Lacustrine Environment Reservoir Properties on Sandstone Minerals and Hydrocarbon Content: A Case Study on Doba Basin, Southern Chad

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Abstract. The contribution of lacustrine environment as the hydrocarbon reservoir has been widely known. However, despite its growing importance, the lacustrine petroleum geology has received far less attention than marine due to its sedimentological complexity. This study therefore aims in developing an understanding of the unique aspects of lacustrine reservoirs which eventually impacts the future exploration decisions. Hydrocarbon production in Doba Basin, particularly the northern boundary, for instance, has not yet succeeded due to the unawareness of its depositional environment. The drilling results show that the problems were due to the: radioactive sand and waxy oil / formation damage, which all are related to the lacustrine depositional environment. Detailed study of geological and petrophysical integration on wireline logs and petrographic thin sections analysis of this environment helps in distinguishing reservoir and non-reservoir areas and determining the possible mechanism causing the failed DST results. The interpretations show that the correlation of all types of logs and rho matrix analysis are capable in identifying sand and shale bed despite of the radioactive sand present. The failure of DST results were due to the presence of arkose in sand and waxy oil in reservoir bed. This had been confirmed by the petrographic thin section analysis where the arkose has mineral twinning effect indicate feldspar and waxy oil showing bright colour under fluorescent light. Understanding these special lacustrine environment characteristics and features will lead to a better interpretation of hydrocarbon prospectivity for future exploration.

1. Introduction

Lacustrine dominated basin is a standing water body surrounded by land that mostly feeds and drains by rivers and streams. They are varied in water depth, size, salinity and sedimentation. Some lake deposits can act as both source and reservoir. The lacustrine reservoir may have high porosity and permeability, thus making it one of the prolific areas for hydrocarbon exploration where many fields in the world have been producing from this type of environment.

This study is conducted on Doba Basin that has potential in becoming a good lacustrine reservoir. It is a Late-Mesozoic basin situated in Southern Chad of Central Africa. The appraisal wells
have been drilled in the study block of Doba Basin (particularly on northern basin boundary), however no hydrocarbon has been produced yet even though the exploration well proved the presence of it. The drilling results show that the problems were all related to the lacustrine depositional environment. This type of environment has some unique characteristics in wireline log as compared to conventional logs. All the geologically related features have significant impact on the concept measures and the future exploration. To address this issue, an integrated reservoir study on petrophysical and petrographical characteristics are needed to reveal more detailed lacustrine reservoir features particularly on the radioactive sand and waxy oil properties for better hydrocarbon exploration in Doba Basin. This study is therefore conducted with the attempt to solve the problems listed in the Table 1.

| Geological Features | Problems Encountered | Explanation |
|---------------------|----------------------|-------------|
| Relatively short transport distance of sedimentation (incomplete weathering cycle) | Differentiation of reservoir and non-reservoir (failed to recognize sand and shale) | Radioactive sand always mistaken as shale due to high gamma ray content. This Doba Basin’s arkosic sand form due to relatively short distance sedimentation. It is believed that the provenance is coming from the basement high. |
| Terrestrial source | Inconclusive of Drill Stem Test (DST) results | 1) The presence of arkose in the formation causes the failure of the cement bond logging (CBL). The poor cementing in-fill causing the failure/inconclusive of DST 2) Waxy oil has tendency to clogs the pore throats thus reducing the permeability, which eventually affects the oil mobility to the surface. |
| | Possible mechanism of formation damage | Usually formation damage occurs due to the unintended impedance to the flow of fluids into or out of a wellbore. E.g: waxy oil which originated from terrestrial sources. |

2. Geological Setting

2.1. Regional Geology

Regional tectonic studies revealed that the lithosphere of the African continent was affected by the staged expansion of Southern Atlantic Ocean in Early Cretaceous which forms the West and Central Africa Rift System (WCARS) [2]. The strong dextral strike slip tension of WCARS developed two genetically related but physically separated Late Mesozoic – Cenozoic passive rift system; the West African Rift System (WARS) and the Central African Rift System (CARS) [5,6,7,10,13]. CARS has been forming a series of sedimentary basins, consists of Bangor, Doba, Doseo and Salamat Basin in southern part of Republic of Chad. The oil and gas exploration and development activities however have been limited to the Doba Basin where over 50% of the country’s wells have been drilled and where all the country’s current oil production is coming from [12].
Figure 1: Map of studied location (red box), Doba Basin of Southern Chad which is a part of Central African Rift System, CAS. (Figure 1a: Modified from Genik 1993, Figure 1b: After Aremu, n.d)

Doba Basin located in southern part of Republic of Chad, northwest of CARS as shown in Figure 1. Stratigraphically, Doba basin has a basement composed of Precambrian metamorphic rocks overlay by, at most over, 7,500 meters continental deposits of thinner Lower Cretaceous (Mangara, Kedeni, Doba and Lower Kome) formations, but thick Upper Cretaceous (Upper Kome and Miandoum) formations [6]. The Lower Cretaceous formations mainly contain lacustrine sediments, the sandstone and mudstone interbeds are major reservoir strata, and especially a large set of thick shales are developed at top of formation, acting as the good regional caprocks. Upper Cretaceous is dominated by abundant fluvial sandstones, with alluvial plain mudstones at the top. Cenozoic formations contain fluvial coarse grained clastics sediments. The petroleum Geology of Doba Basin [1] are made of:

- **Reservoir rock** - Lower Cretaceous of Lower Kome, Kedeni and Mangara Formation and Upper Cretaceous of Miandoum Formation of varyingly arkosic sandstones.
- **Source Rock** - Lower Cretaceous of Doba Shale; early rift lacustrine shales with TOC content of typically 1-4% (type I and III organic matter)
- **Seal** - Lower Cretaceous (lacustrine) Mangara Shale and Upper Cretaceous (flood plain and inter-distributary to lacustrine) Miandoum shale.

2.2. Lacustrine Reservoir

2.2.1. Lacustrine Radioactive Reservoir

The hydrocarbon reservoir potential within lacustrine basins is partially impacted by overall tectonic setting [8 9] where within extensional settings there is limited transport distance. The radioactive sand, resulted from limited transport distance, is coarse-grained detrital rocks that have high affinity of radioactive minerals. In principal, sand composes of quartz which gives low Gamma Ray (GR) reading but the high concentration of radioactive minerals in clean sand causes the rise of GR values. Radioactive sand can be classified into 6 types which are [4]; i) Feldspathic sandstone or arkose, ii) Micaceous sandstones, iii) Mixed feldspathic-micaceous sandstone, iv) Greensand or glauconitic sandstones, v) Heavy minerals within sandstones, and vi) Shaly sand and sandstone [4]. This radioactive sand may originate from basement high within the basin itself, implying that the detrital materials from the sedimentary source have not undergone sufficient transportation and weathering cycle, then the parent minerals like feldspar (K), micas, glauconite and heavy minerals would be retained in the sedimentary rock. In this case, the sands and gravels may be highly arkosic (high feldspar content), with high content of $K^{40}$ which was deposited in lacustrine environment particularly in Kedeni and Mangara Formation of Lower Cretaceous age.
2.2.2. Waxy Oil

The lacustrine environment has been recognized to produce source rock of Type I and III organic matter [11] where:

i) Type I formed from algal remains deposited under anoxic conditions in deep lakes and tend to generate waxy crude oils when submitted to thermal stress during deep burial high.

ii) Type III formed from terrestrial plant material that has been decomposed by bacteria and fungi under oxic or sub-oxic conditions. Petroleum geochemists tend to consider long-chain n-alkanes as being typical of higher plants (from wax coatings of leaves), and often use them as potential indicators of land plant contribution to the source rock of an oil.

In Doba Basin, the hydrocarbon quality had shown that the oils are paraffinic with wax content up to 25% [1] which indicate that the source is highly Type III as it is more waxy-prone than Type I.

3. Methodology

The methodology used in this study comprises of integrated study of wireline logs, mud logs, rock matrixes, DST and CBL results analysis and petrographic thin section analysis as shown in Table 2.

| Methods                          | Descriptions                                                                 |
|----------------------------------|-----------------------------------------------------------------------------|
| Wireline Logs Recognition        | • Natural Gamma Ray Spectroscopy and Wireline Logs Integration              |
|                                  | • Rho matrix analysis                                                      |
| CBL and DST Results Analysis     | • CBL and DST Results analysis integration with wireline logs               |
| Petrographic Thin Section        | • Detailed information about mineralogy of detrital grains matrix and cement composition can be done |
| (Characterisation of Mineral)    | Fluorescent Light                                                           |
|                                  | • The occurrence of waxy oil within the rock matrix can be easily distinguished |

4. Results and Discussions

4.1. Sand Shale Recognition

4.1.1. Natural Gamma Ray Spectroscopy and Wireline Logs Integration

By using natural gamma ray spectroscopy, the individual gamma ray sources can be determined thus help in interpreting the types of sands in the reservoir. In general, in shales, high potassium indicates micaceous clay while high uranium indicates organic shale. As for the sandstones, high potassium means arkosic sands, high thorium and uranium suggest more heavy minerals within the sandstone matrix. In Doba Basin, one of the wells show high gamma ray (>90) value but there is formation of mudcakes which are usually associated with sand intervals (Refer Figure 2). Moreover, the amount of potassium in that interval is the highest compared to the uranium and thorium and this concludes that the interval has arkosic sands.
Figure 2: Conventional well log data (Caliper, Bit Size, Gamma Ray, Resistivity, Density-Neutron, Sonic and Photoelectric) with spectral gamma ray value. At depth of 2510m to 2530m, the potassium (blue line) content is higher than uranium and thorium.

The goal of formation microimager (FMI) interpretation is to characterize formation properties to assist sedimentological interpretation such as structure and lithology. Shale and sandstone for example can be easily defined by comparing the colour contrast as shown in Figure 3. Shale appears to be darker compared to sandstone. Here, by integrating conventional log with FMI data, it is clear, at depth 2619m, is defined as sandstone bed, even though the gamma ray displays a high value.

Figure 3: FMI data shows the presence of sandstones at high gamma ray interval.
Rho matrix analysis is another method of differentiating sandstone and shale bed. Based on the GR log, there is no distinct change in its value (which probably means same lithology), however, by using the rho matrix technique, the sand and shale bed indicates a totally different value as shown in Figure 4.

![Figure 4: Sand and Shale can be easily identified using rho matrix technique as it shows distinct different value even at the constant (slightly different) Gamma Ray value.](image)

4.1.2. Petrographic Thin Section Analysis

Petrographic analysis of thin sections provides detailed information on mineralogy of detrital grains matrix and cement composition. Under microscopic images using normal polarized light, quartz can be easily distinguished as a common mineral in sandstones. It shows no twinning in contrast to images shown in Figure 5 (pictures were taken during analysis). From quick-look petrographic interpretation, the minerals show obvious twinning (lamellar albite, perthite and microcline tartan twinning) which is usually associated with feldspar, a high gamma ray mineral.

![Figure 5: Petrographic thin sections showing obvious twinning that indicates feldspar. All the feldspar twinnings were found in one thin section. High amount of feldspar grains cause increase in gamma ray value](image)

4.2. Failed DST Results

4.2.1. Poor Cement Bond Logging (CBL) Leading to Failed DST Results

Cement bond logs were run to determine the quality of the cement bond to the production casing, and to evaluate cement fill-up between the casing and the reservoir rock. Poor fill-up of cement leaves large channels behind the pipe that, likewise, allows the flow of unwanted fluids, such as gas or water into an oil well. Both poor bond and poor fill-up problems can also allow fluids to flow to other reservoirs.
behind the casing. This causes failed or inconclusive DST which leads to serious loss of potential oil and gas reserves. The interpretation in Figure 6 shows that poor cementation happens at high radioactive sandstones. The arkosic sandstones cause the cement to be non-solidified and leave spaces between the borehole and casing.

4.2.2. Formation of Waxy Oil Leading to Failed DST Results

For the case of waxy oil formation, Figure 7 shows the portion where 10m core was taken from sandstone and basement rock. There is oil drips from the sandstone part which indicates the presence of oil. However, when DST was performed, no oil was produced. This waxy oil formation is one of the major problems in production as it clogs the pores thus preventing oil mobility to surface.
Petrographmic thin section also helps in distinguishing and proving the occurrence of waxy oil. Under the normal polarized light, the sample do not show any distinct feature (oil absent) as shown in Figure 8 (top section). However, under fluorescent light (Figure 8, bottom section), there are obvious bright colours which indicate the presence of wax within the matrix. The existence of waxy oil is believed to be generated from the transported terrestrial organic matter that contributes to the mixed Type I-III [3] but more on Type III kerogens.

![Figure 8: Under fluorescent light (right), the bright colour indicates wax](image)

5. Conclusions

Based on this study, a few conclusions can be made;

1. The reliability in distinguishing reservoir and non-reservoir areas based on the gamma ray log alone will lead to the misinterpretation of the lithology due to the well presence of radioactive sand in the area. Therefore, use of other types of logging tools is necessary.

2. Application of rho matrix technique can help in identifying sand and shale from different density values.

3. The arkosic sandstones are the cause of bad cementation in borehole which affect the DST results. The presence of waxy oil in the formation also leads to DST failures due to formation damage.

4. The petrographic analysis is useful in defining the minerals (e.g: feldspar show twinning features) present in the samples. Not only that, by using fluorescent light, wax is easily distinguished since it gives out a bright colour.

The integration study between geology and petrophysics data will lead to the understanding of the lacustrine reservoir characteristics. It is expected that after the evaluation, a better volumetric calculation of the reservoir and pay zone can be achieved, resulting in more accurate prospectivity of the studied area and also help in solving the problems in other similar lacustrine environment basin.

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