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Field Opinions on Outcrop Reservoir Heterogeneity of Cenomanian-Turonian Yolde Sandstone Facies: Potential implication for Petroleum Exploration Challenge in Parts of Gongola Sub-basin, Upper Benue Trough, NE Nigeria

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Abstract

In the Gongola sub-basin, a recent hydrocarbon discovery in the Kolmani river-2 wellbore penetrated the Yolde formation, and two exploratory drilled wells namely; the Kuzari-1 and Nasara-1 also penetrated, but were both dry holes. Accurate recognition and documentation of meso-scale sedimentary heterogeneities that may potentially create fluid anisotropy and constriction into wellbores are required for accurate reservoir modeling and well placement. This study attempts for the first time to evaluate the Cenomanian-Turonian Yolde sandstone facies heterogeneities to deduce their depositional environment and potential contribution to petroleum exploration challenge through outcrop observations. Results from the field reveal multiple relatively high energy depositional environments with tidal and wave influence of transport sediments and decipher eight (8) sandstones sub facies heterogeneities namely; 1) tilted fault-bounded massive sandstone 2) herringbone crossed bedding, 3) planar crossed stratification, 4) trough crossed bedding, 5) blocky mudrock, 6) hummocky crossed stratification and bioturbated sandstone, 7) tabular crossed-bedded sandstone and 8) shale-sandstones intercalated sandstones within the formation that hold potential challenge on hydrocarbon dynamic flows into the wellbores of the drilled exploratory wells. These heterogeneities at subsurface suggest will contributes reservoir permeability anisotropy & barriers, compartmentalization, poor connectivity, pressure gradient variations, flow channelling & bypassing, stratigraphic trapping, diagenetic alteration, migration, reservoir lateral discontinuity and erroneous modelling that will hampers accurate well placement and flow of hydrocarbon into Kuzari-1 and Nasara-1 wells. Therefore, thoughtfulness on their distribution and internal architecture of reservoir sandstones facies are crucial for surface and subsurface data integration for an accurate reservoir modeling/simulation in overcoming erroneous well placement, reservoir deliverability challenges and future optimum recovery plans in the Gongola basin of Upper Benue Trough.

Keywords: *Petroleum exploration challenge; Upper Benue Trough; Sedimentary reservoir heterogeneities; Gongola basin; Yolde sandstone facies.*

1. Introduction

The Nigeria inland basins include the Mid-Niger (or Bida) Basin, Sokoto Basin, Anambra Basin, the Lower, Middle and Upper Benue Trough (Fig.1). These basins are mainly part of the Cretaceous sequence and later rift basins linked to the opening of the South Atlantic sea [1-3]. The Kolmani-River-1 well is the first to be drilled in the Benue Trough, by Shell Nigeria Exploration and Production Company to a depth of about 3,000 m in 1999, where some 33 billion standard cubic feet of gas and little oil were encountered [2]. Two other exploratory wells, the Kuzari-1 and Nasara-1, were drilled within the same Gongola arm by Elf Petroleum Nigeria Ltd (TotalFinaElf) in 1999 and Chevron Nigeria Ltd (ChevronTexaco) in 2000 to depths of 1666 m

and 1700 m, respectively [2]. Both were found to be dry. However, for over 2 decades, neither explanations nor postmortem reports where proposed for cause of the failure (dry holes), in spite of presence of all petroleum system elements and conditions for exploration success within the basin [4]. Moreover, while successful discoveries are abundant [4-6], there is a dearth of literature on dry exploration wells. Hence, we propose that despite the presence of critical petroleum system elements (source charge, reservoir rock, migration pathway, seal and trap); the potential of the reservoir to generate and accumulate hydrocarbon may be undermined by tectonics and macro/microscale geologic heterogeneities that are observable in the fields. The integration of subsurface information with a structural features identified in the field can provide valuable information that support our hypothesis that these geologic heterogeneities could contribute to poor reservoir potential in frontier inland basins.
Furthermore, integration of surface and subsurface information will enhance the accuracy and comprehensive subsurface reservoir modeling. Therefore, the key objective of this study is to carry out field assessment of the reservoir potential of Cenomanian-Turonian Yolde facies in the segment of the Kuzari-1 and Nasara-1. It has been suggested that the reservoir heterogeneities (impervious lithological intercalations) could impair permeability and obstruct fluid flow, despite the presence of the Yolde formation, which is a potential reservoir rock [4]. This is imperative as not only subsurface structures can contribute significantly to dry holes [6-8].

2. Geological setting

The Gongola and Yola arm make up the Upper Benue Trough is situated in the Northeastern of the Benue Trough (Fig. 1). It is a rift basin that trends NNE-SSW of about 800 km long and 150 km wide, and contains up to 6000 m of the Cretaceous to Tertiary sedimentary sequences. The Gongola sub basin is pre-dated to a mid-Santonian structurally folded, faulted and perhaps locally uplifted period, that resulted in over 98 anticlines and synclines [1]. Subsequently, the mid-Santonian tectonics and volcanism, the depositional sub basin bloc in the Benue Trough was deviated westwards consequential in subsidence of the Anambra Basin [9].

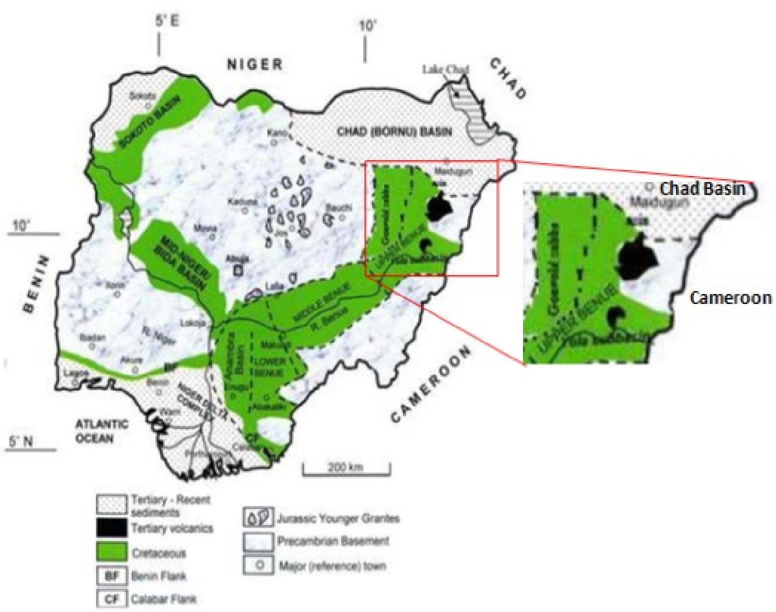

Fig. 1. A geological map of Nigeria presenting the location of the all inland basins. Inset shows the upper Benue Trough with the locations of exploratory wells drilled with the basin (modified after [2]).

The Albian Bima Sandstone is deposited on Precambrian basement complex as shown in the stratigraphic sequence of the Gongola and Yola arms within the Upper Benue Trough (Fig. 2). Bima formation was deposited under fluvial, deltaic, and lacustrine (continental conditions) and is characterize by medium to coarse-grained sandstones intermixed with carbonaceous clays, mudstones and shales. The Bima formation was further sub grouped by Carter [10] into Upper, Middle and Lower units with Cenomanian age formation conformably deposited on the Bima Sandstone known as the Yolde Formation.

The Yolde formation translates to the beginning of a marine invasion into this segment of the Benue Trough, and thus deposited in a coastal marine transitional environment. The formation is characterizing with lithologies such as sandstones, shales, limestones, clays and claystones lithofacies. However, investigation revealed that the Cenomanian-Turonian Yolde formation has the best reservoir potential. In the Gongola segment of the Upper Benue Trough, the distal-equivalent Gongila, Pindiga Formations and Fika Shale is deposited directly on the Yolde Formation.

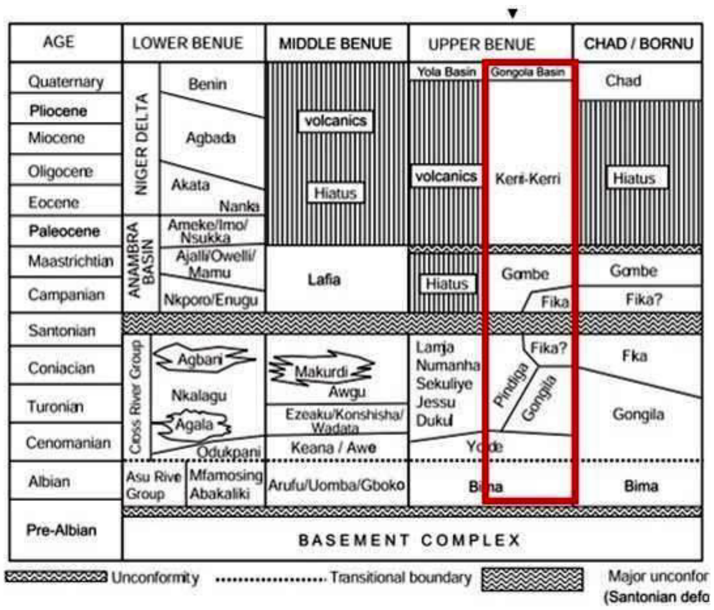

Fig. 2. Lithostratigraphic successions in the Benue Trough with unique reference to the Gongola Basin. (modified after [2]).

The Fika shales signify a fully-marine invasion into the Upper Benue Trough throughout the Turonian–Santonian era. These formations characterize with lithologies of dark and black carbonaceous limestones and shales, intermixed with pale limestones, shales and slight sandstones.

The Fika Shale is characterized mainly bluish-green carbonaceous, sporadically pale-coloured gypsiferous, highly fissile shales with intermittent limestones in places. In the Yola segment of the Upper Benue Trough, the Sekuliye, Dukul and Jessu Formations, the Lamja Sandstone and Numanha Shale are the Turonian to Santonian distal equivalents of both the Gongila and Pindiga Formations respectively in the Gongola arm. The Turonian – Santonian sequence in the Yola arm are similar in terms of lithology and palaeoenvironment to those in the Gongola "segment", with the exemption of the Lamja Sandstone which characterize of marine sandstones with intermixed coal piles. Post-Santonian sedimentary sequences are represented by the continental Gombe Sandstone (Maastrichtian) and Kerri-Kerri (Tertiary age) Formations correspondingly. The Gombe Sandstone exhibits similarities to the Bima Sandstone, intermixed with coal, lignite and coaly shale lithofacies. The Kerri-Kerri Formation is characterized with whitish gray sandstones, siltstones and claystones with the claystones overwhelming the lithology in most places within the Gongola arm of the Upper Benue Trough. The two dry hole exploratory wells namely, the Nasara-1 situated in Futuk village proximal to Pindiga was reported to have penetrated the Pindiga and Yolde Formations and to maybe upper section of the Bima formation, and while Kuzari-1 situated southwest ward of the Kolmani river 1 well to have penetrated similar Lithostratigraphic with the Kolmani river-1 well (Fig.3).

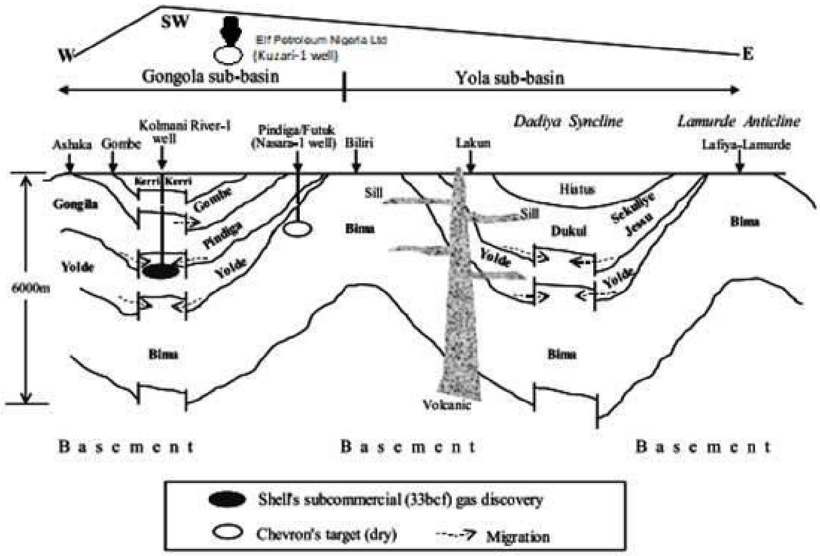

Fig. 3. West-east regional cross-section through the upper Benue Trough presenting the locations of wells Nasara-1, Kolmani-river-1 and Kuzari-1 along with a regional structural pattern (modified after [2])

2.1. The study area: Pantami River Section

The Pantami stream section is located within the Gombe inlier which is examine as a geological sub-unit of the Gongola basin [11]. The inlier displays geologic features in terms of stratigraphic and structural styles that are moderately small, easily reachable section (Fig.4). The Cretaceous lithologic sequences that made up the Gongola segment within the inlier has been impacted by sinistral strike-slip faults (Fig.4) mainly as the Gombe and Wuro Ladde-Wurin Dole faults [11].

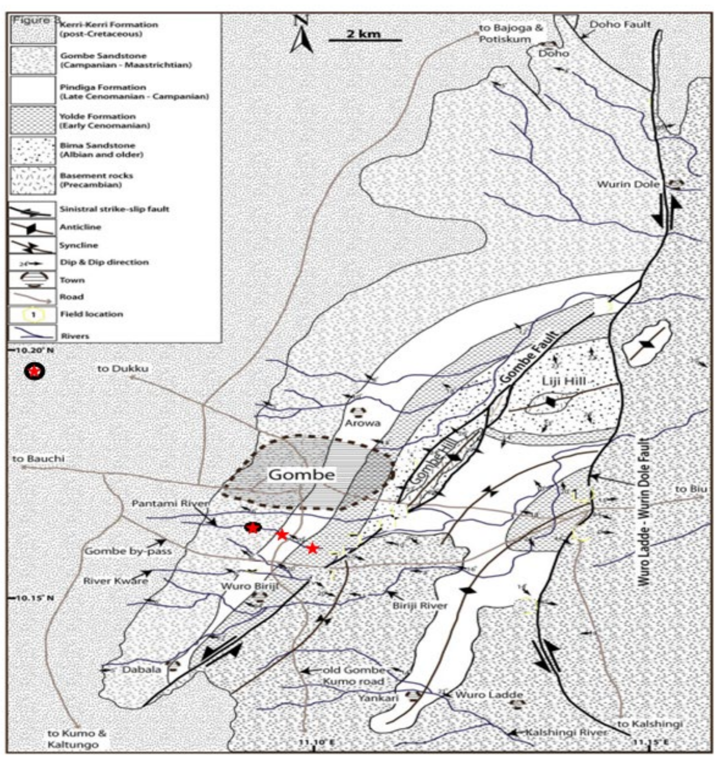

Fig. 4. Geological map of the Gombe inlier and adjacent areas (modified from [11]) presenting the sinistral strike-slip faults and field locations of exposures along the Pantami River channel.

3. Materials and methods

A total of five (5) locations exposure sections of the Cenomanian –Turonian Yolde formation in the sub basin are visited along the river section. A standard geological and sedimentological approach is adopted, which involved the acquisition of coordinates and elevations, in addition to logging and description of sedimentary sub lithofacies from the base to the topmost sections of the exposures and outcrops. The strike and dip directions of the exposed formations; degree of tilting of the beds in response to the mid-Santonian deformation tectonic event [12], and the geologic map of the inlier in Fig. 4 shows a sinistral strike-slip faults along the river section and environs.

4. Results and discussion

At the Pantami river section, lithostratigraphic sequence of the Cenomanian-Turonian Yolde Formation, considered as the potential reservoir [12] are well exposed by the Pindiga Formation (potential source rock) at the stream. This exposure of Yolde Sandstone has a lateral extent of over 80 m which was observed and logged.

4.1. Sedimentary structures and Depositional environment

The structures observed include herringbone crossed bedding, tabular cross-bedding, planar crossed stratification, hummocky cross-stratification and massive structures. Herringbone crossed bedding structures are mostly characterized by dynamic flow conditions, such as river channels or tidal flats. In river channels of varying flow velocities during period of high discharge, sediments are transported downstream as river meanders reduces flow velocity for sediments to settle out. Thus, flow shifts during the stage processes creating alternating sets of sedimentary layers with a herringbone distinctive pattern (Fig 6). Tabular cross-bedded sandstone is characterized by strong, unidirectional currents in river or tidal channels. It reflects the migration of the river channel over time.

However, as the rivers meander across their floodplains, it erodes sediment from the outer bank (cut-bank) and deposited it on the inner bank (point-bar). The sediment is thereby reworked by the river's current, leading to the formation of cross-bedding with inclined layers that dip downstream. Furthermore, in planar crossed stratification is also a river channel where the river flow dynamics result in the deposition of sediments in multiple directions. The Fluctuating flow velocities and varying sediment loads lead to the development of cross-stratification as sediment grains are deposited at variable angles within the channel (Fig 5). The Hummocky cross-stratification (HCS) structures are characterized by a series of irregularly shaped hummocks and troughs within sedimentary layers. The structure is typically formed in marine environment during storm events at the continental shelves and near shores. At time of storms, high-energy waves and currents generate turbulent flow circumstances near the seabed (Fig 11a). These turbulent flows rework and redistribute sediment, leading to the development of HCS. Also at a point when the environment is exposed to air, burrowing mollusks, crustaceans, and worms thrive in these habitats, creating intricate burrow systems as they feed, reproduce, or seek refuge as exhibited on Bioturbated sandstones (Fig 11b). The Trough cross-bedding is formed by the migration of bed forms such as ripples or dunes in a unidirectional flow in a river channel. The trough cross-bedding repeatedly forms in the downstream portions where the flow velocity is high enough to mobilize sediment. As the water flows in the river channel, transports sediment particles accumulate and form bed forms like a ripples and dunes (Fig 14). The shale-sandstone lithology mainly involves alternating periods of quiet sedimentation and more energetic depositional conditions. However, transitional environment, such as tidal flats, may exist between the low energies shale deposition and the more energetic sandstone deposition. These transitional environment experiences periodic shifts in energy levels due to changes in sediment supply, sea level fluctuations, or tectonic activity that have occurred during the Santonian era (Fig 15). Furthermore, blocky mud blocky textures can

arise from various depositional or diagenetic processes. The low-energy environment is characterized by quiet water conditions, with minimal energy for sediment transport. These environments can include marine mud flats, and partly lakes or lagoons (Fig 12-14).
The above descriptions of observed sedimentary structures reveal that the Yolde Sandstone facies experienced multiple energy cycles relatively more of high-waves than low energy event. Thus, indicates multiple depositional environments and varying sediment loads from river channel, tidal flat, marine to tidal environments.

Fig. 5. Yolde formation (a) Tabular cross-bedded sandstone facies dipping at an angle 60° intercalated with a mudrock indicated with red lines (b) deep buried part experienced a strike slip fault standing along the fault plane indicated by the reversed red arrows.

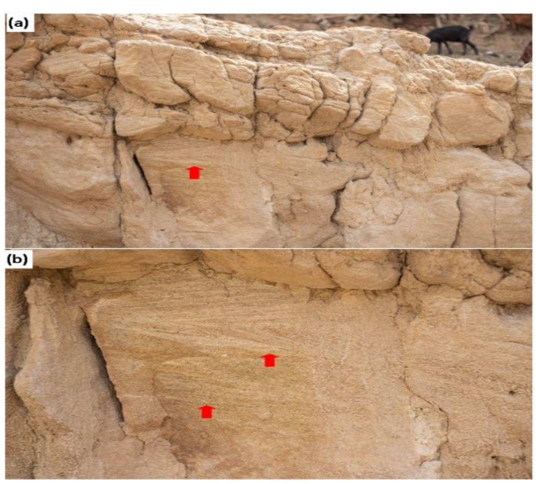

Fig. 6. Yolde sandstone facies (a) massive sandstone with Herringbone structure (b) Herringbone cross-stratification with a reactivation surface indicated with red arrows at close range.

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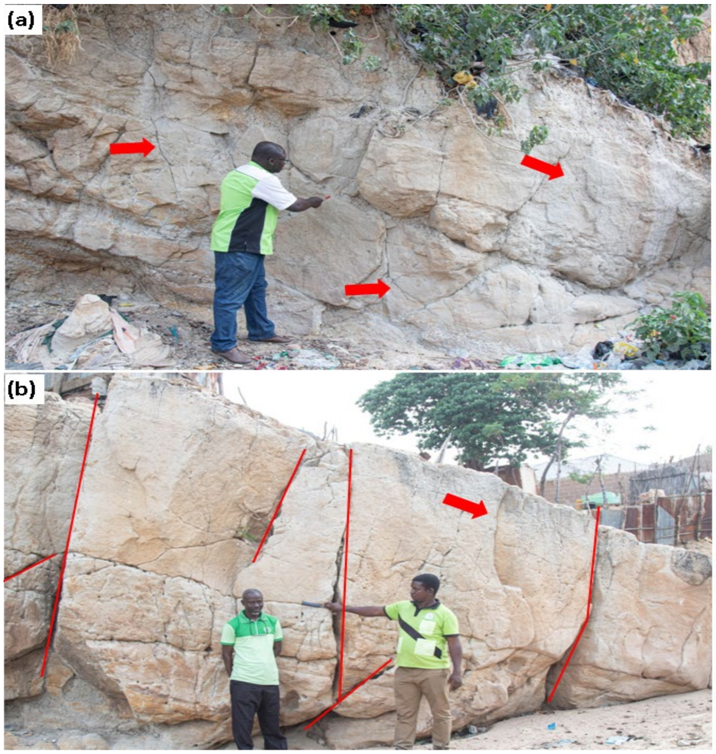

Fig. 7. Yolde sandstone facies (a) tilted massive sandstone with faults and fractures indicated with red arrows (b) Massive sandstone facie clearly fractured and faulted dipping at an angle 55^{o}.

Fig. 8. Yolde sandstone facies (a) Deformed by series of thrusts at almost vertically-dipping fault-bounded wedge rocks (in red arrow) (b) fault plane of deformed thrusted fault-bounded rock eroded by erosion within the river channel section indicated doubled headed arrow.

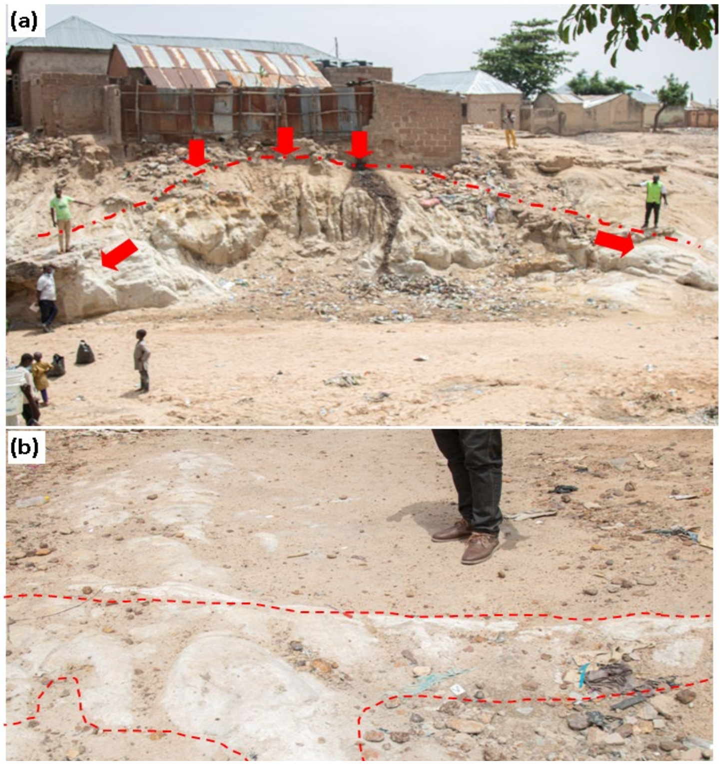

Fig. 9. Yolde sandstone facies (a) Ruptured crest of an anticline structure with limbs dipping in opposite directions (in red arrow) (b) Buried fault-bounded rock eroded by erosion within the river channel section indicated dotted redlines.

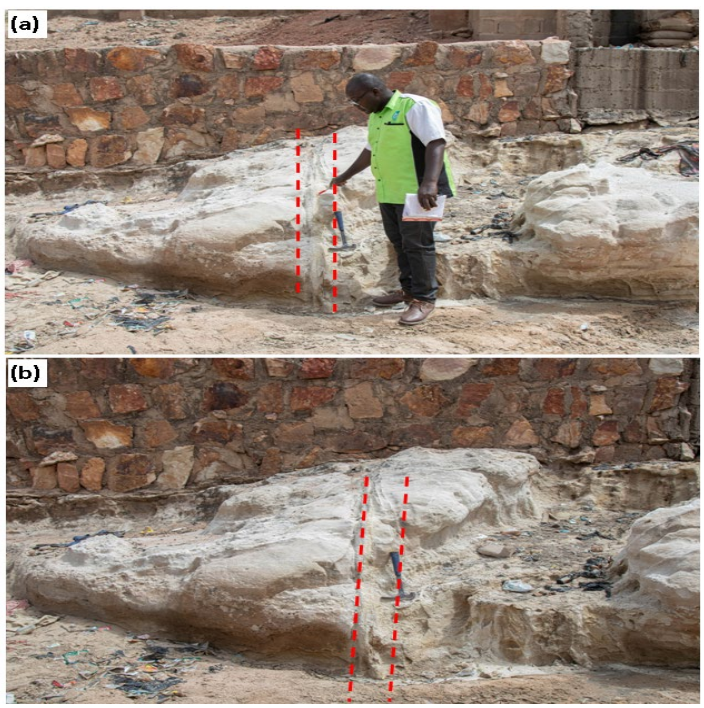

Fig. 10. Yolde sandstone facies (a) and (b) Buried fault-bounded rock at almost vertical within surrounding rock indicated with red dotted lines.

Fig. 11. Yolde sandstone facies (a) Hummocky cross stratification facies (b) bioturbated sandstone facie above the Hummocky cross stratification facies.

4.2. Field classification

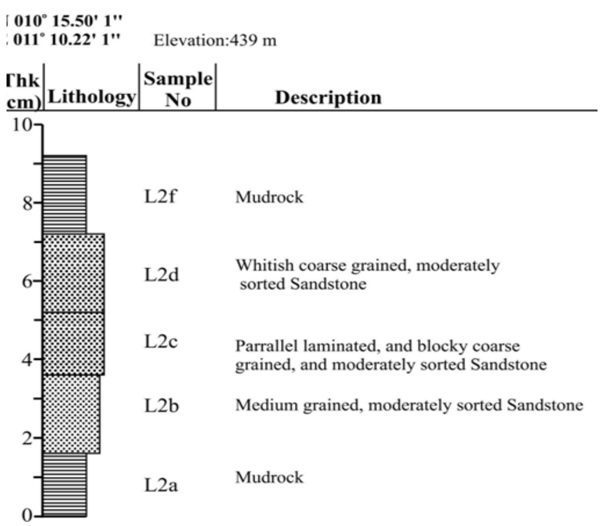

Fig. 12. Yolde log1 presents lithological heterogeneity in succession within the study area.

The log sections at the different coordinates reveals eight (8) sub facies sandstones namely; 1) tilted fault-bounded massive sandstone 2) herringbone crossed bedding, 3) planar crossed stratification, 4) trough crossed bedding, 5) blocky mudrock, 6) hummocky crossed stratification and bioturbated sandstone, 7) tabular crossed-bedded sandstone and 8) shale-sandstones intercalated sandstones within the formation. At the first location within the River section (coordinates: N 010°15.50'1", E 011°10.22'1"; elevation: 439 m), the Yolde log 1 (Fig. 12) consists of a lenticular bedded grey to purple mudrock at the base, transiting into medium grained, moderately sorted sandstone, which is overlain by parallel laminated, and blocky coarse grained, and moderately sorted sandstone, whitish coarse grained, moderately sorted sandstone, capped with a mudrock.

At the second location (Yolde log 2), the base is characterized by intercalations of thinly bedded grayish coarse grained sandstone, pebbly, very fined grained sandstone, cross stratified fine to coarse grained sandstone, conglomeratic sandstone, cross stratified fine to coarse grained sandstone, conglomeritic sandstone, coarse grained sandstone, very coarse sandstones, poorly sorted coarse grained sandstone, mudrock and coarse grained sandstone up to about 4 cm. It is overlain by another thinly mudrock followed by the massive, coarse grained sandstone, massive fine grained sandstone up to 11.5 cm, which is then overlain by intercalations of mudrock, coarse grained sandstone and mudrock. This section is capped with crossed stratified, pebbly, very coarse grained sandstone (Fig 13).

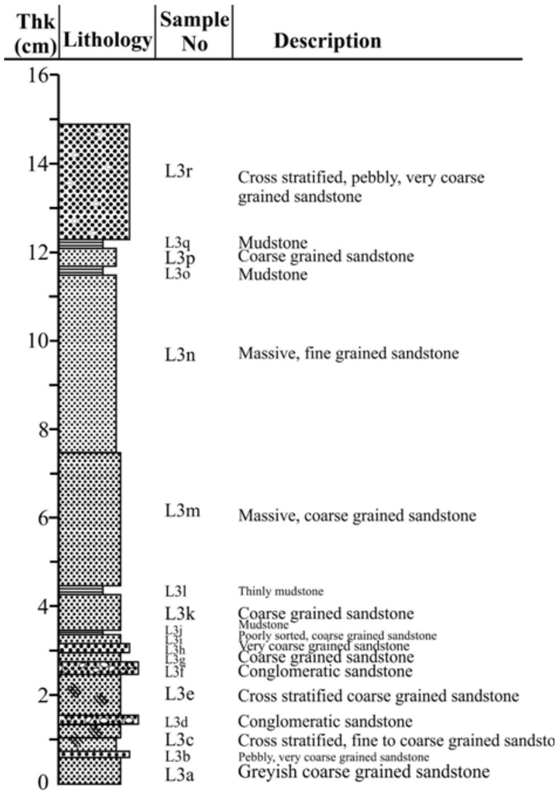

Fig. 13. Yolde log 2 lithological heterogeneity in succession of an exposure within the study area.

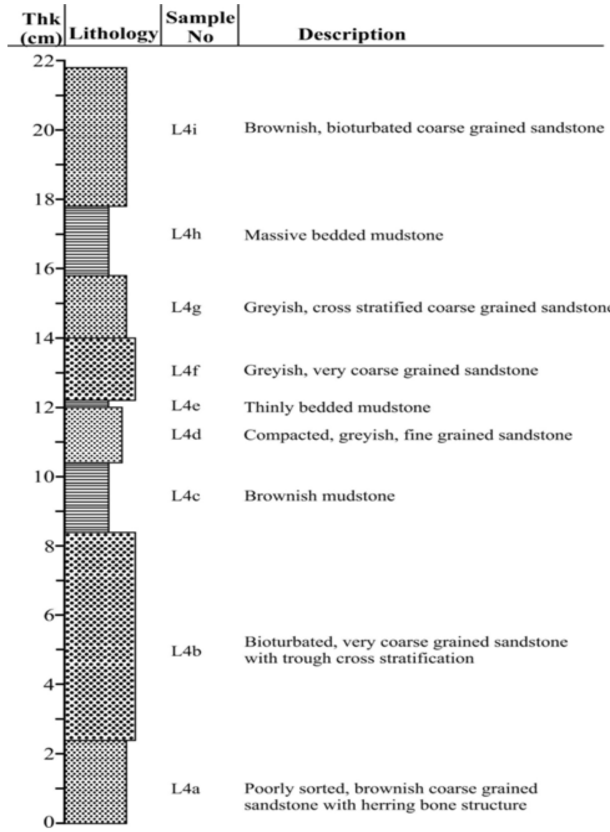

Fig. 14. Yolde log 3 lithological heterogeneity in succession of an exposure within the study area.

At location 3, Yolde log 3 reveals from the base characterized by poorly sorted, brownish coarse grained sandstone with herringbone structures. It is overlain by bioturbated, very coarse grained sandstone with trough crossed stratifications, and capped by a brownish mudrock at 10.5 cm. The mudrock is overlain by compacted, grayish fine grained sandstones, thinly bedded mudstone, grayish very coarse sandstone. This unit is overlain by another massive mudrock and capped with a brownish, bioturbated coarse grained sandstones (Fig. 14).

At another Yolde section (Yolde log 4) shown in Fig. 15, the base starts with bioturbated fine grained sandstone up to about 4 cm. It was overlain by intercalations of mottled colored shales, grey fine sandstone; mottled colored shales within thinly bedded grey fine grained sandstone and bedded grey shales. It was overlain by massive grey blocky sandstone, massive grey shale and grey fine grained sandstone intercalations up till 29 cm. This transit into grey fine grained sandstone intercalated with moderately thick massive bedded grey shales, which is overlain by massive brownish, moderately sorted, coarse grained sandstone with herringbone and planar stratifications and capped with massive grey shales.

At location 5 (Yolde log 5), the outcrop section was mainly characterized by sandstones and shale intercalations. The base is composed of grey shales with thickness of 6 cm, which is then overlain by 9 cm thick brownish coarse grained sandstones and 9 cm thick massive grey shale. This is followed by brownish coarse grained sandstone, thinly bedded grey shale and then capped with a 3 cm thick brownish coarse grained sandstone (Fig. 16)

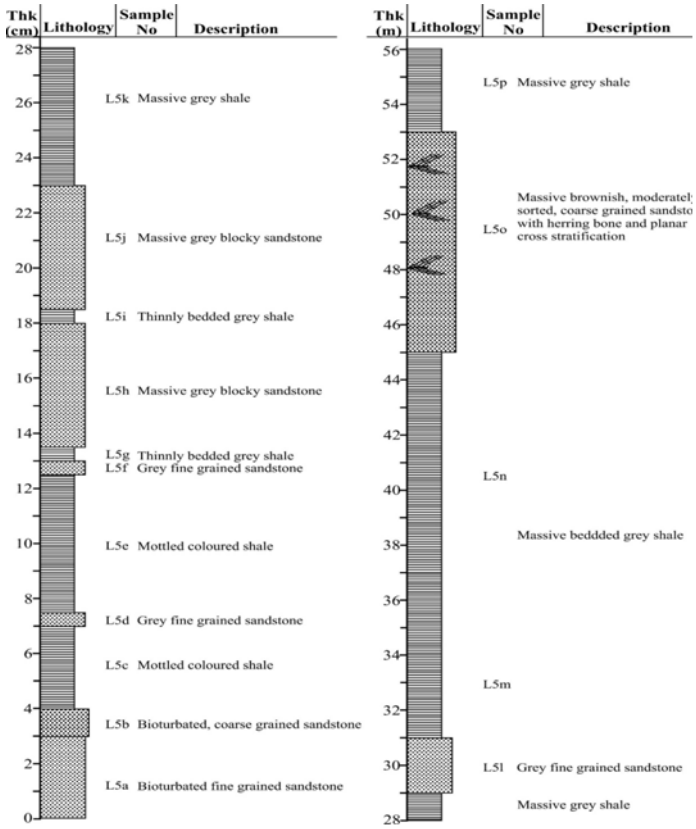

Fig. 15. Yolde log 4 lithological heterogeneity in succession of an exposure within the study area

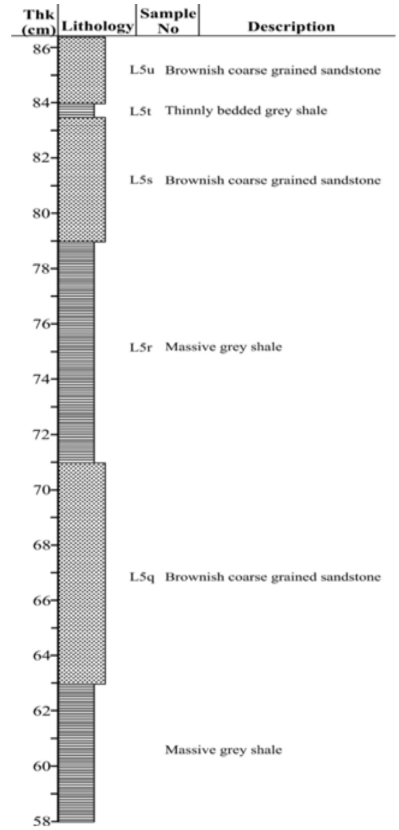

Fig. 16. Yolde log 5 lithological heterogeneity in succession of an exposure within the study area.

4.3. Potential impact on petroleum exploration challenges

In general, tectonics, lithofacies and their associated characteristics observed in the field provide insight on the potential impact of subsurface geological heterogeneities on the commerciality of hydrocarbon discovery and production [13]. Therefore, understanding the potential risks and negative impacts associated with sedimentary heterogeneities are critical for any exploration companies. These heterogeneities need to be captured in field studies and incorporated into reservoir development plans and subsurface modeling for accurate prediction of reservoir flow.

4.3.1. Tilted potential reservoir rock; the Yolde sandstone lithofacies

As observed in Fig. 5 and 7, the reservoir rocks dip in alternate directions (i.e. same bed dipping eastward and westward) to reveal an anticline structure, which suggests the influence of the mid Santonian tectonic event [12]. The dip measurement possibly indicates two failed limbs of an anticline with an eroded crest (Fig. 9) and buried fault-bounded rock eroded by erosion (Fig.10) due to compressional tectonic inversion [12] that occurred during the Santonian Era (see Fig.2). Also observed is the uplifting of the faulted and fractured rocks (Fig.7) at almost 90° (Fig.10). This will impair reservoir permeability, pore interconnectivity and create pressure gradient variations that affect the flow of hydrocarbon towards the Nasara-1 and Kuzari-1 wellbore, resulting in dry holes. Also, the tilting, faults and fractures may result in reservoir compartmentalization, which can reduce production rates within the reservoir segment or wellbore. Thus, these potential disruptions of hydrocarbon flow paths may possibly alter the trajectory of a wellbore deep within the subsurface, thus potentially creating an exploration challenge in the Nasara-1 and Kuzari-1 wells, leading to dry holes. Other places in the world have experienced similar challenges of tilted reservoir units such as Ekofish field, North sea [14], Prudhoe Bay field in Alaska [15] and Ghawar field in Saudi Arabia [16].

4.1.2.2. Fault, Strike-slip fault and Fault bounded Potential Reservoir Rock; the Yolde sandstone lithofacies

The presence of faults, strike-slip faults and fault-bounded rocks can have a significant negative impact on petroleum exploration (Fig. 5b, 7, 8 and 10). The magnitude of their impact depends on their orientation, throw (vertical offset), and permeability contrast across the fault (Fig.10). The presence of strike-slip fault and fault bounded (Fig.10) rocks can increase the risk of exploration challenge [17] by impeding lateral reservoir connectivity, as indicated by dotted red lines in Fig 10. It would have consequences when the faults extend deeper at subsurface, resulting in reservoir compartmentalization and offsetting the wellbores, potentially causing misalignment or displacement of reservoir lithofacies [18] thereby obstructing lateral reservoir continuity [19]. This creates a barrier [20] to fluid flow, resulting in development of secondary structure such as faults and fractures (Fig. 7), which further complicate the geology of the basin and make it difficult to find and extract the hydrocarbon (dry hole), which possibly occurred in the Nasara-1 and Kuzari-1 wells in the Upper Benue Trough. These type of faults have also uncooperatively contributed significantly to the exploration challenges in the North Sea [21], and Gulf of Mexico [22].

4.1.2.3. Herringbone, Trough and Planar Crossed Bedding Lithofacies

This sedimentary lithofacies features are usually associated with fairly to high energy depositional environment (Fig. 6). It is characterized by brownish, poorly sorted coarse grained sandstones, indicative of tidal deposits as a results of dual-directional cross stratification [23].They have potential impact on porosity and permeability distribution [24]. The sandstone lithofacies with these features varies in thickness from 2 cm to 8 cm (Fig. 14 -15) within the Yolde formation. Planar cross stratification (L5o)`, Trough (L4b) and Herringbone crossed bedding (L5o) are sedimentary primary structures characterized by sets of inclined strata that intersect at an acute angle, and that intersect each other at relatively high angles, typically ranging from 10 to 30 degrees for them respectively.

This sedimentary structures characterized by the presence of an alternating layers, which can make it challenging to identify and tract potential hydrocarbon reservoirs [25]. At large scale in the subsurface, the orientation of bedding planes in planar, trough and herringbone crossed bedding will introduces anisotropy (the rock properties that varies depending on the direction) into the reservoir units, thereby will potentially influence the directionality of fluid flow, affecting how hydrocarbons migrate towards within the reservoir units. The intersecting sets of inclined strata creates preferential flow pathways or channels for hydrocarbons within the reservoir units, thus, may lead to bypassing of hydrocarbons, where fluids migrate along these channels, leaving other areas of the reservoir less depleted. The presence of crossed-bedding make it difficult to determine the direction of fluid flow contributes to poor reservoir connectivity [26], lateral change in critical petrophysical properties [27] and compartmentalization [28], stratigraphic traps [29] where distinct blocks of reservoir rock are separated by barriers to fluid flow [30] into the wellbore [31]] which may lead to an unsuccessful exploration effort [32] in the Nasara-1 and Kuzari-1 wells within Gongola arm of the Upper Benue Trough.

However, such sandstone lithofacies have been ascribed to have contributes to exploration challenges as a result of their complex and unpredictable nature [33] in Rotliegend sandstones of the Southern Permian, North Sea [34], Upper Jurassic Fulmar sandstone, Magnus field, North Sea [35] and Lower Cretaceous Ness sandstone of the Schiehallion Field, West of Shetland [36] respectively

4.1.2.4. Hummocky cross stratification and Bioturbated Lithofacies

The Hummocky cross stratification sandstone (HCS) was overlaid by the bioturbated sandstone lithofacie (Fig. 11). Hummocky cross- sedimentary structure is typically found in marine settings (L3k) in Fig.13, especially in areas affected by storm events. It’s characterized by sets of inclined layers that exhibit an attribute "hummocky" topography, resembling irregular, rounded mounds formed due to the reworking of sediment by turbulent storm waves on the seafloor. Hummocky cross stratification sandstone are common reservoir type in hydrocarbon – producing basins [37]. The complex geometry of hummocky cross-stratification introduces heterogeneity into the reservoir, resulting in variable flow paths for hydrocarbons [37] depending on the orientation and distribution of inclined layers. Thus, impede fluid movement as they composed of series of alternating sand (whitish) and shale(dark brown) beds, which vary significantly in thickness and composition [38] as shown in Fig.11. Nonetheless, the irregular nature of HCS poses challenges [39] in reservoir characterization and accurately predicting fluid flow behavior in the wellbore of the Nasara-1 and Kuzari-1 wells in part of the Gongola arm of the Upper Benue Trough Basin. Furthermore, HCS sandstone lithofacies is difficult to be identified and map using seismic data [40]. It often displays chaotic signatures [41] which can make it difficult to distinguish reservoir rock types.

Bioturbation is simply a disturbance and mixing of sediment layers by biological activity such as burrowing, feeding, or grazing by organisms like marine worms, crustaceans, and bivalves. However, it is common in marine environments and can profoundly influence sedimentary architecture and reservoir properties. This sub lithofacies is log within the section at L4b, L4i, L5a and L5b in Fig.14-15 respectively. It exhibit dual impact, either improve porosity and permeability or decreases when it's intense (Fig.11b). The irregular nature of bioturbation complicates reservoir modeling and simulation efforts. The spatial distribution and intensity of bioturbation vary widely within a reservoir, making it challenging to accurately represent its effects on fluid flow behavior. Although, it is still important to be conscious of the challenges associated with HCS sandstone and bioturbation in order to mitigate the risk of exploration challenge and that it has lead to exploration dry holes in Gulf of Mexico [42], North Sea [43], and Middle East [44].

4.1.2.5. Mudstones and Blocky Mudrock Bedding Lithofacies

Mud rocks are fine grained sedimentary rocks that are composed of clays, silts and sand-sized particles [45]. Typically deposited in low-energy environment, such as lake, rives, and delta. It is characterized by the presence of well-defined, block-like layers or beds within mudrock (Fig.5). These bedding patterns can significantly impact hydrocarbon flow into a drilled wellbore [46].At the study area, there are abundantly found in association with other sandstone sub facies at variable thickness (Fig 12 – 13) in different locations. Blocky mudrock bedding and mudstones contributes to reservoir heterogeneity, which resulted into spatial variations in rock properties such as porosity, permeability, and fluid saturation.

Nevertheless, they typically have low permeability due to their fine-grained nature, and within blocky bedding, there can be variations in permeability between different layers. While, some the layers may have slightly higher permeability due to differences in grain size and compaction, mineralogy, or fracturing, allowing for preferential flow paths for hydrocarbons. Thus, it impacted to create anisotropic permeability, as permeability varies in different directions within the sub facies. Consequently, this anisotropy influences the direction and rate of hydrocarbon flow into a wellbore [46]. Presence of mudstone and blocky mudrock in the investigated formation can lead to reservoir compartmentalization by creating barriers within the Yolde sandstone potential reservoir (Fig. 12-13) at large scale in greater depth, which can prevent hydrocarbon from flowing from one part of the reservoir to another. It makes difficult to produce hydrocarbon from a reservoir that contains mudrock as probably may have contribute in the Nasara-1 and Kuzari-1 dry hole challenge in the part of the Upper Benue Trough. Exploration challenge associated mudstone and blocky mudrock in the Sichuan basin in China [47], Williston basin USA [48], and Cooper basin in Australia [49] respectively. Thus, understanding the orientation and distribution of bedding planes is crucial for optimizing well placement as may have contribute to the exploration challenge experienced in the Nasara-1 and Kuzari-1 well in part of the Upper Benue Trough.

4.1.2.6. Tilted Tabular cross-bedded Sandstones facie

Titled tabular cross bedded sandstone intercalated with mudrock was the common sedimentary deposit formed in the variety of the environment, including fluvial, deltaic and shallow marine setting. These deposits were characterized by their distinct bedding structures, which consisted of alternating layers of sand and mud (Fig. 13). Tilted tabular cross-bedded sandstone intercalated with mudrock can significantly impact hydrocarbon flow into a drilled wellbore. There are characterized by its inclined layers of sedimentary rock, often exhibits varying permeability within and between layers. The intercalation of mudrock within the sandstone layers creates permeability barriers or zones of reduced permeability (Tschopp, 1953). This contrast in permeability can affect the flow behavior of hydrocarbons in the reservoir and into wellbore.

The tilted tabular cross-bedded sandstone and intercalated mudrock results in significant heterogeneity; act as natural barriers, compartmentalizing the reservoir into distinct zones or compartments with different fluid compositions and pressures within the reservoir units. This probable suggest to have contribute to exploration challenge in the Nasara-1 and Kuzari-1 drilled wells without oil and gas discovery therein both in part of the Upper Benue Trough. The negative contribution by such lithofacies to the exploration challenge in the North Sea [35], Gulf of Mexico [50], Middle East [51], North Slope of Alaska [15] and western Canada [52] respectively.

4.1.2.7. Shale and sandstone intercalation

The deposition of shale and sandstone intercalation (Fig.14-15) is a complex process that is influenced by variety of factors including the climate, rate of sediment deposition and nature of underlying rock [53]. The intercalation of the two lithofacies can occur when the environment changes, such as a river floods and deposits sand over a later of shale [53]. However, if such intercalation are not well discriminated it can significantly affect the flow of hydrocarbons into a drilled wellbore as probably experienced in the Nasara-1 and Kuzari-1 wells within part of the Upper Benue Trough. . Shale can also acts as a sealing layer [54], limiting fluid migration and trapping hydrocarbon, while sandstone acts as a reservoir unit (Fig.15), because of coarser grain size, allowing hydrocarbons to flow more easily towards the wellbore. Therefore, understanding these effects is crucial for successful oil and gas exploration and production. The observed occurrence of shale and sandstone intercalations can have significant impact on exploration challenge as shale is a relatively impermeable rock, and do not allow fluid to flow through it easily [53]. It have lower porosity and permeability due to its finer grain size and higher clay content, which tends to clog pore spaces and restrict fluid flow. Alternating layers of shale and sandstone create a heterogeneous reservoir that affects fluid flow patterns, with hydrocarbons preferentially migrating through more permeable sandstone layers and encountering barriers in shale layers can result in complex flow paths and reservoir compartmentalization because connectivity between sandstone layers is crucial for effective hydrocarbon production. Thus, this is probably contributes to exploration challenge in Nasara-1 and Kuzari-1 exploratory wells. Examples around the world the exploration challenge in the Eocene Tay sandstone of the Montrose Field, UK [55], Central North Sea [56] and Paleocene Forties sandstone [57] of Forties Field, Central North Sea [58] respectively.

5. Conclusions

Field assessment of Cenomanian Yolde reservoir facies potential role to petroleum exploration challenge in parts of the Upper Benue Trough in the Gongola Arm; along the Pantami River section in Northeastern Nigeria was carried out for the first time in more than 2 decades to understand why the Nasara-1 and Kuzari-1 exploratory wells were dry holes. The potential reservoir rock of the Yolde formation was mapped and logged around the basin.

Field assessment identified variable potential geologic contributors to the petroleum exploration challenge related to tectonics features and sedimentary lithofacies heterogeneities ranging from observable tilted reservoir beds, fault, strike-slip fault, fault-bounded reservoir rock, herringbone, planar, cross stratification, trough crossed bedding, blocky mudrock, hummocky cross stratification and bioturbated lithofacies, tabular cross-bedded sandstone within the basin and shale-sandstones intercalation lithofacies. These heterogeneities make it difficult to predict the distribution of critical petrophysical properties (permeability barrier) that will hamper the fluid flow of hydrocarbon into wellbore. Such might have contributed to the experienced exploration challenges in part of the Upper Benue Trough. It is therefore very important to be aware of such challenges associated with such complicated lithofacies before embarking on exploring hydrocarbons and thus take all necessary steps to mitigate these challenges for future exploration success in the part of Upper Benue trough.

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