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A Review of 3G Data on The Nigerian Benue Trough in View Of Renewed Hydrocarbon Exploration Campaigns

By

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Abstract

The Nigerian National Petroleum Corporation (NNPC) has commenced another round of exploration campaigns for possible hydrocarbon deposits in the Nigerian Benue Trough. The Benue Trough, divided into lower, middle and upper portions, is a SW-NE trending intracratonic basin containing Cretaceous-Tertiary sediment fill of up to 6,000 m. Appreciable volumes of 3G[1] data had been generated on the basin by several previous attempts by NNPC and its joint venture partners. Geological profiles juxtaposed against geophysical data have delineated more prospective areas in the basin where sediment thicknesses vis-à-vis depths to basement are relatively large. Organic geochemical data have been interpreted in terms of organic matter maturation, hydrocarbon generation, expulsion, and migration culminating in the understanding of the volume and stratigraphy of potential source rocks. Consequently, in the Middle Benue Trough, source rock facies have been identified in the carbonaceous shales of the Keana-Awe, Ezeaku and Awgu Formations, with most prospective parts covering the areas within and around Lafia, Loko, Dedere, Doma and Shabu where the Lafia Formation has added to the sediment thickness. In the Upper Benue Trough, source rock facies comprise the carbonaceous intervals within the Gongila, Pindiga and Fika Formations with more prospective areas covering the areas within and around Gombe, Gombe-Aba, Dukku, and Akko where the Kerri-Kerri Formation has added to the sediment thickness. Previous efforts by Shell (SNEPCO) has tested little oil and more gas in the Kolmani River-1 well drilled at Futuk near Alkaleri, spudding on the Kerri-Kerri and bottoming on the Yolde. Considered against analogs in similar rifted basins in Chad Republic, Sudan, Uganda and Kenya, there are possibilities for commercial oil and gas discoveries in the Benue Trough.

Keywords: Hydrocarbon, Cretaceous-Tertiary sediment, carbonaceous shales, Cenomanian, claystones.

1.0. INTRODUCTION

Until recently petroleum (oil and gas) accounted for up to 95% of Nigeria's foreign exchange earnings. Although efforts are being made by the government to diversify the economy, petroleum is still expected to continue to play a significant role as a major supporter of the economy. Despite

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its dwindling fortunes globally, petroleum as an energy source will continue to dominate other primary energy sources and is expected to account for up to 60% of the world energy demand at least up to ~~in~~ the year 2030. As reserves in the Niger Delta are gradually diminishing, the other sedimentary basins of the country present opportunities to increase the national reserve base.

The Benue Trough (Fig. 1) is one in 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. 2). Commercial hydrocarbon accumulations have been discovered in Chad, Niger and Sudan within this rift trend. In South West 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. Kenya's Turkana field and its Ngamia-1 well are buoying up prospects in many African interior rifted basins.

The Benue Trough contains up to 6000 m of Cretaceous - Tertiary sediments of which those pre-dating the mid-Santonian have been compressionally deformed, faulted, and uplifted in several places. Compressional folding during the mid-Santonian tectonic episode affected the whole of the Benue Trough and was quite intense, producing over 100 anticlines and synclines[2, 3]. Following mid-Santonian tectonism and magmatism, depositional axis in the Benue Trough was displaced westward resulting in subsidence of the Anambra Basin. The Anambra Basin, therefore, is a part of the lower Benue Trough containing post-deformational sediments of Campano-Maastrichtian to Eocene ages. It is logical to include the Anambra Basin in the Benue Trough, being a related structure that developed after the compressional stage[4]. The Benue Trough is subdivided into a lower (southern), middle (central) and an upper (northern) portion (Fig. 1). A generalized stratigraphic succession in the Benue Trough and the relationship to the Chad Basin and the Niger Delta is shown on Figure 3.

This paper attempts to review available essential 3G data on the Anambra Basin and the Middle and Upper Benue Troughs where the NNPC is currently progressing with exploration campaigns with the aim to providing essential guiding data and inputs into the work programmes. Shell's work programme in the early 1990s led to the drilling of Kolmani River-1 well that spudded on the Kerri-Kerri and bottomed in the Yolde Formation respectively in the Gongola sub-basin of the Upper Benue Trough with appreciable little oil and 33bscf of gas discovery.

[2] Benkhelil, J. 1989. The origin and evolution of the Cretaceous Benue Trough, Nigeria. Journal of African Earth Sciences 8, 251–282.

[3] Ofoegbu, C. O. 1990. The Benue Trough: Structure and Evolution. Vieweg, 368pp.

[4] Akande, S. O., Ojo, O. J., Erdtmann, B. D. and Hetenyi, M. 1998. Paleoenvironments, source rock potential and thermal maturity of the Upper Benue rift basins, Nigeria: implications for hydrocarbon exploration. Organic Geochemistry 29, 531-542;

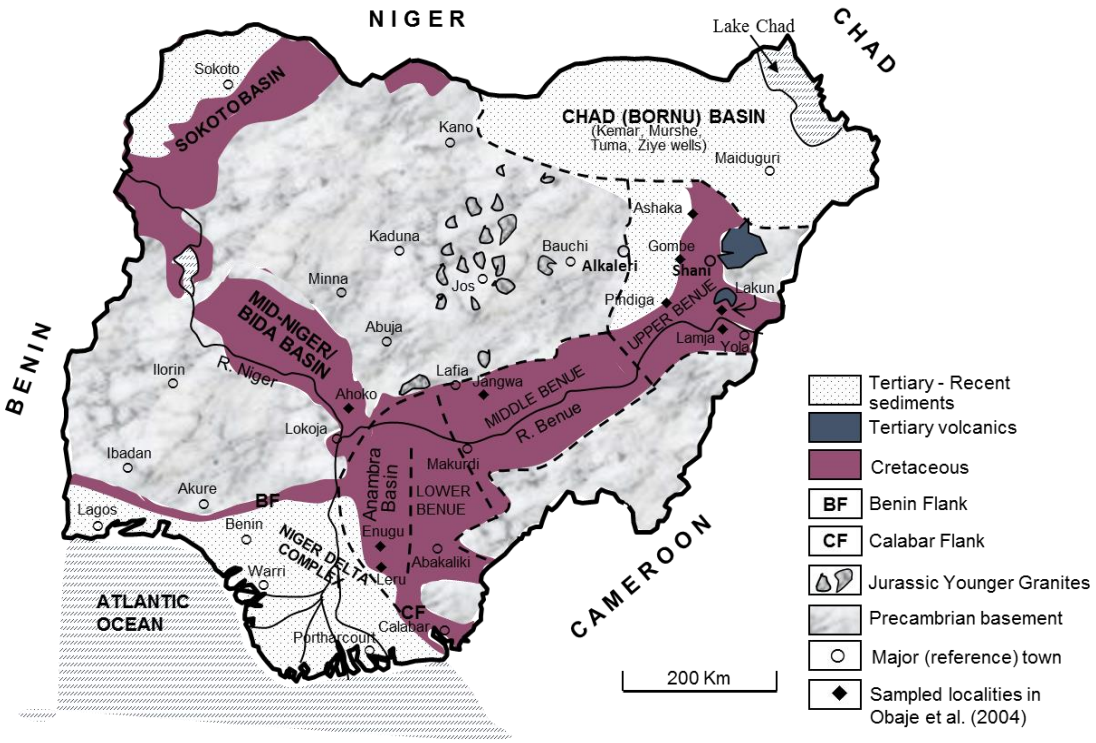

Fig. 1. Generalized geological map of Nigeria showing the location and sub-divisions of the Benue Trough (after Obaje et al., 2004)

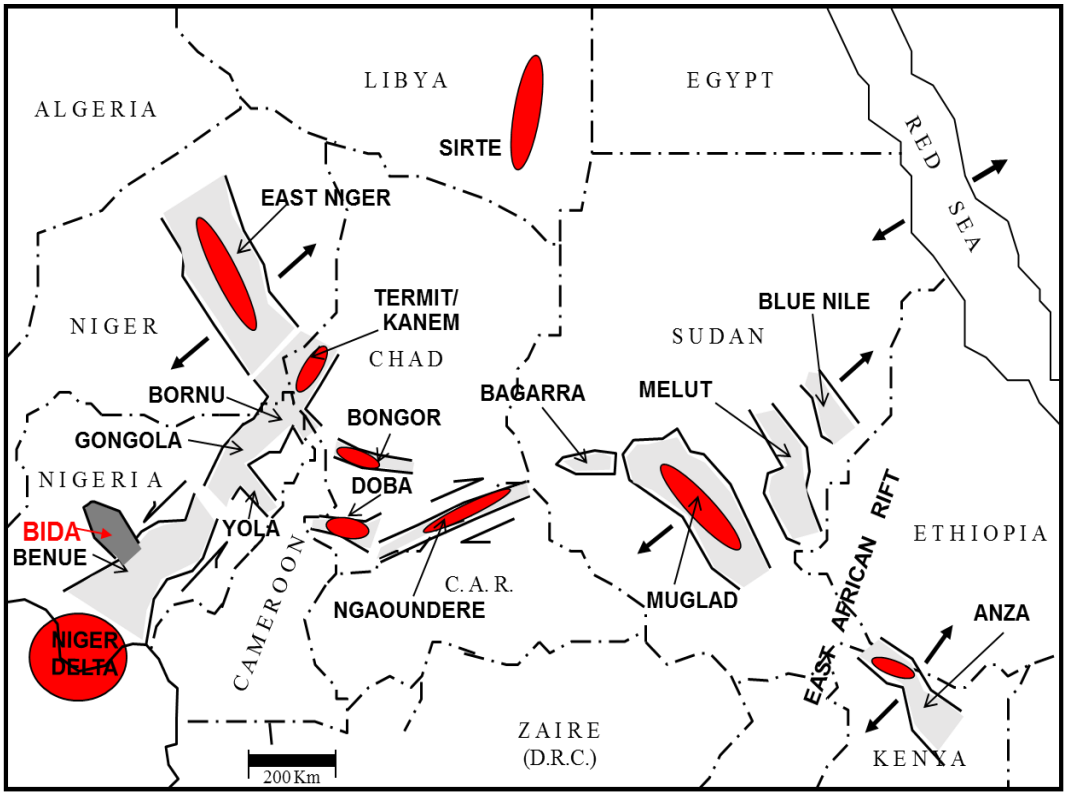

Fig. 2. Regional tectonic map of western and central African rifted basins showing the relationship of the Muglad, Doba and East Niger Basins to the Bida Basin. Locations of regional shear zones (marked with half-arrow) and major zones extension (complete arrow) are shown. (Adapted from Schull, 1988).

The source of Figs 1 and 3 is Obaje, N. G. 1994[5]. Coal petrography, microfossils and paleoenvironments of Cretaceous coal measures in the Middle Benue Trough of Nigeria. Tuebinger Mikropalaeontologische Mitteilungen 11, 1-165; and source of Fig 2 is Schull, T. J. 1988. Rift basins of interior Sudan: Petroleum exploration and discovery. AAPG Bulletin 72, 1128-1142.

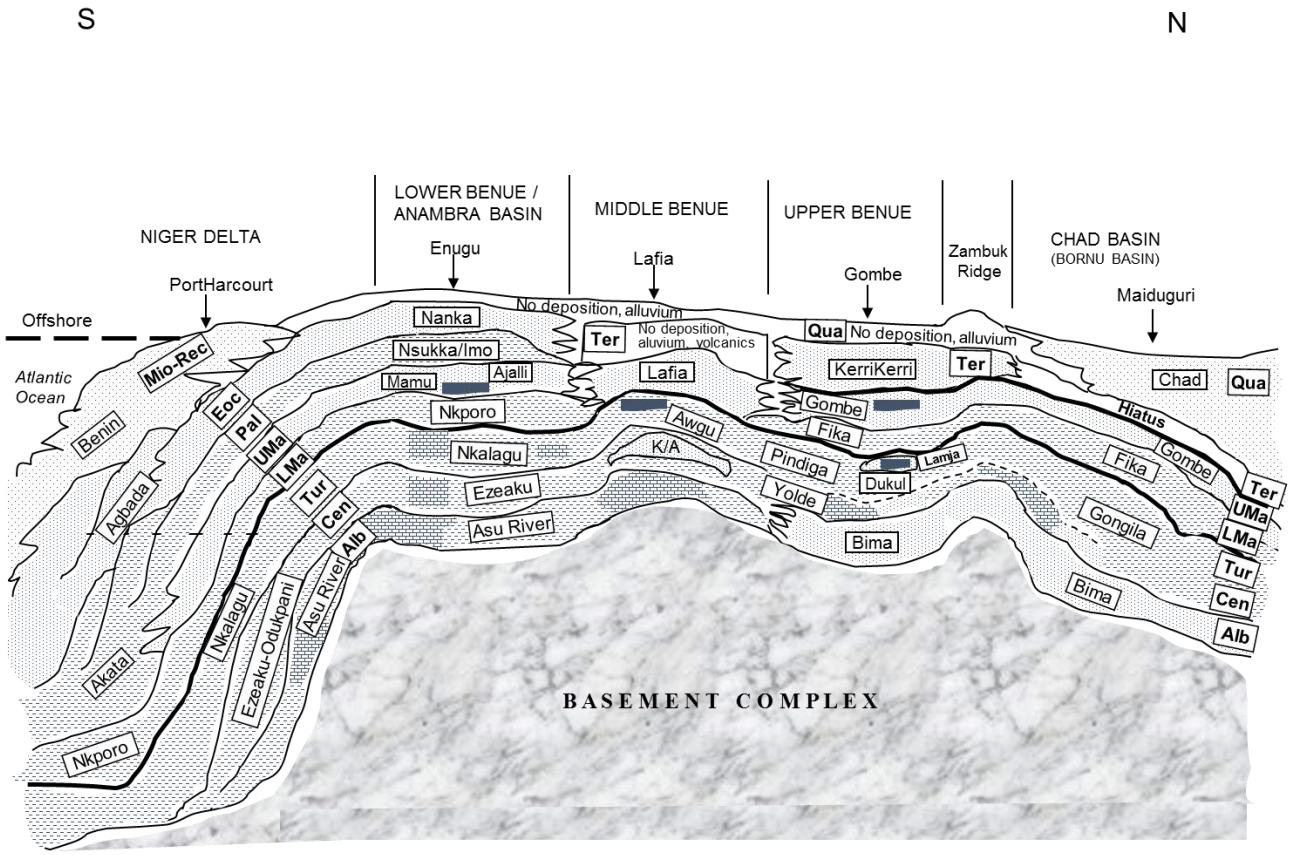

Fig. 3. Idealized N-S stratigraphic cross-section across the Benue trough and the relationship to the Niger Delta and the Chad Basin (vertical scale exaggerated; erosion and uplift not considered) (After Obaje et al., 2004)

The Anambra Basin (being part of the Lower Benue Trough) has recorded some measurable E&P programmes by operating companies and Orient Petroleum has commenced production in some blocks within the basin.

2.0. LOWER (SOUTHERN) BENUE TROUGH / ANAMBRA BASIN

Geology/Stratigraphy

The Anambra Basin (Fig. 4) covers parts of Anambra, Enugu, Imo, Abia, Delta, Edo, Kogi and Benue States (See Nigeria Political Map). Cretaceous stratigraphy of the Anambra Basin comprises eight lithostratigraphic units based on the works of Ofoegbu[2], Akande and Erdtmann[3].

[5] Obaje, G. N. Coal petrography, microfossils and paleoenvironments of Cretaceous coal measures in the Middle Benue Trough of Nigeria. Tuebinger Mikropalaeontologische Mitteilungen 11, 1-165

Obaje et al.[4] and Akande et al.[6] These include the Asu River Group, the Odukpani Formation, Eze-Aku Shale, Awgu Formation, Enugu/Nkporo Shale, the Mamu Formation, Ajali Sandstone and the Nsukka/Imo Formation. The pre-Santonian Anambra platform received only thinner Albian to Turonian sediments. In the adjacent Abakaliki Basin the oldest Albian to Cenomanian sediments of the Asu River Group consists of arkosic sandstones, volcaniclastics, marine shales, siltstone and limestones which overlie the Precambrian – Lower Paleozoic basement complex, representing the first depositional cycle of Petters[7]. The pre-Santonian sedimentary sequence within the Anambra Basin contains up to 3000m of sediments of the first depositional cycle unconformably overlain by about 2000m successions of sediments of the second depositional cycle[8]. These are in turn overlain by the Eze-Aku and Awgu Formations (Late Cenomanian - Coniacian) consisting predominantly of marine shales, calcareous siltstones, limestones, marls representing the second depositional cycle.

These sediments of the first and second depositional cycle have been folded, faulted and uplifted during the Santonian forming major anticlinal and synclinal structures in the Abakaliki Basin e.g. the Abakaliki and Afikpo synclines consequent to tectonism. The Post-Santonian collapse of the Anambra platform and the formation of the Anambra Basin led to the emergence of several parts of the Lower Benue Trough and a shift in the depositional axis of sedimentation to the Anambra Basin for the third depositional cycle of sediments.

The Campanian – Eocene sediments consist of the marine Nkporo/Enugu Formation and the marginal marine to deltaic Mamu, Ajali and Nsukka/Imo Formations. The Upper Cretaceous sediments of the Anambra Basin are overlain by the transgressive Paleocene – Eocene shales, sandstones and siltstones of the proto-Niger Delta in the southern fringes of the basin.

Geochemistry

Obaje et al.[4] presented some organic geochemical results on samples obtained from the Nkporo Shale and the Mamu Formation from surface outcrops. Rock Eval pyrolysis results showed high TOC contents (up to 60.8wt%) and hydrogen indices (HI) of between 266 and 327mgHC/gTOC characterized the coal beds of the Mamu Formation. The underlying Nkporo and Enugu shales had TOC contents of 1.35 to 3.51wt% and HI values between 22 and 65mgHC/gTOC. The regression equation based on the S_2 vs. TOC diagrams gave an average HI value of 364mgHC/gTOC for the

[6] Akande, S. O., Egenhoff, S. O., Obaje, N. G., Ojo, O. J., Adekeye, O. A. and Erdtmann, B. D. 2012. Hydrocarbon potential of Cretaceous sediments in the Lower and Middle Benue Trough, Nigeria: Insights from new source rock facies evaluation. Journal of African Earth Sciences 64, 34–47.

[7] Petters, S.W. 1978. Mid-Cretaceous paleoenvironments and biostratigraphy of the Benue Trough, Nigeria. Geol. Soc. America Bulletin, v. 89, p.151-154.

[8] Agagu, O.K. and Adighije, C. 1981. Tectonic and sedimentation framework of the Lower Benue Trough, south east Nigeria. Journal of African Earth Sciences 1, 267-274.

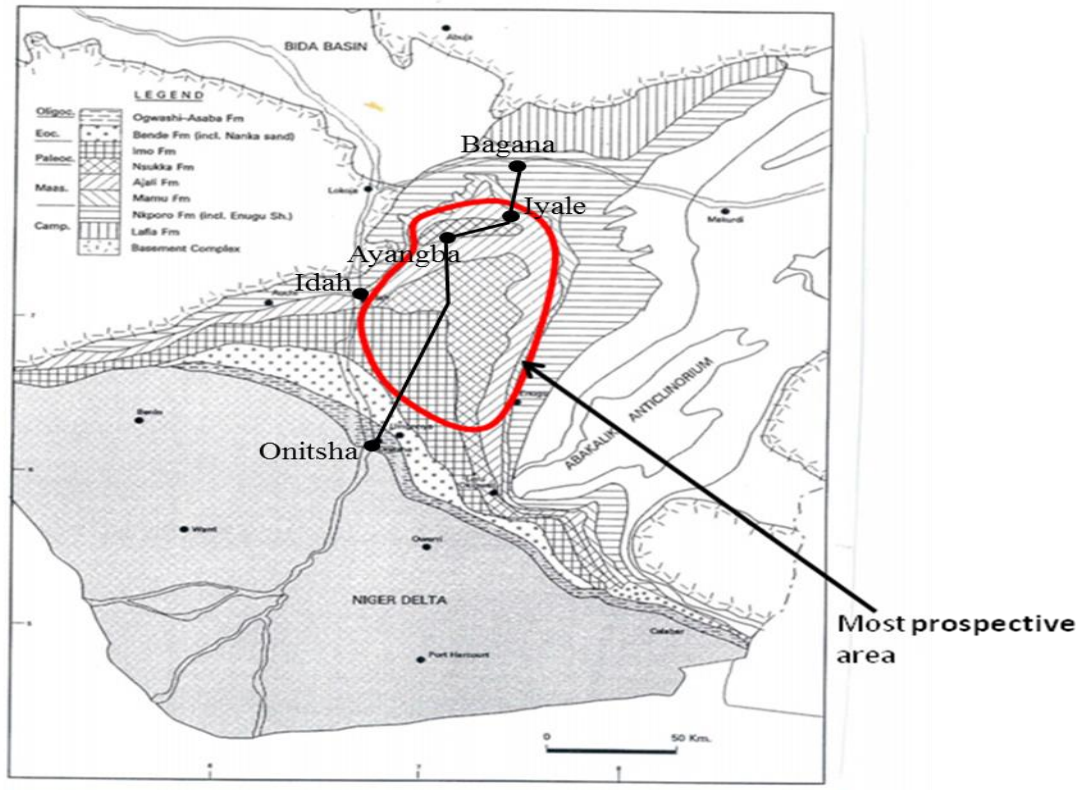

Fig. 4. Geological map of the Anambra Basin showing the most prospective

Mamu coals and 84mgHC/gTOC for the Nkporo and Enugu shales. Tmax and vitrinite reflectance values obtained on the coals indicate immature to early mature stages (early oil window) for the successions in the Anambra Basin. Peters[9] has suggested that at a thermal maturity equivalent to vitrinite reflectance of 0.6% (Tmax 435°C), rocks with HI above 300mgHC/gTOC will produce 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 are inert. However, Sykes and Snowdon[10] are

[9] Peters, K. E. 1986. Guidelines for evaluating petroleum source rocks using programmed pyrolysis. AAPG Bulletin 70, 318-329.

[10] Sykes, R. and L. R. Snowdon, 2002, Guidelines for assessing the petroleum potential of coaly source rocks using Rock-Eval pyrolysis: Organic Geochemistry, v. 33, p. 1441-1455.

of the opinion that coaly source rocks are sufficiently different from marine and lacustrine source rocks in their organic matter characteristics to warrant separate guidelines for their assessment based on Rock-Eval pyrolysis. Based on a study of some New Zealand coals, they concluded that the rank threshold for oil generation in coals is indicated at Tmax of 420-430°C (Ro 0.55-0.6%), and the threshold for oil expulsion at Tmax 430-440°C (Ro 0.65-0.85%).

Plots on the modified Van Krevelen diagram for samples from the Anambra basin showed a mixed range of type I – type II – type III organic matter with a dominance of type II (Fig. 5). A corresponding plot on the HI – Tmax diagram based on the values given by Peters (1986) indicates an oil and gas generative potential for some of the samples from the Anambra Basin (Fig. 6). GC and GC-MS analyses of the lipid extracts reported biomarkers with a dominance of long-chain n-alkanes (C24-C31) with obvious odd-over-even predominance (OEP). This points to high inputs of terrestrial humic / higher plants organic matter as well as maturity levels below the conventional begin of oil generation (Ro 0.6%). Pristane/phytane ratios range from 5.58 to 16.88 and steranes are mainly of the C_{29} forms[4] all of which confirmed a considerable input of terrestrial organic matter and gas-prone hydrocarbon sources.

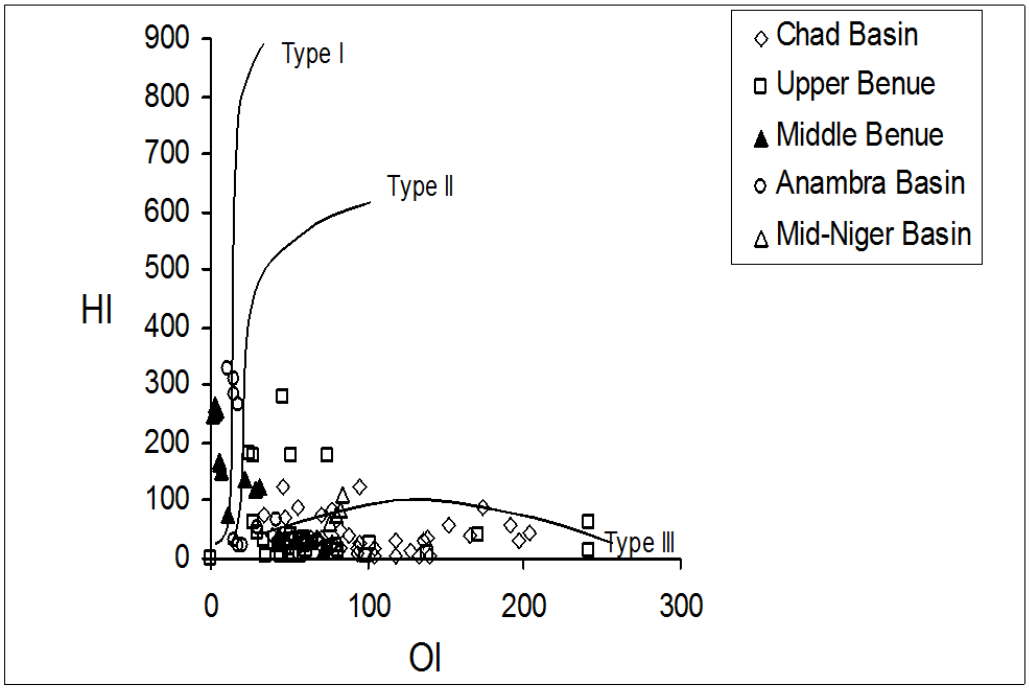

Fig. 5. HI vs. OI plots on the modified Van Krevelen diagram of samples from the inland basins of Nigeria (After Obaje et al., 2004)

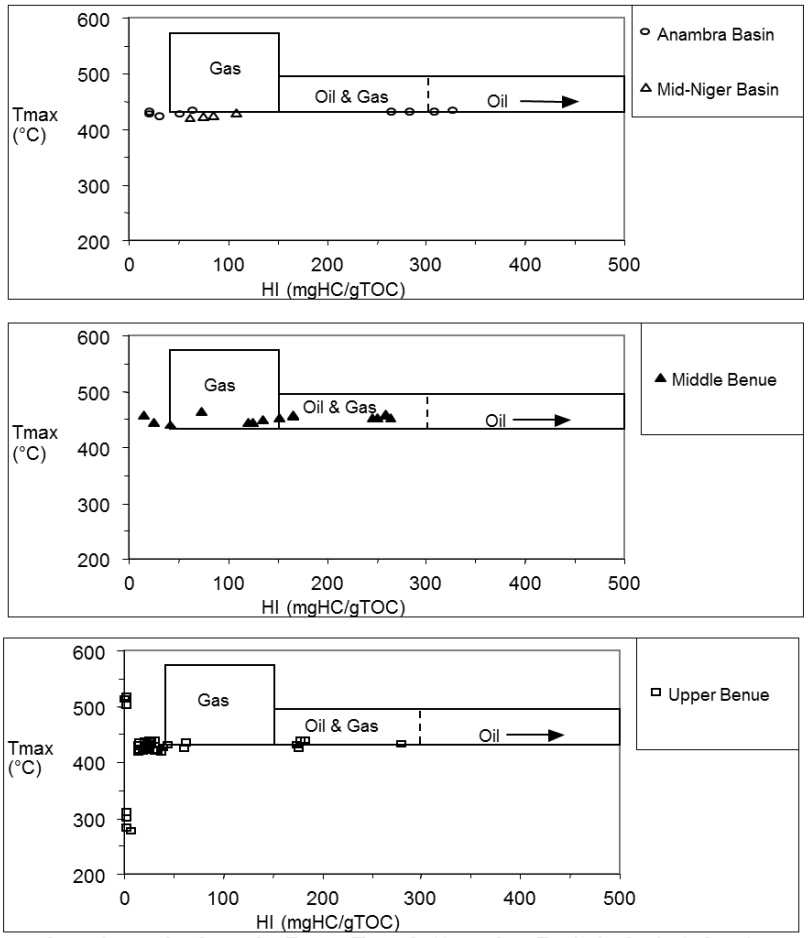

Fig. 6. HI-Tmax plots of samples from the Benue Trough (Anambra Basin inclusive) showing the different types of potentially generated hydrocarbons (After Obaje et al., 2004)

Geophysics / Prospectivity Evaluation

Geophysical data are not readily available on the Anambra Basin. Those that may be available and essential are proprietarily held by operating companies. Gravity and magnetic studies by Agagu and Adighije (1981) and Onuoha and Ofoegbu[11] revealed ca. 8000 – 9000m sediment pile around Onitsha for both pre and post-Santonian sediments in the Anambra Basin. The sediment pile thickens / the basin deepens toward the Niger Delta which imperatively makes the prospectivity increase towards the Niger Delta. A northern bright sport occurs around Anyanga-Iyale (Fig. 7) and in the Ibaji-Alade-Odlu areas of Kogi State. Some marginal fields are already being developed in the basin and Orient Petroleum along with the Anambra State Government have already started marginal production from some wells in the basin on the basis of which a refinery has been constructed to refine the produced oils for local consumption and possible export. The most

[11] Onuoha, K. M. and Ofoegbu, C. O. 1987. Structure, subsidence and evolution of the Nigerian continental margin. In Current Research in African Earth Sciences: In G. Matheis and H. Schandelmeir eds. A.A. Balkema, Rotterdam 287 – 291.

prospective areas in the Anambra Basin comprise those areas covered by the Nsukka and Imo formations, namely around Anyigba, Iyale, Egume, Odolu, Alade, Akpanya, and most of Ibaji Local Government Area (Kogi State), Awkuzu (Anambra), Okigwe (Imo), and Lekwesi (Abia) (See Nigeria Political Map to identify named locations). Petroleum source rock facies in the Anambra Basin are made up of carbonaceous intervals with above discussed geochemical parameters with the Nkporo / Enugu Shale and the Mamu Formation, while the clean well-sorted sandstone of the Ajalli Formation would constitute reservoir units. The Nsukka Formation / Imo Shale would generally provide regional seals for prospects in the Anambra Basin.

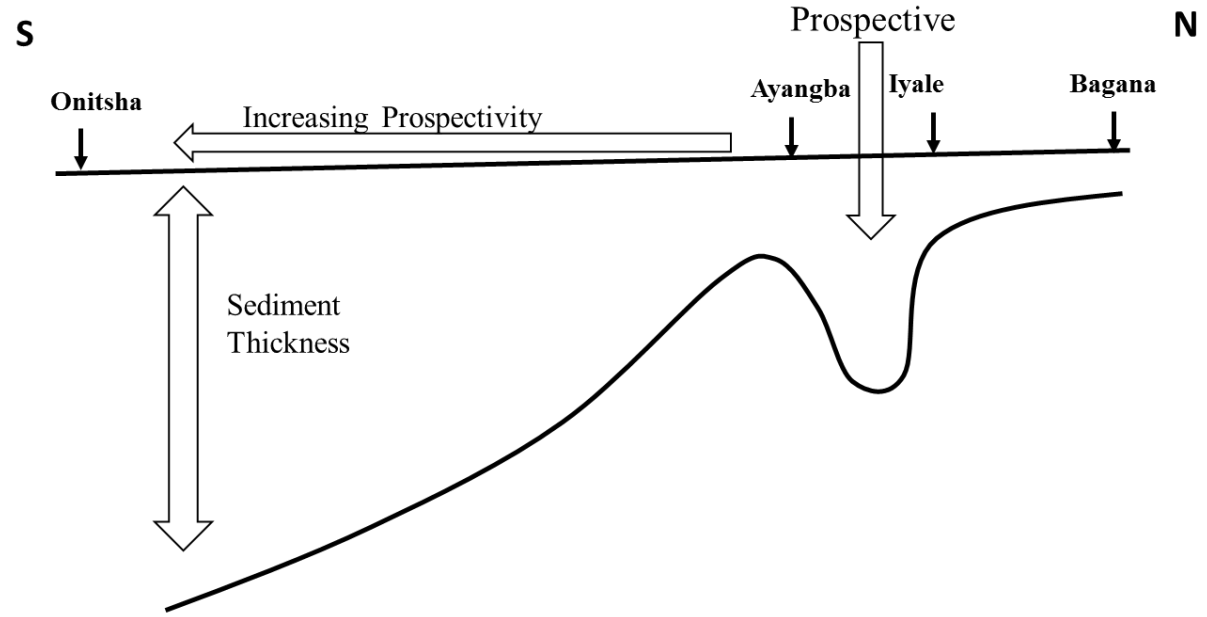

Fig. 7. Geologic cross-section from Bagana to Onitsha across the Anambra Basin (not-to-scale) depicting sediment stacking pattern from the Northern Anambra Basin towards the Niger Delta, Drawn from Fig. 2

3.0. THE MIDDLE (CENTRAL) BENUE TROUGH

Geology / Stratigraphy

The Middle Benue Trough covers Nigerian geopolitical states of Benue, Nasarawa, Plateau and Taraba. Six Upper Cretaceous lithogenetic formations comprise the stratigraphic succession in the Middle Benue Trough (Figs. 3, 8). The succession is made up of the Albian marine Arufu, Uomba, Gboko formations, generally referred to as the Asu River Group[12, 13]. These are overlain by the

[12] Offodile, M. E. 2005. Groundwater geology of the Middle Benue Trough. Paper presented at the 2nd Groundwater Isotope Geology Workshop organized by the Federal Ministry of Water Resources, New Keffi Hotel, Keffi. 13-15 May, 2005.

[13] Nwajide, C. S. 1990. Sedimentation and paleogeography of the Central Benue Trough, Nigeria. In: Ofoegbu, C. O. (Ed.), The Benue Trough Structure and Evolution. Vieweg, Braunschweig, pp19-38.

Cenomanian paralic Keana and Awe formations and the Cenomanian - Turonian marine Ezeaku Formation.

The Ezeaku Formation is coterminous with the Konshisha River Group and the Wadata Limestone in the Makurdi area. The late Turonian - early Santonian coal-bearing Awgu Formation lies conformably on the Ezeaku Formation. In the Makurdi area, the Makurdi Sandstone interfingers with the Awgu Formation. The mid-Santonian was a period of folding throughout the Benue trough. The post-folding Campano-Maastrichtian Lafia Formation, deposited under continental conditions, ended the sedimentation in the middle Benue trough, after which widespread volcanic activities took over in the Tertiary. The Asu River Group is exposed in a locality of about 10 km from Kanje on the Kanje-Awe road. The Keana Formation at Keana and the Awe Formation at Awe (Fig. 9). The Ezeaku Formation of mainly black shales (baked) and limestones are exposed under the bridge before the village of Ribi (Fig. 10) and 8 km after Ribi on the Ribi to Jangwa road. The Awgu Formation is exposed massively with the coaly units at the bank of River Dep at Shankodi near Jangwa in Nasarawa State (Fig. 11) while the Lafia Formation sandstone units are massively exposed along the bank of River Amba on the Lafia-Doma road at Lafia with the clayey units covering the areas within and around Shabu on the Akwanga-Lafia road at about 10km to Lafia. The surface geology as composed by the stratigraphic formation is shown on Figure 8.

Geochemistry

Previous organic geochemical and organic petrological studies by Obaje and Abaa[14], Obaje and Hamza[15], Ehinola et al.[16], Obaje et al.[4] and Akande et al.[17] on coals, shales and carbonates obtained from the Awgu Formation in the Middle Benue Trough show that organic matter are generally Type II-III (Fig. 5), with proneness for dry gas and associated gas (Fig. 6). Obaje et al.[14] reported vitrinite reflectance values of 0.7-1.25%Ro indicating maturity within the main oil generating window. Although a high percentage of liptinitic macerals were reported by Obaje[18], biomarker parameters available in Obaje et al.[4] indicate that any hydrocarbon generated in the Middle Benue Trough would be overwhelmingly gaseous with some potential for coal-derived liquid hydrocarbons similar to such coal-derived liquid hydrocarbons in the Karoo Basin of Tanzania, Taranaki Basin of New Zealand and the Cooper Basin in Australia.

Geophysics / Prospectivity Evaluation

Geophysical data on the Middle Benue Trough are also not readily available. However Geological cross-sections drawn across the Middle Benue Trough indicate that the most prospective areas in

[14] Obaje, N. G. and Abaa, S. I. 1996. Potential for coal-derived gaseous hydrocarbons in the Middle Benue Trough of Nigeria. Journal of Petroleum Geology 19, 77-94.

[15] Obaje, N. G. and Hamza, H. 2000. Liquid hydrocarbon source-rock potential of mid-Cretaceous coals and coal measures in the Middle Benue Trough of Nigeria. International Journal of Earth Sciences 89, 130-139

[16] Ehinola, O.A., Ekweozor, C.M., Oros, D. R. and Simoneit, B.R.T., 2002. Geology, geochemistry and biomarker evaluation of Lafia-Obi coal, Benue Trough, Nigeria. Fuel 81, 219–233.

[17] Akande, S. O., Egenhoff, S. O., Obaje, N. G., Ojo, O. J., Adekeye, O. A. and Erdtmann, B. D. 2012. Hydrocarbon potential of Cretaceous sediments in the Lower and Middle Benue Trough, Nigeria: Insights from new source rock facies evaluation. Journal of African Earth Sciences 64, 34–47.

[18] Obaje, N. G. 1994. Coal petrography, microfossils and paleoenvironments of Cretaceous coal measures in the Middle Benue Trough of Nigeria. Tuebinger Mikropalaeontologische Mitteilungen 11, 1-165.

terms of sediment thickness comprise the areas within and around Lafia, Loko (Fig. 12), Shabu, Dadere, Doma, Obi, Agwantashi and Shendam.

Source rock facies in the Middle Benue will be provided by the carbonaceous intervals in the Keana Formation, Ezeaku Formation (Fig. 10) and Awgu Formation (Fig. 11). Reservoirs would comprise significant volumes of porous and permeable sandstones and limestones in the Awe / Keana Formation and shelf sandstones in the Awgu Formation. Plastic clays as mapped in the Shabu areas and other clay and shale facies within the Awgu and Lafia Formations will provide regional seals. Geochemical parameters as discussed earlier indicate that any generated hydrocarbons would be overwhelmingly gaseous with some potential for coal-derived liquid hydrocarbons similar to such coal-derived liquid hydrocarbons in the Karoo Basin of Tanzania, Taranaki Basin of New Zealand and the Cooper Basin in Australia. Opportunities within and around Lafia and Shendam are enhanced by their close proximity to basement rocks which could constitute barrier to further hydrocarbon migrations that can ensue in significant accumulations, similar to the Kolmani River discovery in the Upper Benue Trough (Fig. 14).

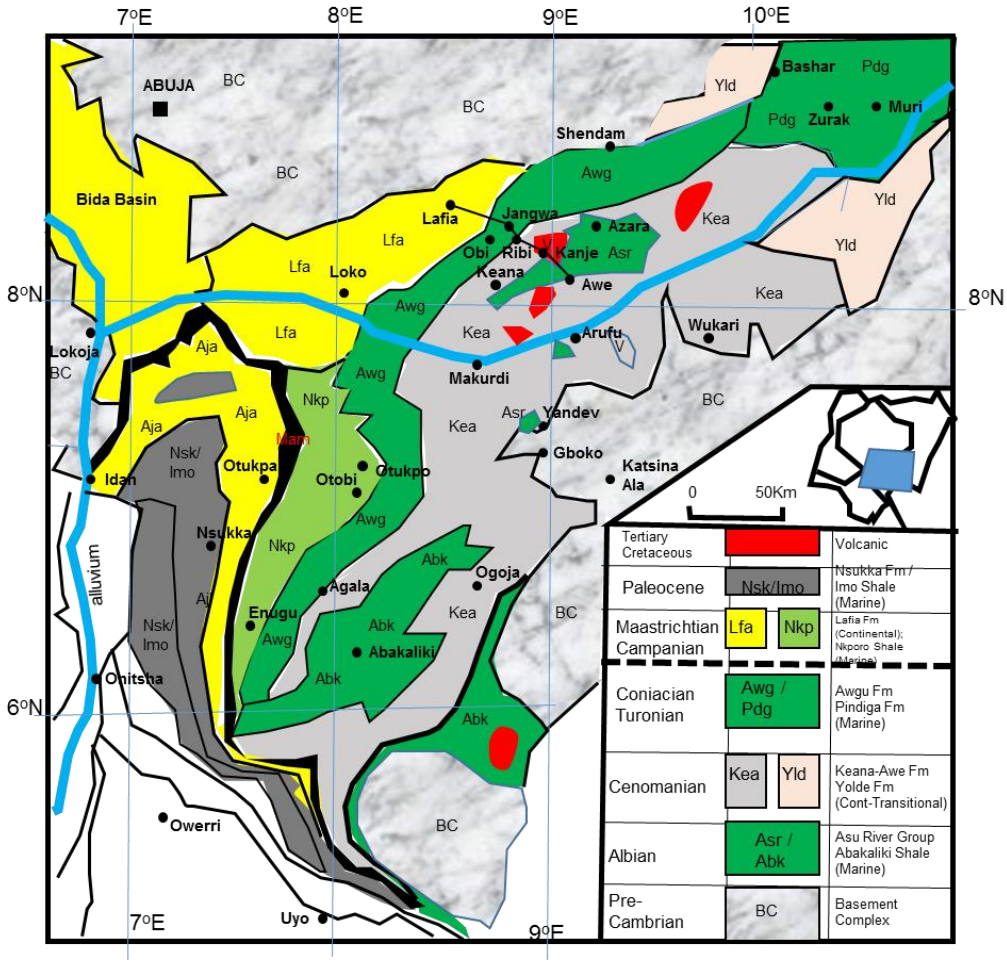

Fig. 8. Geological map of the Middle Benue Trough and portions of the Anambra Basin (After Nwajide, 2013)

Fig. 9. The Awe Formation at an up-dip exposure at Old Awe; a potential reservoir facies

Fig. 10. Exposure of the Ezeaku carbonaceous shale unit at under the bridge before the village of Ribi; a potential source rock

Fig. 11. Outcrops of the Awgu Formation with coal intercalations at the bank of River Dep at Shankodi near Jangwa; Potential source facies

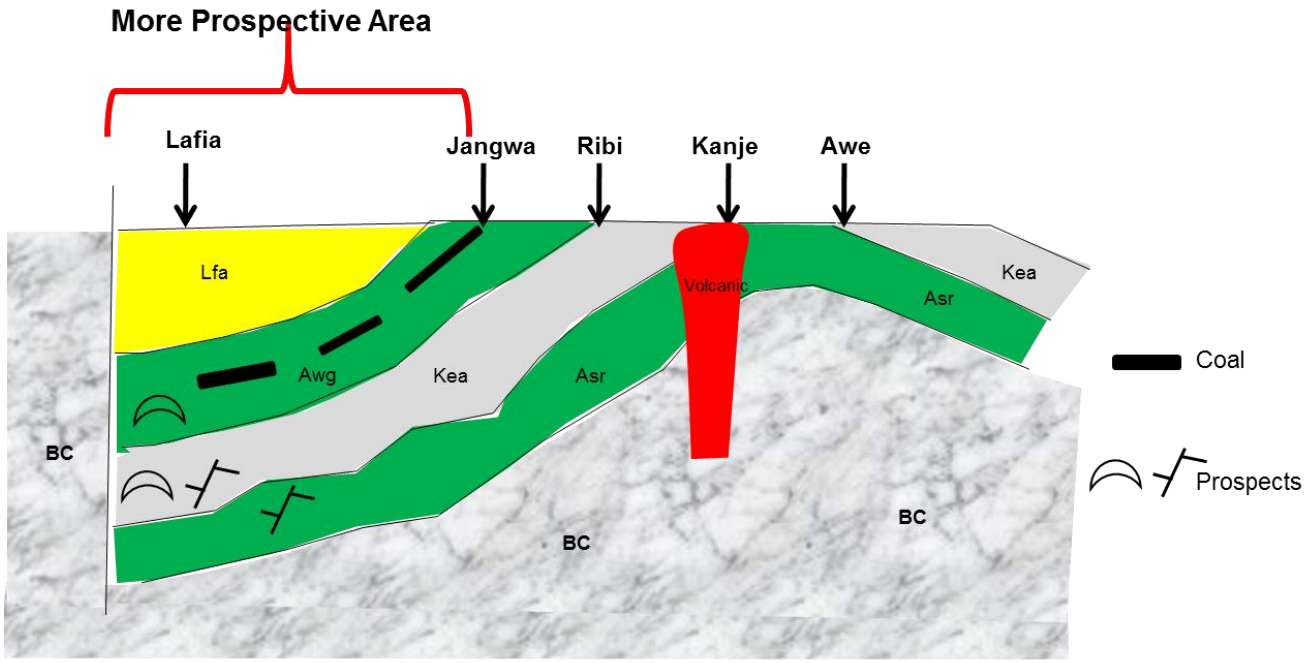

Fig. 12. Cross-section showing geology, straigraphy and most prospective areas from Awe theough Kanje, Ribi, Jangwa to Lafia (NB: Aeromagnetic and seismic may show different scenarios)

4.0. THE UPPER (NORTHERN) BENUE TROUGH

Geology / Stratigraphy

The Upper Benue Trough covers Nigerian geopolitical states of Bauchi, Gombe, Adamawa, Taraba, Borno, Yobe and some little portions of Jigawa. The trough here is made up of two sub-basins, the Gongola sub-basin and the Yola sub-basin (although some authors have subdivided this to include a third central Gombe-Lau sub-baisn, eg. Akande et al.[3]). In both sub-basins, the Albian Bima Sandstone lies unconformably on the Precambrian basement. This formation was deposited under continental conditions (fluvial, deltaic, lacustrine) and is made up of coarse to medium grained sandstones, intercalated with carbonaceous clays, shales, and mudstones. The Bima Sandstone was subdivided by Carter et al.[19] into a Lower, Middle and Upper Bima. The Middle Bima is reported to be shaley in most parts with some limestone intercalations and was assumed to be deposited under a more aqueous anoxic condition (lacustrine, brief marine). The Bima Sandstone is widely exposed in outcrops on the Lamurde anticline (2 km to the town of Lafiya, on the Gombe- Numan-Yola road) and at Shani and Filiya. The Yolde Formation lies conformably on the Bima Sandstone. This formation of Cenomanian age represents the beginning of marine incursion into this part of the Benue trough. The Yolde Formation was deposited under a transitional/coastal marine environment and is made up of sandstones, limestones, shales, clays and claystones.

In the Gongola sub-basin, the laterally equivalent Gongila and Pindiga formations and the possibly younger Fika Shale lie conformably on the Yolde Formation. These formations represent full marine incursion into the upper Benue during the Turonian – Santonian times. Lithologically, these formations are characterized by dark/black carbonaceous limestones and shales, intercalating with pale colored limestones, shales and minor sandstones. The type locality of the Gongila Formation is at the quarry of the Ashaka Cement Company at Ashaka, while that of the Pindiga Formation is at Pindiga village. The Fika Shale is lithologically made up of bluish-greenish carbonaceous, sometimes pale gypsiferous, highly fissile shales and occasional limestones in places with good exposures at the village of Nafada.

In the Yola sub-basin, the Dukul, Jessu, Sekuliye formations, Numanha Shale, and the Lamja Sandstone are the Turonian – Santonian equivalents of the Gongila and Pindiga formations. The Turonian – Santonian deposits in the Yola sub-basin are lithologically and palaeoenvironmentally similar to those in the Gongola arm, except the Lamja Sandstone which has a dominating marine sandstone lithology with intercalated coal deposits. The type locality of the Dukul Formation is in the village of Lakun with good exposures also at Bambam on the Gombe - Yola road. All the other formations have their type localities in the villages named after them. The Santonian was a period of folding and deformation in the whole of the Benue trough. Post-folding sediments are represented by the continental Gombe Sandstone of Maastrichtian age and the Kerri-Kerri Formation of Tertiary age. The Gombe Sandstone is lithologically similar to the Bima Sandstone, but contains also coal, lignite, and coaly shale intercalations. The type locality is in the valley of

[19] Carter, J. D., W. Barbar, E. A. Tait, and G. P. Jones, 1963, The geology of parts of Adamawa, Bauchi and Borno Provinces in northeastern Nigeria: Geological Survey of Nigeria Bulletin, v. 30, p. 1-108.

River Pantami in Gombe town. The Kerri-Kerri Formation is made up of whitish grey sandstones, siltstones, and claystones with the claystones dominating the lithology in most places. Exposures of this formation are also encountered widely in and around Gombe, Alkaleri, Gombe-Aba and Dukku.

Geochemistry

Geochemical results obtained on outcrop samples from the Upper Benue Trough have generally low TOC and HI contents, except the coals of the Lamja Formation and those form the coaly units within the Gombe Formation as well as some Dukul Formation samples, all of which have very good to good source rock qualities. Akande et al.[3] and Obaje et al.[20] had independently reported TOC values of to 4.5wt% from the Yolde Formation and 2.4wt% from the lower Pindiga Formation, respectively. In the Lamja Formation, TOC contents attain values of up to 50.7wt% and a mean HI of 183mgHC/gTOC for the coals in the upper Benue Trough combined[21]. Tmax and vitrinite reflectance measurements by Obaje et al.[22] indicate maturity in the middle/peak oil window for the coals of the Lamja Formation. Outcrop samples from the Bima, Yolde, Pindiga and Gongila formations used in the study by Obaje et al.[23] yielded poor source rock quality. Plots on the modified Van Krevelen diagram for samples from the Upper Benue Trough show mainly type III organic matter with some type II attributable to the Lamja coals (Fig. 5). The corresponding HI – Tmax diagram indicates some potentials between oil and gas with gas dominating (Fig. 6). The Lamja and Gombe coals are of special attention, especially the Lamja which yielded the highest amount of soluble organic matter during solvent extraction. Biomarkers show a dominance of both short and long-chain n-alkanes (C_{14}-C_{31}) with negligible OEP[4]. Pristane/phytane ratios range from 0.84 in the Pindiga Formation to 6.65 in the Lamja coals. C_{27}/C_{29} ratios range from as low as 0.2 in the Lamja coal to 1.9 in the Pindiga pointing potential oil and gas-prone source rocks. Geochemical results obtained on samples collected from Nasara-1 well (LWD) drilled by Chevron Nigeria Limited drilled near Futuk gave TOC values of between 52.1 and 55.2wt% in the depth interval between 4,710 and 4,770ft[22]. These values are characteristic of coals. Hls were between 564 and 589 mgHC/gTOC and Tmax was 423-428C. Although hydrogen indices can be misleading in assessing the oil-generative potential of a coal, values as high as those recorded in Nasara-I permit oil-generative capabilities to be inferred (Fig. 13).

Geophysics / Prospectivity Evaluation

Like in the other parts of the Benue Trough, geophysical data are not readily available. Seismic data acquired by Shell, Chevron and Elf (Total E&P) around 1992 have remained proprietary. NNPC is currently working on modalities to acquire 3D seismic around the Kolmani block in the basin. However, it can already be deduced that potential source rocks in the Upper Benue Trough comprise lacustrine facies of the Middle Bima, shales and carbonates in the Gongila and Pindiga

[20] Obaje, N. G., O. K. Ulu and S. W. Petters, 1999, Biostratigraphic and geochemical controls of hydrocarbon prospects in the Benue trough and Anambra basin, Nigeria: Nigerian Association of Petroleum Explorationists (NAPE) Bulletin, v. 14, p. 18-54.

[21] Jauro, A., Obaje, N. G., Agbo, M. O., Abubakar, M. B. And Tukur, A. 2007. Organic geochemistry of Cretaceous Lamza and Chikila coals, Upper Benue Trough, Nigeria. Fuel, 86, 520-532.

[22] Obaje, N. G., Wehner, H., Abubakar, M. B. and Isah, T. 2005. Nasara-1 well, Gongola Basin: Petroleum source rock assessment. Journal of Petroleum Geology 15, 23-34.

[23] Obaje, N. G. 2009. Geology and Mineral Resources of Nigeria. Springer, Heidelberg, 241pp.

formations, shales of the Fika Formation and the coaly facies in the Lamja Formation. Potential reservoir rocks would deltaic and fluvial sandstones of the Bima Formation, interbedded shelf sandstones in the Gongila and Pindiga formations as well as carbonates in the Gongila and Pindiga formations. Most prospective areas in the Upper Benue Trough are those with supposedly thickest sediment piles covered by the Kerri-Kerri Formation in the Gongola sub-basin (Fig. 14). The prospects in these areas are further enhanced by the termination of the sequences at basement boundary disallowing further migration and enhancing accumulation.

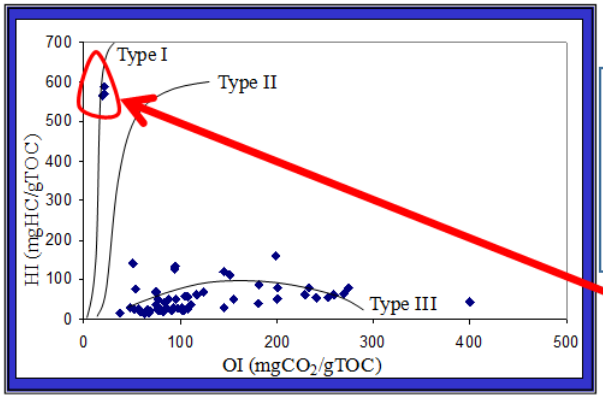

Fig. 13a. HI vs. OI plots on the modified van Krevelen diagram for Nasara-1 well samples migrated oil, generated from a lacustrine source

There is a possibility of deep-seated lacustrine source rock in the Benue Trough

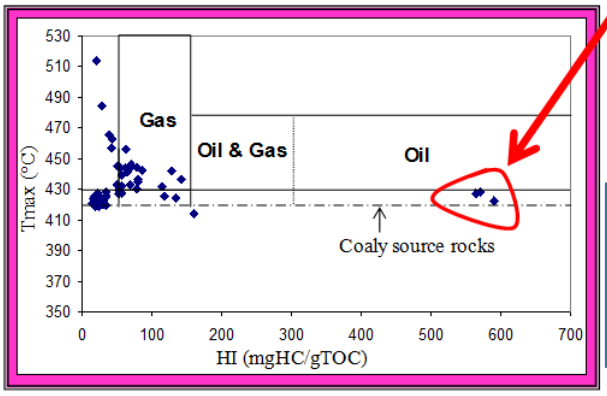

Fig. 13b. HI vs. Tmax plots of samples from Nasara-1 well showing potential for lacustrine sourced oil (After Obaje et al., 2004; Abubakar et al., 2008)

[25]Abubakar, M.B., Dike, E.F.C., Obaje, N.G., Wehner, H., Jauro, A., 2008. Petroleum prospectivity of Cretaceous formations in the Gongola Basin, Upper Benue Trough, Nigeria: an organic geochemical perspective on a migrated oil controversy. Journal Petroleum Geol. 31, 387–407.

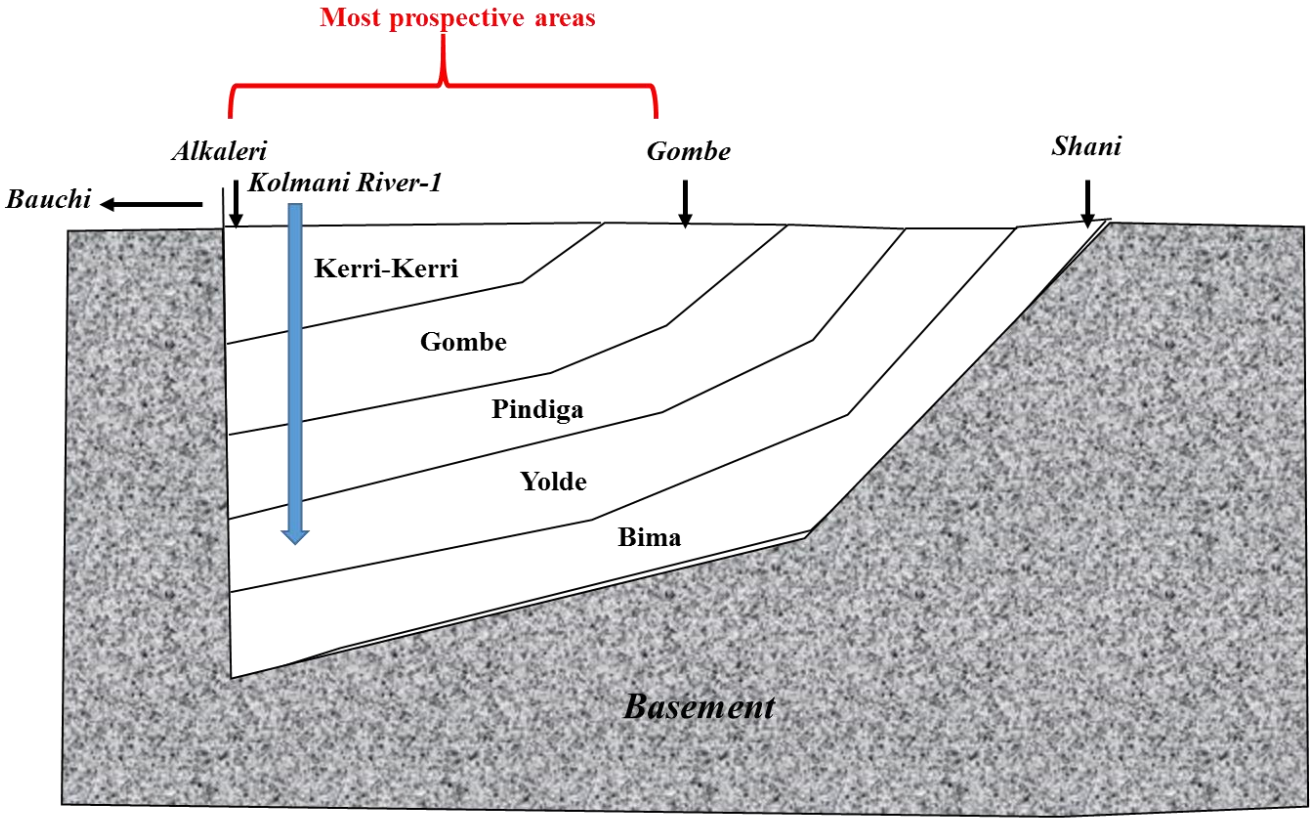

Fig. 14. A geological cross-section (drawn from Fig. 1; scale exaggerated) from Shani through Gombe to Alkaleri showing the most prospective areas to be mainly at those areas covered by the Kerri-Kerri Formation (NB: Aeromagnetic and seismic may show different scenarios)

5.0. CONCLUSIONS

The Nigerian government through the NNPC has drawn up work-programmes to re-enter the Benue Trough in search of hydrocarbon deposits. Sediment fills of up to 9,000m, 4000m and 6,000m deposited in the Anambra Basin, Middle Benue Trough and Upper Benue Trough, respectively, are available to form the required petroleum systems for producible hydrocarbons in the Benue Trough. Geochemical reviews show that overwhelmingly gaseous hydrocarbons with some oil may have been generated. Geophysical data are not readily available on any parts of the Benue Trough. Cross sections across the geological formations show that prosepectivity increases southwards towards the Niger Delta for the Anambra Basin with a possible bright spot in the Ayangba-Iyale-Ibaji-Alade-Odolu areas in the northern part. Similarly, the most prospective areas in the Middle Benue Trough comprise the areas within and around Lafia, Loko, Doma, Dadere, Obi, Shabu and Shendam. Those areas with supposedly thickest sediment piles covered by the Kerri-Kerri Formation constitute the most prospective areas in the Upper Benue Trough. These areas include but not limited to Gombe, Alkaleri, Gombe-Aba, Dukku, Akko, etc. Prospects that may exist in the inferred prospective areas in the Middle and Upper Benue Trough are further enhanced by the termination of the sequences at basement boundary disallowing further migration and enhancing hydrocarbon accumulation. Delineation of more/most prospective areas in this

review will assist ongoing exploration programme in the Benue Trough by enabling the companies to focus seismic data acquisitions on the defined areas and thereby reducing exploration cost considerably. Nigeria will surely need these hydrocarbons to enhance her reserve asset and diversify her E&P geographical locations. Discoveries in contiguous basins in Chad Republic, Sudan, Kenya, Uganda, etc., support this optimism.