

## Field, Petrographic and Geochemical Studies of Basement, Clastic and Carbonate Petroleum Reservoirs in The Northern Benue Trough, Nigeria.

By

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### *Abstract*

*Petroleum exploration have been ongoing in the northern Benue Trough Nigeria, with little success in locating commercial oil pool. Clastic petroleum reservoir has been the main exploration target in the region, despite existence of other possible petroleum reservoir rock types. In this study, field, petrographic and geochemical evidences were presented to show the occurrences of oil in basement reservoir rocks (Precambrian Older Granite), clastic reservoir rocks (Cretaceous Bima Formation) and carbonate reservoir rock (Cretaceous Yolde Formation) of the region. The studied oils which occurs as brittle solids and viscous fluids in the fractures and/or pore spaces of the studied rocks are believed to have been emplaced into fractures and pore spaces of the studied rocks as conventional light oils that have now been degraded to bitumen by biodegradation and water washing processes. TIC fragmentogram of the saturate fractions of the studied oils show the presence of unresolved complex mixture (UCM) humps, consistent with biodegraded oils. The sterane maturity parameters for the studied oils and their corresponding trisnorhopane thermal indicators (Ts:Tm ratio) are consistent with the thermal maturity values of petroleum source rocks within the oil window. Ternary plot of the relative amounts of C<sub>27</sub>, C<sub>28</sub>, and C<sub>29</sub> regular steranes in the studied oils show marked resemblance for oils occurring in the Precambrian granitic rocks and the Bima Formation, suggesting the two oils originated from the same petroleum source rock. Oils occurring in the studied Yolde Formation is observed to have originated from a different petroleum source rock, implying the existence of multiple petroleum source rocks in the Northern Benue Trough.*

**Keywords:** Northern Benue Trough; Petroleum Exploration; Clastic petroleum reservoir; Basement petroleum reservoir; Carbonate petroleum reservoir; Unresolved complex mixture UCM.

### **1. Introduction**

Globally, petroleum as energy source will continue to dominate other primary energy sources and global demand for petroleum products will continue to rise. In a bid to diversify the exploitation of hydrocarbons in Nigeria due to the over-dependence on Niger Deila petroleum reserve since its discovery in 1956; the Federal Government has mandated the Nigerian National Petroleum Corporation (NNPC) to continue petroleum exploration in the Benue Trough. This came shortly after the NNPC was given a similar task to intensify petroleum exploration in the Chad Basin. Earlier, three exploration wells (Kolmani River-1, Kuzari-1 and Nasara -1) were drilled in the Gongola arm of the Northern Benue Trough. The Kolmani River-1 well drilled by Shell Nigeria Exploration and Production Company was reported to have encountered about 33B standard cubic feet of gas and little oil while the two other wells (Kuzari-1 and Nasara-1), drilled by Elf Petroleum Nigeria Limited (TotalFinaElf) and Chevron Nigeria Limited respectively, were reported as dry<sup>1</sup>.

Oil and gas discoveries in basins contiguous to the Benue Trough had earlier on triggered exploration activities in the Benue Trough which is genetically, structurally and stratigraphically identical to other basins belonging to the West and Central African Rift System (WCARS). They include the Termit Basin of Niger and western Chad, the Bongor, Doba and Doseo Basins of southern Chad, the Salamat Basin of Central African Republic and the Muglad Basin of Sudan. Recent studies on oil occurrences in Nigerian inland basins,<sup>2</sup> documented that the Benue Trough is a very good prospect for oil exploration. This study is aimed at presenting field, petrographic and geochemical evidences of petroleum occurring in basement, clastic and carbonate petroleum reservoir rocks of the Northern Benue Trough, Nigeria,

## 2. Tectonic and Stratigraphic Setting

The Benue Trough is a sediment-filled northeast trending rift basin in Nigeria that stretches for about 800 km in length and about 150 km in width. It is believed to have developed from incipient rifting that occurred during the Cretaceous breakaway of South America from Africa and the opening of the South Atlantic Ocean<sup>3</sup>. The Benue Trough which borders Chad Basin to the north, and the Niger Delta to the south has been a subject of several academic discussions related to palaeogeography, sedimentology, structural geology, mineral and hydrocarbon explorations<sup>4,5,6</sup>; is roughly divided into Southern, Central and Northern parts<sup>7</sup>. 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 (Fig. 1).

In all the sub-basins of the Northern Benue Trough, 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 conformably overlain by the transitional/coastal Yolde Formation (Cenomanian) which marks the onset of marine incursion into the northern Benue Trough. In the Gongola Basin, Gongola and Pindiga Formations conformably overlie the Yolde

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<sup>1</sup> Obaje, N.G., Wehner, H., Hamza, H., Scheeder, G., 2004. New geochemical data from the Nigerian sector of the Chad basin: implications on hydrocarbon prospectivity. *J. Afr. Earth Sci.* 38, 477–487.

<sup>2</sup> Bata, T. P., Lar, U. A., Samaila, N. K., Abubakar, M. B., Elijah, E. H., Dibal, H. U., Ikyoive, S. Y. 2017. Global occurrence of Cretaceous petroleum systems: Implication for oil exploration in the Nigerian inland basins. Accepted conference paper for 35<sup>th</sup> NAPE annual international conference holding at EKO Hotels and Suites Lagos, 19 -23<sup>rd</sup> November 2017.

<https://www.nape.org.ng/bookofabstracts/NAPE2017/mobile/index.html#p=123>

<sup>3</sup> Whiteman, A.J., 1982. Nigeria: Its Petroleum Geology, Resources and Potential, 1 and 2. Graham and Trotman, London.

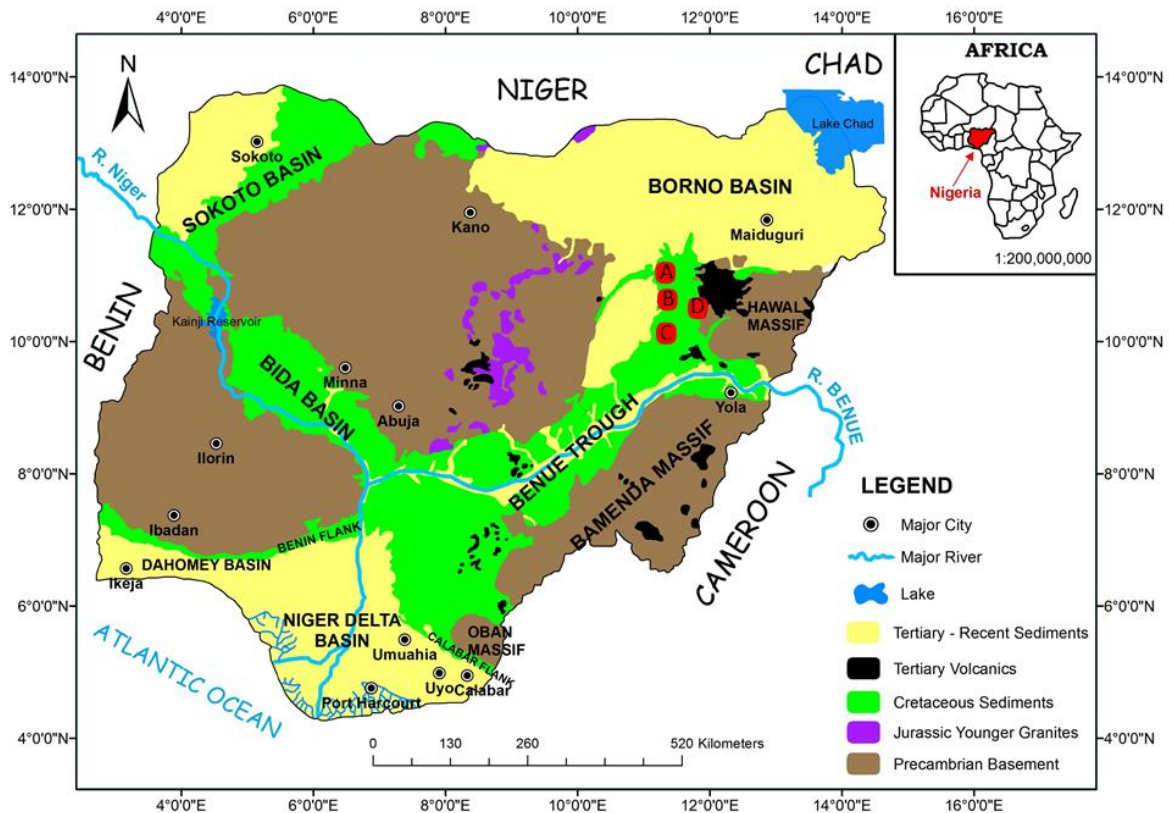
<sup>4</sup> Samaila, N.K., Dike, E.F.C., Obaje, N.G., 2008. Microstructures in the Cretaceous Bima Sandstone, Upper Benue Trough, NE Nigeria: Implication for hydrocarbon migration. *J. Afr. Earth Sci.* 50, 6–15.

<sup>5</sup> Abubakar, M.B., Dike, E.F.C., Obaje, N.G., Wehner, H., Jauro, A., 2008. Petroleum prospectivity of Cretaceous Formations of Gongola Basin, Upper Benue Trough, Nigeria; an organic geochemical perspective on a migrated oil controversy. *J. Pet. Geol.* 31, 387–408.

<sup>6</sup> Akande, S.O., Egenhoff, S.O., Obaje, N.G., Ojo, O.J., Adekeye, O.A., Erdtmann, B.D., 2012. Hydrocarbon potential of Cretaceous sediments in the Lower and Middle Benue Trough, Nigeria: Insights from new source rock facies evaluation. *J. Afr. Earth Sci.* 64, 34–47.

<sup>7</sup> Nwajide, C. S., 2013. Geology of Nigerian Sedimentary Basins. CSS Bookshops Ltd., Lagos, Nigeria. 565p.

Formation. Both the Gongila and Pindiga Formations are believed to have been deposited by a major marine incursion that occurred in the region during the upper Cenomanian, Turonian to Santonian times. Lateral equivalents of the Gongila and the Pindiga Formations in the Yola arm of the Upper Benue Trough are the Dukul, Jessu, Sekuliye, Numanha and Lamja Formations (Fig. 2).

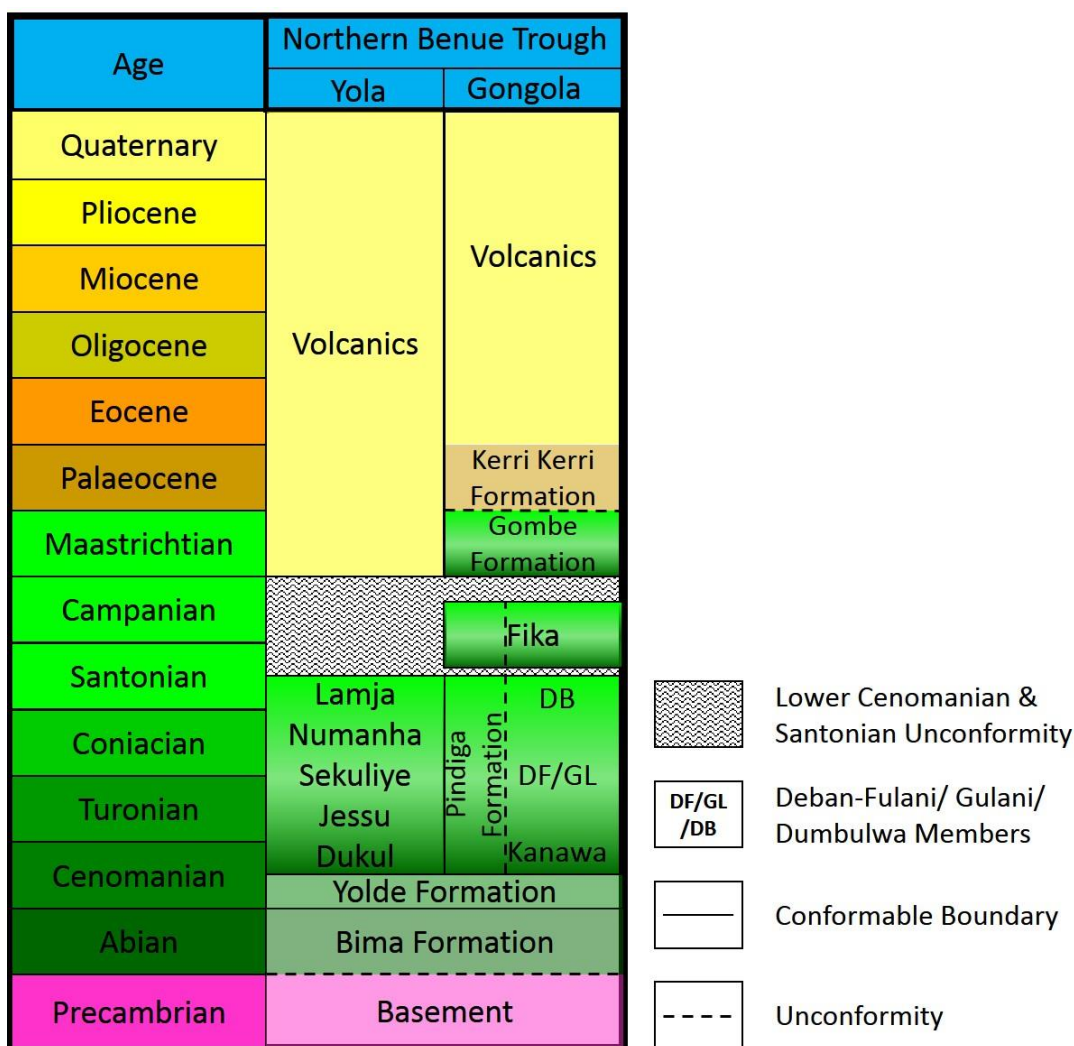


**Figure 1** Generalized geological map of Nigeria showing studied localities in the Northern Benue Trough. A: Yaranduwa 3, Northern Benue Trough, B: Yaranduwa 1, Northern Benue Trough, C: Gombe Inlier, Gombe, Northern Benue Trough, D: Sabon Gari, Northern Benue Trough.

The Benue Trough witnessed tectonic deformation and folding during the mid-Santonian. Cretaceous sediments which pre-dates the mid-Santonian were folded, faulted and uplifted in several places<sup>8</sup>. This was followed by a compressive phase that occurred at the end of the Maastrichtian<sup>9</sup>. Post-Santonian sediments in the northern Benue Trough are represented by the Fika Shales, deltaic coal bearing Gombe Formation and the Paleogene Kerri–Kerri Formation (Fig. 2).

<sup>8</sup> Abubakar, M. B., Luterbacher, H. P., Ashraf, A. R., Ziedner, R., Maigari, A. S., 2011. Late Cretaceous palynostratigraphy in the Gongola Basin (Upper Benue Trough, Nigeria). *Journal of African Earth Sciences* 60, 19-27.

<sup>9</sup> Zaborski, P.M., 2003. "Guide to the Cretaceous System in the Upper Part of the Upper Benue Trough, North-eastern Nigeria," *African Geosciences Review*, Vol. 10, No. 1-2, 2003, pp. 13-32.



**Figure 2.** *Stratigraphy of the Benue Trough, Nigeria*

### 3. Methodology

This study started with a fieldwork to the Gongola Sub-Basin of the northern Benue Trough, where evidence of oil residue in fractured Precambrian rocks, passive oil seep, oil-stained sandstones and oil-stained limestone were examined (Fig. 1). Samples obtained were prepared as polished block section and examined using petrographic microscope. Photomicrographs were obtained. Oils from the studied rocks (fractured Precambrian basement, Bima Formation and Yolde Formation) were solvent-extracted using 93:7 (v/v) dichloromethane and methanol. The extracted oils were then separated into saturate, aromatics, and polar fractions using thin layer chromatography. The saturate oil fractions were further examined by gas chromatography-mass spectrometry (GC-MS).

The GC-MS analyses were carried out with an Agilent 6890N GC fitted with a J & W DB-5 phase 50-m-long column that is linked to a 5975 MSD and a quadrupole mass spectrometer working in selected-ion monitoring (SIM) mode with ionization energy of 70 eV. Samples were manually injected with a split/splitless injector working in splitless mode (purge 40 ml min<sup>-1</sup> for 2 min). The temperature range of the GC oven varied between 80 and 295 °C. The GC oven was held at the initial temperature of 80 °C for two minutes, increasing by 10 °C min<sup>-1</sup> for 8 min, then by 3 °C min<sup>-1</sup>, and finally at the highest temperature of 295 °C for 10 minutes.

Compounds were identified by matching retention times to well-characterized materials that served as reference samples.

#### 4. Results

##### 4.1 *Field evidences of petroleum systems in northern Benue Trough:*

Oil seepages, oil residues in fractured basement rocks, oils stained sandstones as well as oil stained limestones occur within the Gongola Sub-Basin of the northern Benue Trough (Figs. 3- 5). Passive oil seeps from the Bima Formation occurs close to Yarandua Village in the northern Benue Trough (Fig. 3a). Oil seepages are known to suggest the existence of a petroleum system in a region. The discovery of some of the world's great oil fields, such as the Dezful Embayment (SW Iran), and the Bagua Basin (north-central Peru) were a direct consequence of seepage drilling<sup>10, 11, 12, 13</sup>.

Field evidences demonstrating the occurrence of oil residue within fractures and weathered zones of Precambrian basement rocks at the Gombe Inlier of the northern Benue Trough have been presented in this study (Fig. 3b). Recent interest in unconventional petroleum reservoirs includes a focus on the potential of fractured basement reservoirs. Initially, petroleum basement reservoirs were discovered by accident at the bottom of wells but drilling into the basement is now a deliberate plan in several oilfields. Field examples of basement petroleum reservoirs occur in Venezuela, Argentina, Brazil, China, Egypt, Angola, Morocco, Libya, Yugoslavia, Hungary, Romania, USSR and the USA<sup>14,15, 16</sup>.

Works of Bata et al. (2015) presented evidences of a Cretaceous Bima oil sand in the Chad Basin, Nigeria. In this study, field evidences were presented to show that the Cretaceous Bima oil sands extend into the Northern Benue Trough (Fig. 4). Like in the Chad Basin Nigeria, the Bima oil sand observed in the Gongola Sub-Basin pinches out on the flanks of the Bima hills scattered around the Zambuk Ridge (Fig. 4b).

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<sup>10</sup> Escobar, M., Márquez, G., Inciarte, S., Rojas, J., Esteves, I., Malandrino, G., 2011. The organic geochemistry of oil seeps from the Sierra de Perijá eastern foothills, Lake Maracaibo Basin, Venezuela. *Org. Geochem.* 42, 727–738.

<sup>11</sup> Salati, S., van Ruitenbeek, F.J., Carranza, E.J.M., van der Meer, F.D., Tangestani, M.H., 2013. Conceptual modeling of onshore hydrocarbon seep occurrence in the Dezful Embayment, SW Iran. *Mar. Pet. Geol.* 43, 102–120.

<sup>12</sup> Gentzis, T., 2013. Geochemical characterization of an oil seep from the Bagua Basin, north-central Peru. *Int. J. of Coal Geol.* 108, 18–26.

<sup>13</sup> Bata, T., Parnell, J., Samaila, N. K., Abubakar, M. B., Maigari, A. S., 2015. Geochemical evidence for a Cretaceous oil sand (Bima oil sand) in the Chad Basin, Nigeria. *Journal of African Earth Sciences*, 111, 148-155.

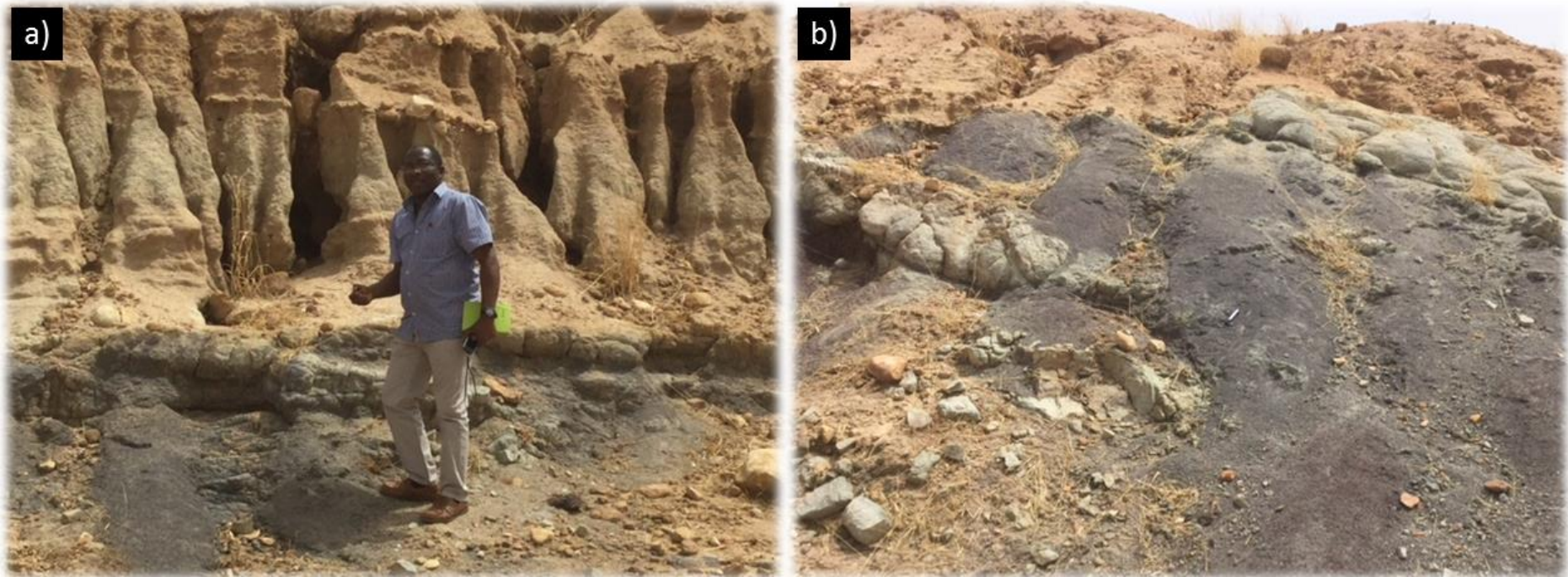
<sup>14</sup> Tong, K., Zhao, C., 2012. Reservoir evaluation and fracture characterization of the metamorphic buried hill reservoir in Bohai Bay Basin. *Petroleum Exploration and Development*, 39, 62–69.

<sup>15</sup> Trice, R. 2014. Basement exploration, West of Shetlands: progress in opening a new play on the UKCS. In: Cannon, S.J.C. & Ellis, D. (eds) *Hydrocarbon Exploration to Exploitation West of Shetlands*. Geological Society, London, Special Publications, 397, 81–105, <https://doi.org/10.1144/SP397.3>

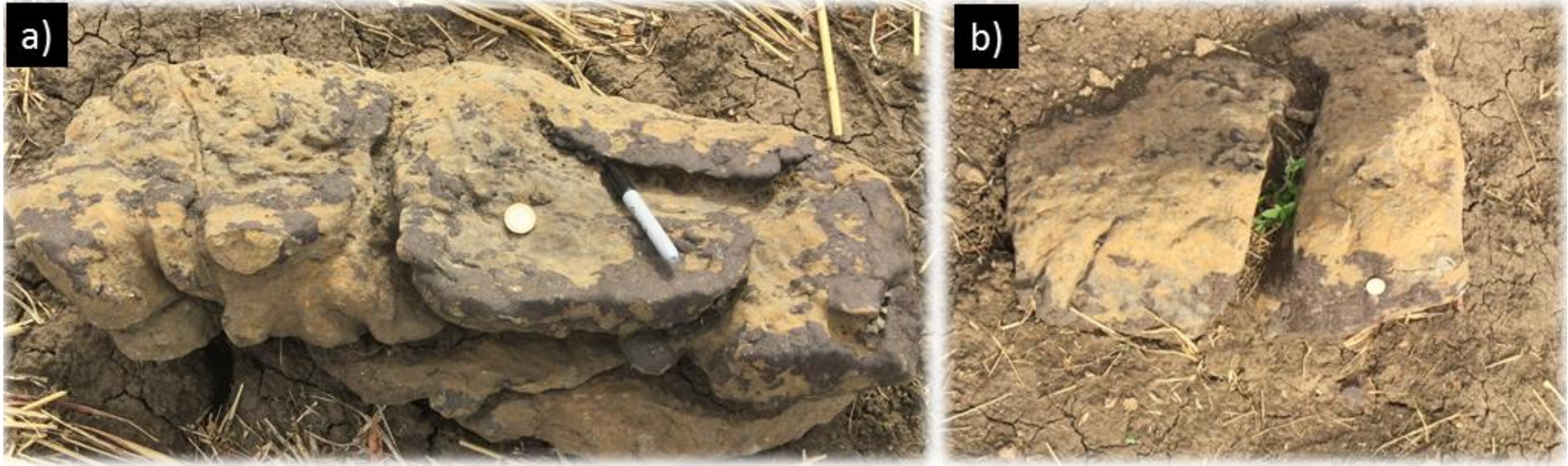
<sup>16</sup> Parnell, J., Baba, M., Bowden, S., Muirhead, D., 2017. Subsurface biodegradation of crude oil in a fractured basement reservoir, Shropshire, UK. *Journal of Geological Society*, 174, pp 655 -666.



**Figure 3.** Field Photographs showing (a) Passive oil seepage close to Yaranduwa Town in the northern Benue Trough. (b) Traces of bitumen (heavy oil) in Fractures and within the weathered zone of Precambrian granite at the Gombe Inlier, northern Benue Trough.



**Figure 4** *Field photographs showing outcrops of the oil-stained Bima Formation close to Yaranduwa Town of the northern Benue Trough.*

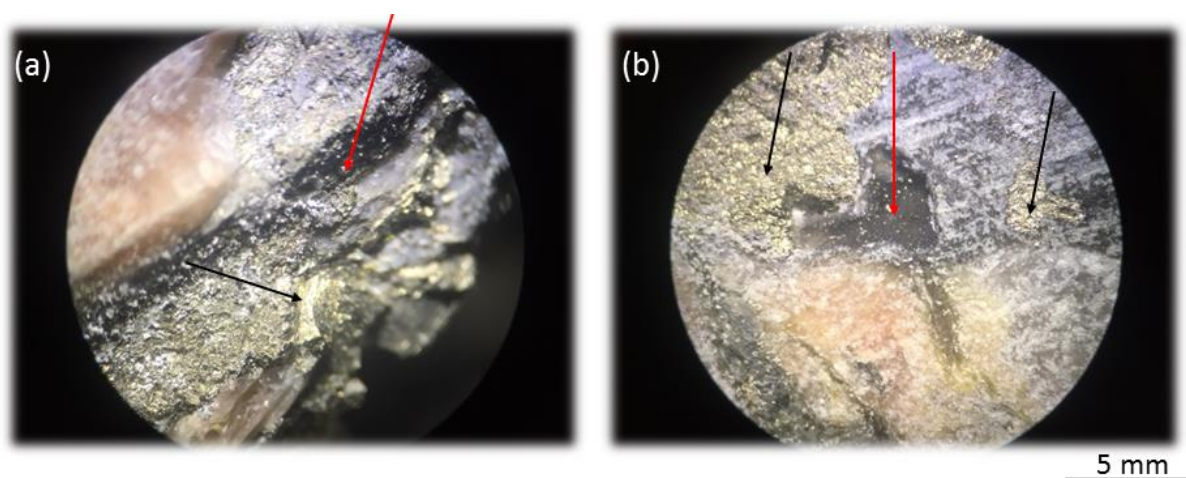


**Figure 5** Field photographs showing samples of oil-stained Yolde Formation (limestone) close to Sabon Gari Town of the northern Benue Trough.

Oil stained limestones of the Yolde Formation were also observed close to Sabon Gari in the Northern Benue Trough (Fig. 5). These observed oil shows occurring within the Gongola Sub-Basin of the northern Benue Trough, Nigerian are of great significance to hydrocarbon exploration in the region.

#### 4.2 *Reservoir Petrography:*

Photomicrographs of the studied Precambrian granitic rock show evidence of oil residue within the fractures and weathered zones of the studied Precambrian rock (Fig. 6). The observed fractures range from a few millimeters to up to several centimeters in diameter. Oil residues occurring in the studied basement rocks are closely associated with pyrite crystals (Fig. 6b). Authigenic pyrite crystals are known to be closely associated with oil residues and biodegraded oils<sup>17,18,19,20</sup>



**Figure 6** Photomicrograph showing traces of heavy oil (red arrows) in (a) fractures and (b) weathered zones of Precambrian granites of the northern Benue Trough. Note pyrite crystals (black arrows) closely associated with the studied heavy oil

The studied Bima Formation is very dark in colour throughout its outcrop (Fig. 4). It consists of black coarse to fine grained sandstone. Photomicrographs of the studied Bima Formation shows the occurrence of oil residue in its pore spaces (Fig 7). The observed dark organic matters are not admixed with inorganic mineral matter (e.g. silicates), so does not represent clasts of carbonaceous shale in the Bima Formation (Fig. 7),

Authigenic silica is observed to occupy most of the pores of the studied Bima Formation (Fig. 7b). Silica is known to occur at several stages of diagenesis in sandstones and may have a variety of origins, which include: volcanogenic, biogenic, clay mineral transformations in

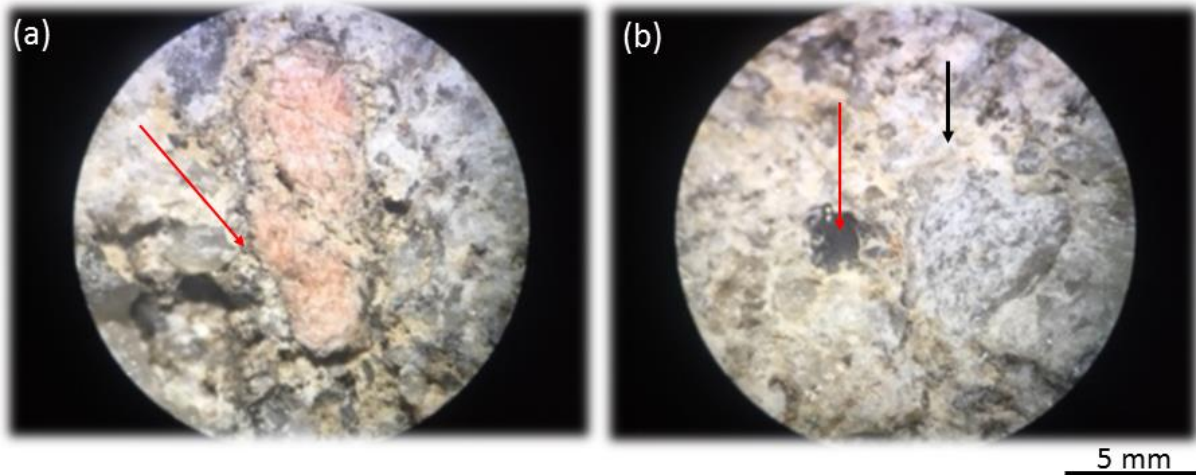
<sup>17</sup> Fallick, A.E., Boyce, A.J. Mcconville, P. 2012. Sulfur stable isotope systematics in diagenetic pyrite from North Sea hydrocarbon reservoirs revealed by laser combustion analysis. *Isotopes in Environmental and Health Studies*, 48, 144-165.

<sup>18</sup> Bata, T., Parnell, J., 2014. A Neoproterozoic Petroleum System in the Dalradian Supergroup, Scottish Caledonides. *Journal of the Geological Society*, 171, 145-148. <http://dx.doi.org/10.1144/jgs2013-087>

<sup>19</sup> Parnell, J., Bellis, D., Feldmann, J., Bata, T., 2015. Selenium and tellurium enrichment in palaeo-oil reservoirs. *J. Geochem. Explor.* 148, 169–173

<sup>20</sup> Bata, T., Parnell, J., Bowden, S., Boyce, A., 2016. Origin of Heavy Oil in Cretaceous Petroleum Reservoirs. *Bulletin of Canadian Petroleum Geology*, 64 (2), 106-118. <http://dx.doi.org/10.2113/gscpgbull.64.2.106>

adjacent shales, sedimentary abrasion of quartz, grain to grain pressure solution, feldspar alteration, geothermal alteration, ascending solutions, weathering, circulating groundwater, etc.,<sup>21,22,6</sup>. Silica is volumetrically important in sandstones, because it is responsible for the consolidation of most sandstones. Silica is also a major destroyer of porosity in sandstones as it chokes off the flow paths of fluids<sup>23</sup>.



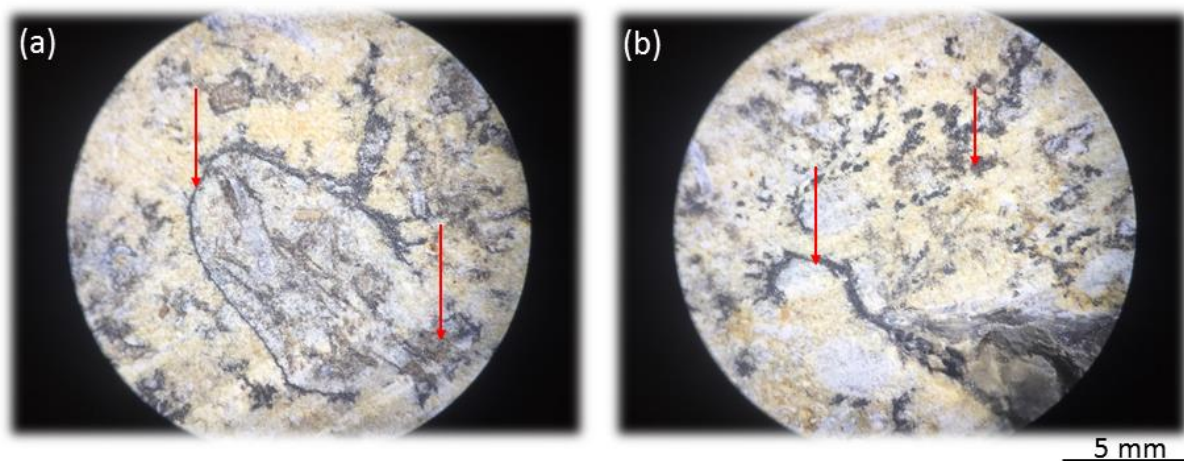
**Figure 7.** Photomicrograph showing traces of oil residue (red arrows) in pore spaces of the studied Bima Formation from Yaranduwa locality in the northern Benue Trough. Note authigenic silica (black arrow) associated with the studied Bima Formation sandstone.

Photomicrographs of the studied limestones of the Yolde Formation show evidence of oil residue occurring within the fractures of the Yolde Formation (Fig. 8). Carbonate rocks usually have complicated depositional rock fabrics with diverse diagenetic modifications resulting in a complex pore system as observed in the studied Yolde Formation limestone (Fig. 8). Diversities of the pore types, pore sizes and pore origins in the studied limestone resulted in the complicated pore structures observed in Figure 8.

<sup>21</sup> McBride, E.F., 1989. Quartz cement in sandstones: a review. *Earth Sci. Rev.*, v. 26, p. 69-112

<sup>22</sup> Vagle, G. B., Hurst, A., Dypvik, H., 1994. Origin of quartz cements in some sandstones from the Jurassic of the Inner Moray Firth (UK), *Sedimentology* v. 41, p. 363-317.

<sup>23</sup> Zhang, B., Zhang, J., Yan, S., Gu, Z., Wang, X., 2012. Detrital quartz and quartz cement in Upper Triassic reservoir sandstones of the Sichuan basin: Characteristics and mechanisms of formation based on cathodoluminescence and electron backscatter diffraction analysis. *Sedimentary Geology*, v. 267, p. 104-114.



**Figure 8** Photomicrograph showing traces of oil residue (red arrows) in fracture of the studied Yolde Formation from Sabon Gari locality in the northern Benue Trough. Note the complicated pore structure of the studied limestone, consistent with limestone petroleum reservoirs.

#### 4.3 Oil Geochemistry:

Total ion current (TIC) fragmentograms of representative studied samples are presented in Figure 9. The TICs showed the presence of unresolved complex mixture (UCM) humps, which is a common characteristic of oils that have undergone biodegradation<sup>24,25,26</sup>. Shown in Figure 10 are  $m/z$  217 fragmentograms of representative samples plotted on a ternary diagram to show the relative abundance of regular steranes in the studied samples. Summary of the sterane maturity parameters are presented in Table 1. Values for the trisnorhopane thermal indicator (Ts:Tm ratio) and the corresponding homohopane isomerization ratios for the studied oils are also presented in Table 1. These ratios are comparable to equivalent vitrinite reflectance of oils sourced from petroleum source rocks that are within the oil window<sup>27</sup>; <sup>24</sup>.

<sup>24</sup> Gouch, M.A., Rhead, M.M., Rowland, S.J., 1992. Biodegradation studies of unresolved complex mixtures of hydrocarbons: model UCM hydrocarbons and the aliphatic UCM. *Org. Geochem.* 18, 17–22.

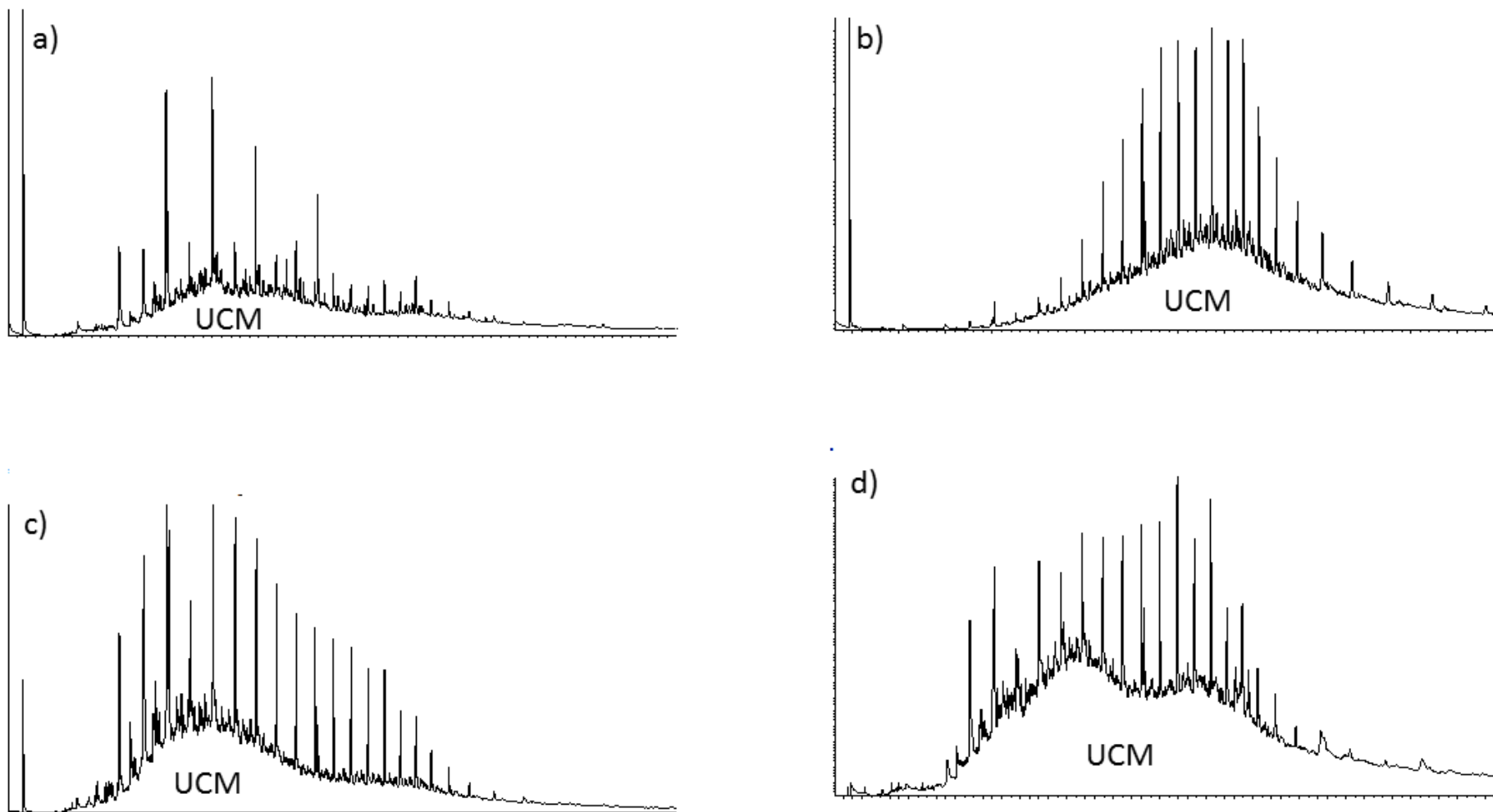
<sup>25</sup> Fry singer, G.S., Gaines, R.B., Xu, L., Reddy, C.M., 2003. Resolving the unresolved complex mixture in petroleum-contained sediments. *Environ. Sci. Technol.* 37, 1653–1662.

<sup>26</sup> Ventura, G.T., Kenig, F., Reddy, C.M., Fry singer, G.S., Nelson, R.K., Van Mooy, B., Gaines, R.B., 2008. Analysis of unresolved complex mixtures of hydrocarbons extracted from Late Archean sediments by comprehensive two-dimensional gas chromatography (GC × GC). *Org. Geochem.* 39, 846–867.

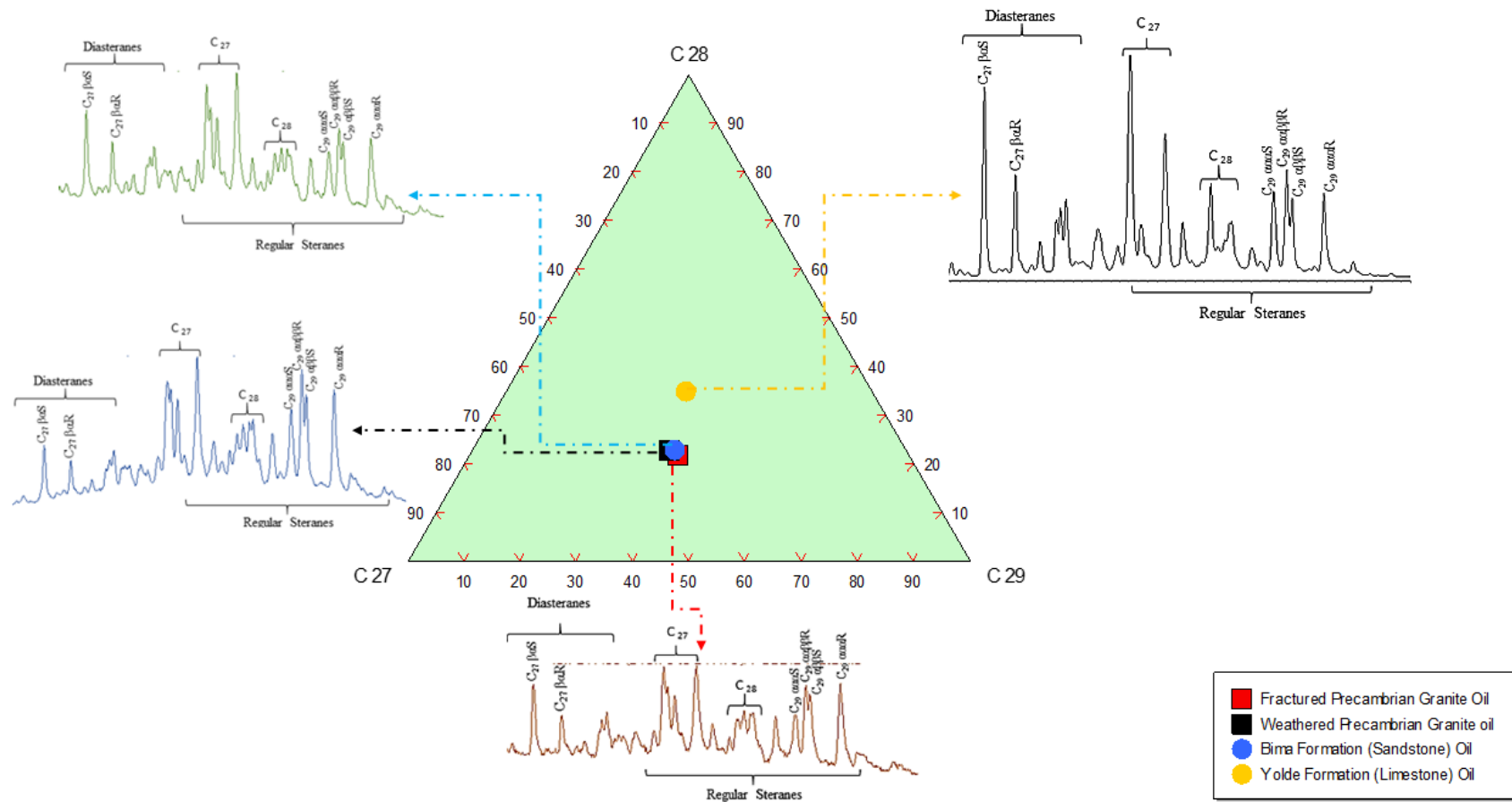
<sup>27</sup> Machel, H. G., Krouse, H. R., Sassen, R., 1995. Products and distinguishing criteria of bacterial and thermochemical sulfate reduction. *Applied geochemistry*, 10, 373–389.

**Table 1** Sterane maturity parameters

S/No	Sample	$\alpha\alpha\alpha$ C <sub>27</sub> 20S/(20S+20R)	$\alpha\alpha\alpha$ C <sub>28</sub> 20S/(20S+20R)	$\alpha\alpha\alpha$ C <sub>29</sub> 20S/(20S+20R)	Ts/Tm	C <sub>32</sub> 22S/(22R+22S) homohopane isomerization ratios
1	Fractured Basement Rock Oil	0.53	0.50	0.38	1.05	0.62
2	Weathered Basement Oil	0.44	0.39	0.42	1.26	0.61
3	Bima Formation Oil Clastic (Sandstone)	0.49	0.40	0.41	1.21	0.63
5	Yolde Formation Oil Extract Carbonate (Limestone)	0.36	0.25	0.43	1.43	0.58



**Figure 9.** Total ion current (TIC) fragmentogram of the saturate fractions of the studied oils showing UCM (a) The fractured Precambrian granite oil occurring at the Gombe inlier, (b) The weathered Precambrian granite oil occurring at the Gombe inlier, (c) Bima Formation oil occurring at Yaranduwa Town, (d) Yolde Formation oil occurring at Sabon Gari.



**Figure 10.** Ternary plot showing the relative amounts of C<sub>27</sub>, C<sub>28</sub>, and C<sub>29</sub> regular steranes in the studied oils. Note similarities in sterane distribution between the studied Precambrian granite oils and oils extracted from sandstones of the Bima Formation.

## 5.0 Discussion

In the three exploratory wells drilled within the northern Benue Trough Nigeria, clastic petroleum reservoirs were the main exploration targets<sup>5,28</sup>. However, evidences presented in this study (Figs. 3 - 10) demonstrate the occurrence of petroleum in carbonate and basement prospective petroleum reservoir rocks. This implies that some important petroleum reservoirs could have been excluded from the ongoing petroleum exploration in the northern Benue Trough Nigeria.

Highly fractured igneous and metamorphic rocks are now known to be very important petroleum reservoirs globally in places such as in Venezuela, Argentina, Brazil, China, Egypt, Angola, Morocco, Libya, Yugoslavia, Hungary, Romania, USSR and the USA<sup>18,19,20;29</sup>. Recent interest in unconventional reservoirs includes a focus on the potential of fractured basement reservoirs. Initially, petroleum basement reservoirs were discovered by accident at the bottom of wells but drilling into the basement is now a deliberate plan in several oilfields. Carbonate rocks are vital petroleum reservoirs and can be said to “fight above their means” because they constitute only about 20% of global sedimentary rocks yet, they host more than 60% of global petroleum<sup>30,31</sup>.

Traces of oil residue observed in the studied samples (Figs. 6 - 8) are brittle solids inferred to have been emplaced into the fractures and pores of the studied rocks as conventional light oils but are now degraded to bitumen because the studied rocks occur at a shallow depth. Such petroleum reservoirs occurring at shallow depths are known to provide nutrients for microbes that are capable of degrading hydrocarbon<sup>22;24</sup>. Where the studied petroleum reservoirs occur at depths greater than 2000 m and are appropriately sealed, it is possible to find non-biodegraded oils in them if they are connected to active petroleum source rocks and have good structures that result in oil traps<sup>32</sup>. Pyrite crystals closely associated with the studied fractured basement reservoir (Fig. 6) are believed to have a biogenic origin. Some specialized chemoorganotrophic sulphate-reducing bacteria are known to biodegrade oils occurring at shallow depths and precipitate pyrite during the biodegradation process<sup>33; 22, 20, 24</sup>.

UCMs observed in the TIC fragmentograms presented in Figure 9 are common features of oils that have undergone biodegradation. Such UCMs of biodegraded oils typically contain a low

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<sup>28</sup> Alalade, B., Tyson, R.V., 2013. Influence of igneous intrusions on thermal maturity of Late Cretaceous shales in the Tuma well, Chad Basin, NE Nigeria. *J. Afr. Earth Sci.* 77, 59–66.

<sup>29</sup> Bata, T., M.B. Abubakar, A. S. Maigari, Nuhu K. Samaila, Ahmed Isah Haruna, Babangida M. Sarki Yandoka Bappah Adamu Umar, Nuru Nabage, Umar Sambo Umar, Simon Y. Ikyoive, Ezekiel H. Elijah, Mustapha Aliyu, Abdulmajid Isah, Yusuf Abdulmumin, Abdulkarim Haruna Aliyu, Idris Ismail Kariya, Mohammed Rabi, Ameh Daniel Peter, Jabbo Josiah Nuhu, 2018. Oil residue in exhumed fractured Precambrian basement rock of the Northern Benue Trough, Nigeria: Implication for oil exploration in the Northern Benue Trough. *Petroleum Technology Development Journal*, 8 (1), 65 – 81. <http://www.ptdjournal.com/download/oil-residue-in-exhumed-fractured-precambrian-basement-rock-of-the-northern-benue-trough-nigeria-implication-for-oil-exploration-in-the-northern-benue-trough/>

<sup>30</sup> Ahr, W. M., 2008. *Geology of carbonate reservoirs*, Hoboken, Wiley, pp. 277.

<sup>31</sup> Jia, C., 2012. *Petroleum geology of carbonate reservoir*. Zhejiang University Press, Hangzhou and Springer Heidelberg New York Dordrecht London.

<sup>32</sup> Wilhelms, A., Larter, S.R., Head, I., Farrimond, P., Di-Primio, R., Zwach, C., 2001. Biodegradation of oil in uplifted basins prevented by deep-burial sterilization. *Nature*, 411(6841), 1034–1037.

<sup>33</sup> Mason, G. M., Kirchner, G. 1992. Authigenic pyrite: evidence for a microbial origin of tar sand. *Fuel*, v. 71, p. 1403-1405.

abundance or complete absence of aliphatic compounds<sup>34,35</sup>. The selective removal of these constituents of the oils by biodegradation processes amounts to removal of about 32% of the total hydrocarbon composition on average<sup>36</sup>. These processes result in concentration of preexisting complex mixture to yield the amplified chromatographic baseline observed in the UCMs of the studied oils (Fig. 9).

The sterane maturity parameters for the studied oils, and their corresponding trisnorhopane thermal indicators (Table 1) are consistent with the thermal maturity values of petroleum source rocks within the oil window<sup>37</sup>. This again agrees with our earlier inferences that the studied oils were generated as conventional light oil, which later degraded into heavy oils, rather than thermally cracked oils from over matured petroleum source rocks. Marked resemblance in regular steranes for oils occurring in the studied Precambrian granitic rock and Bima Formation implies that the oils occurring in the studied Precambrian granitic rocks and Bima Formation originated from the same petroleum source rock. On the other hand, oils occurring in the studied Yolde Formation do not match the oils occurring in the studied Precambrian granitic rock and the studied Bima Formation. This suggests the possible existence of multiple petroleum source rocks in the northern Benue Trough as have been reported by several workers<sup>6,17</sup>.

The delay in finding commercial oil discoveries in the northern Benue Trough is because some important prospective petroleum reservoirs have been excluded as exploration targets. The studied Precambrian granitic rocks and limestones of the Yolde Formation are deeply buried in the greater part of the northern Benue Trough and so should also be targeted for drilling. Seismic surveys being conducted at present in the region should look to identify localities where the Precambrian basement rocks are associated with good structures that should be tested for possible petroleum traps.

## 6.0 Summary and Conclusions

This study reports the occurrence of oil residues in basement, carbonate, and clastic prospective petroleum reservoirs of the northern Benue Trough Nigeria. Specifically, this study demonstrates the following:

- i) Field, petrographic and geochemical evidences were presented to show the occurrences of oil in basement reservoir rocks (Precambrian Older Granite), clastic reservoir rocks (Cretaceous Bima Formation) and carbonate reservoir rock (Cretaceous Yolde Formation) of the northern Benue Trough Nigeria.
- ii) Traces of oil residue observed in the studied samples are brittle solids inferred to have been emplaced into the fractures and pores of the studied rocks as conventional light oils but are now degraded to bitumen because the studied rocks are occurring at a shallow depth.
- iii) Where the studied prospective petroleum reservoirs occur at depths greater than 2000 m in the basin and are appropriately sealed, it is possible to find non-

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<sup>34</sup> Bost, F.D., Frontera-Suau, R., McDonald, T.J., Peters, K.E., Morris, P.J., 2001. Aerobic biodegradation of hopanes and norhopanes in Venezuelan crude oils. *Organic Geochemistry* 32, 105–114.

<sup>35</sup> Reddy, C.M., Eglinton, T.I., Hounshell, A., White, H.K., Xu, L., Gaines, R.B., Fryxinger, G.S., 2002. The West Falmouth Oil Spill after thirty years: the persistence of petroleum hydrocarbons in marsh sediments. *Environmental Science and Technology* 36, 4754–4760.

<sup>36</sup> Killops, S.D., Killops, V.J., 2005, 2nd ed. *Introduction to Organic Geochemistry*, vol. 152 Blackwell Publishing.

<sup>37</sup> Peters, K.E., Walters, C.C., Moldowan, J.M. 2005. *The Biomarker Guide: Biomarkers and isotopes in petroleum exploration and Earth history*, v. 2. Cambridge, Cambridge University Press.

- biodegraded oils in them if they are connected to active petroleum source rocks and have good structures that result in oil traps.
- iv) Obvious similarities observed in the regular steranes for oils occurring in the studied Precambrian granitic rocks and Bima Formation implies that the two oils originated from the same petroleum source rock. Steranes of oils occurring in the studied Yolde Formation does not match the oils occurring in the studied Precambrian granitic rock and the studied Bima Formation. This suggests the possible existence of multiple petroleum systems within the northern Benue Trough.

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