics of this sequence especially the fining upward character, compositional and textural immaturity and unidirectional paleocurrent trends, suggest a fluvial depositional environment dominated by braided streams with sands deposited as channel bars consequent to fluctuating flow velocity. The fine grained sandstones, siltstones and clays represent flood plain overbank deposits. However, Petters[23] reported the occurrence of some low diversity arenaceous foraminifera from clayey intervals of the Lokoja Formation indicating some shallow marine influence. These foraminiferal microfossils identified by Petters[24] are however more common in the overlying Patti Formation where shallow marine depositional conditions are known to have prevailed more.

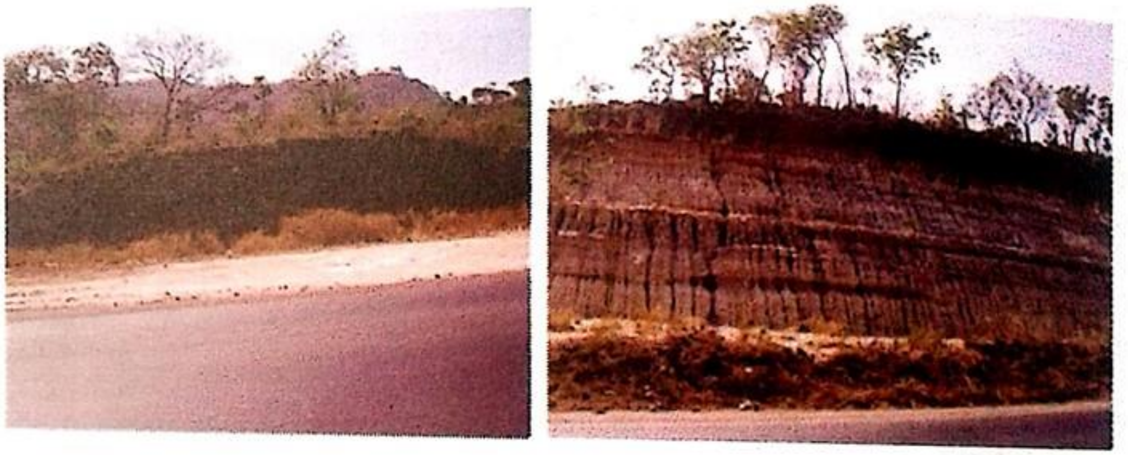

Fig. 14. Basal conglomerates (0) and poorly sorted muddy sandstones of the Lokoja Formation exposed 1 Km from the Lokoja-NATACO junction on the Lokoja - Abuja expressway

The Lokoja Formation, which correlates with the Bida Formation, occurs mainly in the areas from Lokoja up to Kotonkarfe. These areas have the same prospectivity interpretation as the areas covered by the Bida Sandstone.

The Patti Formation

Outcrops of the Patti Formation occur between Kotonkarfe and Gada-Biyu (Fig. 15). This formation consists of sandstones, siltstones, claystones and shales interbedded with bioturbated ironstones. Argillaceous units predominate in the central parts of the basin. The siltstones of the Patti Formation are commonly parallel stratified with occasional soft sedimentary structures (e.g. slumps), and other structures such as wave ripples, convolute laminations, load structures. Trace fossils (especially *Thallasinoides*) are frequently preserved. Interbedded claystones are generally massive and kaolinitic, whereas the interbedded grey shales are frequently carbonaceous. The subsidiary sandstone units of the Patti Formation are more texturally and mineralogically mature compared with the Lokoja sandstones. The predominance of argillaceous rocks, especially siltstones, shales and claystones in the

[23]Petters, S. W. 1986. Foraminiferal biofacies in the Nigerian rift and continental margin deltas. In: Oti, M. N. and Postma, G. (Eds.), Geology of Deltas. AA Balkema, Rotterdam, pp219-235.

[24]Ibid.

Patti Formation requires suspension and settling of finer sediments in a quiet low energy environment probably in a restricted body of water[25]. The abundance of woody and plant materials comprising mostly land-derived organic matter, suggests prevailing fresh water conditions. However, biostratigraphic and paleoecologic studies by Petters[26] have revealed the occurrence of arenaceous foraminifera in the shales of the Patti Formation with an assemblage of *Ammobaculites, Milliamina, Trochamina* and *Textularia* which are essentially cosmopolitan marsh species similar to those reported in the Lower Maastrichtian marginal marine Mamu Formation (the lateral equivalent) in the adjacent Anambra Basin[27]. The Patti Formation therefore appears to have been deposited in marginal shallow marine to brackish water condition identical to the depositional environments of similar lithologic units of the Mamu and Ajali Formations in the Anambra Basin[28].

The Patti Formation encompasses the Ahoko Shale (Ahoko Member), a dark-grey, black shale unit (Fig. 16) envisaged to be, along with the Kudu Shale, the potential source rock for any hydrocarbons that might have been generated in the Bida Basin. The Ahoko Shale in the Southern Bida Basin correlates with the Kudu Shale in the Northern Bida Basin. Outside the outcrops / sections of the Patti Formation which occur along road-cuts from Kotonkarke – Gada-Biyu on the Lokoja – Abuja Expressway, the Patti Formation is also excellently exposed at Gerinya on the GeguBeki – Muye – Gulu road (Fig. 17).

The Agbaja Formation

The Agbaja Formation forms a persistent cap for the Campanian - Maastrichtian sediments in the Southern Bida Basin as a lateral equivalent of the Batati Formation in the Northern Bida Basin. The formation consists of sandstones and claystones interbedded with oolitic, concretionary and massive ironstone beds in this region. The sandstones and claystones are interpreted as abandoned channel sands and overbank deposits influenced by marine reworking to form the massive concretionary and

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[25] Braide, S. P. 1992c. Alluvial fan depositional model in the northern Bida Basin. Journal of Mining and Geology 28, 65–73.

[26] Op. Cit

[27] Gebhardt, H. 1998. Benthic foraminifera from the Maastrichtian Lower Mamu Formation near Leru (Southern Nigeria): paleoecology and paleogeographic significance. Journal of Foraminiferal Research 28, 76–89.

[28] Ladipo, K. O. 1988. Paleogeography, sedimentation and tectonics of the Upper Cretaceous Anambra Basin, south-eastern Nigeria. Journal of African Earth Sciences 7, 865–871.; Adeniran, B. V. 1991. Maastrichtian tidal flat sequences from the northern Anambra Basin, Southern Nigeria. Nigerian Association of Petroleum Explorationists (NAPE) Bulletin 6, 56–66.; Nwajide, C. S. and Reijers, T. J. A. 1996. Sequence architecture in outcrops: examples from the Anambra Basin, Nigeria. Nigerian Association of Petroleum Explorationists Bulletin 11, 23–33.

oolitic ironstones observed[29]. Minor marine influences were also reported to have inundated the initial continental environment of the upper parts of the Lokoja Sandstone and the Patti Formation[30]. The marine inundations appear to have continued throughout the period of deposition of the Agbaja ironstones in the Southern Bida Basin.

The sporadic occurrences of surface exposures of the Agbaja Formation, just like the Batati Formation, and its equally tight contoural relationship to the Patti and Lokoja Formations wherever it occurs show that the Agbaja Formation occupies "rifted sinks" (grabens) in the Southern Bida Basin. These areas, just like in the Northern Bida Basin, present the thickest sediment piles and consequently the most prospective for hydrocarbons in the Southern Bida Basin (see geological / prospectivity map). Although these areas may be interpreted as synforms, they are actually rifted structures, where the Agbaja Formation remains deposited in the grabens and eroded on the horsts.

On the basis of the geological mapping and identification of the different formations in the basin as discussed above, the first complete geological map of the Bida Basin has been prepared as shown in Figure 18.

[29] Ladipo, K. O., Akande S. O. and Mucke, A. 1994. Genesis of ironstones from the Mid-Niger sedimentary basin: evidence from sedimentological, ore microscopic and geochemical studies. Journal of Mining and Geology 30, 161-168

[30] Braide, S. P. 1992b. Syntectonic fluvial sedimentation in the central Bida Basin. Journal of Mining and Geology 28, 55–64.; Olaniyan, O. and Olobaniyi, S. B. 1996. Facies analysis of the Bida Sandstone Formation around Kajita, Nupe Basin, Nigeria. Journal of African Earth Sciences 23, 253–256.

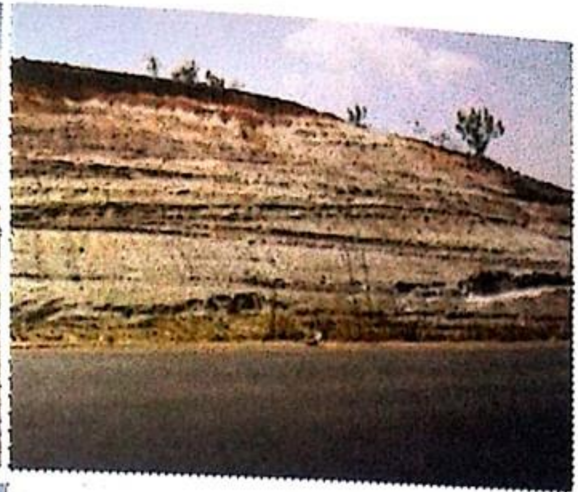

Fig. 15. Patti Formation sections exposed between Kotonkarfe and Gada-Biyu
(a) Flood plain siltstone deposits near Ahoko
(b) Channel sandstones at Abaji
(c) Flood plain claystone and siltstone deposits at Gada-Biyu

Fig. 16. Dark-grey, black shales of the Ahoko Shale Member (Patti Formation) exposed at a Quarry to Ahoko on the Lokoja-Abuja express (envisaged source rock in the Bida Basin equivalent to the Kudu Shale Member)

Fig. 17. Mapping and logging the Patti Formation (Enagi Formation equivalent) at Gerinya, near Gegu-Baki

Interpretation of Prospectivity Map

The prospectivity interpretable from the geological map in Figure 18 shows that th Bida Basin is made up horst and graben structures, whereas the deepest grabens li bellow the Batati and Agbaja Formation outliers. These outliers which may b considered as "geological bright-spots" represent the most prospective areas in th Bida Basin. Pattishabakolo, Edozighi, Kandi and Enwan make up the localities withi these geological bright-spots in the Northern Bida Basin (Fig. 19), whereas Agba and some localities around Gegu-Beki constitute the geological bright-spots in th Southern Bida Basin (Fig. 20).

Most of the areas covered by the Enagi and Patti Formations are presumed to be relatively moderate depth to basement, with the depth increasing towards the cent of the basin (Fig. 21). These areas are prospective in terms of sediment thickness b relatively less prospective than those areas covered by Batati / Agbaja Formations b more prospective than the areas covered by the Bida Sandstone. Such prospecti areas include localities around Adogo, Pizhi, Duba, Kachegi, Kutigi, Ndaba, Bade Agaie, Gulu, Muye, Gerinya, Abaji, Ahoko and Gegu-Beki.

The least prospective areas are those localities covered by the Bida Sandstone. Th least prospective areas include Bida, Doko, Jima, Baro, Wushishi, Pategi, Kotonka and Lokoja (Fig. 18).

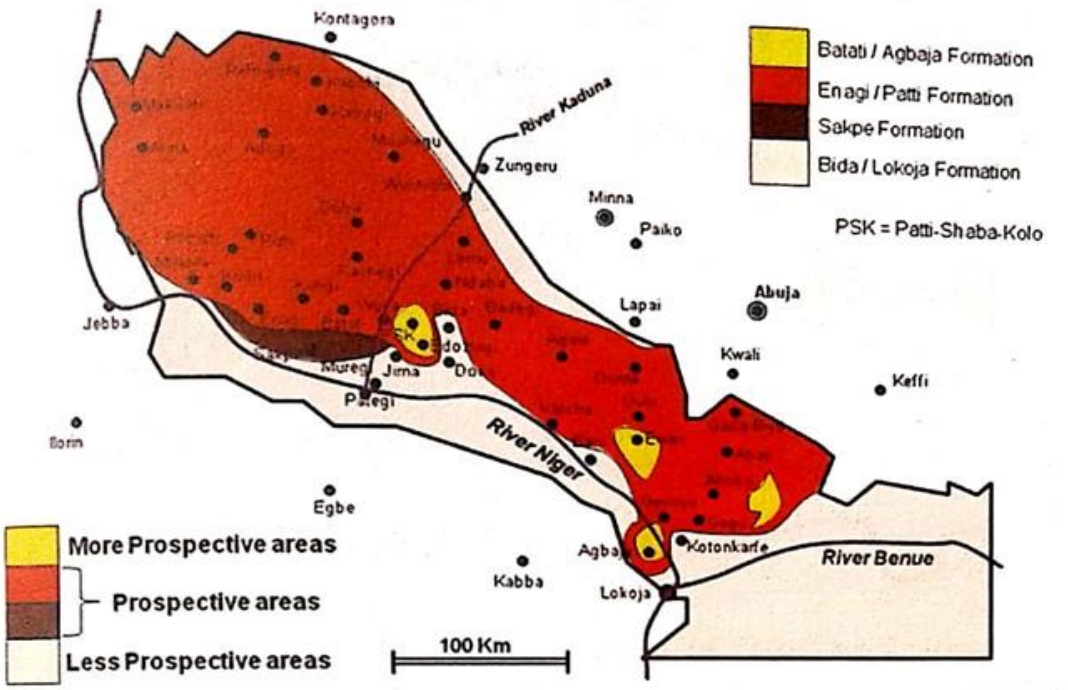

Fig. 18. Constructed preliminary geological map of the Bida Basin based on the surface geological mapping.

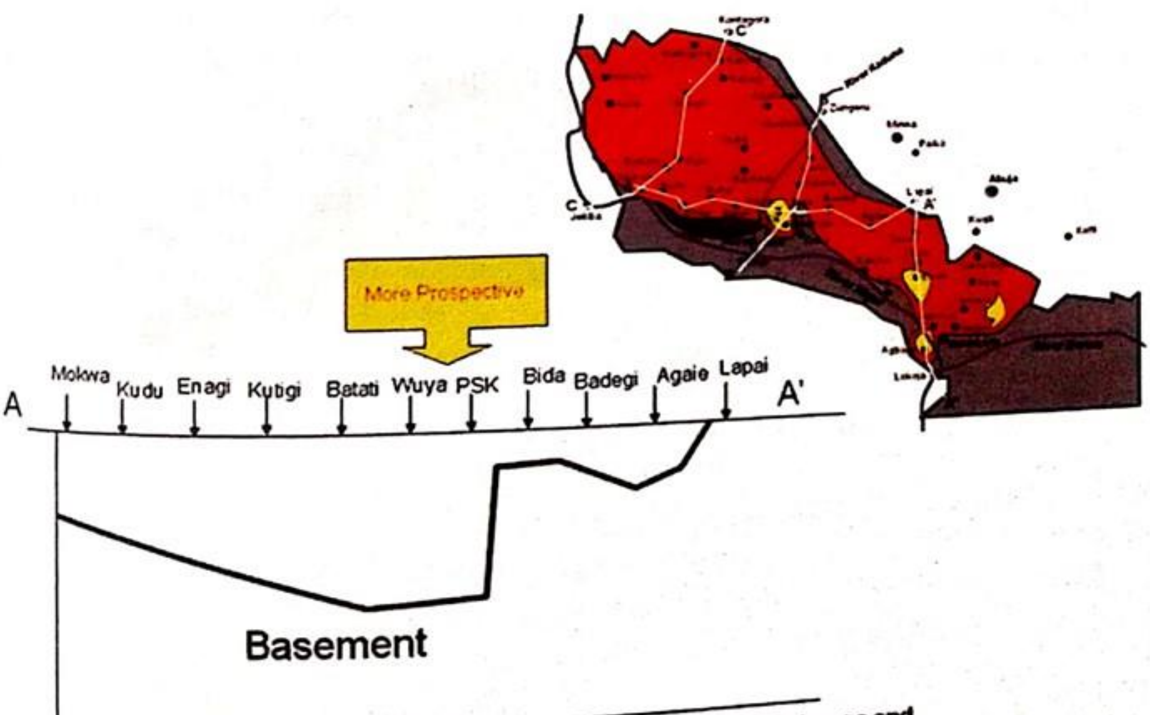

Fig. 19a. Estimated subsurface topography, relative sediment thickness and delineation of prospective areas for the section A-A': Mokwa - Lapai

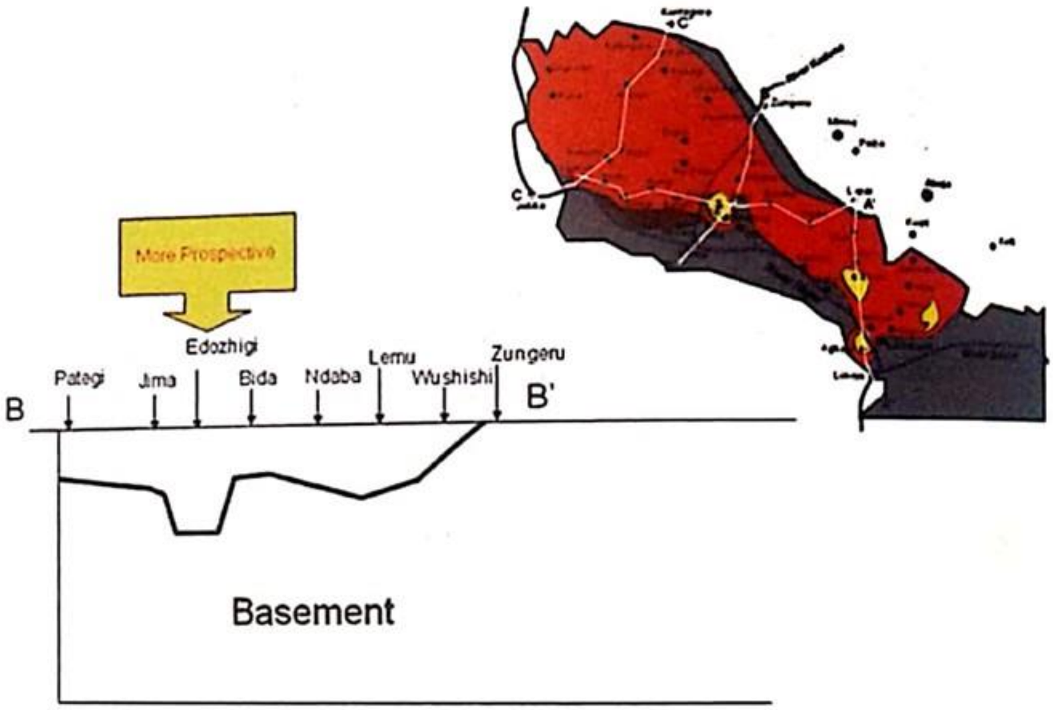

Fig. 19b. Estimated subsurface topography, relative sediment thickness and delineation of prospective areas for the section B-B': Pategi - Zungeru

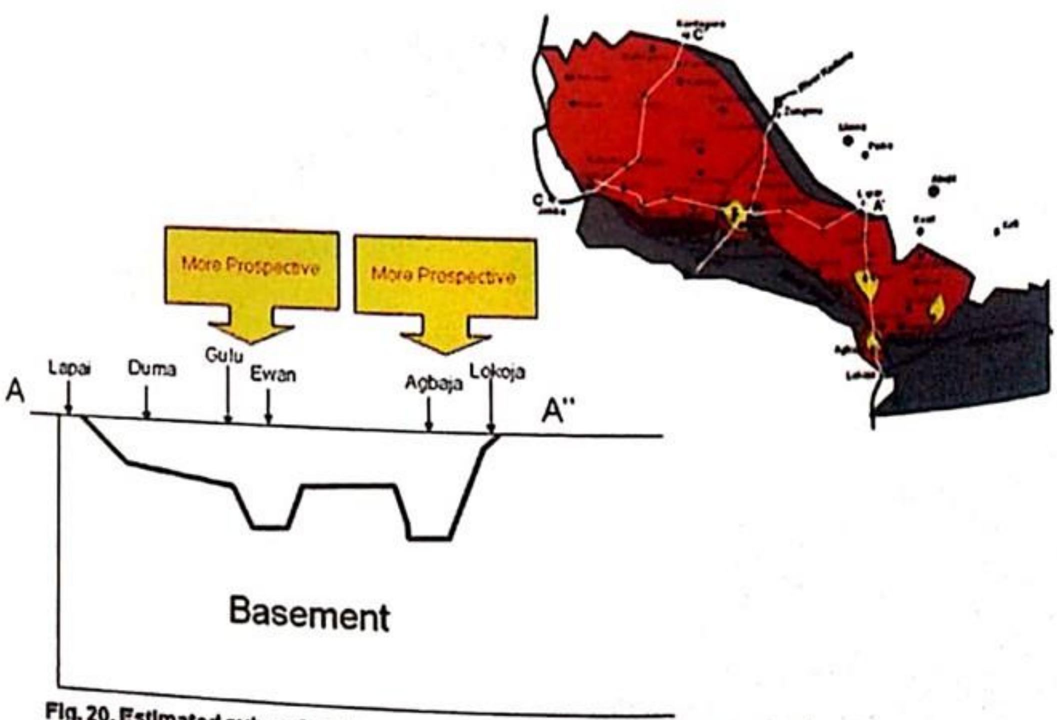

Fig. 20. Estimated subsurface topography, relative sediment thickness and delineation of prospective areas for the section A-A': Lapai - Lokoja

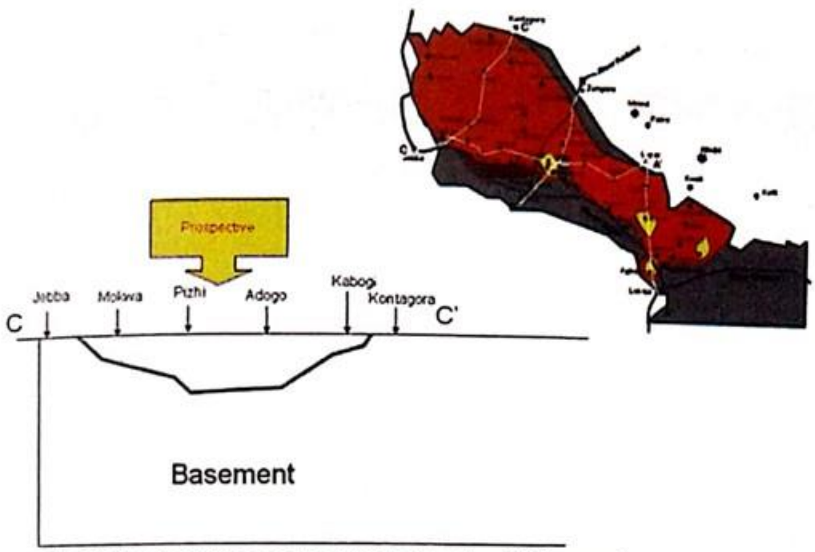

Fig. 21. Estimated subsurface topography, relative sediment thickness and delineation of prospective areas for the section C-C': Jebba - Kontagora

Geochemical Data

Table 1 shows the Rock-Eval pyrolysis results of some representative samples obtained from shallow wells drilled in Agaie and Kudu within the Northern Bida Basin and from outcrop sections at Ahoko in the Southern Bida Basin. Eighty five percent (85%) of the samples have TOC values of more than 0.5wt%, the minimum limit required for hydrocarbon generation (Fig. 22). All samples from the Agaie well (Enagi Formation, sandy units) have no potential to generate hydrocarbons. The Kudu Shale, which is expected to be the major source rock in the Northern Bida Basin, lies probably still deeper down than the 70m depth penetrated by the Agaie well.

Based on hydrogen indices (HI) evaluation, 40% the hydrocarbon generated in the Bida Basin would be gas, 35% oil and gas and 5% oil (Fig. 23). Twenty percent (20%) have no potential to generate any hydrocarbons. Based on Petters[31] and Obaje et al.[32], source rocks with minimal thermal maturity of Tmax 435 degree C and HI of 300 mgHC/gTOC and above will generate oil; those with HI between 300 and 150 will produce oil and gas; those with HI between 150 and 50 will produce gas; and those with HI less than 50 have no hydrocarbon generative potential.

On the above assumption, juxtaposition of the HI against the Tmax (thermal maturity) (Fig. 24) shows that the source rocks in the Bida Basin are below the entrant of the oil window (slightly immature to early mature). The diagram, however, represents results on samples obtained at the surface to maximum 70m depth. It is expected that at depths where oil generation and entrapment would take place (2000-4000m), the source rocks would have entered the oil window, whereby majority would be in the gas and oil and gas zones (Fig. 24).

[31] Op. Cit

[32] Op. Cit; Also Obaje, N. G. 2009. Geology and Mineral Resources of Nigeria. Springer, Heildelberg,

Table 1. Rock Eval pyrolysis results of some selected samples from the Bida Basin

Client ID	Sample Type	Leco TOC	RE			Tmax (°C)	HI	OI	S2/S3	S1/TOC *100	PI
			S1	S2	S3						
Agaie 30	Well	0.08	0.05	0.08	0.28	403	96	337	0.3	60	0.38
Agaie 38	Well	0.07	0.06	0.11	0.24	342	149	324	0.5	81	0.35
Agaie 40	Well	0.07	0.03	0.09	0.44	404	138	677	0.2	46	0.25
Ahoko 11(c)	Outcrop	1.84	0.04	0.76	1.00	419	41	54	0.8	2	0.05
Ahoko 13 (A)	Outcrop	1.90	0.05	0.48	1.28	416	25	67	0.4	3	0.09
Ahoko 17 (A)	Outcrop	2.40	0.06	1.83	1.23	423	76	51	1.5	2	0.03
Ahoko 19 (B)	Outcrop	2.56	0.08	2.10	1.02	425	82	40	2.1	3	0.04
Ahoko 1 (A)	Outcrop	0.70	0.03	0.29	0.24	418	41	34	1.2	4	0.09
Ahoko 3 (B)	Outcrop	1.60	0.05	0.85	0.88	418	53	55	1.0	3	0.06
Ahoko 9 (D)	Outcrop	1.23	0.04	0.37	0.39	416	30	32	0.9	3	0.10
Kudu 30	Well	2.41	0.12	3.78	0.82	424	157	34	4.6	5	0.03
Kudu 36	Well	54.19	0.52	77.24	8.64	386	143	16	8.9	1	0.01
Kudu 38	Well	1.45	0.08	2.41	0.53	425	167	37	4.5	6	0.03
Kudu 51	Well	4.62	0.24	18.59	1.10	430	402	24	16.9	5	0.01
Kudu 53	Well	38.09	1.54	102.17	6.60	413	268	17	15.5	4	0.01
Kudu 54	Well	21.28	0.77	57.07	4.81	418	268	23	11.9	4	0.01
Kudu 56	Well	12.84	0.49	32.61	3.17	422	254	25	10.3	4	0.01
Kudu 60	Well	1.82	0.11	3.56	0.46	422	195	25	7.7	6	0.03
Kudu 65	Well	0.67	0.05	0.72	0.34	427	108	51	2.1	7	0.06
Kudu 71	Well	0.73	0.07	1.54	0.57	429	212	79	2.7	10	0.04

Notes:
"-1" – not measured or invalid value for Tmax
TOC - Total Organic Carbon, wt. %
S1 - volatile hydrocarbon (HC) content, mg HC/ g rock
S2 - remaining HC generative potential, mg HC/ g rock
S3 - carbon dioxide content, mg CO2 / g rock

* - comments regarding contamination
** - low S2, Tmax is unreliable
Meas. %Ro - measured vitrinite reflectance
HI - Hydrogen index = S2 x 100 / TOC, mg HC / g TOC
OI - Oxygen Index = S3 x 100 / TOC, mg CO2 / g TOC
PI - Production Index = S1 / (S1+S2)

Pyrogram:
f - flat S2 peak
n - normal
ltS2sh - low temperature S2 shoulder
htS2sh - high temperature S2 shoulder
ltS2p - low temperature S2 peak
htS2p - high temperature S2 peak

LECO – TOC on Leco Instrument
RE - Programmed pyrolysis or TOC on Rock-Eval instrument
SRA – Programmed pyrolysis by SRA Instrument
EXT - Extracted Rock
NOPR - Normal Preparation

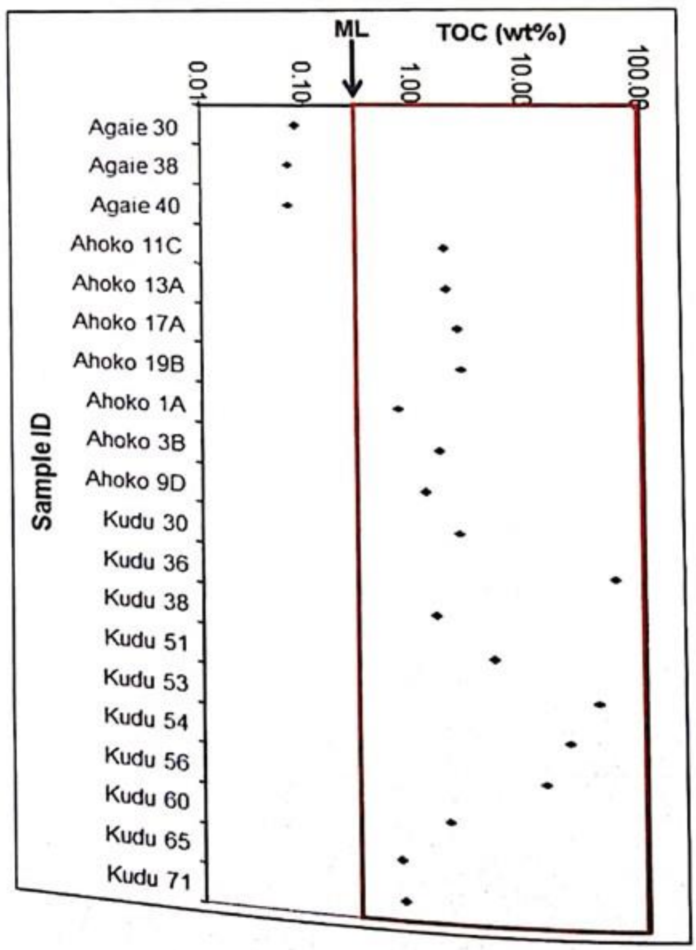

Fig. 22. Plot of TOC values against samples from the Bida Basin. Agaie and Kudu samples are from shallow wells with the numbers against them indicating the depth in meters. Ahoko samples are from outcrop. All the samples from Ahoko and Kudu have met the minimum TOC value limit for hydrocarbon generation (making up 85% of all the samples).

ML = Minimum limit for hydrocarbon generation.

TOC = Total Organic Carbon.

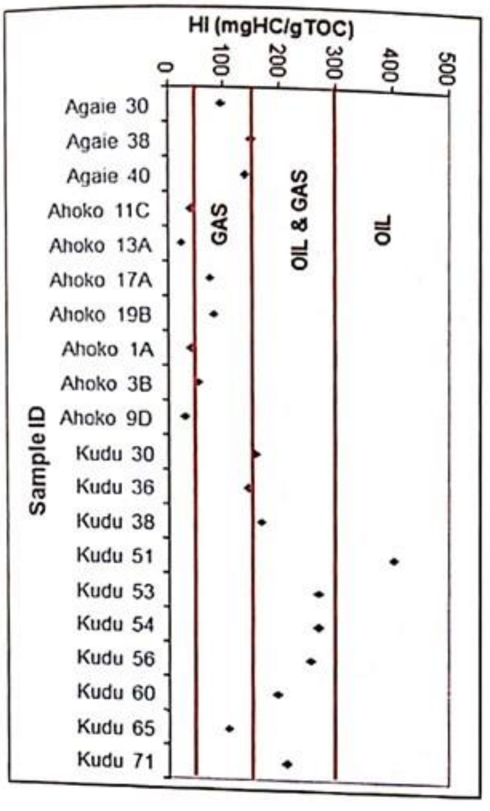

Fig. 23. Plot of HI values against samples from the Bida Basin. Majority of the samples plot within the Gas and Oil & Gas fields.

HI = Hydrogen Index

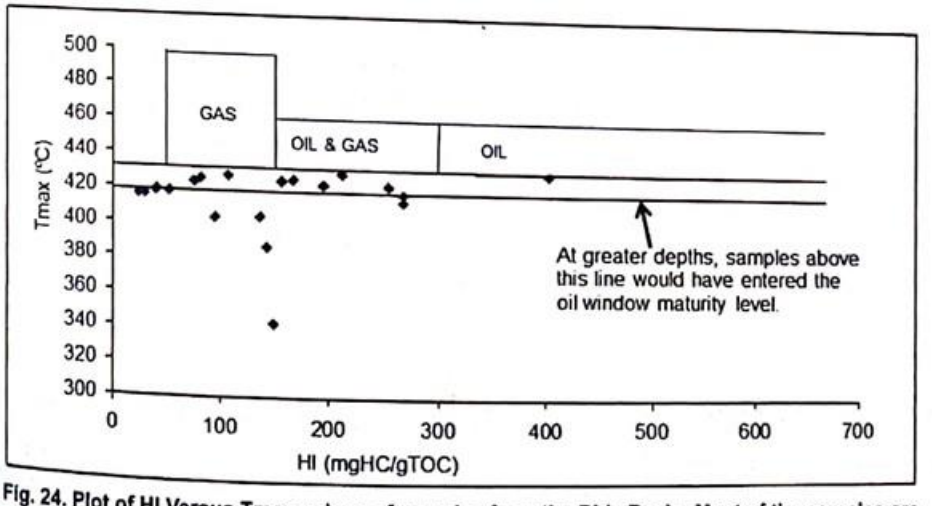

Fig. 24. Plot of HI Versus Tmax values of samples from the Bida Basin. Most of the samples are late immature to early mature (early oil window). At greater depths, most of the samples would have entered maturity in the Gas and Oil & Gas fields.

Geophysical Aeromagnetic Data

The geophysical aeromagnetic data comprised the raw data (acquired/purchased from the Nigerian Geological Survey Agency – NGSA) (Fig. 25) and the processed and interpreted data that shows the depth to basement in colour index (Fig. 26). Raw data were obtained on most of the sheets (individually) covering the sedimentary cover of the Bida Basin and merged together for a composite interpretation. The results of the aeromagnetic processing and interpretations have assisted to refine and redefine the earlier geologically postulated prospective areas. Aeromagnetic geophysical measurements normally target magnetic materials (magnetic minerals and rocks), which are normally most abundant in basement rocks and least in sedimentary rocks. Most interpretations assume zero value for sedimentary cover, such that lesser values are interpreted for deeper lying basement and higher values for near-surface basement or higher concentration of magnetic minerals (magnetic, haematite, ironstones, etc). For this reason, the aeromagnetic data for the Bida Basin must be carefully juxtaposed against the geological map. This is so because the Bida Basin is the only sedimentary basin in Nigeria with abundant ironstones in the formational lithologies (Sakpe Ironstone, Batati Ironstone, Agbaja Ironstone; with the other formations also containing significant amount of ferruginous components). Data over these areas may be interpreted as near-surface basement whereas the high magnetic values may be as a result of thick sections of sedimentary ironstones.

Preliminary interpretation of the geophysical aeromagnetic data over the Bida Basin agrees generally with the geological mapping interpretation, except that the aeromagnetic interpretation has widened the extent of prospective areas (Fig. 27). The interpreted aeromagnetic data map is divisible into four prospective zones (Fig. 27) which generally correlate with the geologically defined prospective areas. Zone 1 is made up of a deep NW-SE trough comprising the Pattishabakolo prospective area extending through Wuya, Ndaba, Badegi, Egbati, Agaie, etc. Zone 2 is the East-West trench of the Gulu – Kandi – Enwan – Muye – Gerinya prospective area. Zone 3 prospective areas correlate with the Gulu – Duma – FCT – Ahoko – Agbaja trough while Zone 4 is the geologically mapped Enagi surface cover in the northwestern portion of the basin with prospective areas covering Kutigi, Kudu, Bokani, Robizi, Pizhi, Adogo,

Kwati, Lemu, etc. Most parts of the Zone 1, Zone 2 and Zone 3 prospective areas are expected to have been filled with the Batati Formation at the top (on the surface) but as can be seen in Figure 18, the Batati Formation was mapped only as isolated outliers. It is probable the depths to basement are independent of formational correlation or the Batati Formation was eroded in most parts that it should have been encountered. The geological map in Figure 18 already indicates that the central part of the northwestern portion of the Bida Basin widespreadly covered with the Enagi Formation would have isolated deep sections of prospective areas. This interpretation conforms to the aeromagnetic data interpretation for that zone. Although the aeromagnetic interpreted data did not give exact depth to basement, it has indicated that most of the identified prospective areas have sediment thickness beyond 2,000 meters (>2 km).

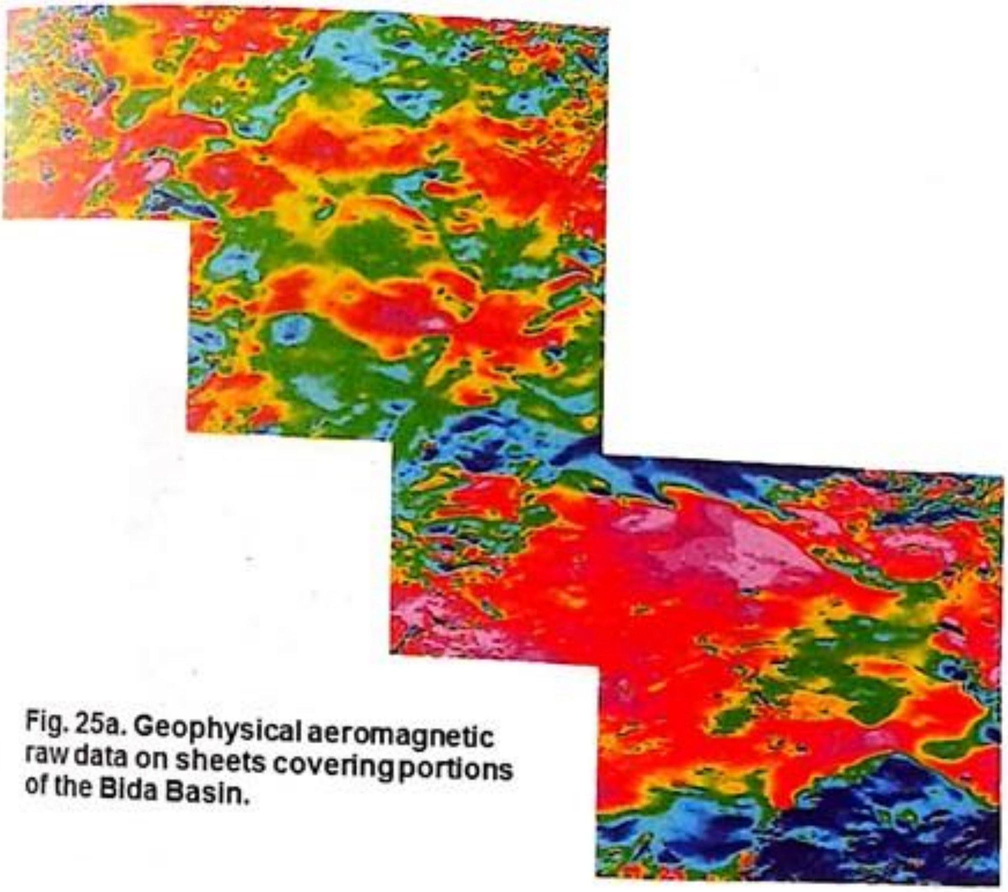

Fig. 25a. Geophysical aeromagnetic raw data on sheets covering portions of the Bida Basin.

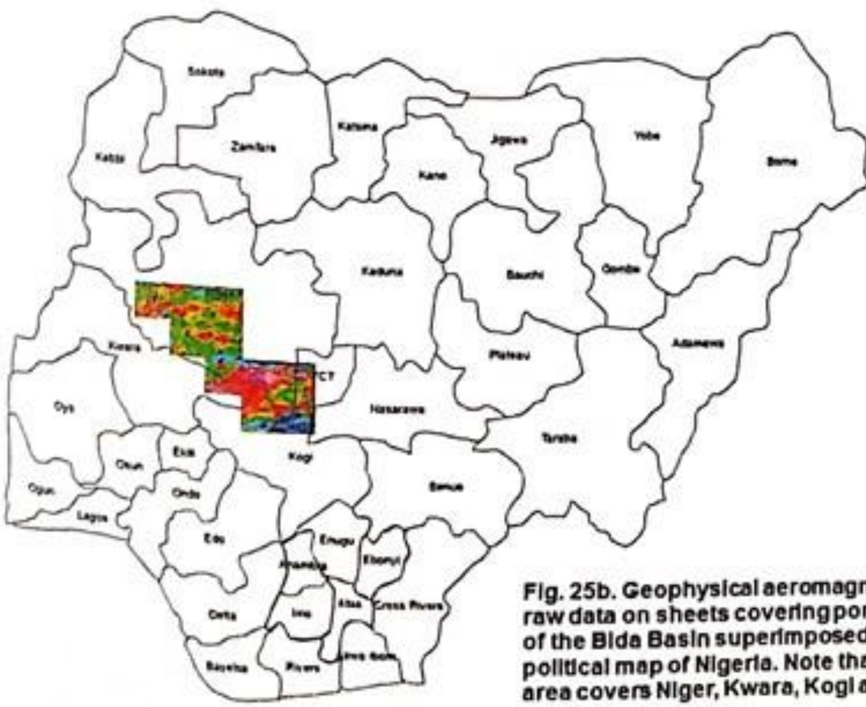

Fig. 25b. Geophysical aeromagnetic raw data on sheets covering portions of the Bida Basin superimposed on the political map of Nigeria. Note that data area covers Niger, Kwara, Kogi and FCT.

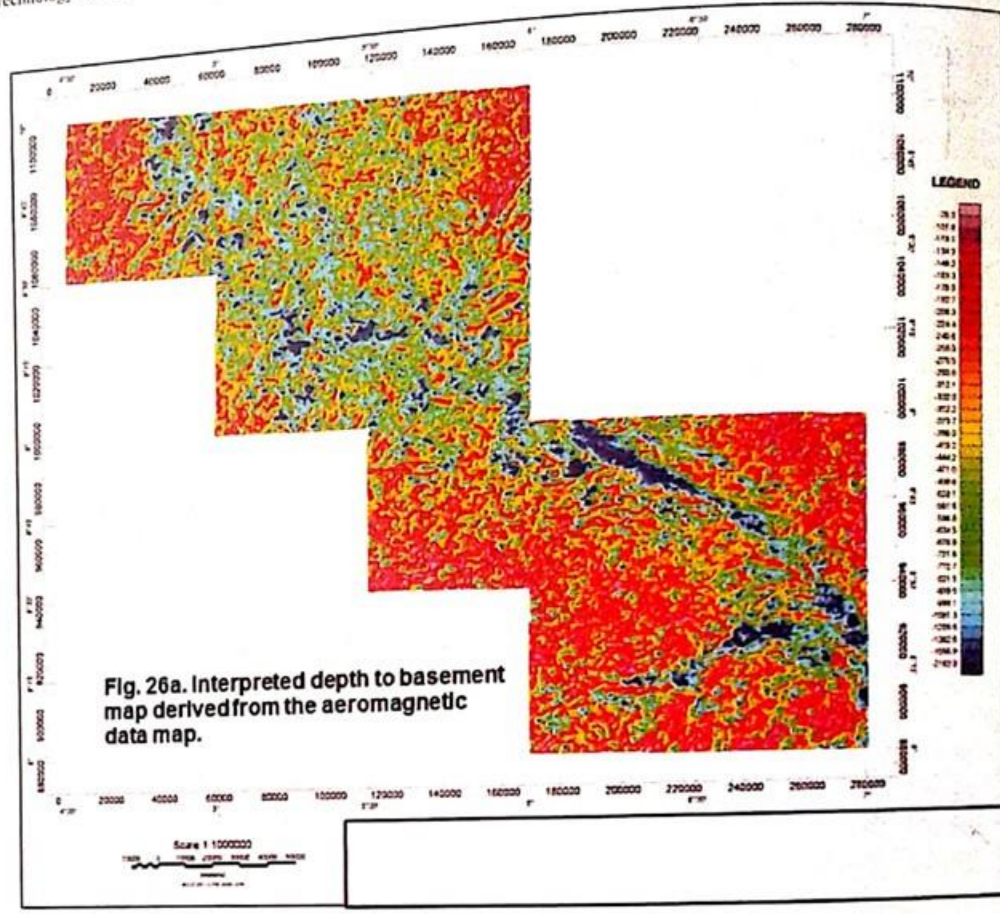

Fig. 26a. Interpreted depth to basement map derived from the aeromagnetic data map.

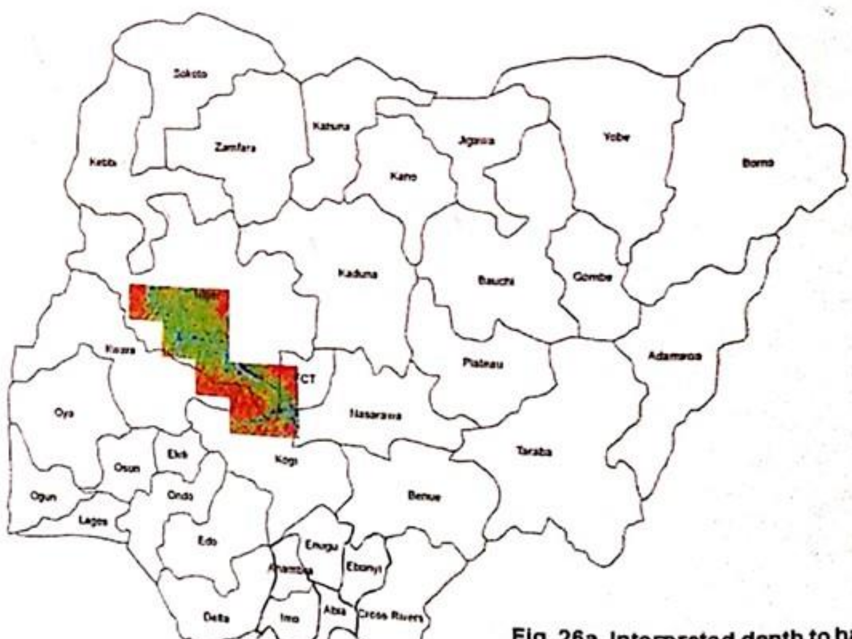

Fig. 26a. Interpreted depth to basement Map superimposed on the political map of Nigeria. Note that data area covers Niger, Kwara, Kogi and FCT.

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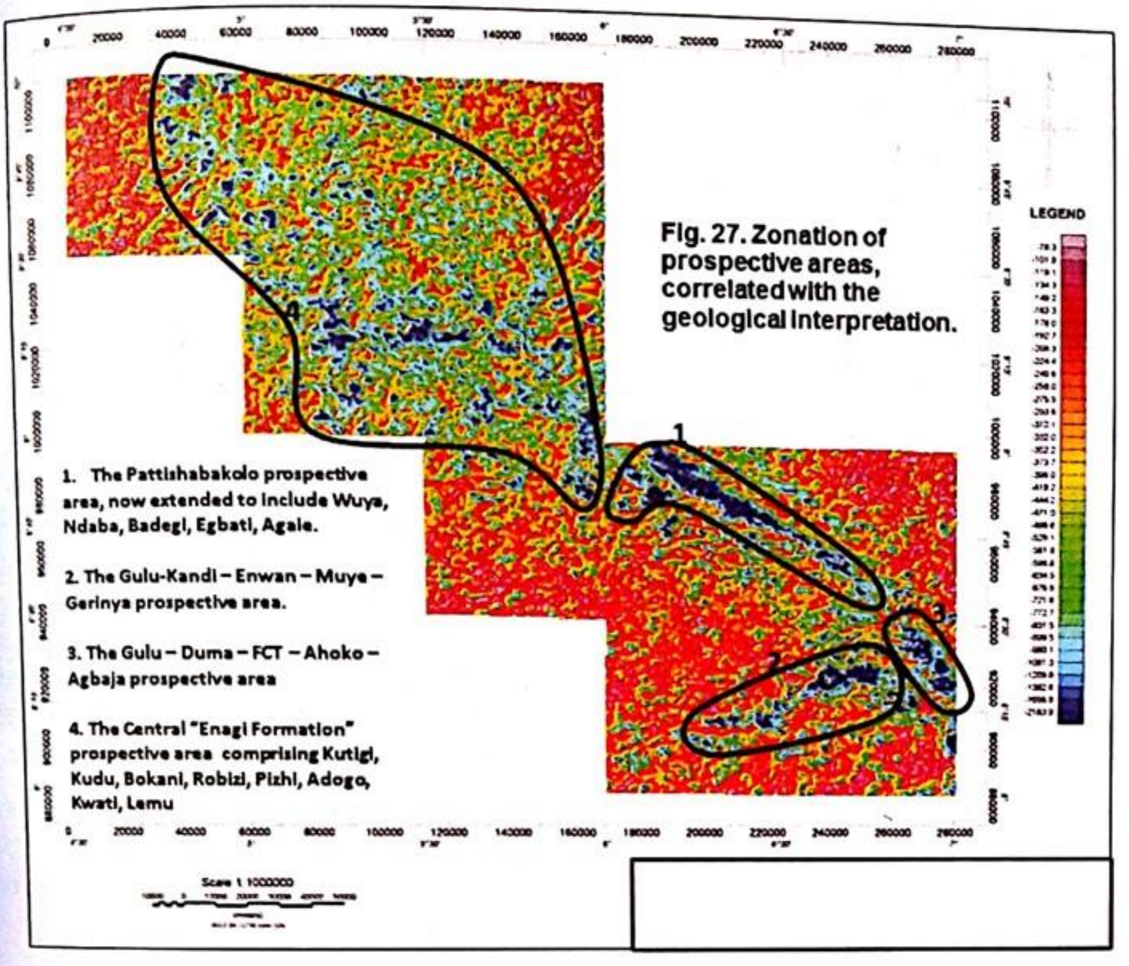

Fig. 27. Zonation of prospective areas, correlated with the geological interpretation.

6.0. Conclusions

The Bida Basin is the least studied of all Nigeria's inland frontier basins. This is because not a single exploratory well has penetrated the sequences in the Bida Basin, making access to subsurface data very difficult. This project has carried out preliminary geological mapping and completed a prospectivity map for the Bida Basin. Geochemical evaluation has also been carried out to assess the source rock qualities and the potential of the rocks to generate hydrocarbons (oil and/or gas). This preliminary study of the Bida Basin was completed with interpretation of geophysical aeromagnetic data with the aim to assess the depth to basement, basement topography and refining of locational prospectivity evaluation necessary for the selection of drillable sites.

From the preliminary geological map prepared, prospective areas, ranked as Less Prospective, Prospective and More Prospective are discernable. Pattishabakolo, Edozighi, Kandi and Enwan make up the More Prospective localities (geological bright spots) in the Northern Bida Basin, whereas Agbaja and some localities around Gegu-Beki constitute the geological bright-spots in the Southern Bida Basin. Most of the areas covered by the Enagi and Patti Formations constitute the Prospective areas. These areas are prospective in terms of sediment thickness but relatively less prospective than those areas covered by Batati / Agbaja Formations but more prospective than the areas covered by the Bida Sandstone. Such prospective localities include the areas around Adogo, Auna, Pizhi, Duba, Kachegi, Kutigi, Ndaba, Badegi, Agaie, Gulu, Muye in the Northern Bida Basin and Gerinya, Abaji, Ahoko and Gegu-Beki in the Southern Bida Basin.

Geochemical data show that mainly gas and some oil would have been generated within the Prospective and More Prospective sections in the basin. These data also show that the Kudu Shale Member within the Enagi Formation and Ahoko Shale Member within the Patti Formation constitute the source rocks for hydrocarbon generation in the Northern and Southern Bida Basin, respectively. Geophysical aeromagnetic data evaluation indicates a depth of up more than 2,000m (> 2 Km) within the identified prospective areas.

It is recommended that the first wells to be drilled in the basin should be located at Pattishabakolo (near Bida) and at Kandi (near Gulu) at co-ordinate localities to be determined by further lease operator-determined prospectivity studies (2-, 3-, 4-D seismic studies, etc).

Acknowledgements and Dedication

This study was funded by the Ibrahim Badamasi Babangida University, Lapai and in the greater part by the Niger State Government through the Gubernatorial Committee on Bida Basin Development (GCBBD), chaired by Lt. Gen. M. I. Wushishi (rtd), with the Etsu Nupe, His Royal Majesty, Alhaji Yahaya Abukakar and other distinguished Nigerlites as members. This report is dedicated to the Chief Servant of Niger State, Dr. Mu'azu Babangida Aliyu, OON, CON, Talba Minna.