IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 10, Issue 1 Ser. I (Jan. – Feb. 2022), PP 39-56
www.iosrjournals.org

Southern Bida Basin, Nigeria: Depositional Cycles, Reservoir Facies Distribution and Application To Exploration Efforts.

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Abstract:
Apart from the outcropping proximal Fanglomerates deposits of Campanian-Maastrichtian Bida and Lokoja Formation, other exploration reservoir types are not defined and understood. In this study, major surface river drainage areas, outcrop thicknesses, subsurface GR / Res borehole log data were evaluated and integrated to define the reservoir types, thicknesses, distribution and application to exploration campaigns in Southern Bida Basin (Okoto Sub-Basin). Rivers Kaduna, Kampe and others have extensive 395 – 60,575 Km^2 drainage areas, which directly supported the developments of the Fanglomerates complex deposits named Bida and Lokoja Formations respectively. When these Formations are eroded and sediments transported, they deposited as Channel and distal Fan complexes within the symmetrical rift basin. Within Okoto Sub-Basin, up to five correlatable gravity-driven second-order Fanglomerates deposits are documented from 10 Outcrops which are in 17-31 m and 3-109 m thick ranges respectively. These second-order Complexes are in 3 – 38 m thick range, with basal Conglomerates / very coarse Sandstone package fining upwards to Claystone / Shale level at the top. Separating the Bida and Lokoja Formations, are the 20 m thick Maastrichtian Siltstone / Shale section in Ahoko outcrop, 152 m Shale in Achabo subsurface Gamma Ray / Resistivity data and 10 – 15 Km wide by 80 – 90 Km long shale corridor. River Gurara and tributaries with 15,245 Km^2 sediment catchment area contributed sediments to Bida Formation package where subsurface 80 m thick proximal Fanglomerates deposit is logged in Abaji-1 Borehole. From the South, River Kampe covering 9560 Km^2 sediment catchment area is the key clastics supplier for the development of Lokoja Formation. Regional Geological Maps show recent Channel complex and distal Fan deposits of 2 – 12 Km wide / 6 – 70 Km long and 6 – 25 wide / 20 – 130 Km long ranges respectively along River Kaduna. Along River Gurara in Okoto Sub-Basin, only the Channel complex deposit is 10 - 12 Km wide and 30 - 40 Km long is noted. Subsurface GR / Resistivity log data of Abaji, Achabo and Ahoko Boreholes documented the Channel sand deposits in 6 – 17 m range, and the deeper distal Fan deposit with more than 9 m thick. This pioneering outcrop and subsurface data integration study provides a 3D geological model, information on the exploration reservoir types in Bida Basin, can be used as analogs for other inland rift basins, in reservoir thickness estimations and for potential resource Gross Rock Volume (GRV) modelling.
***Key Words**: Kwali High, Okoto Sub-Basin, Second-order Fanglomerates Deposits, Channels, Distal Fans.*

Date of Submission: 08-01-2022 Date of Acceptance: 22-01-2022

I. Introduction:

Bida Basin is one of the unexplored inland rift basins in Nigeria, and it is related to the Early Cretaceous evolution of the SW – NE Benue Trough. Many authors have focused on the regional geological and stratigraphic studies of Bida Basin and other Nigerian Cretaceous inland basins including some recent studies [25, 26, 19, 11, 1, 31, 22]. They have provided the sound geological bases for detailed understanding of the different formations for exploration activities. The evolution of ideas, data-supported and ground-truth understanding of this basin, is in line with established technical approaches and geological knowledge-based efforts and successes recorded in Cretaceous West Africa basins and prolific Tertiary Niger Delta Basin of Nigeria. This is a pioneering work to integrate outcrop and subsurface shallow GR / Resistivity borehole log data for better understanding of the reservoir facies types and distribution in Okoto Sub-Basin [30].

Neither seismic data nor deep well data is available in the Bida Basin, as common in most inland rift basins of Nigeria [20] (Figure 1). Therefore, it is very critical to commence the exploration efforts by studying the outcrops, and use the observations, results and understanding to project into the subsurface, adequately and technically constrained with quality data from proven analogue basins. With the well-documented regional essentially lithostratigraphic information [4, 25, 26, 31], a natural progression is the detailed understanding of the sands / sandstone, claystone and shales at the finer second-order scale. The potential exploration objectives should be at this smaller scale within the formations, and as can be documented in the subsurface and road-cut outcrops. This study provides basic information on the objective reservoirs, their structural and stratigraphic features and can be used to build depositional models. It is important to also understand these reservoir facies and seals for adequate spatial data coverage and optimal imaging in the planned regional 2D seismic program. As at early 2020, scouting efforts reported plans and activities to acquire exploration 2D seismic data in this Basin.

In this paper, based essentially on southern Bida Basin (Okoto Sub-Basin), a second-order level of understanding of the Fanglomerates complex deposits within the Lokoja / Bida Formation, is presented as documented in the 10 outcrops. The Sandstone package thickness variation is consistent at both regional and second order scales across the southern Bida basin area, and the distribution of siltstone-rich Maastrichtian Ahoko facies is better understood. This siltstone – marine shale section separates the Bida Formation from Lokoja Formation, as they thin away from the flanks, and overly central Campanian and older shale sections. Series of sea / water level drops eroded sands and sediments from the top the Fanglomerates complex deposits, to form regional unconformity surfaces / sequence boundaries and the related Braided Channel System, which subsequently got filled with younger clastic deposits. In order to balance the reservoir material budget, the eroded Fanglomerates sediments were further transported basinwards through exposed braided - subsurface channel systems towards and into the depocenters.

The eroded sands were deposited as fluvial confined Channel deposits, and further downdip as distal unconfined Fan deposits noted in the subsurface GR / Resistivity logs of Ahoko, Achabo and Abaji shallow boreholes. These are the deeper exploration objectives within thick underlying Campanian and older shale sections. These observations and results from Bida Basin studies, with the application of sequence / seismic stratigraphy principles, can be used to define such subtle fluvial reservoir deposits in other inland basins. Documented reservoir facies can hold appreciable oil and gas resources, as noted in other inland rift basins such as Mesozoic Barmer Basin, Rajasthan, India [10].

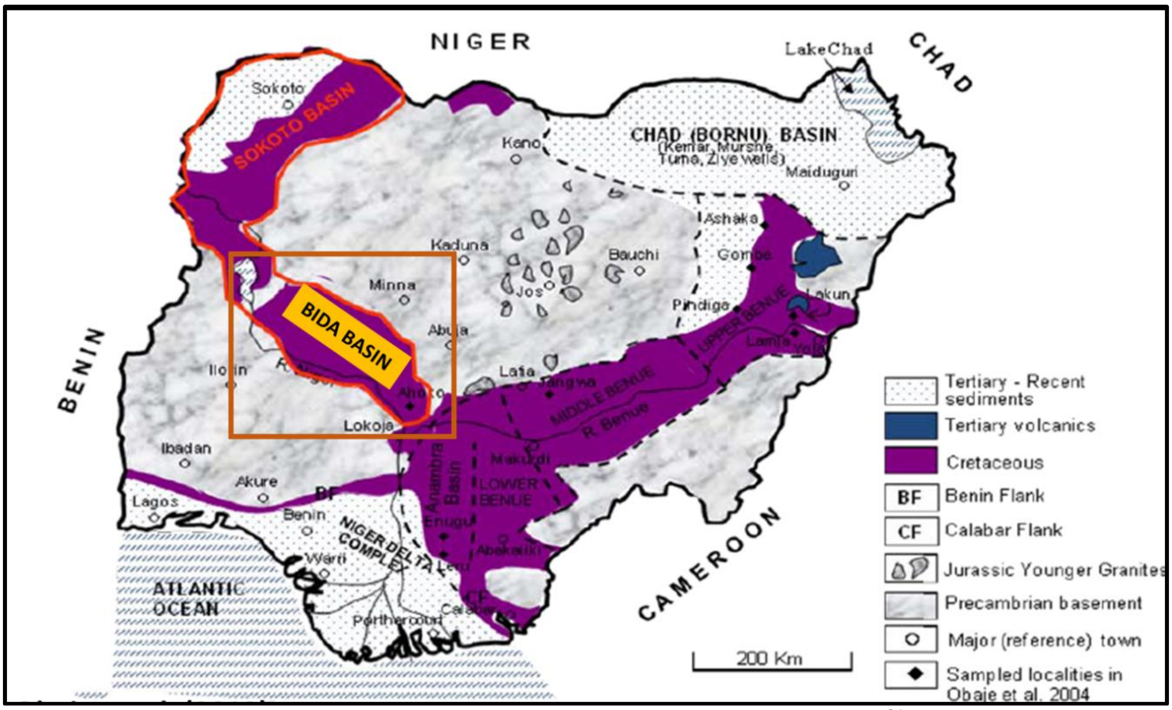

Figure 1: Location of Bida Basin and other Inland Basins [21].

REGIONAL GEOLOGICAL SETTING

Basin Evolution

The well-defined NW-SE Kotangora – Kwali northern Flank of Bida Basin is the western continuation of the NW-SE Gboko Line [37, 7, 8] which also marks the northern limit of the Southern Benue Trough. They all evolved during the Late Jurassic - Early Cretaceous Rifting episode of West Africa – South America continental masses [34]. Intra-cratonic sediment wedges which thin to the North towards the Basement Complex are evidences of the Neocomian – Barremian Syn-Rift phase with marine – lacustrine environment of deposition, as documented in Benin Basin [14, 2] and in the pre-Bima Sandstones of Gongola Sub-Basin of Northern Benue Trough [35]. The

Barremian is essentially an erosional period as sediments of the age are not commonly reported. Some school of thought opined that the Syn-Rift period continues to the Aptian-Albian period [13]. Generally, the Post-Rift (Drift) period with marine – continental lithofacies, is accepted to commence in the Benue Trough and Chad Basin during the Albian times [7] to present day with the older sediments of Bida Basin covered by the Campanian – Maastrichtian sediment blanket. In Ahoko area, some near-surface black sub-bituminous coal seams are reported, indicative of uplift and the erosion of about 1000 m of marginal marine Maastrichtian sediments from Bida Basin. Tilted thick ironstone bands below regional unconformity surface and flat reddish sandstone beds are documented in Mokwa outcrop, supporting major tectonic event during the Maastrichtian times. The missing sediment thickness, related paleo-temperatures and uplifts should be factored into petroleum generation and expulsion modelling efforts in this Basin (Unomah 2020, personal communication).

Structural Framework

Several authors have offered ideas on the structural setting of Bida Basin, and their hypotheses are documented [30]. In 2012, the Nigerian Geological Survey Agency (NGSA) published an aeromagnetic spectral evaluation [15] which gave details of the basement topography of Bida Basin without any fault interpretation. However, in view of the Kotangora - Gboko regional fault which is related to the rift development of the Southern Benue Trough, and the recognised linear patterns within the basin, a possible regional fault interpretation of the NGSA map has been made (Figure 2). This suggests that Bida Basin is underlain by symmetrical, full graben rift setting bounded by NW-SE regional faults. Three major Lows namely Batamegi, Gadza and Okoto Sub – Basins are noted, and are in 2000 m – 3500 m depth range[24, 37, 39, 40]. During the 2019 Annual Nigerian Association of Petroleum Explorationists Conference, it was reported that about 7000m sediment thickness has been estimated from a recent Full Tensor Gradiometry (FTG) Survey in Bida Basin. This new depth information is also documented in a recent publication [22]. These structural Lows are separated by the Bida, Kwali and Dalcada Highs (see Figure 2). Ezhigi High [30] is a down-thrown fault block part of "Zungeru Mylonites" Trend, and it is isolated in the NE part of the extensive Batamegi Sub-Basin.

The almost East-West oriented Kwali High [30] is connected to the Dalcada High in the West, and continues as subsurface 150 Km long by 40-50 Km wide Basement High which outcrops in Kwali village to the East. It forms the natural divide of the Basin into Northern (Batamegi and Gadza Sub-Basins) and Southern (Kpada Flank and Okoto Sub-Basin) areas. The Bida High [19] is however noted to be a NW-SE oriented deeper low-relief High separating the Gadza Sub-Basin from Wuya Low of the Batamegi Sub-Basin, and it also links the Ezhigi and Kwali Highs. Dalcada High is an extensive horst block which separates the Batamegi Sub-Basin from Kpada Flank - Okoto Sub-Basin. It is postulated that the NE-SW Romanche Fracture Zone continued onshore [18], following the Neocomian syn-rift trend and separates the Fage – Adebo High from the Batamegi Sub-Basin, which also forms the western limit of the Sub-Basin.

At the recent September 2021 NAPE Technical Session, technical staff of Savannah Energy [6] presented the Gravity Map of the West Central Africa Rift Basins. Focusing on inland Bida Basin, the rift setting, Kwali High and Okoto Sub-Basin (Southern Bida Basin) are clearly documented, much in line with the Bida Basin aeromagnetic data architecture [15]. However, this recent gravity data presented shallower depths in the Batamegi Sub-Basin (Northern Bida Basin) than the NGSA studies. Also identified from aeromagnetics data, a NW – SE 950 m deep structural "Low" connection [32, 33] between Sokoto and Bida Basins, below the Lake Kainji area and now covered by recent sediments. From the same dataset, potential rift blocks at the flanks of the "Low" were also inferred. This "Low" is estimated to be around 40-50 Km wide [12].

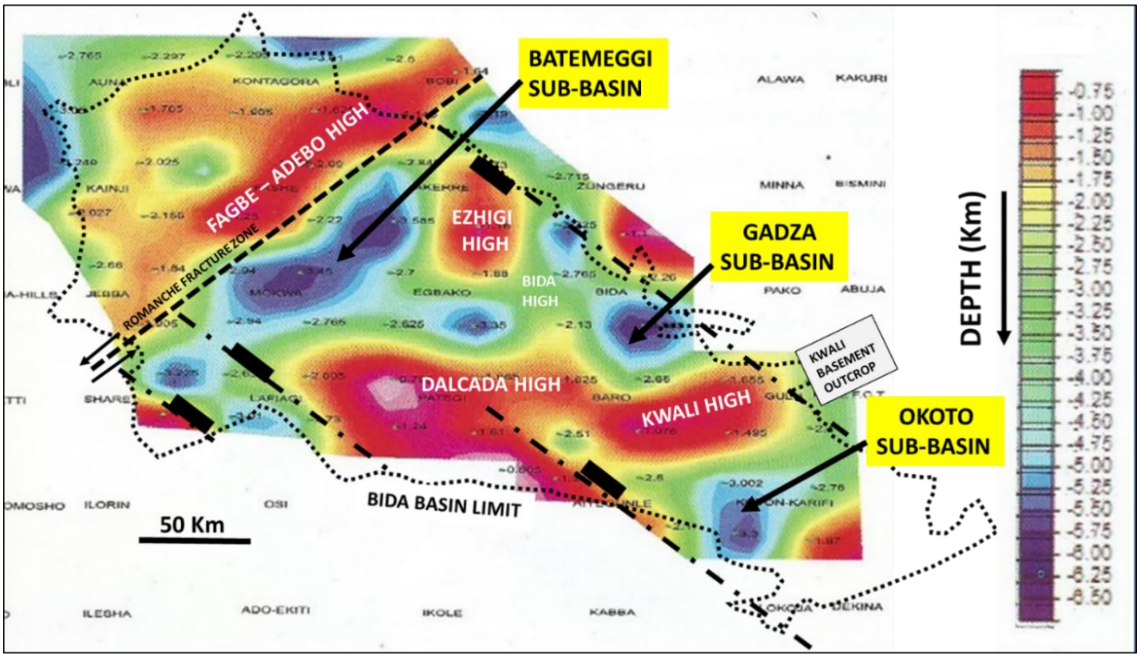

Figure. 2: Basement Architecture of Bida Basin. (Modified after NGSA 2012)

Stratigraphic Framework

Only the Late Cretaceous Campanian – Maastrichtian package consisting of basal Lokoja / Bida Formation, overlain by Sakpe Formation / Agbaja Ironstone [27], and capped by Enagi / Ahoko Formation [31] (former Patti Formation) have been documented within the Basin. The different lithofacies of these Formations are carefully reviewed[11]. The Kotangora – Gboko Hinge Line [37] defines the northern limit of the Southern Benue Trough where thick Pre-Santonian sediments are recorded. In Okoto Sub-Basin, marine Upper Turonian – Coniacian sediments are postulated to have been deposited by shelf sea incursion guided by the NW-SE Hinge Line. These pre-Santonian deposits are also speculated in Filele and Open University outcrops, near Lokoja [30]. The more recent regional marine incursion of Campanian-Maastrichtian period flooded the Bida Basin cul-de-sac area. Many erosional unconformity surfaces are documented within the Lokoja Fanglomerates deposit, Ahoko siltstone - shale series and the thick claystone sections with sharp vertical lithofacies relationship. Continued sediment inputs and related higher energy from the three major rivers: Kaduna, Jatau and Gurara in northern flank, possibly caused the non-axial position of River Niger, which is noted to be closer to the southern flank where the shorter weaker rivers are located. The adjoining rivers over the Basement Complex, their lengths and drainage area sizes are very important in understanding that the Bida and Lokoja lithofacies developments are very separate contemporaneous depositional packages as documented in this study.

II. Materials And Method

This study is based essentially on 10 Outcrop Lithofacies description and their composite logs, Aeromagnetic maps by Nigerian Geological Survey Agency (NGSA, 2012). Five major fieldwork trips in years 2015 - 2020 across the Basin, and Geological Maps of Bida Basin area (GSN, 1974; NGSA 2015) editions. In the outcrops, the different lithofacies packages and their bed thicknesses, terminations, areal extents, stratigraphic contact relationships, major erosional unconformity surfaces, visual grain-size distributions were estimated and documented. GSN (1974) and NGSA (2011) maps were used to define and calculate the river lengths, drainage / sediment capture areas, sizes of recent channel and fan deposits. The Abaji, Achabo and Ahoko shallow-water Gamma Ray (GR) / Resistivity (Res) borehole logs with 155 m maximum depth, are available to define subsurface reservoir and shale levels in the study area. These technical data were integrated and related to other published geological information in order to provide the results and inferences highlighted in this paper.

III. Results

Source – Sink Connections

The adjoining rivers and their precursors were the major clastic sediment suppliers into Bida Basin as noted from their different drainage sizes and systems, for the developments of Bida and Lokoja Formations. The smallest and largest are Rivers North of Mimi and Kaduna with 395 and 60,575 Km^2 respectively (Figure 3 and Table 1), as their areal extent data are directly proportional to the river lengths which are in 50 – 490 Km. range respectively. On the South flank, are the short rivers while the long rivers are on the North flank. Five river systems namely Oro, Oyi, Oshin, Mariga / Kaduna, Chanchaga / Jatau feed sediments into the wider Batamegi and Gadza Sub-Basins. Only three systems, the Kampe, Gurara and unnamed rivers are connected to the smaller southern Okoto Sub-Basin.

Second-order Fanglomerates deposits

Within the Okoto Sub-Basin, ten (10) outcrop locations were evaluated to understand the regional distribution of the exposed Fanglomerates deposits, the internal gravity deposit expressions and units (Figure 4) with total thicknesses in 3 – 109 m range. From Abaji to Kpada outcrops, two to five distinct second-order Fanglomerates packages defined by regional unconformity at the base, fining upwards lithofacies and 3 - 5 m shale / claystone at the top, with 3 - 38 m thickness range respectively, are documented within the separated Bida and Lokoja Formations. Only three of these lithofacies packages can be correlated within each of the formations in the study area, as the thicker outcrop deposits are noted within Lokoja Formation (Figure 5).

Table 1: Bida Basin – Rivers and Fluvial Deposit Data.

RIVER	AREA (Km2)	LENGTH (Km)	CHANNEL DEPOSIT		DISTAL FAN DEPOSIT	
			Length (Km)	Width (Km)	Length (Km)	Width (Km)
Kaduna	60,575	490	60 - 70	06 - 10	100 - 130	08 - 25
Gurara	15,254	280	30 - 40	10 - 12	NONE	
Kampe	9,560	175	18 - 20	06 - 10	Merged with Kaduna Fan	
Jatau	7,100	156	06 - 20	04 - 06	Merged with Kaduna Fan	
Oro (East of R. Oyi)	5,950	113	16 - 18	06 - 08	Merged with Kaduna Fan	
Oshin	2,132	125	NONE		NONE	
Oyi	570	90	08 - 10	02 - 04	20 - 25	06 - 08
North of River Mimi	395	50	NONE		NONE	

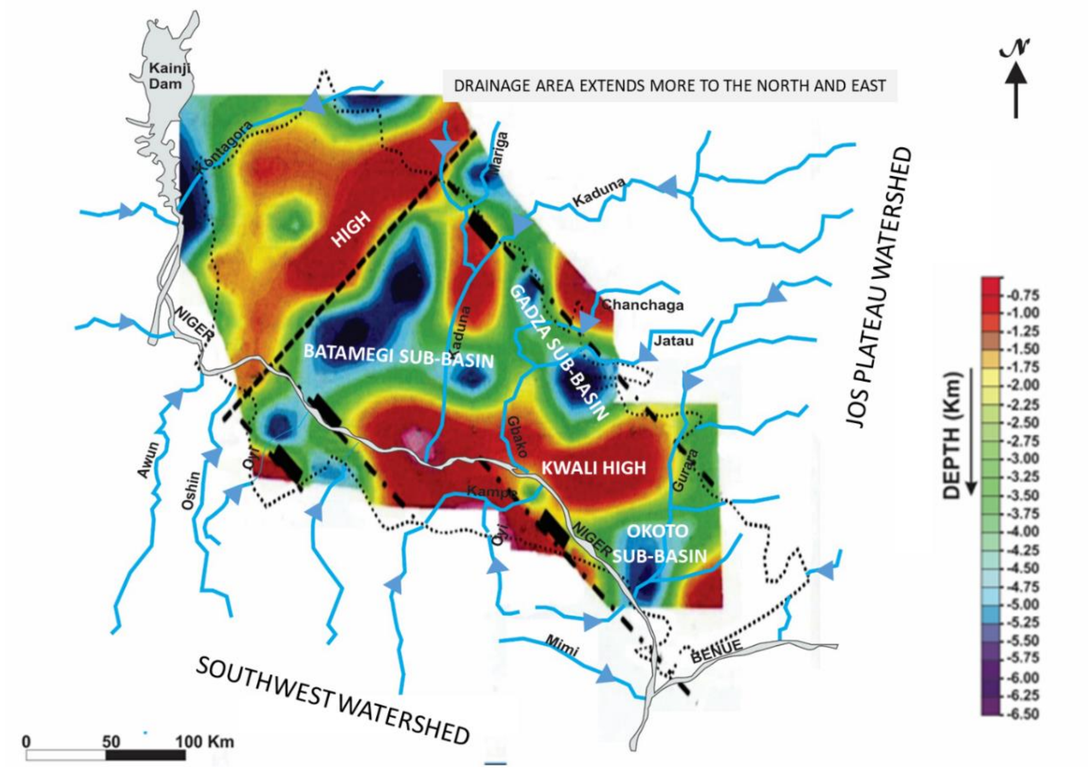

Figure. 3: The Rivers and related Depocenters in Bida Basin

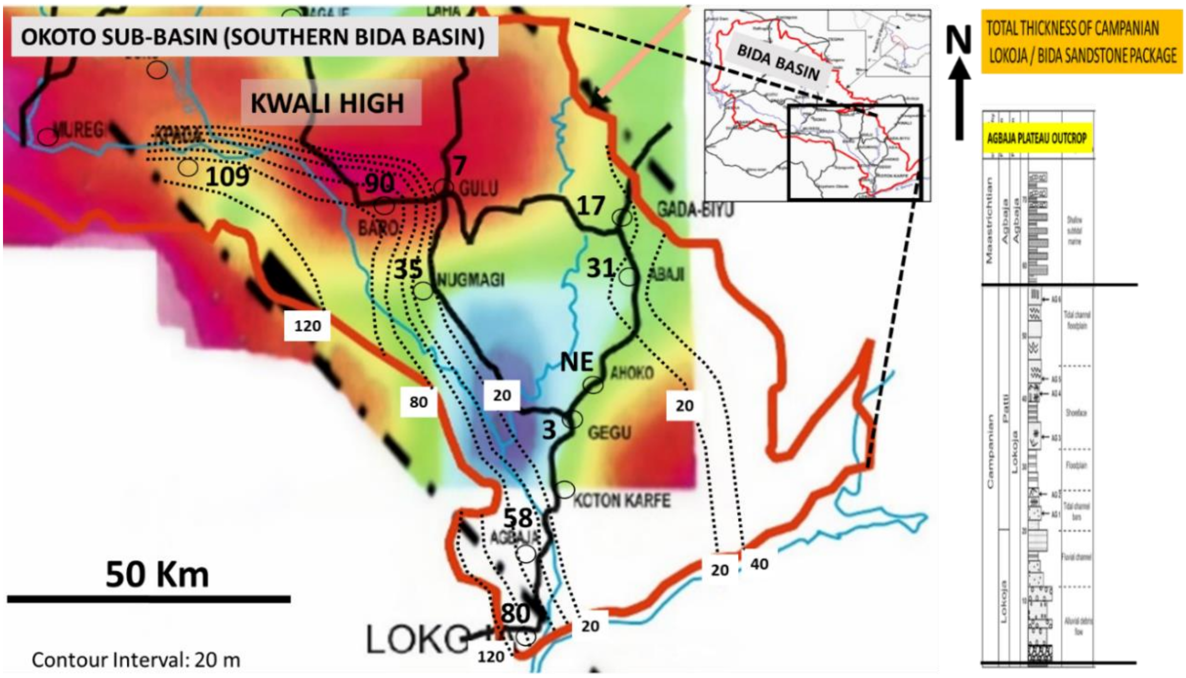

Figure 4: Total Thickness of Fanglomerates Deposit Outcrops in Okoto Sub-Basin

These second-order deposits are not documented in Maastrichtian siltstone / shale Gegu Gerinya, Achabo and Ahoko outcrops. None of the field outcrops show gradual contact relationship of the Fanglomerates with the underlying Shale / Claystone deposits, but sharp vertical contacts are clearly documented due to rapid gravity depositional process and erosional activities. Rivers Gurara and Kampe have been major suppliers of clastic sediments and terrigenous materials into Okoto Sub-Basin for the development of the second-order Fanglomerates deposits with the NW-SE oriented Bida and Lokoja Formations respectively, which are separated by about 10 – 15 Km Maastrichtian shale rich corridor.

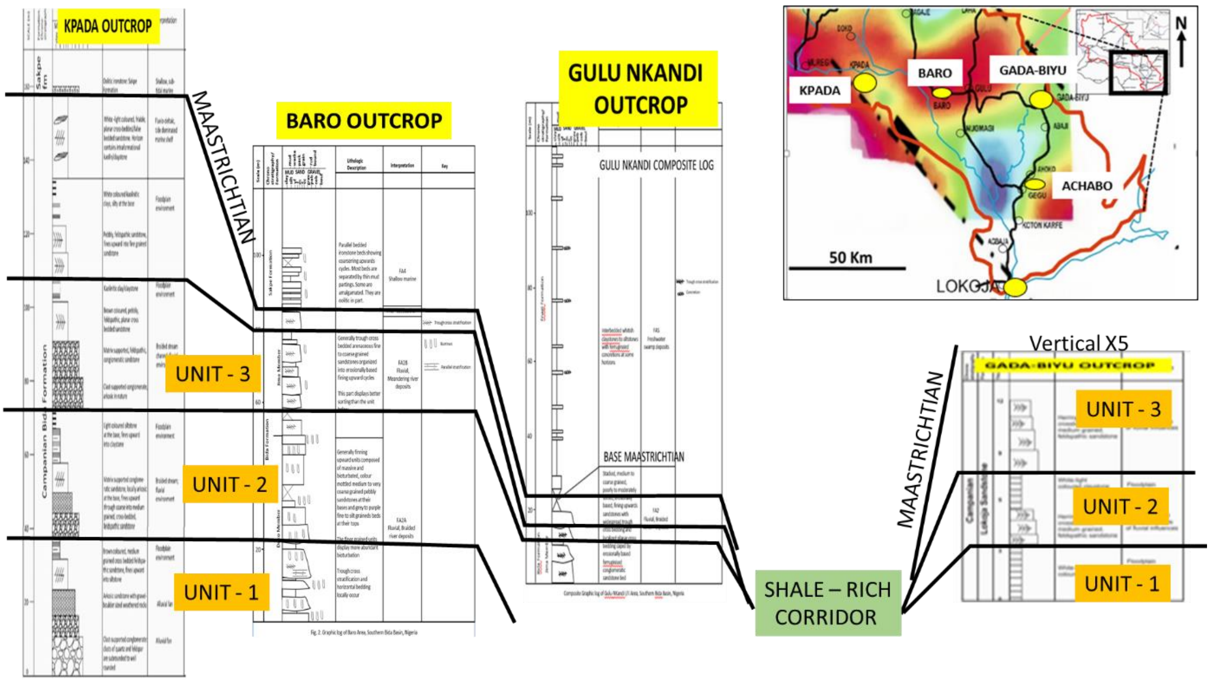

Figure 5: Correlation of Second-order Fanglomerates deposits in the northern part of Okoto Sub-Basin.

Subsurface Exploration Objective Reservoir Facies Definition

Three boreholes namely Abaji, Achabo and Ahoko have GR / Resistivity log data [23] showing the different subsurface lithofacies down to a maximum of 155 m depth (Figure 6). Abaji borehole logged five second-order

Fanglomerates packages of 80 m total thickness, Channel deposit of 6 m and bottomed within a distal Fan complex of more than 9 m thick. These reservoir levels are separated by 7 and 52 m shale sections respectively. In Achabo borehole, only 17 m Channel deposit is logged with the 135 m thick Shale interval. Two 13 m Channel sand levels and 43 m thick Shale are documented in Ahoko borehole. The GR / Resistivity Logs of the reservoir types are very diagnostic, with the fining upwards signature of the second-order Fanglomerates deposits, "serrated box" responses for the coarse-medium grained Channel deposit sand level and "less serrated box" pattern of the deeper medium-fine grained distal Fan complex level. This a pioneering contribution to understand and define the three candidate exploration reservoir objectives from subsurface wireline logs acquired within the Bida Basin.

Lateral Stratigraphic Relationship of Lokoja and Bida Formations

The integration of outcrop and subsurface lithofacies data clearly showed the separation of the Lokoja Formation from Bida Formation, as documented by siltstone / shale package of 20 – 100 m and 43 – 135 m thick respectively and laterally by about 10 – 15 Km wide and 80 – 90 Km long shale rich corridor (see Figures 4-6). In Achabo borehole located in the middle of the Okoto Sub-Basin, below the 20 m siltstone / shale outcrop as estimated from nearby Ahoko location, the maximum continuous subsurface shale section of 135 m is recorded down to 152 m depth (Figures 6). From both surface and outcrop data in this study, the relationship of Bida Formation, Lokoja Formation, Channel and distal Fan Complex deposits is demonstrated in a 3-D stratigraphic model (Figure 7).

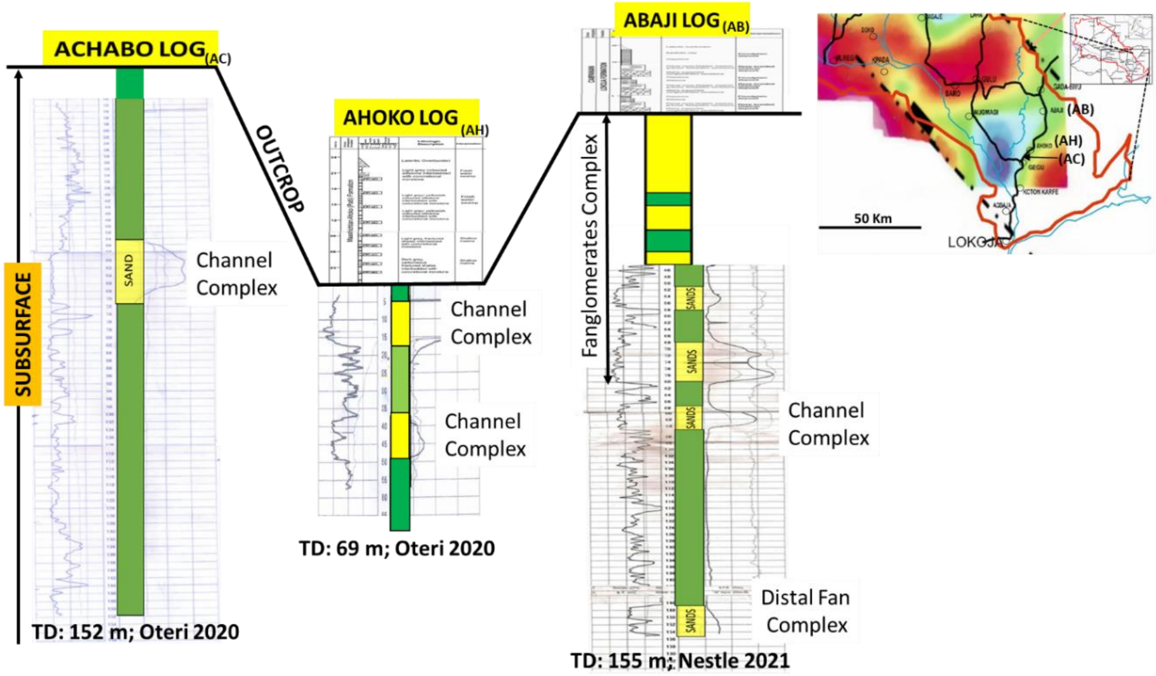

Figure 6: Subsurface GR / Resistivity Logs of Fanglomerates, Channel and Distal Fan Complex deposits.

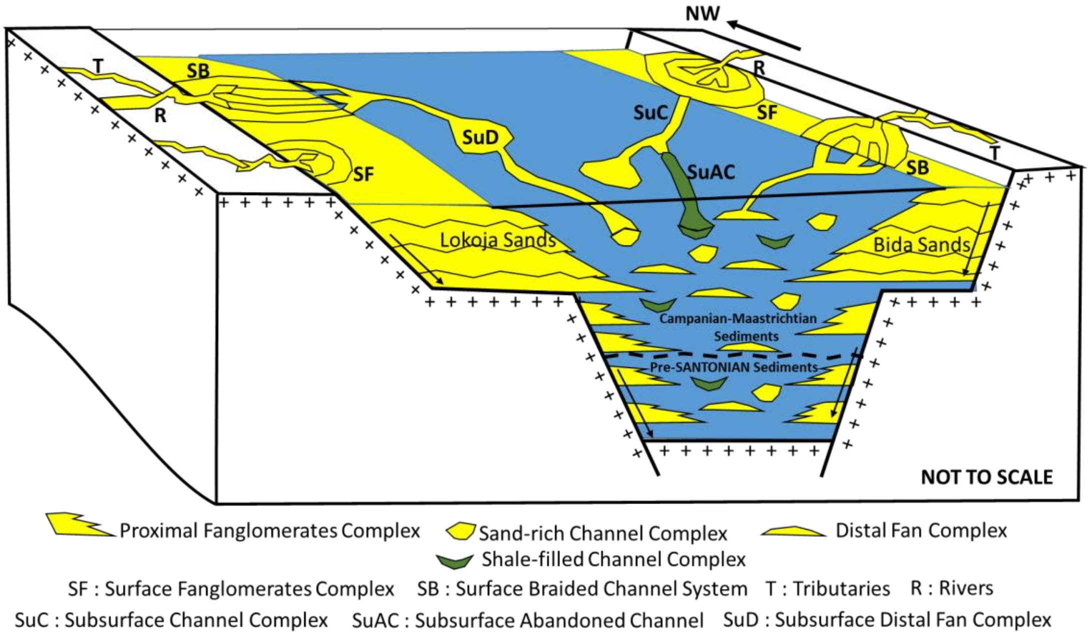

Figure 7: Distinct Relationship of Bida Formation from Lokoja Formation and related Reservoir Objectives.

IV. Discussion

Source – Sink Systems

Bida Basin is a cul-de-sac system connected in the SE to Albian – Santonian Southern Benue Trough and overlying Campanian – Maastrichtian Anambra Basin. However, the subsurface East-West Kwali High, separates the closed northern Batamegi and Gadza Sub-Basins from the open southern Okoto Sub-Basin. The closed Sub-Basins must have favoured the development of lakes / lacustrine setting during Early Cretaceous period, while the open Okoto Sub-Basin had marine connection and influences from Southern Benue Trough since their related inception. The Turonian global flooding episode must have caused some incursion [28], if not covered the entire Basin from Southern Benue Trough, as speculated for the Filele and Open University outcrops of Okoto Sub-Basin [30]. Also in the outcrops, the Maastrichtian shales have documented the related Late Cretaceous seaway, and possible connection to Sokoto Basin through the narrow structural Low as defined from recent aeromagnetic data analysis but presently covered by Kainji Dam waters and sediments [32, 33] (Dada 2021, personal communication). Bida Basin is documented to have three major depocenters namely the Batamegi, Gadza and Okoto Sub-Basins which estimated to be in 2000 – 7000 m depth range. Earlier aeromagnetic and gravity studies estimated about 2000 – 3500 m depth range [24, 37, 39, 40]. However, during the 2019 Nigerian Association Petroleum Explorationists (NAPE) International Conference, a government Agency official reported that a recent Full Tensor Gravimetry (FTG) survey recorded about 7000 m thick sedimentary pile in Bida Basin. This same figure is documented in the recent publication [22], but the source of such depth information was not mentioned. In the recent September 2021 NAPE Technical Meeting, a gravity map of central West Africa Rift systems [6] including well-defined Okoto Sub-Basin, was presented showing relatively shallower Batamegi Sub-Basin and clear rift margins. There is room for both good reservoir and source rock facies development within the sub-basins.

Eight river drainage systems supply clastics and other terrigenous materials into Bida Basin. Rivers Kaduna, Chanchaga / Jatau and Gurara in the North Flank are longer that 150 Km. and widespread catchment areas of greater than 7,000 Km^2 (Table 1). From this Flank, only Rivers Kaduna / Jatau and their precursors are speculated to bring copious fine-coarse grained sediment supplies into the isolated Batamegi / Gadza Sub-Basins where lacustrine setting is favoured (See Figure 4) before the Turonian marine global flooding episode. Shallow Kudu Borehole located in the center of Batamegi Sub-Basin, logged thick black shale with coal seams [22] as noted in the ditch cuttings near the location by Kudu Health Centre. Long distance sediment transportation as noted for the three major rivers, produced the more petrographically matured [9, 38] Bida sands / Sandstone with better reservoir qualities, than the immature Lokoja sands / Sandstone [5] which were sourced by short rivers with smaller catchment areas in the South Flank. The 280 Km. long River Gurara has 15,245 Km^2 wide sediment catchment system which supplies terrigenous and matured clastics materials into the open Okoto Sub-Basin. From the South Flank, Rivers Oyi, Oshin and Oro with short distances of less than 120 Km. and smaller catchment areas of not higher than 6,000 Km^2 (see Table 1) contribute their sediments into Batamegi Sub-Basin. River Kampe is 175 Km. long within 9,560 Km^2 catchment area; and the River located North of River Mimi is 50 Km long in 395 Km^2 drainage area, both delivering sediments into Okoto Sub-Basin. These rivers characteristics support the accumulation of pebbly, poorly sorted, immature sediments documented along the Lokoja flank [5] and especially in Kpada outcrop (see Figure 5).

Significant changes in water or sea level and rapid sediment accumulation aided regional erosional and channelization activities as noted across the Basin, resulting in the development of aerial – subaerial fluvial Channel complex system, and subsurface Fan complex deposits in the distal and down dip setting of the Sub-basins. River Kampe and ancestral river systems were the major sediment suppliers for the development of Lokoja Formation in southern part of Okoto Sub-Basin, as River Gurara and precursors with wider drainage area supported the Bida Formation accumulation in the northern part of the same Sub-Basin. These thick Sand packages rapidly thin out into thick Shale section in the centre of the depocenter. It is hereby postulated that the hanging wall block experience higher movement, related heavy sediment loading and high subsidence, and/or intense Maastrichtian erosion affected the Bida Flank more than the Lokoja Flank of the Basin, with only smaller 17 – 31 m fine-medium grained sands/sandstone outcrop and 80 m thick Fanglomerates deposit in the subsurface as documented in Abaji location (see Figure 7 below). At Kpada location, the thick basal Conglomerates deposit is indicative of proximity to the Basement Complex and that the 109 m recorded may be thickest deposit in this flank of this Sub-Basin.

Averagely, the total of 82,920 Km^2 river drainage areas in the North Flank, is about five times larger than the total 18,607 Km^2 area of the rivers in the South Flank. Thicker Bida Sands must have been deposited and equally eroded by the stronger River Gurara and tributaries in the Sub-basin, in line with outcrop thickness data. The related heavy sediment deposition from the three major rivers from the North Flank, provide some understanding for the more mature clastic sediments noted in Bida Formation, and the River Niger flow course being pushed towards the South Flank along which less sediments are deposited by shorter rivers with smaller drainage areas. In Nugmagi outcrop, is the basal 28 m thick marine grey shale section with siltstone and fine-grained sandstone interbeds, below the proximal continental Bida Fanglomerates complexes, just as 66 m shale interval is noted in Abaji subsurface log data. These thick shale section with Channel and distal Fan reservoir deposits, completely separates the mature Bida Formation from the immature Lokoja Formation across the Sub-Basin. No biofacies or palynofacies was recovered due to shallow sampling method in the weathered stratigraphic section.

Second-Order Fanglomerates Development

Rivers Kaduna, Chanchaga / Jatau and Gurara in the northern Kotangora-Kwali flank have large catchment areas on the Basement Complex terrain, long sediment transport distances (see Table 1) and carry quantum sediment loads therefore they are the major clastic supplier through their different single discharge positions. These rivers and ancestral / current tributaries must have maintained minimal lateral variations in sediment discharge locations into the sub-basins. The opposite smaller sediment capture, shorter movement and less volume data hold for Rivers Oshin, Oyi, Oro and Kampe which are located in the southern Mokwa-Lokoja Flank. Fanglomerates complexes are developed at the entry points of these rivers, as gravity deposits in the hanging wall setting as fining-upwards packages. Starting with Conglomerates unit at the base, grading to very coarse-grained Sands / sandstone trough medium grained to fine grained Sand / sandstone then to Silt / Siltstone and finally into Shale / Claystone representing the maximum flooding phase of the basin for that short period of deposition. These distinct but repetitive stratigraphic cycles are noted within the Bida and Lokoja Formations. Through time, these single point deposits got redistributed laterally by water level variations, and got amalgamated vertically as they stack on each other preserving their individual depositional phase and characteristics. Across the study area, the bounding regional unconformities and thin-thick shale /claystone levels are diagnostic in defining the Second-order Fanglomerates Deposits. In the Lokoja ABC Park Outcrop of about 80 m high and about 40 m wide, is a classical exposure of the Fanglomerates deposit within Okoto Sub-Basin, and close to the Basement Complex edge of the Basin (Figure 8). The well-defined regional unconformities define the second-order Fanglomerates deposit boundaries because the related terminal claystone / shale sections have been eroded. These often regional argillaceous deposits are often preserved below the turbulent wave base level, and along with the overlying unconformity surfaces, they have been used for the stratigraphic fining-upwards package correlations within this Sub-Basin. This proximal Lokoja Sand package is interpreted as matrix supported Fanglomerates deposits [25]. Further in-board, in Kpada outcrop with relatively more continental setting, the Fanglomerates complexes have conglomerates or large coarse-grained Sands / Sandstone unit at the base, up to well-developed shale sections in 3 – 5 m thick range at the top of the fining upwards gravity flow package. The thicker 3 – 109 m outcrop sections in Gegu Gerinya and Kpada respectively are noted in Lokoja Flank, while only 17 and 31 m sections are documented for the two locations in the Bida Flank (see Figure 4). Across the almost East-West Dalcada / Kwali High and in the Batamegi Sub-Basin, the Lokoja Sandstone facies is only 8 m thick reddish sandstone with dipping ironstone bands in Mokwa outcrop, where no claystone / shale level is documented in order to define the second-order Fanglomerates deposits. River Kampe, the tributaries (see Figure 4) and possible precursor covering 9,560 Km^2 sediment catchment area, were the major clastic sediments suppliers along the narrow Kpada Flank and further down dip into the unconfined Okoto Sub-Basin. With water / sea level changes, the braided channel system develops on top of Fanglomerates deposits, and the eroded sediments are transported further down dip within the Sub-Basin. On Bida Formation, the Abaji borehole (Figure 9), logged 80 m thick stacked second-order Fanglomerates deposits above thick Channel and Fan complex deposits which are separated by thick shale section before the 155 m total depth (TD).

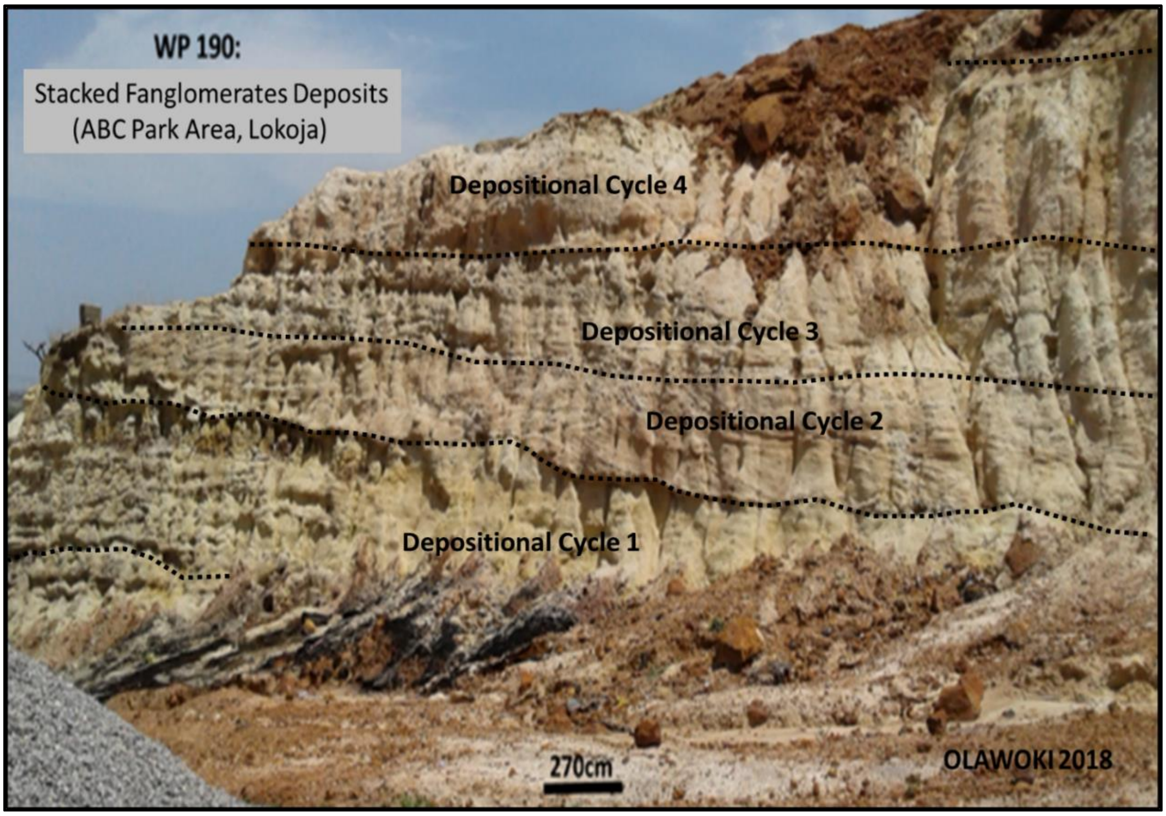

Figure 8: Mature Fanglomerates Deposit within Lokoja Formation, in Lokoja Township.

The typical fine-upwards GR / Resistivity log signature of the subsurface second-order Fanglomerates deposits, is diagnostic as noted in 44-80 m depth interval of complex deposits of Abaji borehole. Achabo and Ahoko GR / Res borehole logs did not record any Fanglomerates deposit. The influence of River Gurara, tributaries and precursor with wider 15,245 Km^2 sediment catchment area, must have primarily favored thicker sand accumulation during the Campanian times, when compared to that of River Kampe drainage area and related sediment thicknesses. However, the secondary erosional activity of River Gurara system must have been more intense and extensive, and possible resulted in the thinner 17 and 31 m in Gada Biyu and Abaji outcrops respectively. In both Gegu Gerinya and Ahoko locations in the center of Okoto Sub-Basin, about 20 m thick Maastrichtian Siltstone / Shale sections are documented in the outcrops. In the northern part of this Sub-Basin, in Gulu-Nkandi outcrop about 95 m of similar Maastrichtian lithofacies is logged. These outcrop and subsurface thick siltstone – shale sections indicate that the Lokoja Sands are laterally distinct from Bida Sands, and should be so reflected in Bida Basin Stratigraphic Column.

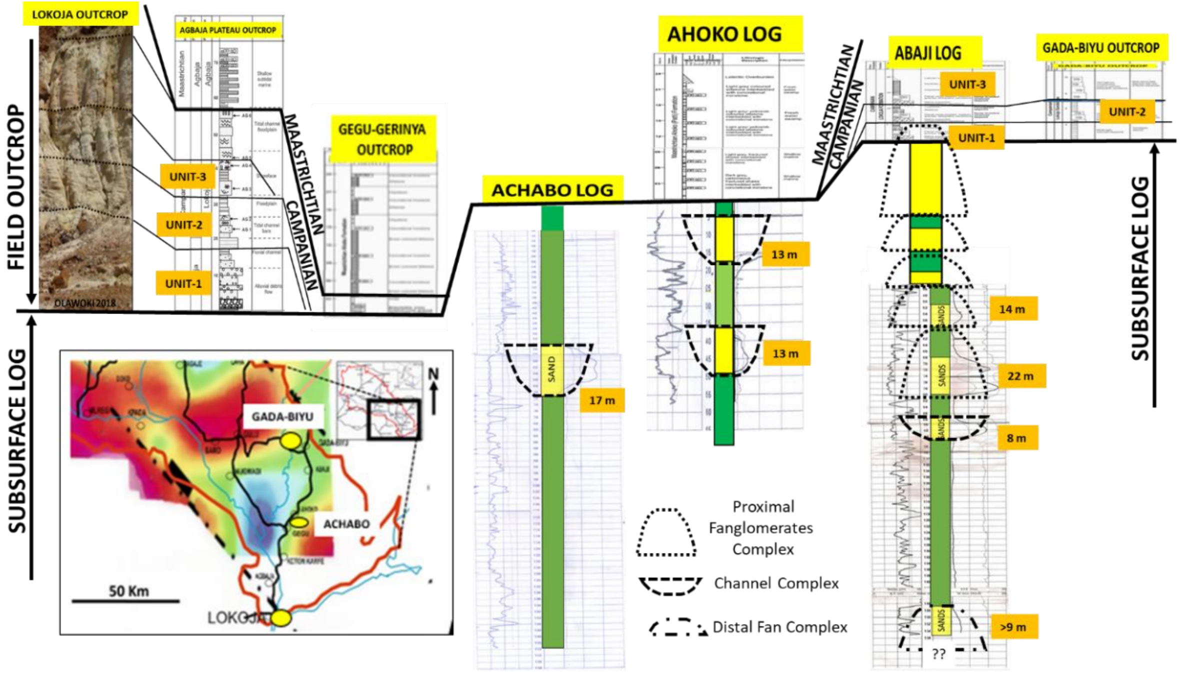

Figure 9: Agbaja – Gegu Gerinya – Ahoko – Abaji – Gada Biyu Outcrop Correlation Chart.

<u>Second Order Fanglomerates Deposit Unit 1</u>

This package is the deepest of the exposed second-order Fanglomerates deposits, with thickness in 3 – 38 m range as noted in Geringa and Kpada outcrops respectively (Figures 10 and 11). This is the basal unit overlying the basement rocks unconformably in various parts of this Basin. It is composed of a conglomeratic base which grades into a very coarse sand sequence and ending in a massively bedded, coarse to medium-grained sandstone at the top of the unit. The clasts are of various sizes and shapes and sometimes clast-supported at the basal part. Compositionally, the clasts include quartz, quartzite, granite, gneiss and feldspars [31]. The conglomeratic base shows some crude cross-stratification as can be seen in the ABC Park outcrop along the Lokoja-Abuja highway. The sandstones are coarse to very coarse grained and granular with clasts ranging from boulder size to cobbles and pebble sizes. The unit displays an overall fining upward sequence, with thin bands of sandy clay beds are common on the top, very poorly sorted and weakly consolidated. Thin conglomeratic bands are noted within the unit and this has been interpreted as intermittent high energy regimes.

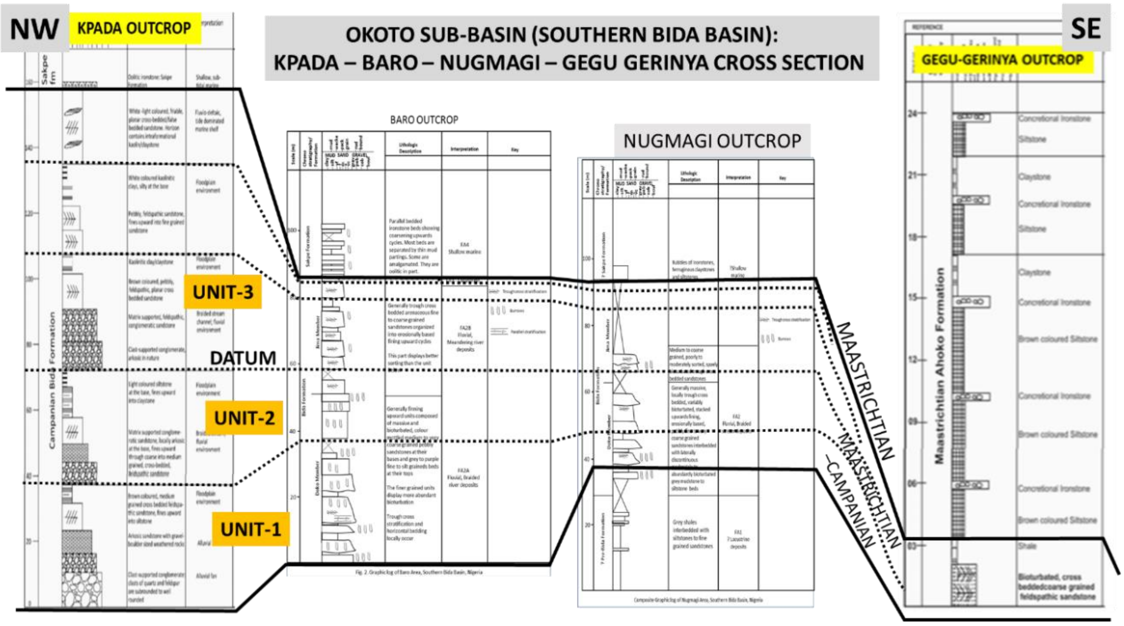

Figure 10: Kpada – Baro – Nugmagi – Gegu Gerinya Outcrop Correlation Chart.

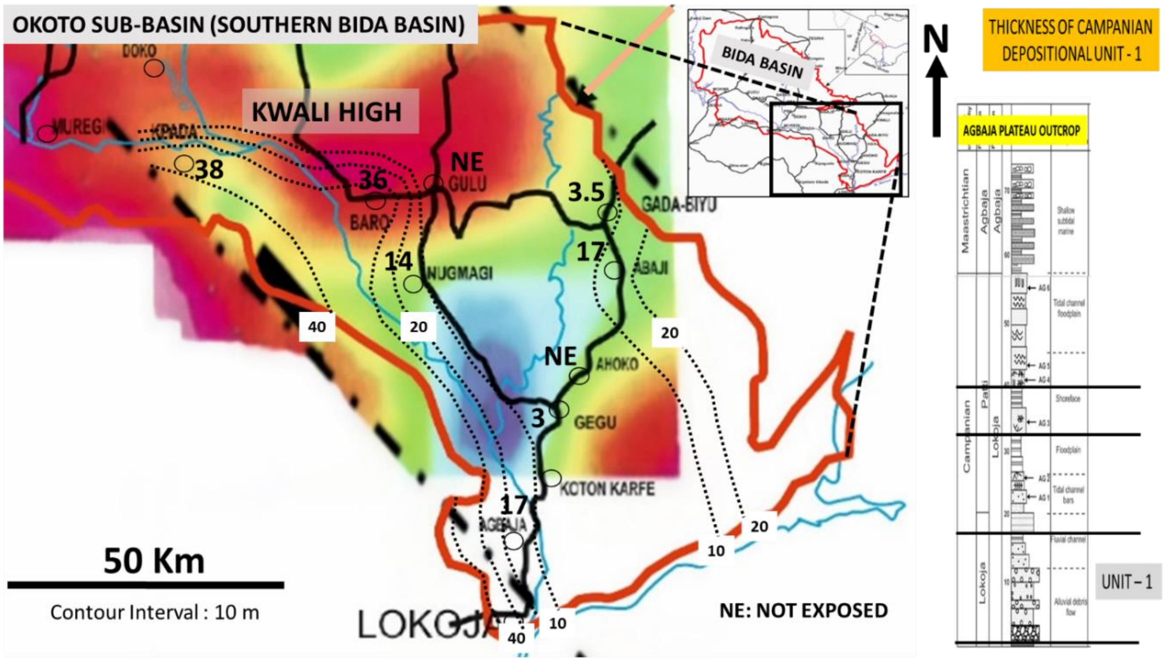

Figure 11: Distribution Map of Unit – 1 Second Order Fanglomerates Deposits in Okoto Sub-Basin.

<u>Second Order Fanglomerates Deposit Unit 2</u>

Across the Study area, this lithofacies is within 5.4 – 35 m thickness range, as documented in Gada-Biyu and Kpada outcrops respectively (Figures 10 and 12). This unit is composed of medium to coarse-grained sandstone / sands which are occasionally granular, angular, poorly sorted and cross bedded. The sandy clay and clayey horizons are thicker and occur frequent in this unit than observed in the underlying unit. The clayey horizons are lensoid and sometimes could attain a thickness up to 5 metres as seen at the Gada-Biyu, Kpada, Lokoja-Agbaja road sections. This unit also displays a rhythmic layering/repetitive stratification, starting mostly with pebbly horizons which grades into the sandstone and clay units. An overall fining upward sequence is observed on all the outcrops with good representation of this Unit-2 lithofacies with no conglomerates deposit.

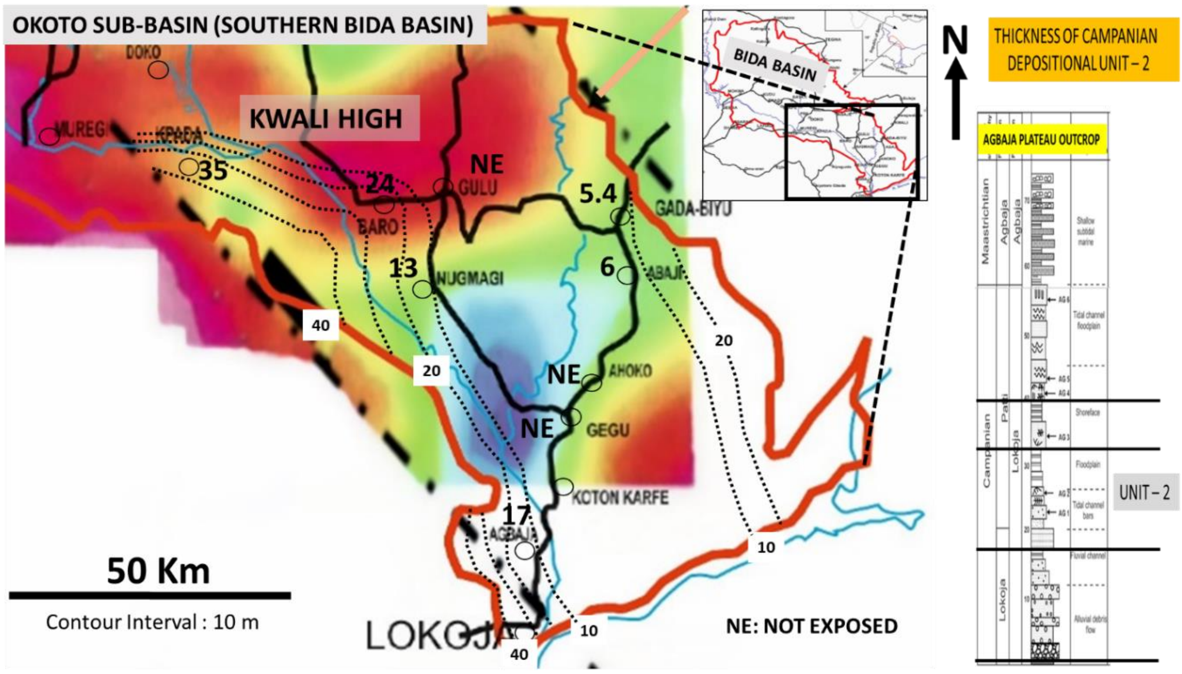

Figure 12: Distribution Map of Unit – 2 Second Order Fanglomerates Deposits in Okoto Sub-Basin.

Second Order Fanglomerates Deposit Unit 3

This is the shallowest of the three lithofacies which can be correlated within the Formations. Thicknesses are in 7 – 36 m range as observed in Gada-Biyu and Kpada outcrops respectively (Figures 10 and 13). The unit is characterized by medium to fine grained sandstone with thick clay units. The sands are clean, medium to fine-grained, occasionally coarse-grained and with weathered feldspars, displaying repetitive fining upward sequence with each cycle ending with a clay section. The sandstones are heavily cross-bedded. This unit is most conspicuous at the Kpada Hill and characterised by strongly cross-bedded clean sands and thick clay bands. Similarly noted on the Jimma Hill underlying the Sakpe Ironstone, and observed in the Agbaja Hill section where it is made up of alternating sand, sandy clay and claystone beds. The upper sand unit underlying the Agbaja Ironstone in this section is strongly cross-bedded tending towards the false-bedded sandstone of the Ajali Formation in the adjoining Anambra Basin. At Gada Biyu, the unit shows an alternating sand and clay units. The clay units are discontinuous and changes laterally into sandstone levels.

These discrete Units 3 to 1 packages clearly represent the overall fining upwards pattern within the distinct Bida and Lokoja Fanglomerates deposits which are separated by more than 20 m thick and 15 – 20 Km wide siltstone /shale corridor, and related to different sediment supply energies from the northern Kontagora – Kwali and southern Mokwa – Lokoja flanks of Bida Basin. In the subsurface, the second-order Fanglomerates Complex deposits should be the key exploration targets.

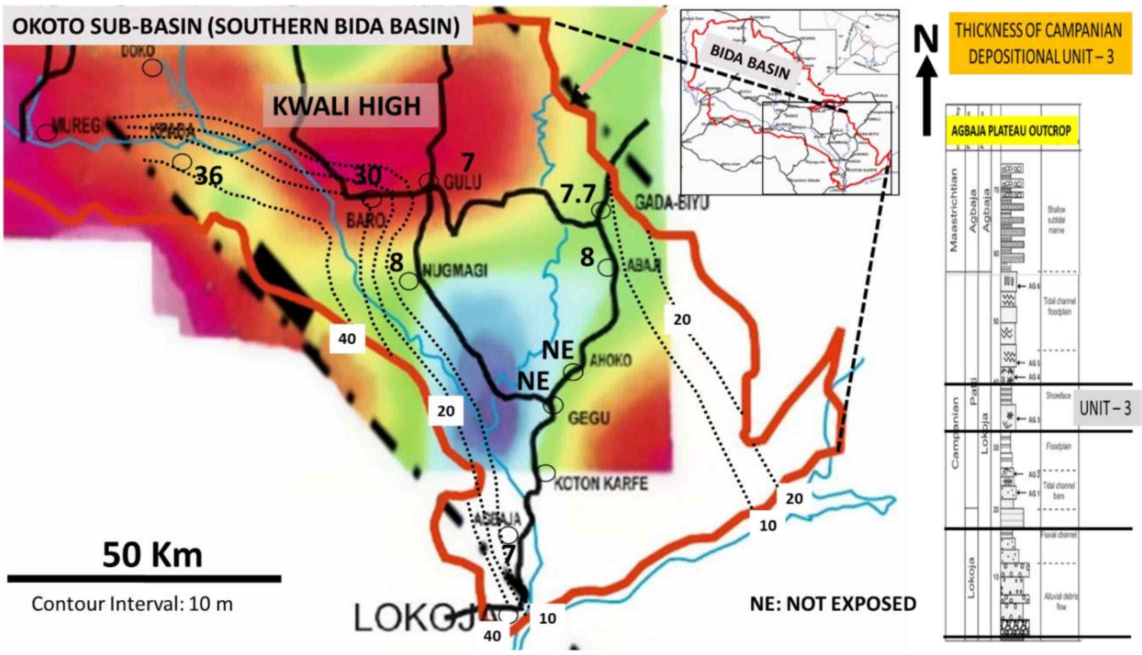

Figure 13: Distribution Map of Unit – 3 Second Order Fanglomerates Deposits in Okoto Sub-Basin.

Channel Complex Deposits

With fall in water level or forced regression, the upper section of the fanglomerates deposit is exposed and eroded by the rivers which cut deep channels into the fanglomerates substratum. These deep, connected cris-cutting channels on top of older fanglomerates deposits, form the Braided Channel System. The entire channel complex is often linked with subaqueous sediment conduits / canyons which transport materials to the deeper mud rich, source rock prone central to distal settings of the basin (Figure 14). Channel complex deposits are expected within Bida Basin, and can be mainly arenaceous, argillaceous or mixed sediments, and have been logged in the subsurface by the shallow Abaji, Achabo and Ahoko boreholes.

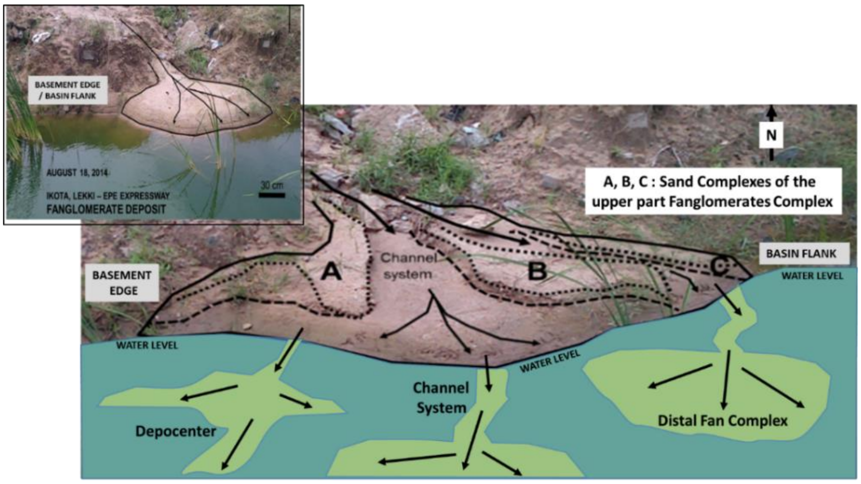

Figure 14: Modelling the Braided Channel System with subaqueous Channels and Fan complex deposits.

On the Geological Maps and along the major rivers (GSN, 1974; NGSA, 2015) flowingwithin Bida Basin, the sand-silt rich Channel complexes are in 2 – 40 Km wide and 8 – 70 Km long range (Table 1). From three water boreholes drilled to maximum of 155 m depth, both Channel and Fan complexes have been logged within thick Shale sections. In the upper 54 – 71 m section of Achabo log, a 17 m thick Channel Sand complex package within thick shale section, is interpreted from borehole ditch cuttings and diagnostic Gamma Ray (GR) / Resistivity (Res) log curve characteristics [23] (see Figure 6). Another 18 m and 24 m thick Channel Complex levels are also documented by Ahoko borehole log within 9 – 66 m depth interval. Abaji-2 logged a Channel Complex section of 6 m within 88 – 94 m depth separated by thick Shale section. These sands have quality reservoir deliverability potential as noted from the water flow rates and tests [23]. In Okoto Sub-Basin, the Channel facies are in 10 – 12 Km wide and 30 – 40 Km long range as documented along River Gurara before the connection to River Niger.

Distal Fan Complex Deposits

Fluvial Fan reservoir complexes generally consist of the confined channel section and unconfined fan-shaped lobe section on erosional surfaces. The shape of the fan complex is generally controlled by multiple factors including the substratum configuration, sediment volume and distance from source positions as predominant factors. In the Okoto Sub-Basin, up hill behind the Kogi State Tax Office in KotonKarfi, some Fan complex deposits were noted and documented in Bida Formation (Figure 15), as they stack up on regional mappable erosional unconformity surface. They thin away in both directions from 0.6 m thick central part over the 5 m length. Some Fan deposits have broad "U-shaped, clays and/or sands-filled channels cut through them but not reaching the erosional bases. In some cases, the softer clays are winnowed out, then replaced by younger sediments and/or plant debris. The sedimentary beds and dips of the infil deposits are not often parallel to the basal erosional surface, but discordant and eventually downlap on sequence boundary surface. These fan complexes have many sand lobes which occur side by side with overlapping facies and distinct lithologic contents. Fan reservoir facies with weakly confined – unconfined lobes are attractive exploration targets of the combination trap type. From geological maps and major rivers in Bida Basin, the distal Fan complex deposits are in 6 – 100 Km wide and 25 – 120 Km long ranges (see Figure 5 and Table 1). In the subsurface within 146 – 155 m (TD) depth interval, the Abaji borehole logged the upper 9 m of distal stacked Fan Complex levels (see Figure 9).

Figure 15: Fan Complex Deposit with Channel Complex in Bida Formation, near Koton Karfi Town.

Bida Basin Stratigraphic Column

In Gegu Gerinya and Ahoko outcrops, not less than 20 m thick Maastrichtian Siltstone / Shale sections are documented. More than 50 Km NW from Ahoko location, the Gulu-Nkandi outcrop has about 95 m of similar Shale lithofacies logged, and located to the East of Baro outcrop where only 15 m of the shale section is recorded. This thick lithofacies section shows the separation of Lokoja Formation from Bida Formation by 10 – 15 km wide and about 80 – 90 Km long surface and subsurface siltstone / shale corridor (see Figure 5). In the subsurface, the thickest Shale section of 135 m is reported in Achabo location which is at the central part of Okoto Sub-Basin. The shale and sand distribution pattern supports the Campano-Maastrichtian shale in-filling and marine flooding of pre-existing structural Low created by flanking Campanian Fanglomerates deposit Highs. This field data supported observation should be reflected in the Stratigraphic Column of Bida Basin (Figure 16).

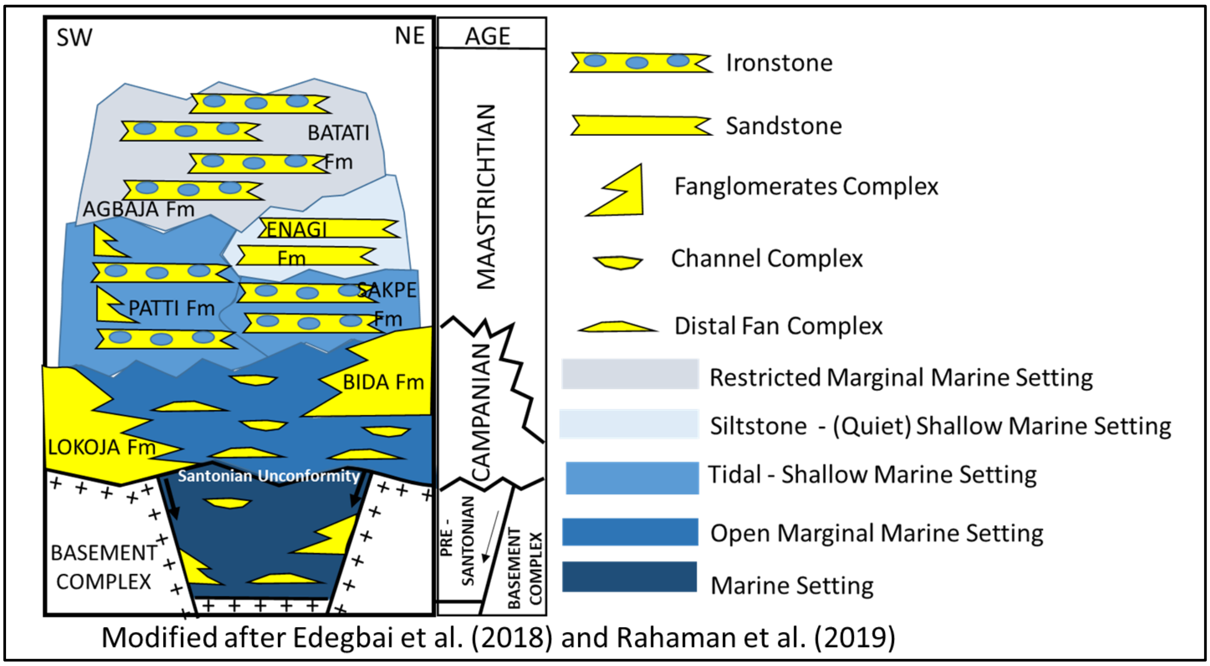

Figure 16: Proposed Revised Stratigraphic Column of Bida Basin

Exploration Objectives

Lokoja Sands / Sandstone facies are texturally and mineralogically immature [5], and can be very different from Bida Sands / Sandstone facies. This is mainly due to long distance transportation (see Table 1) and re-working of the sands by possible Rivers Kaduna, Jatau and Gurara reversals which then re-deposited the more mature Bida Sands / Sandstone sequence along the northern Kotangora – Kwali flank of Bida Basin. The major SW to NE paleo-current direction / sediment flow [3] is documented in Lokoja Formation, as supported by Rivers

Oshin, Oyi and Kampe flowing in the SW-to-NE direction into the southern Lokoja – Mokwa Flank. The paleo-current flow direction of Bida Sands, is in the NE-to-SW direction in line with the flow directions of Rivers Kaduna, Jatau / Chanchaga and Gurara which supplied the sands, and not in any way connected to the Lokoja Sands development (See Figure 7). In Zungeru area, near River Kaduna, a recent proximal Fanglomerates complex deposit is noted. It is sitting on the downthrown Ezhigi High [32], and bounded by the rift fault scarp to the North. Along the hanging wall setting, the Fanglomerates Complex deposit is about 25 Km long and about 15 Km in the dip direction. From Abaji location, some 80 m of Fanglomerates complex deposit is logged in the subsurface and tied to wide River Gurara drainage area. The wider catchment areas (see Table 1) and heavy sediment loads from S-SW flowing Rivers Kaduna, Jatau and Gurara in the northern Kwali - Kotangora flank supported the accumulation of Bida Fanglomerates deposits. Progressive fast and high accumulations of fanglomerates deposits in the northern flank, relative to low-moderate sediment load contributions from the Lokoja – Mokwa flank, must have influenced the River Niger flowing course close to the southern flank of the Basin, where some subsurface River Niger flow path lineaments or structural controls are inferred [29].

In Bida Basin, the exploration objective reservoirs should be the deeper proximal second-order Fanglomerates, intermediate Channel and distal Fan complexes which occur within the deeper mature type I / II / III rich-kerogen source interval (see Figure 7) in central parts of the Sub-Basins. From the spatial distribution in outcrops, vertical relationships in subsurface logs and understanding from analogue rift basins, a 3D modelling of the reservoir development in the Sub-Basins, is presented (Figure 17) to guide potential exploration efforts. These different reservoir facies and sizes should be attractive exploration objectives in Bida Basin, to estimate reservoir thicknesses, calculate Gross Rock Volumes (GRV) and estimate water / possible hydrocarbon resource potential. As more subsurface reservoir data is available, the understanding and modelling efforts will be better constrained.

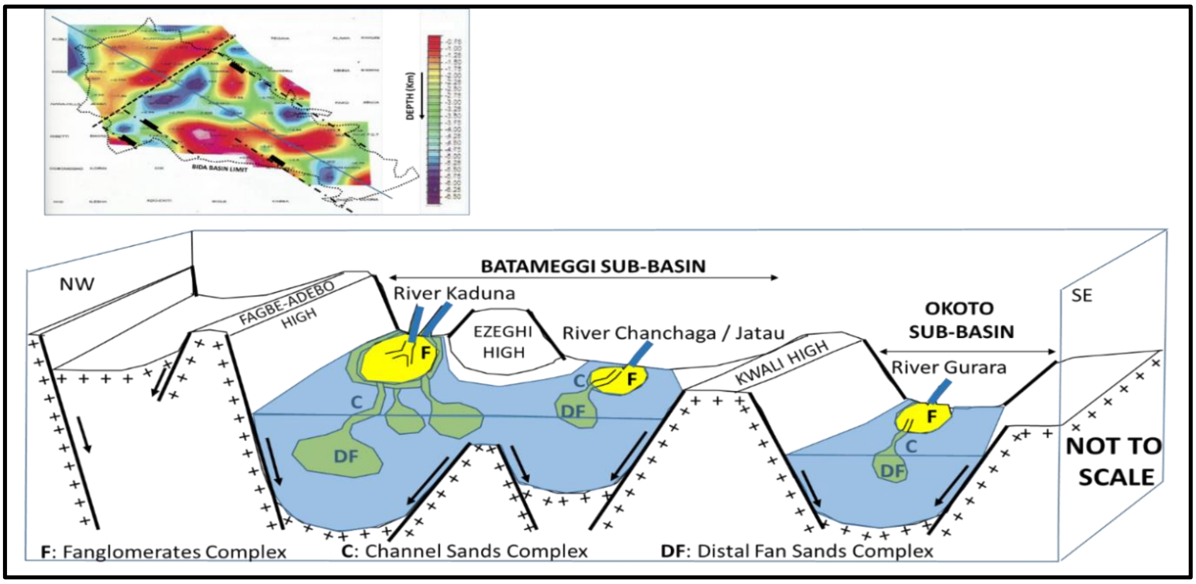

Figure 17: Exploration Objective Reservoir Packages Model in Bida Basin

V. Conclusions

Rivers Kaduna, Kampe and others provided copious terrigenous sediment supplies into Bida Basin, where they supported the developments of separated proximal Bida and Lokoja Fanglomerates deposits along the Kotangora – Kwali and Mokwa – Lokoja flanks respectively in the symmetrical rift setting. Okoto Sub-Basin (Southern Bida Basin) is separated from the Batamegi and Gadza Sub-Basins in the northern part, by the almost East – West oriented Kwali High which is connected in the western part to the Dalcada High. Across Okoto Sub-Basin, three major 3 - 38 m range second-order Fanglomerates deposits were defined, and can only be correlated within Lokoja and Bida Formations which are separated by 15-20 Km wide, 80-90 Km long corridor and about 155 m thick siltstone / shale section in both outcrop and subsurface log data of Achabo location. The sands eroded from the proximal Fanglomerates deposits by low – high changes in water level, were transported downdip and deposited as Channels and distal Fan complexes within the thick shale sections in the central parts of the Sub-Basins. From Abaji (155 m TD), Achabo and Ahoko water borehole logs in Okoto Sub-Basin, the Channel and Fan Complex deposits are in 6 – 17 m thick range and greater than 9 m respectively, with high Net-to-Gross ratio of 0.9. Modern day analogs along River Kaduna and smaller rivers in Bida Basin, show that the Channel and distal Fan deposits are in 8 – 70 Km long and 2 – 40 Km wide ranges and 25 – 120 Km long and 6 – 100 Km wide ranges respectively. Along River Gurara in Okoto Sub-Basin, the Channel deposits are in 10 – 12 Km wide and

30 – 40 Km long ranges. These reservoir sizes are within realistic ranges expected in the subsurface since these rivers have supplied sediments into the different depocenters of the Basin since the pre-Santonian inception, and their occurrence should be reflected in the Stratigraphic Column. The different reservoir facies, their surface areal extents and subsurface GR / Res log thickness data are attractive for exploration projects. They can be used as analogs in other basins and for Gross Rock Volume Modelling of water / possible hydrocarbon resource potentials in Bida Basin.

Acknowledgments

Our sincere appreciation to Prof Harry Doust who reviewed the initial draft, made great contributions and constructive suggestions which significantly improved the direction and quality of this paper. This is to express gratitude to Mr. Harrison Spiller of Azimuth Energy, Houston, Texas, USA, for area, elevation and other data calculations within the different river catchment areas, using the Digital Elevation Models (DEM) applications, and to thank Prof. R. Babatunde Bale of Geology Department, University of Ilorin, for guidance on the correct names of the major rivers which flow into Bida basin. Very sincere appreciation to Nestle Nigeria PLC for the permission to use the Abaji-Borehole logs.

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