

## Review Article

# Attributes of Potential Hydrocarbon Reservoir Sandstones in the Sokoto Sector of the Iullemeden Basin: An Outcrop Analogue Study

Maduka Bertram Ozumba<sup>1\*</sup>, Kevin Ikechukwu Chima<sup>1</sup>, Cornelius Sunday Nwajide<sup>2</sup>, Umaru Zaki Farouk<sup>3</sup>, Abdul Rahman Umar<sup>3</sup>

<sup>1</sup>Department of Geology, Federal University, Ndufu-Alike, Nigeria

<sup>2</sup>Geoscan Technical Services Ltd, Awka, Anambra State, Nigeria

<sup>3</sup>Usman Danfodiya University, Sokoto, Nigeria

\*Corresponding author: Bertram Maduka Ozumba, Department of Geology, Federal University, Ndufu-Alike, Ikwo, Ebonyi State, Nigeria. Tel: +2348136576861; Email: bertram.ozumba@sbcglobal.net

**Citation:** Ozumba MB, Chima KI, Nwajide CS, Farouk UZ, Umar AR (2017) Attributes of Potential Hydrocarbon Reservoir Sandstones in the Sokoto Sector of the Iullemeden Basin: An Outcrop Analogue Study. Arch Pet Environ Biotechnol 2017: APEB-124. DOI: 10.29011/2574-7614.100124

**Received Date:** 17 December, 2017; **Accepted Date:** 22 December, 2017; **Published Date:** 28 December, 2017

## Abstract

The Sokoto area of Nigeria is the southeastern margin of the very extensive (ca. 1 million km<sup>2</sup>) Iullemeden Basin - an intracratonic depression in the Precambrian Basement Complex. The basin fill succession consists of the Late Jurassic continental facies and Cretaceous marine deposits topped by Mid-Paleogene continental facies. Impressive outcrops had spurred the search for petroleum in early colonial time but the poor showing of the earliest boreholes discouraged the efforts. This study is, therefore, aimed at providing more information on one of the prerequisite attributes- reservoir characteristics using outcropping analogues for assessing the lithostratigraphic units that bear the potential reservoirs. Hydrocarbons, possibly generated from carbonaceous fine clastics and carbonate facies of the marine deposits, could have migrated to the sandstones of the Illo and Gundumi Formations of the Continental Intercalaire Group, the Taloka and Wurno Formations of the Rima Group and the Gwandu Formation of the Continental Terminal Group, as well as the carbonate unit of the Kalambaina Formation. However, only the shales of the Taloka and the Wurno Formations may constitute effective seal facies. Additionally, the coarse to medium sandstones of the Gwandu Formation may constitute suitable reservoir facies if the interbedded ironstones prove to be good seals.

## Introduction

Oil exploration started in Nigeria in early twentieth century when the whole country was a single acreage concessioned solely to Shell D'Arcy. As with all exploration activities, initial efforts in the Sokoto area included outcrop mapping and reconnaissance geophysical survey. Despite excellent rock exposures, the studies revealed a relatively shallow depth to basement, a fact confirmed by borehole drilling. This made the company abandon the search in that area. Later efforts by Mobil Oil Company Ltd and Elf Petroleum Ltd using aerial survey of the area did not achieve any better results. Even with rekindled interest in the 1960s when new

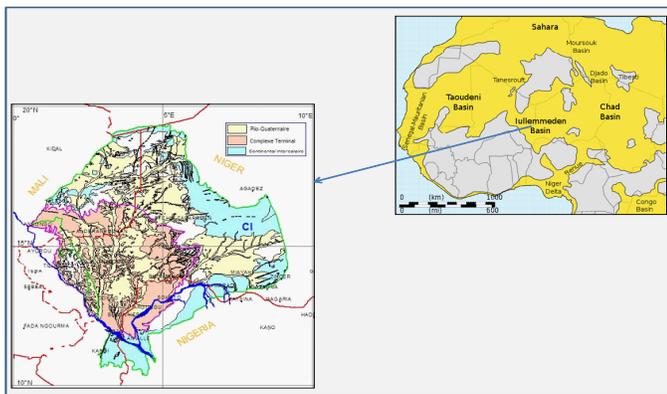
concessions were created and other oil companies were allowed to carry out studies, the same discouraging results were achieved. In the mid-1980s, following the discovery of liquid hydrocarbons in the deeper parts of the basin within Mali, some of these companies returned to re-evaluate the Nigerian sector. These companies finally moved out to the prospective Niger Delta.

Even when acquiring acreages in the deep offshore Niger Delta was tied to taking up blocks in the inland basins, Sokoto area was still considered unattractive and so failed to benefit from the re-invigorated studies of the Nigerian inland sedimentary basins. Thus, the area has not undergone rigorous evaluation

using modern technologies. Nevertheless, results of subsequent outcrop mapping, sampling and laboratory studies, including geochemical analyses, carried out by the academic community [1,2], have very strongly indicated that the Sokoto sector of the basin is prospective in hydrocarbons. This has been reinforced by the recent discoveries of apparent petroleum seepages in Kebbi State. However, the exact nature, quantity and producibility or commerciality of the hydrocarbons can only be ascertained through more studies. This study is, therefore, aimed at providing more information on one of the prerequisite attributes reservoir characteristics using outcropping analogues -for assessing the lithostratigraphic units that bear the potential reservoirs.

### Regional Geological Setting

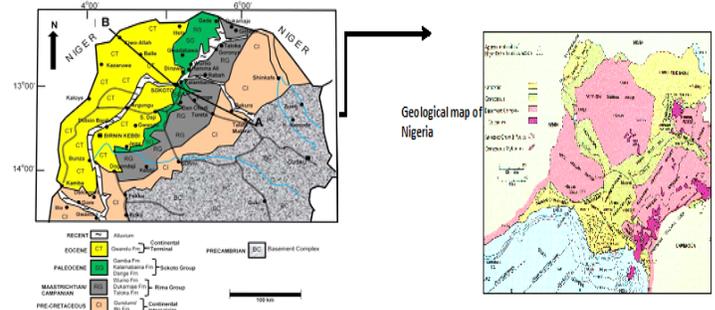
The Iullemeden Basin is a major sub-Saharan inland basin in western Africa. It extends about 1000 km north to south and 800 km east to west and covers the western part of Niger Republic and portions of Algeria, Mali, Benin and Nigeria [3] (Figure 1).



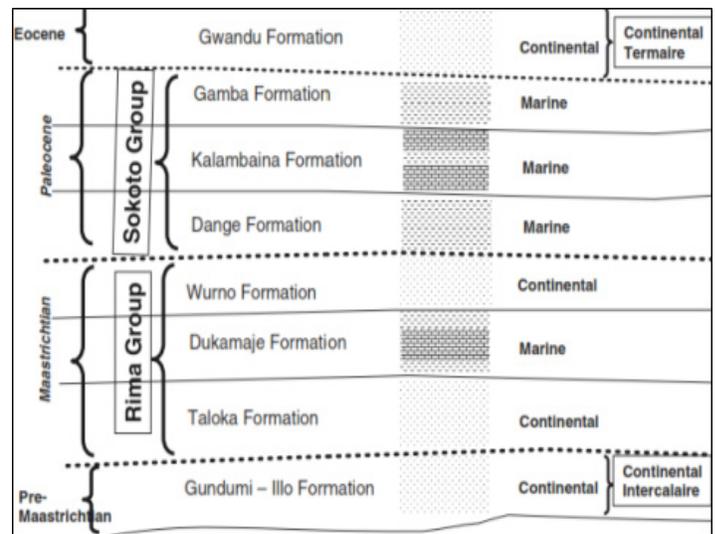
**Figure 1:** Geological map of the Sokoto sector of the Iullemeden Basin [3].

The geology of the Sokoto sector of the basin has been discussed by several authors (Okosun, 1999; Obaje, 2009, 2013; Obaje et al., 2014; Okosun and Alkali, 2013; Nwajide, 2013) [4-8,2]. The basin is tectono-epirogenic in origin and had been inundated by epicontinental transgressions during the Cretaceous

and the Cenozoic. In the Nigerian sector, the lithic fill comprises three major subdivisions (1) the Late Jurassic - Early Cretaceous Continental Intercalaire, (2) Early to Mid-Paleogene intermediate marine and brackish water deposits and (3) Late Paleogene - Neogene Continental Terminal (Figures 2-4, Table 1).



**Figure 2:** Geological map of the Iullemeden Basin showing Sokoto sector study area [9] Section AB showing roughly the traverse taken during field work.



**Figure 3:** Stratigraphy of the Sokoto sector of the Iullemeden Basin [5].

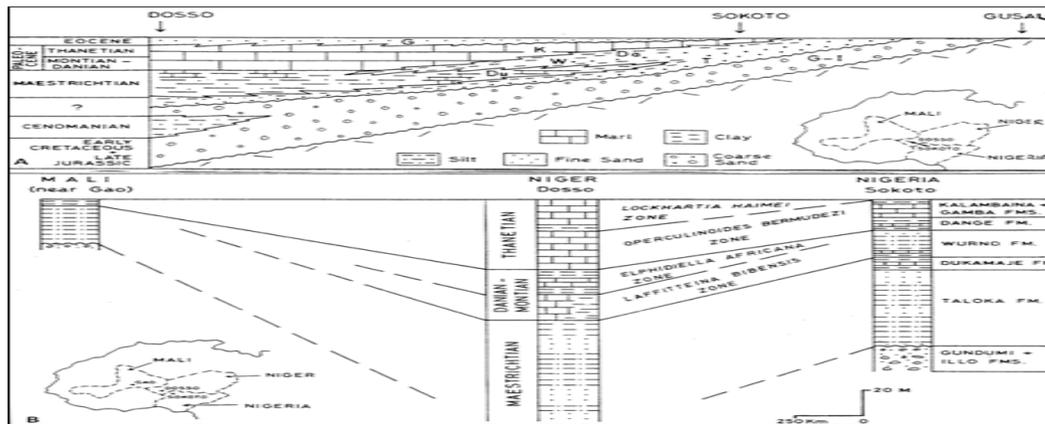


Figure 4: A) Southeast–northwest section from Nigeria into Niger Republic; G = Gwandu Fm., K = Kalambaina Fm., DA = Dange Fm., Wurno Fm., DU = Dukamaje Fm., T = Taloka Fm., G = Gundumi and Ilo Fms. B) Correlation of stratigraphic units from Nigeria into Niger Republic and Mali [10].

Age	Formation	Lithology	Group	Fossils	Sedi-mentary Structures	Environment of deposition	Analogues	Thickness (m)	Deduced Porosity	Deduced Permeability
Quaternary-Eocene	Gwandu	Mottled massive clays, with coarse-medium grained ssts.	Continental Terminal	-	Lateritic ironstones and unconformable base	Fluvio-lacustrine setting	-	-	Poor	Very Poor
Early Paleocene	Gamba	White clayey 1st interbedded with shales, gypsum & phosphatic pellets	Sokoto	-	-	Marginal-up to marine (littoral) and sabkha environment for the 1st facies.	-	-	May contain secondary porosity (vuggy)	-
Early Paleocene	Kalam-baina	White clayey limestones interbedded with gypsum & phosphatic pellets	Sokoto	Richly fossiliferous (benthic foraminifera), oolitic, fish teeth, and scales & moulds of bivalves mainly echinoids, lamelli-branches & gastropods	Phosphatic pellets & coprolites, and vuggy porosity inducing slumping and folding appearance	Marginal-up to marine (littoral) and sabkha environment.	-	25	May contain secondary porosity (vuggy)	-

Early Paleocene	Dange	Indurated shales with gypsum & numerous irregular phosphatic nodules and pellets. Shales also interbedded with thin layers of yellowish-brown limestone	Sokoto	Richly fossiliferous with agglutinated benthic foraminifera & ostracods	Phosphatic nodules and pellets, small-scale load casts, bioturbation structures and flaser bedding	Marginal marine up to marine (littoral) and sabkha environment (transitional/marginal marine, shallow marine to inner neritic environment)	-	45	-	-
Maastrichtian	Wurno	Friable fine grained sandstones, siltstones and interbedded mudstones	Rima	-	-	Marginal marine (marsh & tidal flats)	-	-	Fairly Good	Fairly Good
Maastrichtian	Dukamaje	Shales with gypsum interbeds, middle marl & limestones or mud	Rima	Miliamina, Trochammina, Textularia, Ammobaculites, Ammodiscus, Hapla-phragmoides spp. & planktic forams: Guembelitra, cretacea, Orbignya inflata, and benthic forms: Nonion, Nonionella, and Gavelinella spp. Reptilian bones	Vuggy porosity, concretionary limestone	Marginal hypersaline setting with marshes, lagoons, tidal flats and estuarine	Patti Fm/ Nkporo Shale	-	-	-

Maastrichtian	Taloka	Loosely consolidated sandstones and siltstones, claystones and shales	Rima	Reptilian bones	Thinly bedded or laminated siltstones with small load casts, lenticular and flaser bedding, & wavy bedding, bioturbation (Skolithos, Ophiomorpha, Thalassinoides), faecal castings	Transgressive shallow sublittoral complex (beaches and mudflats)	Patti Formation/ Nkporo shales	-	Fairly good	Fairly good
Early Cretaceous -Jurassic	Illo	Clays & sandstones	Continental Intercalaire	Fish teeth and podocarpian fossils, wood	Cross-bedding	Alluvial Fans-Lacustrine	Bima Sandstones, Nubian sandstones	240	Good	Good
Early Cretaceous - Jurassic	Gundumi	Gravels or basal conglomerates, pebbly sst, mudstone, clayey sst, claystone	Continental Intercalaire	-	Unconformable base	Fluviatile-Alluvial Fans to Lacustrine	Karoo series of S/Africa	350	Good	Good

**Table 1:** A summary of the stratigraphic attributes of the lithic fill of the Iullemeden Basin within Nigeria.

### The Sokoto Sector: Basic Stratigraphy, Structural and Petroleum System Elements

The overall thickness of the sedimentary succession in the Sokoto sector is 700 to 750 m. Although there are considerable variations in the thicknesses of the various stratigraphic units in the Iullemeden Basin as a whole, most of them are really restricted and the overall thickness of the sedimentary succession is 1 km or less. Exceptions are the Gao Trench with 3500 to 4000 m, and areas in the proximity of the trans-Saharan lineament where the thickness exceeds 2 km. The greater part of these sediments, however, comprises the “Continental Intercalaire.” A complete succession of marine Upper Cretaceous to Paleocene sediments is exposed in the central sector of the Iullemeden Basin within Niger Republic [11].

The Sokoto sector has potential source rocks. The shales of the Dukamaje (Figure 5) and the Taloka Formations have recently been proven (Nuhu, 2013; Faruk, oral communication) while Dange Formation has marginal source rocks. The Dukamaje Formation is exposed in several localities in Goronyo Local Government Area and commonly consists of limestones, bone beds, and gypsiferous carbonaceous mudrocks.

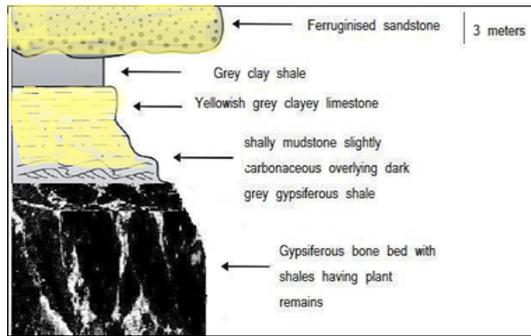


Figure 5: A lithostratigraphic section of the Dukamaje Formation [12].

The Taloka Formation (Figures 6-9) consists of carbonaceous shales and thin-bedded, poorly consolidated sandstones, which characteristic makes its exposures rather crumbly. Preferentially ferruginised bands interbed some of the examined sections of reddish grey to purple siltstones.

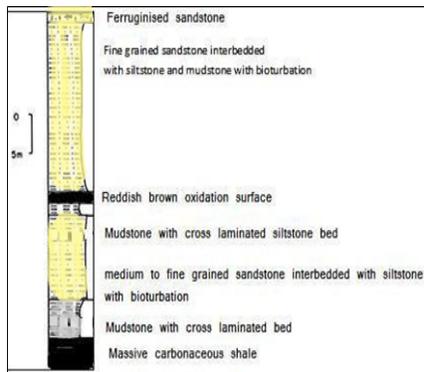


Figure 6: A stratigraphic section of the Taloka Formation [12].



Figure 7: An exposure of the Taloka Formation showing black carbonaceous shales



Figure 8: Reddish brown oxidation bands within reddish grey to purple siltstone, a facies unit of the Taloka Formation.



Figure 9: An exposure of the sandstone facies of the Taloka Formation.

The argillaceous units discussed above have the following attributes that constitute challenges to commerciality:

- i) low sediment thicknesses, the Dukamaje attains a thickness of only 25 m, and the Taloka up to 45 m,
- ii) organic matter is dominantly Type III characterised by the preponderance of brackish-water foraminifera and their general paleo geographic setting,
- iii) shallow burial depths, probably not exceeding 450 m.

The more northerly parts of the basin within Nigeria may be significantly richer in source rocks since the Upper Cenomanian to Coniacian here is partly represented by marine shales. However, thicknesses are only 300 to 400 m, and the depositional setting was predominantly brackish water, coupled with shallow burial depths. Structurally the Sokoto sector is very simple. All lithostratigraphic units are sub horizontally disposed, with a gentle regional dip to the northwest, *i.e.* towards the central parts of the basin. No major faulting has been reported.

The only semblance of folding displays low amplitudes and short wavelengths and, rather than being tectonic in origin, has been ascribed to the collapse of the Gamba Formation into solution hollows developed in the Kalambaina Formation. This structural simplicity may be only apparent, however, the real structure of the basin requires seismic data for confirmation. Elsewhere in the Iullemmeden Basin folding is also rare, being restricted mainly to

the northern and northeastern parts resting on the western flank of the Air Massif, although dips rarely exceed 5°; those that do mainly affect pre-Mesozoic beds [13]. Faulting in this area affects mainly beds of the pre-Mesozoic age. All the major lithostratigraphic units of the Sokoto sector are unconformity-bounded, which presents the prospect of stratigraphic traps for any hydrocarbons generated locally or sourced from deeper parts of the basin. The recommended prospect evaluation requires the use of high resolution tools, specifically 3D seismic and a suite of wireline logs.

### Potential Reservoir Rocks

The potential reservoir units are the clayey sandstones of the Illo and the Gundumi Formations (Figure 10, 11), which are lateral equivalents within the Continental Intercalaire Group), as well as the fine grained sandstones of the Taloka and the Wurno Formations. These would be characterized by low to moderate permeability's. However, the clean sands of the Gwandu Formation (Figure 12) have good porosity and permeability.



**Figure 10:** An exposure of the Illo Formation at the Bandam junction of the Bunza to Dakingari road; note the scoured surface overlain by the fining upward conglomeratic sandstone.



**Figure 11:** An exposure of the Gundumi Formation at its type section in Gundumi village; note the imbricate fabric of the pebbles which are class-supported in the lower coarser part.



**Figure 12:** An exposure of the sandstone facies of the Gwandu Formation; note the clay-draped trough cross-beds.

The carbonate facies of the Kalambaina Formation (Figures 13-15) exhibits solution porosity. Thus both primary and secondary porosity types are present, consistent with the presence of two play types- clastic and carbonate. Seal or trap integrity analyses will confirm the presence or otherwise of effective seals in the trapping configuration, although literature studies point to the Taloka and Wurno Formations having effective sealing in the Dukamaje Formation (see Figure 5) and the Dange Formation due to juxtaposition.



**Figure 13:** The limestone facies of the Kalambaina Formation exposed within the quarry of the Cement Company of Northern Nigeria.



**Figure 14:** The shale facies of the Kalambaina Formation exposed at Maruda near Gagi village.



**Figure 15:** A limestone exposure along the Gagi road.

### **A limestone exposure along the Gagi Road**

The unconformable nature of all or most of the lithostratigraphic units and their wide variation in thicknesses, both along dip and strike, may offer the right trapping configuration for hydrocarbons. However, production may pose some challenges on account of the said thickness variability, although this may be mitigated by the shallow depths to objective sequences and the use of multiple wells for production. The Iullemmeden Basin fill in the eastern Niger Republic is a Late Jurassic to Early Tertiary sedimentary succession affected by a complex rift system with a proven petroleum potential. The source rocks are Cretaceous marine shales and Oligocene lacustrine shales and the reservoirs are Cretaceous to Eocene sandstones [14]. Although the two basal units comprising the Continental Intercalaire lack reliable age indicators some podocarp fossil wood content indicated Late Jurassic to early Cretaceous. From outcrop and laboratory studies, some of the clastic type may be characterized. The sandstone facies of the Illo (Figure 10) and Gundumi (Figure 11) Formations, which are lateral equivalents, are here used as examples, given their very impressive outcrops.

The Illo Formation is characterised by Jones (1948) as consisting of three subunits: - a) white, unconsolidated, cross-bedded, coarse to medium grained quartz sandstone with a conglomeratic and arkosic base, and interbeds of fine sandstone

and clay - all comprising an alluvial fan facies; b) massive, white, chalky, concretionary, pisolitic and highly aluminous clays (>35%  $Al_2O_3$ ); and c) cross-bedded, coarse to medium grained sandstone with subordinate clay content. In a gravel pit half a kilometre north of Libba, an almost complete succession is present. The basal conglomerate is well indurated, the quartz pebbles being sub rounded to well rounded, and calcisilicate-cemented. The predominant clay mineral is kaolinite, with minor illite.

The Gundumi Formation consists of basal conglomerates and gravels with sand and variegated clays increasing upwards. At the type section in Gundumi village the section consists of conglomeratic fine - medium grained sandstone with reddish clayey groundmass. In the lower parts of the exposure, the conglomeratic sandstone exhibits clast-supported fabric which, upwards, gradually gives way to matrix supported fabric. A close inspection also reveals pebble imbrication - the preferred inclination of the long axes of a majority of the clasts. These two units contain considerable thicknesses of both clay and lateritic ironstones which would pose drilling challenges. The quality of the reservoir horizons within these units will undoubtedly be variable, and may range from poor to good. The Tolaka Formation, as described by Obaje et al. (2014) [6], consists of thinly stratified siltstones with load casts and bioturbation structures indicative of a low energy marine setting. The presence of sand lenticles as well as clay flasers and wavy beds in this formation confirm their deposition in tidally dominated shallow marine environment. The low energy entails inherently poor sorting for the sands which makes them of poor reservoir quality. Bioturbation does not seem to have enhanced the reservoir quality [15]. The Wurno Formation consists of pale, friable, fine-grained sandstones, siltstones and interbedded mudstones. Small-scale load casts, bioturbation structures and falser bedding are abundant (Table 1). These are hardly the desirable qualities of a good reservoir rock.

The Gwandu Formation consists predominantly of sandy, lateritic units (red and mottled massive clays, with intercalations of coarse to medium grained sandstone) (Table 1, Figure 12). The top of the formation has widespread lateritic ironstones forming resistant capping's. It is actually a dominantly clayey unit with sandstone intercalations. Its lateral extent and continuity are not yet well known. As the topmost formation, there is the question of sealing potential or trap integrity. The competence of ironstones as seals has not been proven as effective in other hydrocarbon producing regions. This will, however, be a good case study. The Kalambaina Formation consists of marine bio clastic wacke stone interbedded with shales. The formation exhibits solution cavities into which slumping has taken place, giving an impression of folding [8]. However, its maximum thickness (25 m) makes it unattractive as a potential commercial reservoir. The Sokoto Group (Dange, Kalambaina, and Gamba Formations) as a whole may be more suited as seal facies. This is in view of their stratigraphic

position on top of the older potential source facies, such as the mud rocks of the marine Dukamaje Formation. The Dange Formation varies in thickness with locality, but may be over 45 m as shown by the Geological Survey of Nigeria boreholes. The main lithological components are shale (e.g. Figure 16) and limestone. The shales include horizons of fibrous gypsum with abundant calcium phosphate nodules.



**Figure 16:** A section showing typical shale facies of the Dange Formation.

## Summary and Conclusion

From the review of previous published and unpublished studies, as well as considerations based on outcrop analogues, the best potential reservoir rocks of the Nigerian sector of the Iullemmeden Basin are the Taloka and the Wurno Formations. The shales of the Dukamaje and Dange Formations appear to be the main potential source and seal facies respectively. The coarse to medium sandstones of the Gwandu Formation may be good reservoirs if the ironstones are proven to be good seals [16]. These assertions or suggestions can be firmed up in two ways - more intensive field work (followed up with full petrographic studies) and fit-for-purpose geophysical study, specifically seismic surveys.

## Special Recognition

We are grateful to the Petroleum Technology Development Trust Fund for sponsoring this research work.

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