



# Science Forum (Journal of Pure and Applied Sciences)

journal homepage: <https://atbu.edu.ng/science-forum/>



## Diagenetic history and reservoir capability of Bima Formation, Northern Benue Trough, Nigeria

Gideon Gumut Sunday<sup>1</sup>, Timothy Peter Bata<sup>1\*</sup>, Godspower Emmanuel Ubit<sup>1</sup>, Ibrahim Adamu<sup>1</sup>, Joseph Amobi Francis<sup>2</sup>, Celestina Sani Zubairu<sup>1</sup>, Christopher Uche Ezugwu<sup>1</sup>, Saidu Abdullahi<sup>3</sup>, Ezekiel H. Elijah<sup>4</sup>

<sup>1</sup> Department of Applied Geology, Abubakar Tafawa Balewa University, Bauchi, Nigeria

<sup>2</sup> Department of Geology, Federal University, Lokoja, Nigeria

<sup>3</sup> Department of Geological Science, Federal University, Gusau, Nigeria

<sup>4</sup> National Productivity Center Bauchi, Nigeria



### ABSTRACT

The Cretaceous Bima Formation is the oldest and thickest formation within the Benue Trough chiefly made up of sandstone with continental origin. In this study the studied section shows oil infilling pore spaces within the sands as reported by Bata, which further buttress the interest on the reservoir capability of the Cretaceous Bima Formation within the Northern Benue Trough. In the field observation three main section were studied and observed which are the dark grey section (indicating oil charged sands), the reddish brown section (non-oil charged), and the section that has been altered by orogenic events. These sands show minor bioturbation with planar gradational bedding as observed in the field, with a coarsening upward lithostratigraphic sequence typical of fluvial condition the studied section of the Cretaceous Bima sandstones having estimated average porosity of 5.50% having 11.80% as the highest and 0.66% as the lowest. Scanning electron microscope photomicrographs and thin section photomicrograph of the studied sandstones belonging to Cretaceous Bima Formation show that the sandstones are fine to medium grain with grain size ranging from 0.1 to 1.0 mm, moderately to poorly sorted, sub-arkoses, and lithic sub-arkoses. Silica occurs as the main cementing agent in the studied sandstones. The boundaries between the silica overgrowth and the detrital grains are mostly poorly defined.

### ARTICLE INFO

#### Article history:

Received 19 January 2023

Received in revised form

21 January 2023

Accepted 22 January 2023

Published 06 July 2023

Available online 06 July 2023

### KEYWORDS

Northern Benue Trough  
Cretaceous Bima Formation  
Reservoir capability  
Oil charged  
Paragenetic sequence  
Porosity  
Silica overgrowth

## 1. Introduction

The Benue Trough is a sediment-filled northeast trending rift basin in Nigeria that stretches for about 800 km and it is about 150 km in width. The Benue Trough is understood to have developed from incipient rifting that occurred during the Cretaceous break-away of South America from Africa and the opening

of the South Atlantic Ocean (Pearson and Obaje, 1999; Whiteman, 1982). It borders the Chad Basin to the north and the Niger Delta to the south. The Benue Trough is geographically divided into the lower, middle, and upper Benue regions containing up to about 6,000 m of Cretaceous–Palaeogene sediments. The Benue Trough has been the subject of several academic

\* Corresponding author Timothy Peter Bata ✉ [timothybata@icloud.com](mailto:timothybata@icloud.com) ✉ Department of Applied Geology, Abubakar Tafawa Balewa University, Bauchi, Nigeria.

discussions related to paleogeography, sedimentology, structural geology, mineral exploration, and hydrocarbon exploration (Abubakar and Obaje, 2001; Akande et al., 1998, 2012; Bata et al., 2020; Benkhelil, 1982; Burke et al., 1970; Cratchley and Jones, 1965; Nwajide, 2013; Obaje et al., 1999, 2004; Petters, 1982; Samaila et al., 2008; Yandoka et al., 2015; Zaborski, 2000; Zaborski et al., 1997).

At its upper end, the Benue Trough is divided into two arms: the Gongola arm which runs northwards into the Chad Basin, and the Yola arm which runs eastward, terminating against the Cameroon basement rocks. In both basins, Precambrian basement rocks are overlain by the Bima Formation which is the oldest sedimentary succession in the region. Again in both basins, the Bima Formation is and is conformably overlain by the transitional/coastal Yolde Formation (Cenomanian) which marks the onset of marine incursion into the upper Benue Trough. In the Gongola Basin, Gongola and Pindiga Formations conformably overlie the Yolde Formation. Both the Gongola and Pindiga Formations are believed to have been deposited by a major marine incursion that occurred in the region during upper Cenomanian, Turonian to Santonian times (Jauro et al., 2007). Lateral equivalents of the Gongola and the Pindiga Formations in the Yola arm of the Upper Benue Trough are the Dukul, Jessu, Sekuliye, Numanha, and Lamza Formations. The Benue Trough witnessed tectonic deformation and folding during the

mid-Santonian. Cretaceous sediments which pre-date the mid-Santonian were folded, faulted, and uplifted in several places (Abubakar et al., 2011). This was followed by a compressive phase that occurred at the end of the Maastrichtian (Zaborski, 2003). Post-folding sediments in the Upper Benue Trough are represented by the continental coal-bearing Gombe Sandstone (Maastrichtian) and the Paleogene Kerri-Kerri Formation.

Hydrocarbon exploration is a tedious task as oil after generation and migration tends to travel both short and relatively longer distances from the organic-rich fine-grained source rocks to coarser-grained reservoir rocks (Peters et al., 2005). More so, many potential reservoir rocks may be found in any given basin; thereby the reservoir capability of a given potential reservoir rock is essential to any given basin petroleum play system. Petroleum is known to occur at depths beyond 2,000 m (oil window) and temperatures above 60°C (pasteurizing temperature) where the transformation of stabilized organic compounds (kerogen) into oil, and later gas, starts (Bata et al., 2015). The presence of oil residue at surface outcrop exposures of the Cretaceous Bima Formation could provide a clue regarding the generation, migration, and entrapment of petroleum in the Cretaceous Bima Formation; an implication to hydrocarbon exploration in the Northern Benue Trough of Nigeria. This work is aimed at exploring the reservoir capability of the

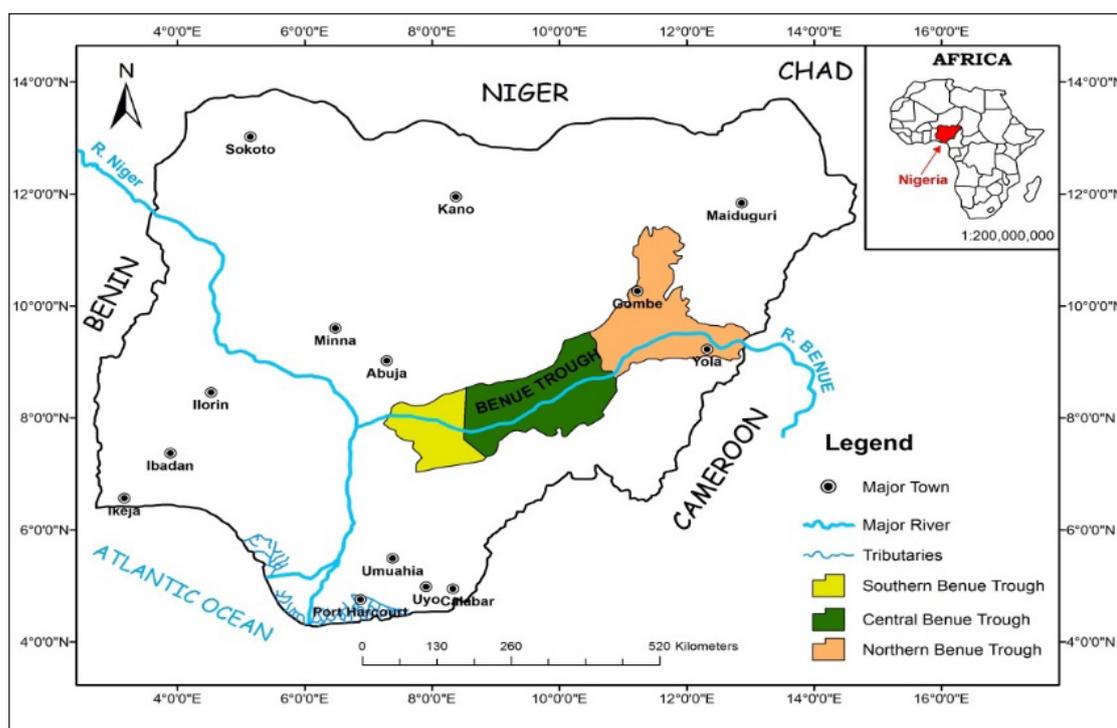


Figure 1. Map of Nigeria showing the proposed study location (red box).

Cretaceous Bima Formation in the Northern Benue Trough. This will be achieved through fieldwork and petrographic examination of the samples obtained in detail.

## 2. Methodology

As stated above, the research work commences with a field mapping study aimed at documenting and delineating field occurrences of both the oil-stained and non-oil-stained Cretaceous Bima Formation within the Northern Benue Trough (Fig. 1). The samples obtained from the fieldwork were prepared as polished blocks and thin sections using the method described by Reed (2005) and Bata et al. (2017). The polished block and thin sections were examined using a petrographic microscope and scanning electron microscope (SEM) that is coupled with a link analytical 10/55S EDAX facility. Distinct minerals related to the oil sands were established using the linked analytical 10/55S EDAX facility. The paragenetic sequence of the studied Cretaceous Bima Formation was then developed based on the observation made from the petrographic study.

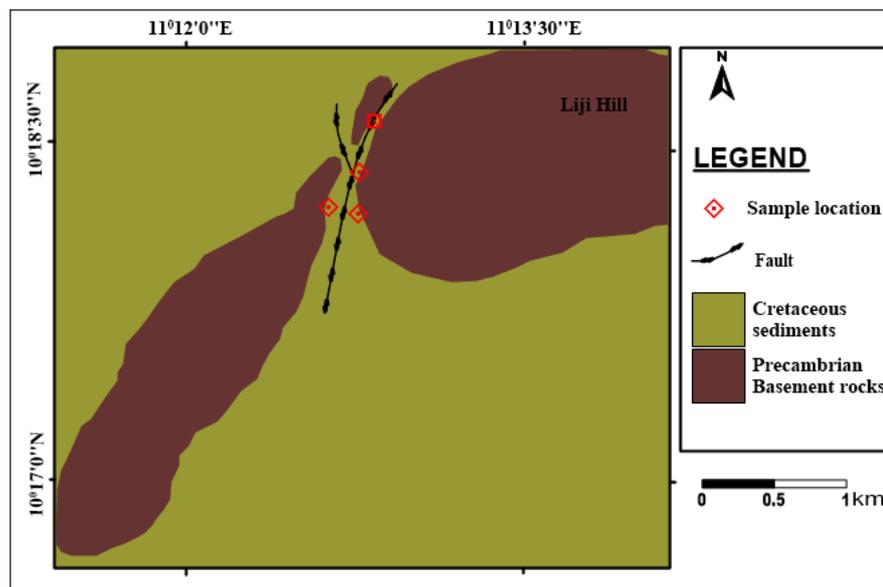
The porosity of the individual studied samples before oil emplacement was obtained by adopting the minus cement porosity determination technique, which involves subtracting the estimated percentage volume of hydrocarbon in the pore spaces of each oil sand from the estimated percentage volumes of

detrital grains and cement (Bata, 2016; Cooper and Hunter, 1995). The minus cement porosity of the studied samples which refers to the original porosity prior to diagenetic modifications (cementation, precipitation, dissolution, and compaction), was calculated from the photo-micrographs using two specialized computer software applications (Adobe Fireworks and Image J).

The “magic wand tool” in the Fireworks application was used to separate the oil residue from the rock matrix and minerals in the photomicrographs. This is achieved by selecting (highlighting) and “cutting” all the perceived oil-bearing pore spaces (dark patches) on the photomicrograph and pasting same on a blank slide; the resultant image is the oil content version while the former is the barren non-oil containing rock image. The Image J application is then used to estimate the total volume of the whole rock from each studied photomicrograph and the total volume of the oil residue in each studied photomicrograph. The volume of the oil residue is then mathematically worked out as a percentage of the whole rock to obtain the minus cement porosity value. It is expressed thus:  $\text{oil} / (\text{oil} + \text{non-oil}) \times 100$ .

## 3. Results and Discussion

These results include a geologic map of the studied area, field photographs, lithostratigraphic logs, photomicrographs, minus-cement porosity information,



**Figure 2.** Geologic map of the study area around Liji Hill Gombe inlier part of the Gongola sub-arm of the Northern Benue trough.



**Figure 3.** Field photograph showing oil-charged sands and the non-oil-charged sands within the Bima Formation within the study area (Liji Hill).



**Figure 4.** Effect of demulsifier on the amount of separated crude oil at different water outlet pipe dimeters.



**Figure 5.** Field photograph showing fluid action within the studied sections of the Bima Formation within the study area.

and paragenetic sequence. The results are presented toward describing the reservoir capability of the Cretaceous Bima Formation. Figure 2 is the geologic map of the studied area showing sampled locations. Samples of both oil-stained and non-oil-stained sandstones were taken from zones with little or no observable alteration in the field. The Bima Formation in the study area is generally underlined by the Precambrian basement rocks. Sedimentation in the studied basin started during the Albian with the deposition of the Bima Formation unconformably on the Precambrian basement rock. This was followed by the deposition of the Cenomanian Yolde Formation consisting of sandstones, shale, and limestone (Akande et al., 2012). The studied Bima Formation is observed to be a very important element of the prospective petroleum system in the studied area due to its thickness and the presence of oil and stains in the sandstones of the studied area.

In the studied area (Fig. 3), oil-charged sandstone of the Bima Formation is seen exposed on the surface with another sequence that is non-oil charged, samples were taken from both sequences and studied in detail using a petrographic microscope and SEM.

Figures 3–5 are field photographs showing the various gradational beds as observed in the field with some of the sequence showing evidence of oil stain and some having no indication of oil stain.

Figures 6 and 7 show the lithostratigraphic log of the studied section with a log motif typical of fluvial channel deposits which gives a coarsening upward log motif and they are generally texturally immature. Figure 8 gives the general classification of the studied sands which are subarkosic to lithic subarkose which are texturally immature.

SEM photomicrographs of the studied sandstones belonging to the Bima Formation are presented in Figures 9–11 below. The sandstones are fine to medium grain, moderately to poorly sorted, sub-arkoses,

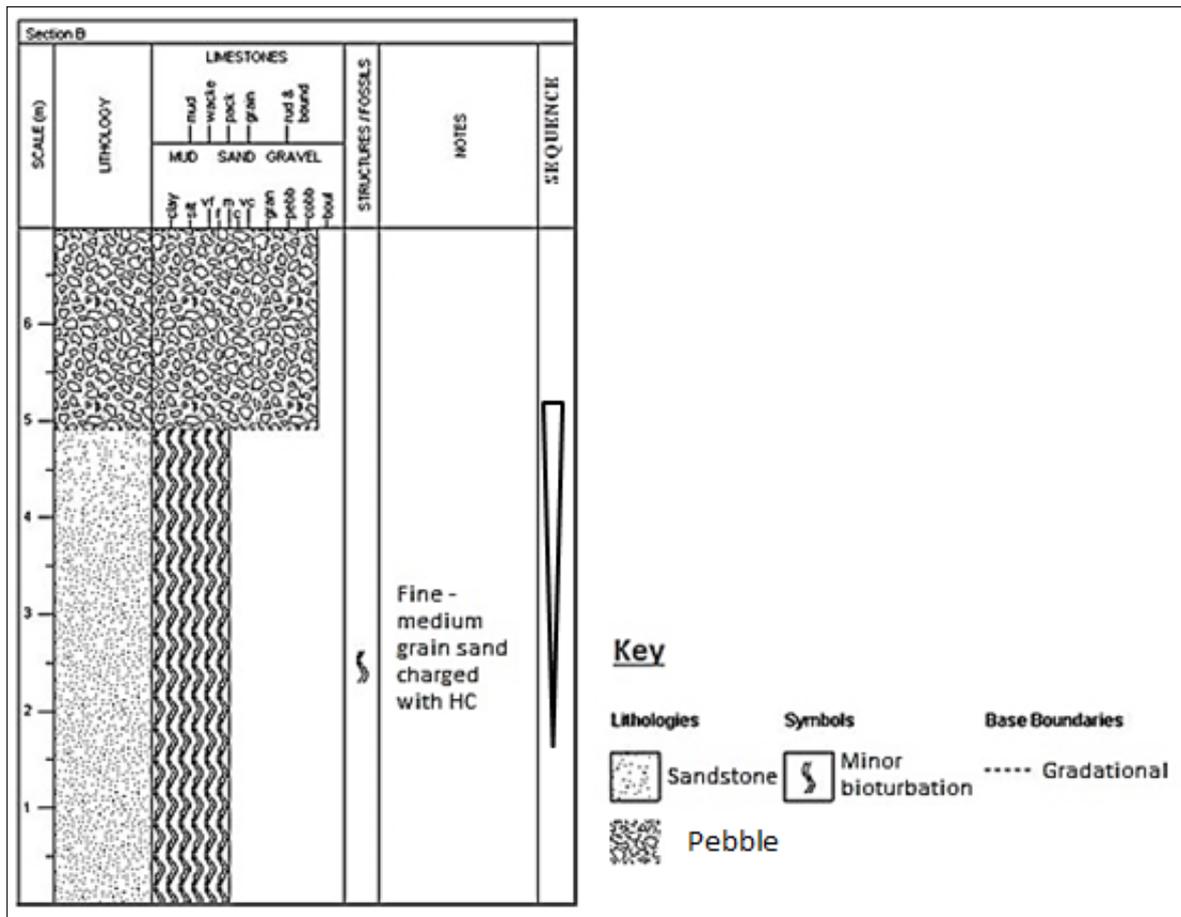
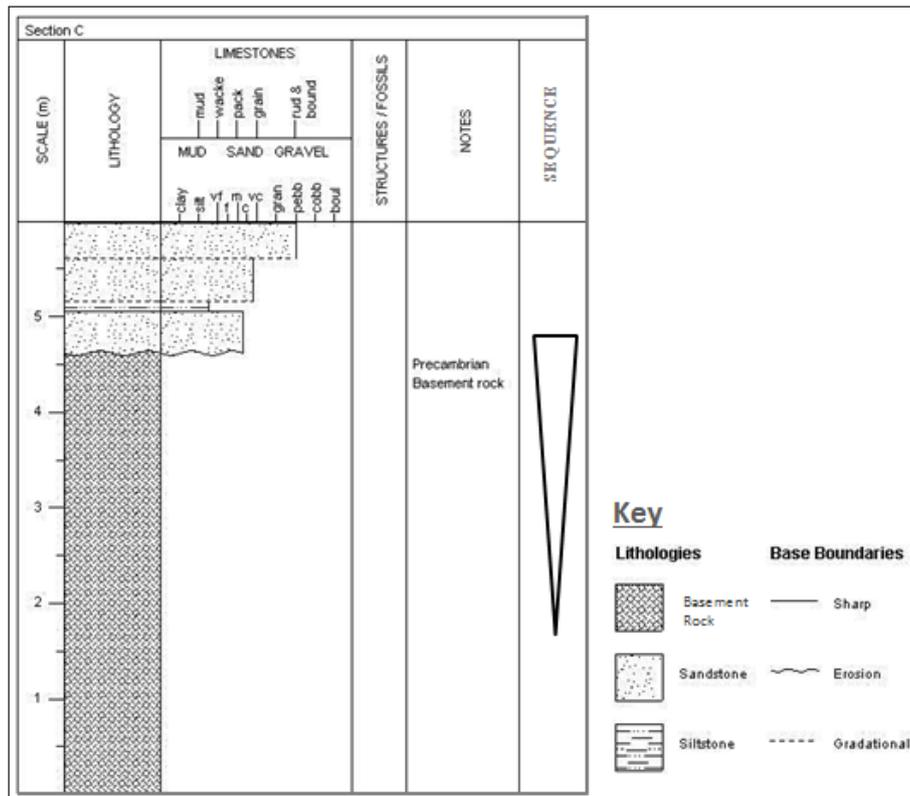
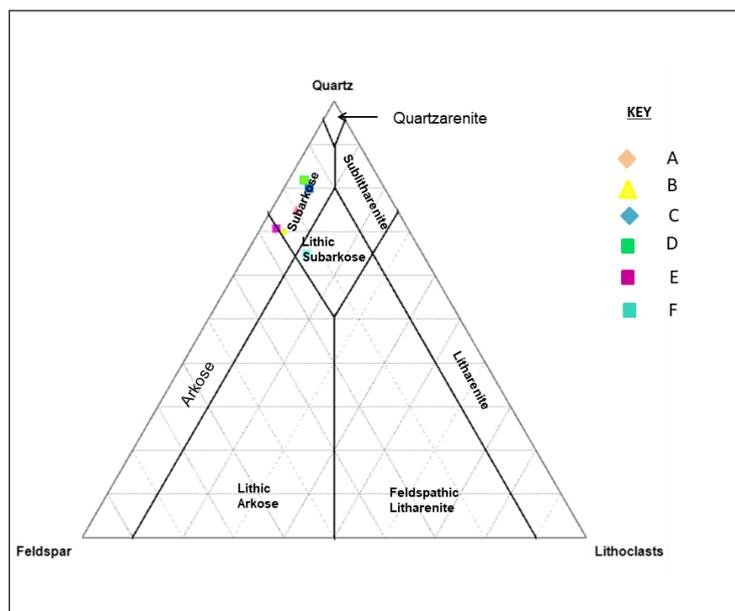


Figure 6. Lithostratigraphic sequence of fine–medium grain sands within the Bima Formation around Liji Hill.



**Figure 5.** Lithostratigraphic sequence of the Bima Formation unconformably overlying the Basement rock around Liji Hill.

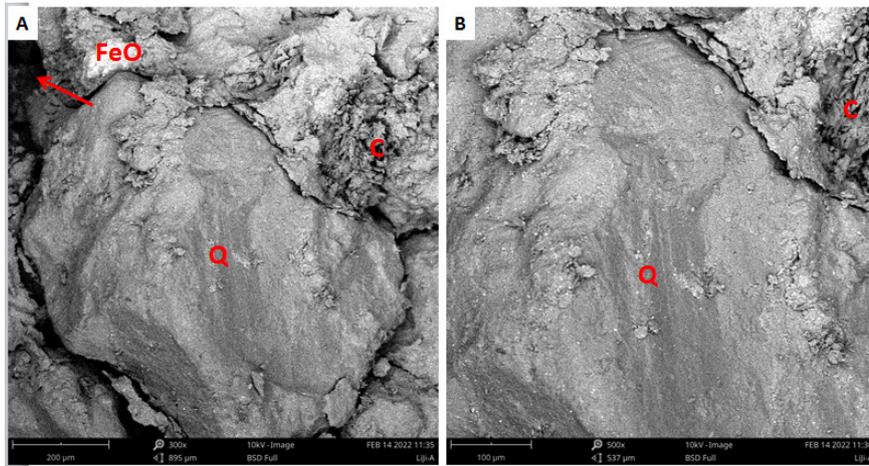


**Figure 8.** Ternary plot of the point count data after Dott (1964) and PettiJohn et al. (1972) sandstone classification chart.

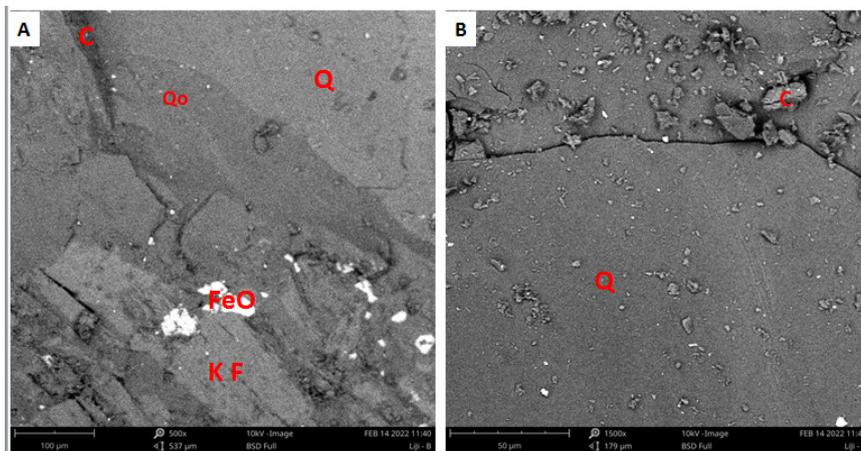
and lithic sub-arkoses. Quartz cement occurs in the studied sandstones as partial to complete syntaxial overgrowth thick around monocrystalline quartz grains. The boundaries between the overgrowth and the detrital core are usually poorly defined. Quartz

overgrowths are known to be most abundant in deeply buried sandstones (Bata, 2016; Bata et al., 2017).

This implies that the studied sandstones of the Cretaceous Bima Formation were deeply buried at sometimes in its geologic history. Feldspars occurring



**Figure 9.** A backscattered SEM photomicrograph of a section from the Bima sandstone showing quartz crystal (Q), pore space filled with hydrocarbon (red arrow), pyrite (FeO), and clay (C). Backscattered SEM photomicrograph of a section from the Bima sandstone showing quartz crystal (Q) and clay matrix (C).

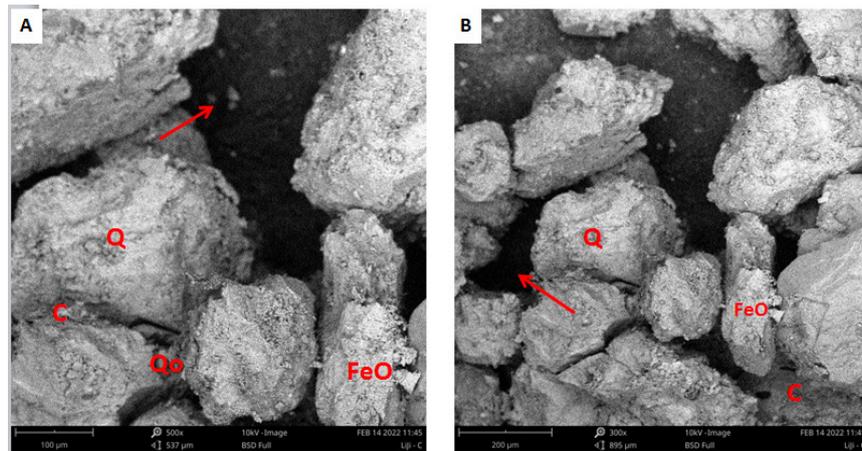


**Figure 10.** Backscattered SEM photomicrograph of a section from Bima Formation showing quartz (Q), clay (C), iron oxide (FeO), K – feldspar (K F), and quartz overgrowth (Qo). (B) backscattered SEM photomicrograph of a section of Bima Formation showing quartz (Q) and detrital clay enclosed with hydrocarbon (C).

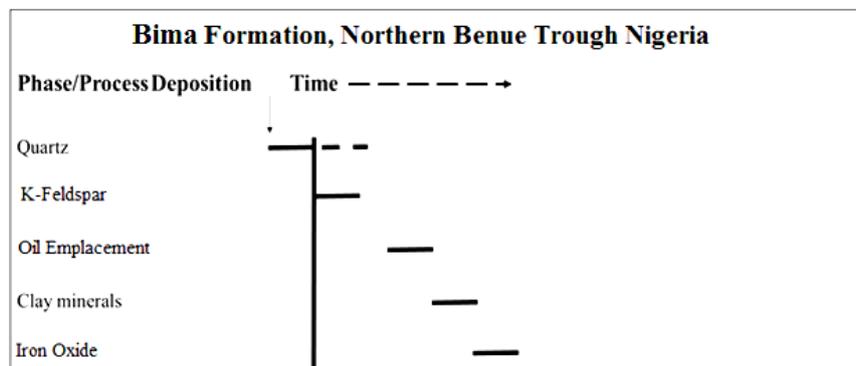
in the studied samples are parallel-arranged euhedral albite crystals within partly to extensively dissolve feldspar grains (Fig 8).

The paragenetic sequence of the studied sandstones belonging to the Cretaceous Bima Formation constructed from petrographic evidence is presented in Figures 9–12 above. The Bima Formation could be a very good petroleum reservoir because not much has happened to it after oil emplacement. Heavy oils are known to be acidic (Bata, 2016; Bata et al., 2015) and can aid in breaking down mineral grains in sandstones. This produces clay minerals which have negative consequences on the reservoir capability of the sandstone.

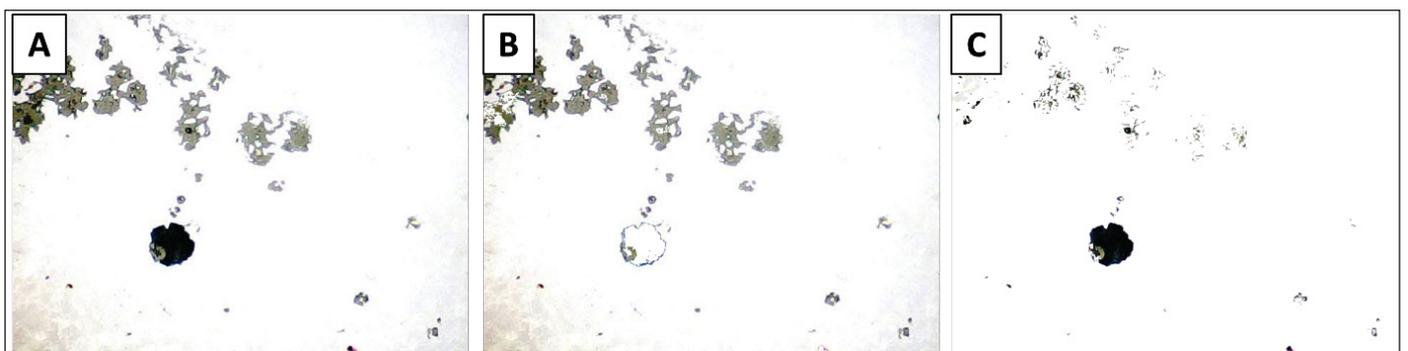
Petrographic data used to generate estimated porosity for the studied samples are presented in Figures 13–16. This data set shows the minus cement porosity information of the studied samples. Porosity, a measure of the empty spaces available in the rock, is usually denoted as a percentage of the total rock taken up by pore spaces. The porosities of petroleum reservoir sands vary from 5% to 30%, but oftentimes are between 10% and 20%. According to Tiab and Donaldson (2011), Bata et al. (2017) porosities of 0%–5% in sandstone are viewed as negligible, porosities of 5%–10% are deemed poor, and 10%–15% porosities are viewed as moderate. Porosity values of 15%–20% in sandstone are considered good and



**Figure 11.** Backscattered SEM photomicrograph of a section of Bima Formation showing quartz (Q), detrital clay (C), iron oxide (FeO), pore spaces filled with hydrocarbon (red arrow), and silica overgrowth (Qo). (B) Backscattered SEM photomicrograph of a section of Bima Formation showing pore spaces filled with hydrocarbon, quartz (Q), iron oxide (FeO), and detrital clay (C).



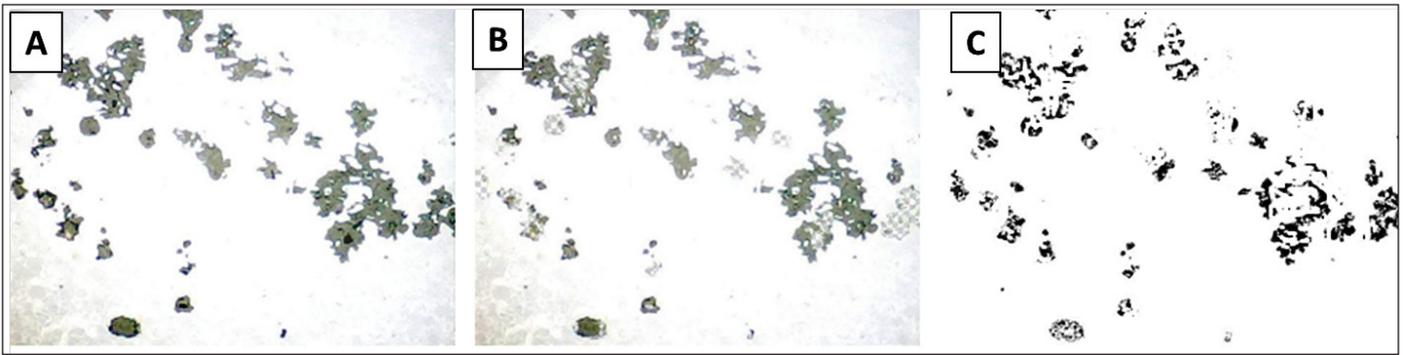
**Figure 12.** Paragenetic sequence for the studied sample of the cretaceous Bima Formation constructed from petrographic evidence.



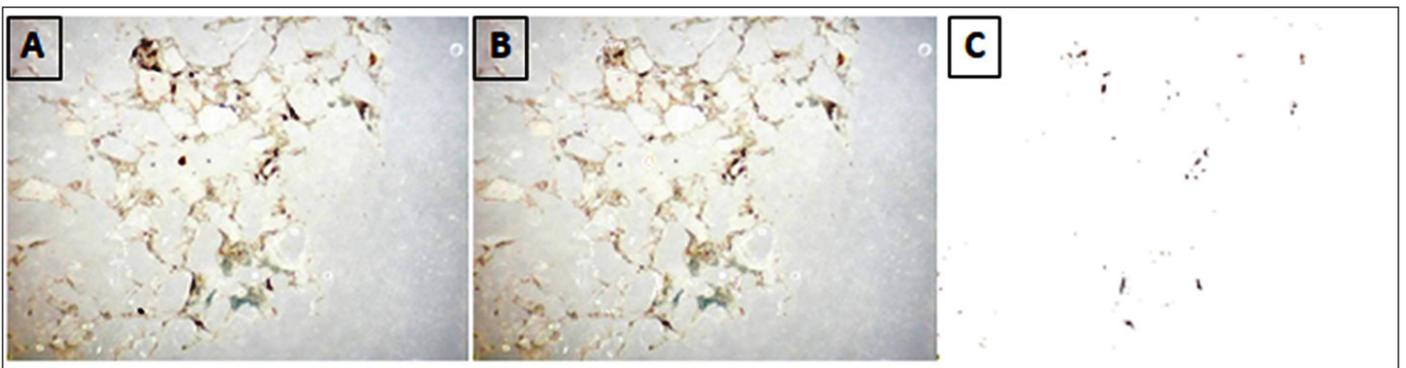
**Figure 13.** Photomicrograph cretaceous Bima sandstone showing: (A) sand with constituent minerals cemented by bitumen, (B) minerals grains of the Bima sand after oil extraction, and (C) the extracted oil residue from (a) above.

porosities of more than 20% are considered to be very good. The minus-cement porosity estimation of the studied samples disclosed an average estimated

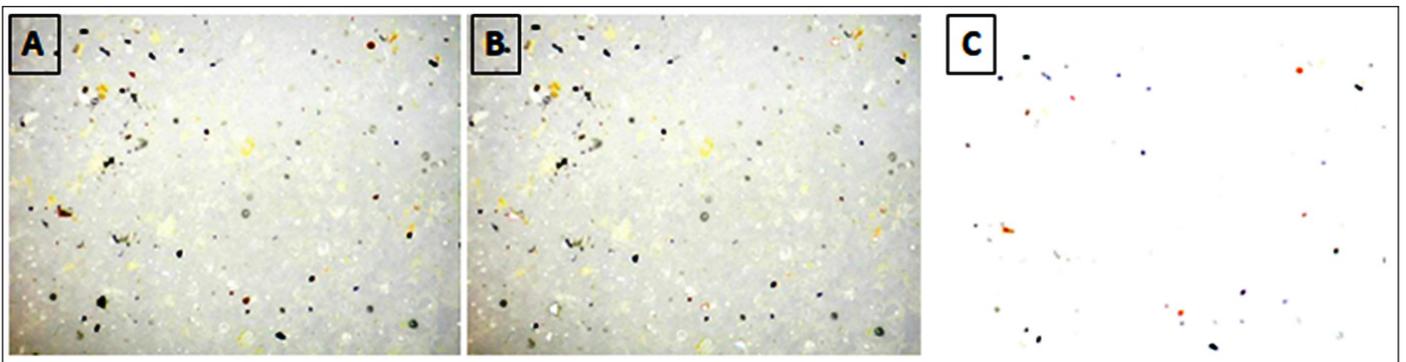
porosity of 5.50% with the highest as 11.80% and the lowest as 0.66% in the studied sandstone samples (Table 1).



**Figure 14.** Photomicrograph cretaceous Bima sandstone showing: (A) sand with constituent minerals cemented by bitumen, (B) minerals grains of the Bima sand after oil extraction, and (C) the extracted oil residue from (a) above.



**Figure 15.** Photomicrograph cretaceous Bima sandstone showing: (A) sand with constituent minerals cemented by bitumen, (B) minerals grains of the Bima sand after oil extraction, and (C) the extracted oil residue from (a) above.



**Figure 16.** Photomicrograph cretaceous Bima sandstone showing: (A) sand with constituent minerals cemented by bitumen, (B) minerals grains of the Bima sand after oil extraction, and (C) the extracted oil residue from (a) above.

**Table 1.** Estimated porosities of studied samples.

S/No	Sample code	Estimated porosity (%)	Remark
1	A1	8.23	Poor
2	A3	11.80	Moderate
3	B3	1.31	Negligible
4	C2	0.66	Negligible

#### 4. Summary and Conclusion

Field and petrographic evidence presented in this study demonstrated that the Bima Formation occurring in the Northern Benue Trough is oil charged with moderate, poor, to negligible porosities. The sandstones of the Bima Formation are therefore prospectively moderate to poor petroleum reservoirs in the studied area.

#### References

- Abubakar MB, Luterbacher HP, Ashraf AR, Ziedner R, Maigari AS. Late cretaceous palynostratigraphy in the Gongola Basin (upper Benue trough, Nigeria). *J Afr Earth Sci* 2011; 60:19–27.
- Abubakar MB, Obaje NG. Preliminary biostratigraphic evaluation of the hydrocarbon potentials of the Cenomanian–Turonian horizon in the Gongola formation, upper Benue trough, Nigeria. *J Min Geol* 2001; 37(2):121–8.
- Akande SO, Adekeye OA, Adeoye JA, Jacob N, Lufadeju, G. Paleocologic and organic geochemical assessment of cretaceous hydrocarbon source rocks in the gulf of guinea: new insights from eastern Dahomey and Benue rift basins with implications for the Cenomanian–Coniacian petroleum system. In: Extended abstract, AAPG annual convention and exhibition, Long Beach, CA, 2012, pp 1–10.
- Akande SO, Ojo OJ, Erdtmann BD, Hetenyi M. Paleoenvironments, source rock potential and thermal maturity of the upper Benue rift basins, Nigeria. Implications for hydrocarbon exploration. *Org Geochem* 1998; 29:531–42.
- Bata T. Geochemical consequences of cretaceous sea level rise. Unpublished PhD Thesis, Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, Scotland, 2016. Available via <http://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.690589>
- Bata T, Parnell J, Samaila NK, Abubakar MB, Maigari AS. Geochemical evidence for a cretaceous oil sand (Bima oil sand) in the Chad Basin, Nigeria. *J Afr Earth Sci* 2015; 111:148–55.
- Bata T, Parnell J, Samaila NK, Still J. Impact of oil emplacement on diagenesis in cretaceous oil sands. *Bull Can Petrol Geol* 2017; 65(2):327–42.
- Bata TP, Ibrahim A, Kuku A, Francis JA, Samaila NK. Oil geochemistry of the cretaceous Yolde formation, Northern Benue trough Nigeria. *J Pure Appl Sci* 2020; 20(4): 416–22.
- Benkheilil J. Benue trough and Benue chain. *Geol Mag* 1982; 112:155–68.
- Yandoka BMS, Abdullah WH, Abubakar MB, Hakimi MH, Adegoke AK. Geochemical characterisation of early cretaceous lacustrine sediments of Bima formation, Yola sub-basin, Northern Benue trough, NE Nigeria: organic matter input, preservation, paleoenvironment and palaeoclimatic conditions. *Marine Petrol Geol* 2015; 61:82–94.
- Burke KC, Dessauvage TF, Whiteman AJ. Geologic history of the Benue valley and adjacent areas. In: Dessauvage TFJ, Whiteman AJ (Eds.). *African geology*, Ibadan University Press, Ibadan, Nigeria, pp 187–205, 1970.
- Cooper MR, Hunter RH. Precision serial lapping, imaging and three-dimensional reconstruction of minus-cement and post-cementation intergranular pore-systems in the Penrith Sandstone of north-western England. *Mineral Mag* 1995; 59(395):213–20.
- Cratchley CR, Jones GP. An interpretation of the geology and gravity anomalies of the Benue valley, Nigeria. *Overseas Geological Surveys Geophysical Paper*. 1, H.M. Stationery Office, Norwich, UK, vol. 1, pp 1–26, 1–26.
- Dott RH. Wacke, Graywacke and matrix; what approach to immature sandstone classification? *J Sediment Res* 1964; 34(3):625–32.
- Jauro A, Obaje NG, Agho MO, Abubakar MB, Tukur A. Organic geochemistry of cretaceous Lamza and Chikila coals, upper Benue trough, Nigeria. *Fuel* 2007; 86:520–32.
- Nwajide CS. *Geology of Nigeria's sedimentary basins*. CCS Bookshop Ltd., Lagos, Nigeria, 2013.
- Obaje NG, Ulu OK, Petters SW. Biostratigraphic and geochemical controls of hydrocarbon prospects in the Benue trough and Anambra Basin, Nigeria. *NAPE Bull* 1999; 14:18–54.
- Obaje NG, Wehner H, Hamza H, Scheeder G. New geochemical data from the Nigerian sector of the Chad basin: implications on hydrocarbon prospectivity. *J Afr Earth Sci* 2004; 38:477–87.
- Pearson MJ, Obaje NG. Onocerane and other terpenoids in late cretaceous sediments from upper Benue trough, Nigeria: tectonic and paleoenvironmental implications. *Org Geochem* 1999; 30:583–92.
- Peters KE, Walters CC, Moldowan JM. *The biomarker guide*. 2nd edition, Cambridge University Press, New York, NY, 2005.
- Petters SW. Central West African cretaceous-tertiary benthic foraminifera and stratigraphy. *Palaeontogr AbtA* 1982; 179:1–104.
- Pettijohn FJ, Potter PE, Siever R. *Petrographic classification and glossary*. In: *Sand and sandstone*, Springer, New York, NY, pp 149–74, 1972.
- Reed SJB. *Electron microprobe analysis and scanning electron microscopy in geology*. Cambridge University Press, New York, NY, 2005.

- Samaila NK, Dike EFC, Obaje NG. Microstructures in the cretaceous bima sandstone, upper Benue trough, N.E. Nigeria: implication for hydrocarbon migration. *J Afr Earth Sci* 2008; 50(1):6–15.
- Tiab D, Donaldson EC. *Petrophysics: theory and practice of measuring reservoir rock and fluid transport properties*. Gulf Professional Publishing, Waltham, MA, 913 p, 2011.
- Whiteman AJ. Nigeria: its petroleum geology, resources and potential. Graham and Trotman, London, UK, p 394, 1982; doi:10.1007/978-94-009-7361-9.
- Zaborski PM. The cretaceous and paleocene transgressions in Nigeria and Niger. *J Min Geol* 2000; 36:(2):153–73.
- Zaborski PM. Guide to the cretaceous system in the upper part of the upper Benue trough, Northeastern Nigeria. *Afr Geosci Rev* 2003; 10(1–2):13–2.
- Zaborski PM, Ugodulunwa F, Idornigie A, Nnabo P, Ibe K. Stratigraphy and structure of the cretaceous Gongola Basin, Northeastern Nigeria. *Bull Centre Rech Explor Prod Elf Aquitaine* 1997; 21(1):153–85.