The Sokoto Basin of Northwestern Nigeria: A Preliminary Assessment of the Hydrocarbon Prospective

By
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Abstract
The Sokoto Basin is the south-eastern portion of the larger Iullemmeden Basin. The Iullemmeden Basin covers northwestern Nigeria, most parts of Niger Republic, Benin Republic, Mali, Algeria and Libya. The Sokoto Basin covers mainly Zamfara, Sokoto and Kebbi States of Nigerian. The possible occurrence of oil and gas in commercial quantities in the basin has been a subject of controversy. This is because very scanty prospectivity data are available. Commercial deposits of oil and gas have been discovered and are being produced from contiguous structurally and stratigraphically related rifted basins of Niger Republic, Chad Republic, Sudan, Uganda, Tanzania and Kenya. Geological mapping, geochemical analysis and aeromagnetic geophysical investigation were carried out to preliminarily assess the hydrocarbon prospectivity of the Sokoto Basin. The geological mapping and interpretation of the geological map indicate that the basin deepens towards the border with Niger Republic. Geochemical analysis shows that 90% of the samples examined have equal or more than the minimum limit of TOC value (0.5wt%) required to initiate hydrocarbon generation from source rocks. The source rocks are generally sub-mature through marginally mature to mature within the main oil window. Juxtaposition of the hydrogen indices (HI) against the Tmax (thermal maturity) shows that at greater depths of more than 1,000m, the source rocks would have entered the main oil window to generate mainly gas and some oil. Geophysical data processing and interpretation allows for the delineation of eight better-ranked prospective areas, namely: the Yerimawa-Sabon-Birni-Isah trough, the Wurno-Rabah trench, the Sokoto-Bodinga-Tambulwa trench, the Tureta-Bakura ditches, the Lema-Tambo sinks, the Koko-Giro sinks, the Gada holes and the Kiwon Allah-Sokwoi-Illela pits. Acquisition of 2D/3D seismic data over the delineated areas will assist to de-risk wild-cats.

1.0. Introduction
The possible occurrence of oil and gas in commercial quantities in the Sokoto Basin has been a subject of controversy due to very scanty prospectivity data. Recently, the Governor of Sokoto State, Nigeria, Alhaji Aliyu Magatarda Wamako, was quoted to have claimed, on the basis of some undisclosed data, the occurrence of commercial hydrocarbon deposit in the Sokoto Basin. Many people including industry experts and technocrats doubted the validity of the claim, premising on the lack of any substantial prospectivity data on the basin. Apart from detailed geological maps produced by previous works on the basin\cite{note1}, any available seismic data is difficult

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to locate, geochemical source rock data are non-existent and no exploratory well has been drilled.

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

In addition to the Niger Delta Basin from which all current production of petroleum is derived, Nigeria is blessed with numerous other sedimentary basins comprising the Anambra, Bida, Sokoto, Bornu (Chad), and Dahomey Basins, as well as, the Benue Trough made up of the Lower, Middle and Upper Benue Troughs. These basins have structural and stratigraphical similarities with contiguous intracratonic rifted basins of Niger Republic, Chad Republic, Sudan, Uganda, Tanzania and Kenya where commercial oil accumulations have been discovered (Fig. 1). In SW Chad, development of the Doba discovery (with estimated reserves of about 1 billion barrels) resulted in the construction of a 1070 km long pipeline to the Atlantic coast. In the Sudan, “giant” fields (including Unity 1 and 2, Kaikang and Heglig) have been discovered in the Muglad Basin.

The present study has been carried to shed more light on the hydrocarbon prospectivity of the Sokoto Basin which should form the basis for investors’ acquisition of prospective blocks and the concomitant detailed seismic data acquisition prior to identifying drillable locations and evaluating the reserves vis-à-vis the stock tank oil-in-place in identified fields.

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

2.0. EXISTING KNOWLEDGE ON THE SOKOTO BASIN

Detailed geological mapping was carried by a team of geologists from the Ahmadu Bello University, Zaria under the leadership of Prof. C. A. Kogbe and the reports published in Kogbe. This information was complemented by the work of Petters and Obaje on the basis of which the geological map shown in Fig. 2 has been prepared. From these studies it is known that the Sokoto Basin is the Nigerian sector of the larger Iullemmeden Basin. The Iullemmeden Basin

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itself is a broader sedimentary basin covering apart from northwestern Nigeria, most parts of Niger, Benin, Mali, Algeria and Libya with the major depocentres situated in Niger. The Sokoto sector is an out-baying marginal basin with reducing sediment thickness and stratigraphic age from the thickest and oldest in Niger while younging towards Nigeria.

The Sokoto Basin is predominantly a gently undulating plain with an average elevation varying from 250 to 400 metres above sea-level. This plain is occasionally interrupted by low mesas. A low escarpment, known as the “Dange Scarp” is the most prominent feature in the basin and it is closely related to the geology.

The sediments of the Iullemmeden Basin were accumulated during four main phases of deposition. Overlying the Pre-Cambrian Basement unconformably, the Illo and Gundumi Formations, made up of grits and clays, constitute the Pre-Maastrichtian “Continental Intercalaire” of West Africa. They are overlain unconformably by the Maastrichtian Rima Group, consisting of mudstones and friable sandstones (Taloka and Wurno Formations), separated by the fossiliferous, calcareous and shaley Dukamaje Formation. The Dange and Gamba Formations (mainly shales) separated by the calcareous Kalambaina Formation constitute the Paleocene Sokoto Group. The overlying continental Gwandu Formation forms the Eocene Continental Terminal. These sediments dip gently and thicken gradually towards the northwest (Figs. 3), with maximum thicknesses attainable toward the border with Niger Republic. The detailed stratigraphic succession in the Sokoto Basin is as shown in Figure 4.

The “Continental Intercalaire” is important in Africa. The Karoo Series of South Africa can be correlated with the upper beds of the lower portion of the “Continental Intercalaire”7. The “Continental Intercalaire” corresponds to the upper part of the Nubian Sandstone, which, in the Arabo-Nubian shield, begins at the base of the Palaeozoic. The Iullemmeden Basin, as well as many other parts of North and South Africa, experienced extensive periods of continental sedimentation with the accumulation of fluvio-lacustrine sediments in pre-Cenomanian times. The northern limits of the continental deposition coincides with the Algeria- Moroccan Sahara and extends eastward into Egypt and the Sudan. The southern limits extend as far as South Africa.

**Synopsis of the Petroleum Geology / Petroleum System**

With respect to petroleum geology/petroleum system, some lacustrine carbonaceous shales within the Continental Intercalaire could constitute potential source rocks, while the sandstone facies are candidates for reservoir rocks. In the Rima Group, continental lacustrine shales in the Taloka and Wurno Formations and marine anoxic shales of the Dukamaje Formation constitute potential source rocks, while the sandstone facies in all the formations are potential reservoir rocks. The Dukamje Formation (Maastrichtian) is correlatable to the Nkporo Shale in the Anambra Basin and the Enagi/Patti Formation in the Mid-Niger (Bida) Basin. Within the Sokoto Group, the Dange Formation is could not have assumed maturity level to be a petroleum source.

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rock but could constitute good seals in any stratigraphically lower plays. The Kalambaina carbonates are potential reservoirs while the Gamba shales may constitute regional seals.

Fig. 2. Generalized geological map of the Nigerian sector of the Iullemmeden Basin (Sokoto Basin) (Line of Section A-B)
Fig. 3. Line of section A-B (Talata Mafara – Kiwo-Allah) showing that the most prospective areas are towards the border with Niger Republic as the sediment piles get thicker. However, this has further been resolved by the aeromagnetic data acquired in the present study and interpreted as shown in the section on Results and Interpretations.

Fig. 4. Stratigraphic successions in the Nigerian sector of the Illummeden Basin (Sokoto Basin)
Palaeobiogeographical Deductions and the Trans-Saharan Seaway

Most workers on Saharan and sub-Saharan geology tend to agree on the existence of several transgressive periods during the Cretaceous when marine waters from the Tethys sea moved southwards into the African continent through the Sahara. Simultaneously, Atlantic waters from the Gulf of Guinea moved northwards through the Benue Trough in the Turonian, and most probably through the Bida Basin in the Maastrichtian, to link up with the Tethys transgression somewhere in Niger Republic. According to Kogbe, the Turonian seaway passed through the east of the Hoggar but field evidence seems to suggest that the seaway was gradually displaced westwards during the Senonian. By the end of the Maastrichtian, it was restricted to the western fringes of the Hoggar as evidenced by the absence of marine deposits of Maastrichtian age east of the Hoggar and none as well in the Upper and Middle Benue where the continental Gombe and Lafia Formations were deposited, respectively. The absence of fossiliferous limestones with the diagnostic Cenomanian ammonite genus Neolobites in the Goa Trench and the abundance of representatives of this genus in well documented beds in the Tenere, Damergou and Adar Doutchi, all east of the Hoggar, constitutes excellent evidence in favour of an eastern passage for the Turonian Trans-Saharan seaway. It is still difficult to establish whether the Turonian sediments of the Damergou and Bilma were deposited in a sea extending from North Africa, or whether they derived from an extension of the sea stretching inland from the Gulf of Guinea. This difficulty does not however, eliminate the strong probability of a linkage of both waters during the Turonian. The Turonian transgression must have passed through the Benue Trough, as there is no record of any marine Lower Cretaceous sediments in the Bida and Sokoto Basins. In these basins continental deposition prevailed at this time with the deposition of the Illo and Gundumi Formations (Continental Intercalaire) in the Iullemmeden Basin. During the Maastrichtian, the connection was definitely through the Bida Basin where the marine Patti Formation alongside the Nkporo Shale of the Anambra Basin and the Dukamaje Formation in the Sokoto Basin were deposited.

All the previous works in the Sokoto Basin are concentrated on geological mapping and biostratigraphical evaluation. However, nowhere were their implications on the hydrocarbon prospectivity evaluated nor were the geological maps interpreted in the context of prospectivity maps. No organic geochemical results of any type on any parts or on any stratigraphic formation in the Sokoto Basin are available; neither are aeromagnetic maps and their interpretation in the context of hydrocarbon prospectivity.

This study has been carried out with the overall aim of fast-tracking and contributing to the Nigerian National Petroleum Corporation’s efforts to open up the acreages in Nigeria’s inland basins for hydrocarbon exploration and production in the soonest possible future, while

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10 Ibid
11 Ibid
providing indigenous and international oil companies the needed data to make investment decisions on the Sokoto Basin.

3.0. SCOPE OF WORK AND METHODOLOGIES ADOPTED
The scope of the preliminary work comprises geological mapping, sample collection, sample processing, data generation and data analyses. The methodologies adopted comprise:

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

4.1. Fieldwork and stratigraphical sample collection
Geological fieldwork and sample collection were carried out in selected portions of the Sokoto Basin with the aim to update the existing geological map and to obtain good quality samples for geochemical analysis. Fresh outcrop samples and samples from drilled shallow wells at Wurno, Goronyo, Gada, Illela and Sokoto were collected. Macrafossil assemblages as they occur on the field were used to validate the correlations of the rock units. Structural analyses were undertaken on the field. Anticlinorial cores were particularly targeted as they afforded opportunities to sample rock units that have been thrust to the surface by tectonic processes and for which their equivalent units generally lie very deep down below the surface. The resultant geological map is used to construct subsurface cross-sections with the objective of delineating areas with thicker sediment piles.

The sampling design covered as much of the area as possible using road cuts and other exposed outcrops to collect stratigraphic samples. Rock types, bed thicknesses, textural features, sedimentary structures, structural features and depositional environments were recorded at every outcrop.

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

Total Organic Carbon (TOC) analysis to determine the level of organic matter richness (quantity): have they met the minimum limit for hydrocarbon generation? Rock Eval pyrolysis for the determination of the Hydrogen Indices (HI), Oxygen Indices (OI), Production Indices (PI) and Tmax as a measure of the organic matter quality: If quantity has met the minimum limit, what type of hydrocarbon would be generated? Oil or Gas? The Tmax is the measure of the organic matter maturity: Where does the maturity level fall with relative to the oil generation window? Immature for oil generation, mature for oil generation or overcooked for oil generation? The geochemical analyses were undertaken at Getamme Laboratory in Portharcourt.

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

4.0. RESULTS AND INTERPRETATIONS
The geological mapping undertaken reveals some details of the composition and aerial extent as well as the inferred boundaries of the formations in the Sokoto Basin. The delineation of inferred boundaries between the formations in the basin is a significant criterion in evaluating the hydrocarbon prospectivity. Subsurface reservoir characteristics were also inferred from outcrop-stratigraphic sections encountered during the geological mapping exercise. The geological map produced (Fig. 2), in a general assessment, conforms to earlier maps produced by previous workers with some minor modifications. For example, the organic matter-rich carbonaceous shales within the Taloka Formation at Goronyo are first identified in this study.

Interpretations from surface outcrops during the mapping indicate that carbonaceous dark shales within the Taloka and Dukamaje Formations constitute potential source rocks (pending outcome of geochemical analysis) while the sandstone facies within the Gundumi/Illo Formation, the Taloka Formation, the Wurno Formation as well as the carbonates of the Kalambaina Formation will constitute the reservoir rocks in the subsurface. The shales of the Dange and Gamba Formations are expected to constitute regional seals to any hydrocarbon generated within the basin. While the sandstones of the Gundumi/Illo Formation are generally coarse-grained, conglomeratic and poorly sorted those of the Taloka and Wurno Formations are medium to fine grained and moderately to well sorted. The limestones of the Kalambaina Formation comprise both very porous and highly permeable intervals and massive non-porous impermeable intervals that are generally marly.

4.2. Geochemical Data
Table 1 shows the Leco-TOC and Rock-Eval pyrolysis results of some representative samples obtained from outcrops and shallow wells drilled at Wurno, Goronyo, Gada, Illela and Sokoto township. Ninety percent of the samples examined have equal or more than the minimum limit of TOC value (0.5wt%) required to initiate hydrocarbon generation from source rocks. TOC decreases with depth in the Gada (GAD) borehole and increases with depth in the Wurno (WUR) borehole down until 27m (Fig. 5).

Evaluation of maturity level by Tmax (Fig. 6) shows that the source rocks (made up of the carbonaceous shale intervals of the Taloka and Dukamaje Formations) are sub-mature (Wurno samples) through marginally mature (Gada samples) to mature within the main oil window (Goronyo and Illela samples).

Juxtaposition of the HI against the Tmax (thermal maturity) (Fig. 7) shows that the source rocks in the Sokoto Basin are slightly below the entrant to the oil window (slightly immature to early mature) (Wurno and Gada samples) to appropriately mature within the main oil window.
(Goronyo and Illela samples). The interpretation, however, represents results on samples obtained at the surface to maximum 120m depth. At greater depths of more than 1,000m, majority of the samples would have entered the main oil window to generate mainly gas and some oil.

<table>
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<th>Sample ID</th>
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Table 1. Leco TOC and Rock Eval pyrolysis data of potential source of the Dukamaje Formation obtained from freshly drilled shallow wells (at Wurno, Goronyo, Gada, Illela and Sokoto) in the Sokoto Basin
Fig. 5. Evaluation of organic richness by TOC wt%: 90% of the samples examined have equal or more than the minimum limit of TOC value required to initiate hydrocarbon generation. TOC decreases with depth in the Gada (GAD) borehole and increases with depth in the Wurno (WUR) borehole down until 27m.
4.3. Geophysical Aeromagnetic Data

The geophysical aeromagnetic data comprise the raw data (acquired/purchased from the Nigerian Geological Survey Agency – NGSA) (Fig. 8) and the processed and interpreted data that shows the depth to basement in colour index (Fig. 9). Raw data were obtained on most of the sheets (individually) covering the sedimentary cover of the Sokoto Basin and merged together for a composite interpretation. The results of the aeromagnetic processing and interpretations have assisted to refine and redefine the earlier geologically postulated prospective areas. Aeromagnetic geophysical measurements normally target magnetic materials (magnetic minerals and rocks), which are normally most abundant in basement rocks and least in sedimentary rocks. Most interpretations assume zero value for sedimentary cover, such that lesser values are interpreted for deeper lying basement and higher values for near-surface basement or higher concentration of magnetic minerals (magnetic, haematite, ironstones, etc). For this reason, the aeromagnetic data for the Sokoto Basin must be carefully juxtaposed against the geological map.
Preliminary interpretation of the geophysical aeromagnetic data over the Sokoto Basin agrees generally with the geological mapping interpretation that shows that prospectivity increases towards the border with Niger Republic (Fig. 3) but with the addition of prospective areas in updip sections of the basin around Tureta, Bakura, SabonBirni and Isah located on the Illo/Gundumi/Taloka Formations. The interpreted aeromagnetic data map shows many troughs, trenches, ditches, sinks and holes (prospective areas) (indicated in blue). However, eight areas are discernibly highly ranked at this stage, pending future seismic investigations. These areas comprise the:

1. Yerimawa-SabonBirni-Isah trough
2. Wurno-Rabah trench
3. Sokoto-Bodinga-Tambulwa trench
4. Tureta-Bakura ditches
5. Lema-Tambo sinks
6. Koko-Giro sinks
7. Gada holes
8. Kiwon Allah-Sokwoi-Illela pits

Although the aeromagnetic interpreted data did not give exact depth to basement, it has indicated that most of the identified prospective areas have sediment thickness up to 3,000m (approx 3 km).
6. 0. CONCLUSIONS

The Sokoto Basin is the least studied of all Nigeria’s inland frontier basins in terms of prospectivity evaluation. This is because not a single exploratory well has penetrated the sequences in the basin, making access to subsurface data very difficult. This study has carried out preliminary geological mapping and attempted a geological prospectivity evaluation of the Sokoto Basin. Geochemical evaluation has also been carried out to assess the source rock qualities and the potential of the rocks to generate hydrocarbons (oil and/or gas). The study was completed with interpretation of geophysical aeromagnetic data with the aim to assess the depth to basement, basement topography and refining of locality prospectivity necessary for the acquisition of more prospective acreages from the Nigerian Department of Petroleum Resources (DPR) and for the selection of drillable sites, after upgrading with investigations.

From the geological map, it is discernable that the areas closer to the border with Niger Republic are more prospective. Geochemical data show that mainly gas and some oil would have been
generated or are still being generated from source rock within the basin deeper in the subsurface. These source rocks are made up of carbonaceous/dark shales within the Dukamaje and Taloka Formations. Geophysical aeromagnetic data evaluation indicates a depth of up to 3,000m (3 Km) within the inferred prospective areas. Such prospective areas include the Yerimawa-SabonBirni-Isah trough, the Wurno-Rabah trench, the Sokoto-Bodinga-Tambulwa trench, the Tureta-Bakura ditches, the Lema-Tambo sinks, the Koko-Giro sinks, the Gada holes and the Kiwon Allah-Sokwoi-Illela pits.

It is recommended that 2D/3D seismic data be acquired and processed on the identified prospective areas, while three deep exploratory/research wells (up to 1,000m each) be drilled at Tureta, Dange and Kiwon-Allah for stratigraphical controls that shall embrace sedimentological, biostratigraphical and further geochemical analyses.