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Geochemical analysis of Cenozoic Usani sandstone reservoirs, Niger Delta Basin, Nigeria: implications for reservoir quality and petroleum geology.

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Abstract
Geochemical (XRD), gamma-ray log, thin section, porosity, and permeability data were integrated to interpreting the depositional environments and evaluate the diagenetic changes, and then assess the reservoir quantity and quality of the wells from the Usani field, Niger delta basin, Nigeria. Gamma-ray log suites and core samples descriptions show that the reservoirs are made up of fine, medium to coarse sandstone lithofacies capped by mudstone and shale lithofacies of different depositional settings ranging from storm dominated shelf, offshore bar to offshore regressive bar depositional environments. The XRD and thin section data show that the dominating mineral is quartz with the presence of feldspar, illite- smectite, siderite, and traces of hematite, pyrites minerals. The high cation exchange capacity values of 8.10 - 8.40meq/100g for reservoirs A, A2, C2, A3, B4, B4 in the wells indicate high clay contents, coupled with the presence of kaolinite, siderite, feldspar, illite-smectite, illite in reservoirs A, A2, C2, A3, B4, B4 at a depth range of 9400 to 11800ft within a temperature range of 98-110°C in the wells in the field. These characteristics make the sediments of the reservoirs respond faster to diagenetic changes such as compaction and cementation which result in variation in reservoir quantity and quality by reducing the primary porosity of the Usani sandstone reservoirs as the depth of burial increases which contribute to a decline in the quantity of hydrocarbon. The presence of sulphur contents from the pyritic coatings affects the quality of hydrocarbon in terms of worldwide ranking.

Keywords: *Reservoir quality, hydrocarbon, diagenetic changes, sandstone, porosity, depositional environment.*

Introduction

Several studies have been carried out on reservoir quality assessment around the sedimentary basins in the world, Africa, and onshore/offshore Niger Delta Basin, Nigeria. (Kim et al., 2007; Higgs et al., 2007; Morad et al., 2010; Iboyi and Odede, 2013; Chudi et al., 2014; Uguwueze et al., 2014; Ekwenye et al., 2015; Ardo, 2016; Aigbadon et al., 2017; Ezenwa et al., 2018; Yu et al., 2018; Ovie and Jerry, 2021). Petrographic and geochemical methods have been widely used to evaluate the characteristics of reservoirs architectures, mineralogical composition, provenance, and reservoir depositional facies (Dutton, 2008; Kim et. al 2007; Aigbadon et. al 2017). Primary-porosity, permeability, mineralogical composition, rock texture, compositional maturity, and sandstone reservoir geometry are affected by diagenetic changes during burial (Morad et al., 2010; Bjorlykke, 2014). The quality of sandstone reservoirs with clay matrices or minerals of smectite - illite is typically poor (Higgs et. al 2007) due to the impact of diagenetic changes such as compaction and lithification at shallower to deeper depths. Also, the higher the degree of mineralogical maturity of the sandstone reservoirs, the better porosity of the reservoirs (Dodge and Loucks 1979). The more stable quartz sandstone reservoirs reduce slowly compares to chemically unstable sandstone reservoirs. Textural maturity, mineralogy and geothermal, and pressure gradients play important roles in reservoir quality assessment. Poorly sorted sandstone reservoirs with abundant clay matrices compact and lithified easily than clean and well-sorted sandstone reservoirs (Dodge and Loucks, 1979). Reservoir facies and geochemical composition of sedimentary rocks are functions of rocks types, weathering, transportation, mineralogical composition, grain sizes, porosity, the interconnectivity of the available pores, and diagenesis. Plate interaction and instability, burial depth, provenance, relief, sorting, geothermal and pressure gradients, and diagenetic modifications govern the compositions of clastic sedimentary rocks. The effects of diagenetic changes on reservoir quality and decline in hydrocarbon production in the Usani field have not been well established and documented. These necessitated this study by integrating data from geochemical analysis (XRD), gamma-ray log, thin section, porosity, and permeability to re-interpret the depositional environments and evaluate the diagenetic changes, and then assess the reservoir quantity and quality of the Usani field. It will also help in ranking hydrocarbonproduction in the field globally.

Study Location

Usani Field is located offshore within the deeper water of the south-western coast of Nigeria with an area of $31km^2$and lies between latitudes 5^{O} 00'N and 5^{O} 20'N and longitudes 4^{O} 45'E and 4^{O} 28 'E respectively. It falls on Oil Mining Lease (OML) 135, in the offshore Niger Delta Basin of Nigeria (Fig.1).

Geological Setting

The Cenozoic Niger Delta complex which is located within the Gulf of Guinea in the continental margin, West Africa is a well-known hydrocarbon habitat in the world. The evolution of the Niger Delta Basin is closely linked with the rifting of the South Atlantic Ocean that separated the South American and the African plates which span from the late Jurassic to the Cretaceous era which resulted in the development of triple junction (Whiteman, 1982). It is enclosed in the west part by the Dahomey basin, in the east by Abakaliki fold belt, in the south by the Atlantic Ocean and in the north by the Anambra Basin (Fig. 2) (Knox and Omotsola, 1989; Burke *et al*., 1971). Three major lithostratigraphic units recognized in the Niger delta from the top to the base are; the Benin, Agbada and the Akata Formations respectively (Fig.3) (Short and Stauble, 1967; Doust and Omatsola, 1990).S

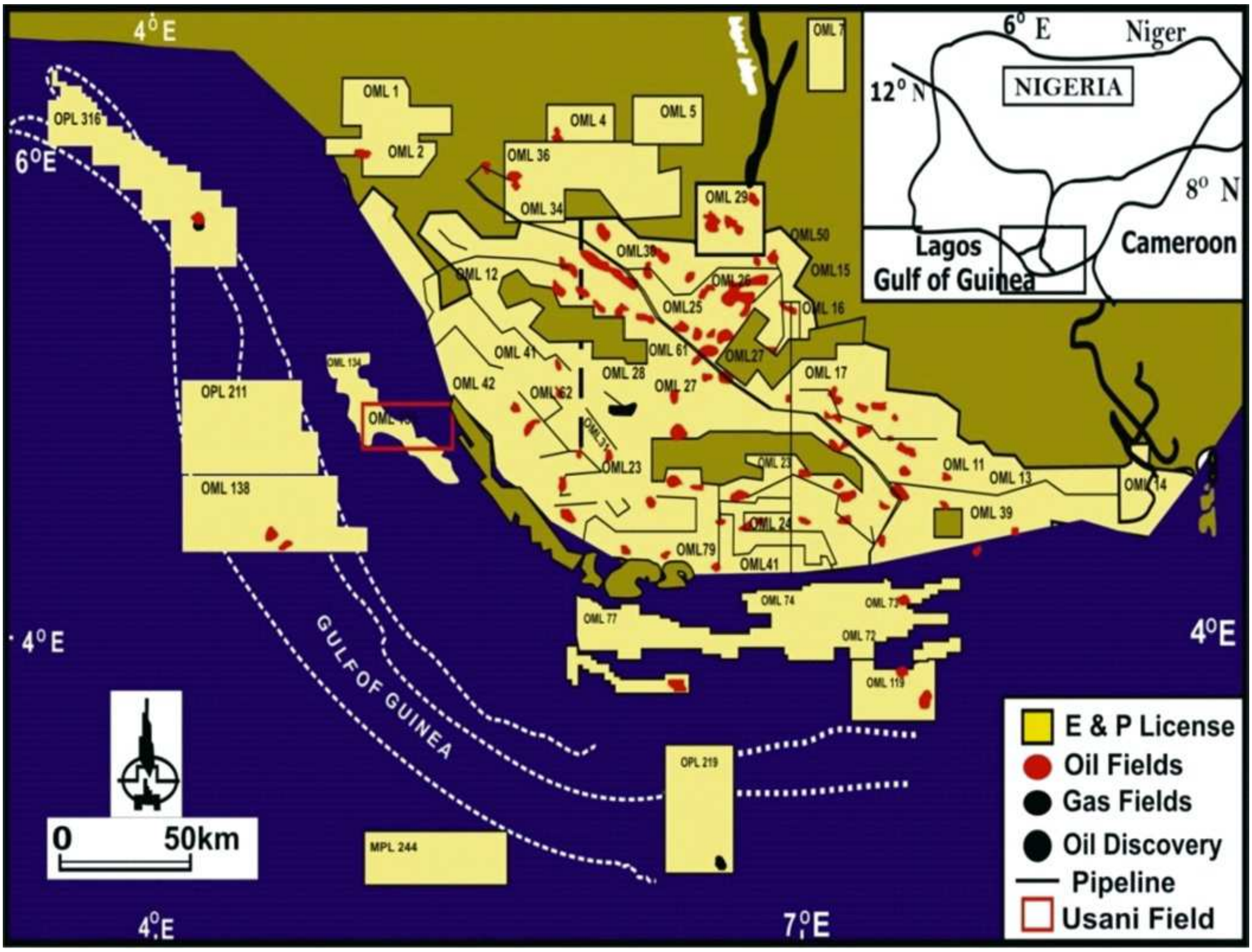


Fig. 1: Concession Map of Niger Delta showing the study area (Doust and Omatsola, 1990; Aigbadon, 2017a; b).

Omotsola, 1990). The Benin Formation consists of Oligocene to recent continental sands and gravels with a thickness of about 2000m (Short and Stauble, 1967; Whiteman, 1982; Doust and Omatsola, 1990).It is underlain by the Eocene to present consisting of alternating sequences of sand and shale Agbada Formation with a thickness of over 4000m (Short and Stauble, 1967; Whiteman, 1982; Doust and Omatsola, 1990). The Agbada Formation is universally regarded as the reservoir that housed the hydrocarbons in Niger

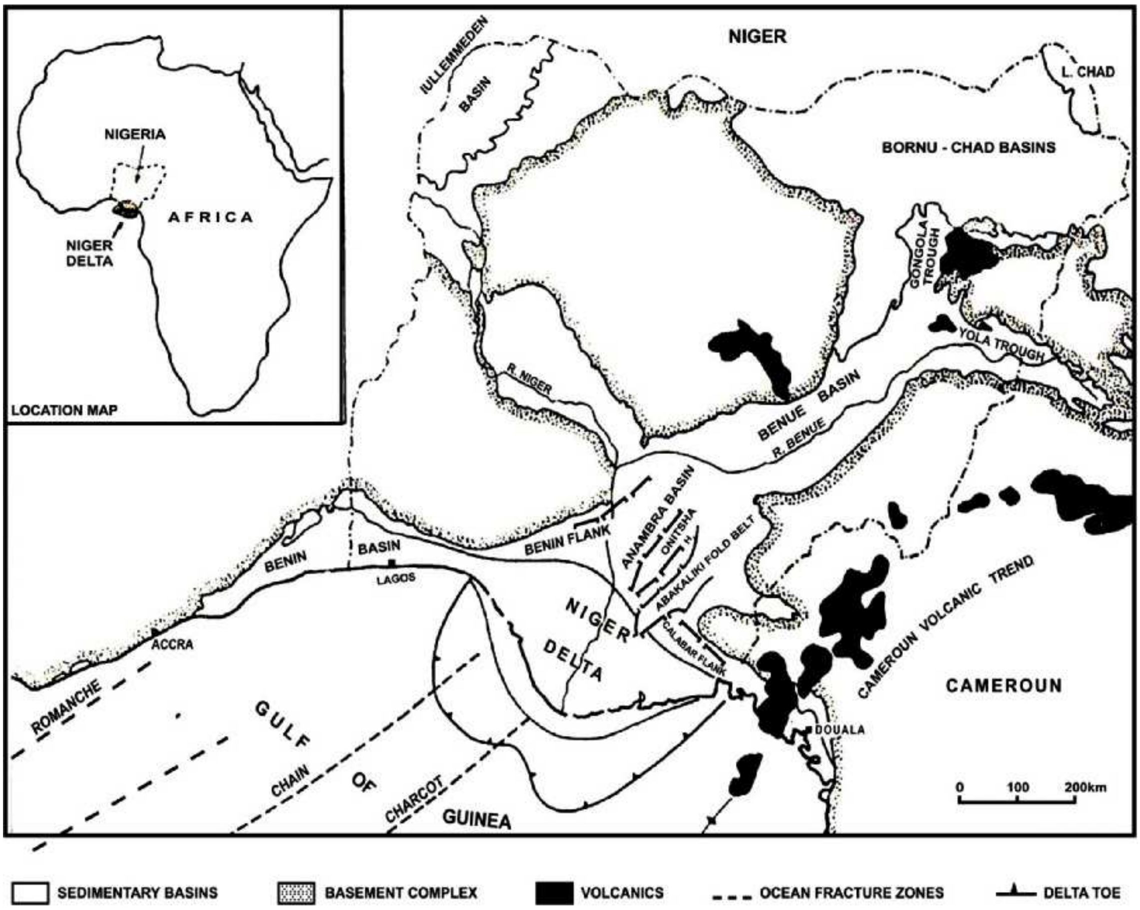


Fig. 2: Regional Tectonic setting of the Cenozoic Niger Delta (Burke et al., 1971; Knox and Omotsola, 1989; Aigbadon et al., 2017a;

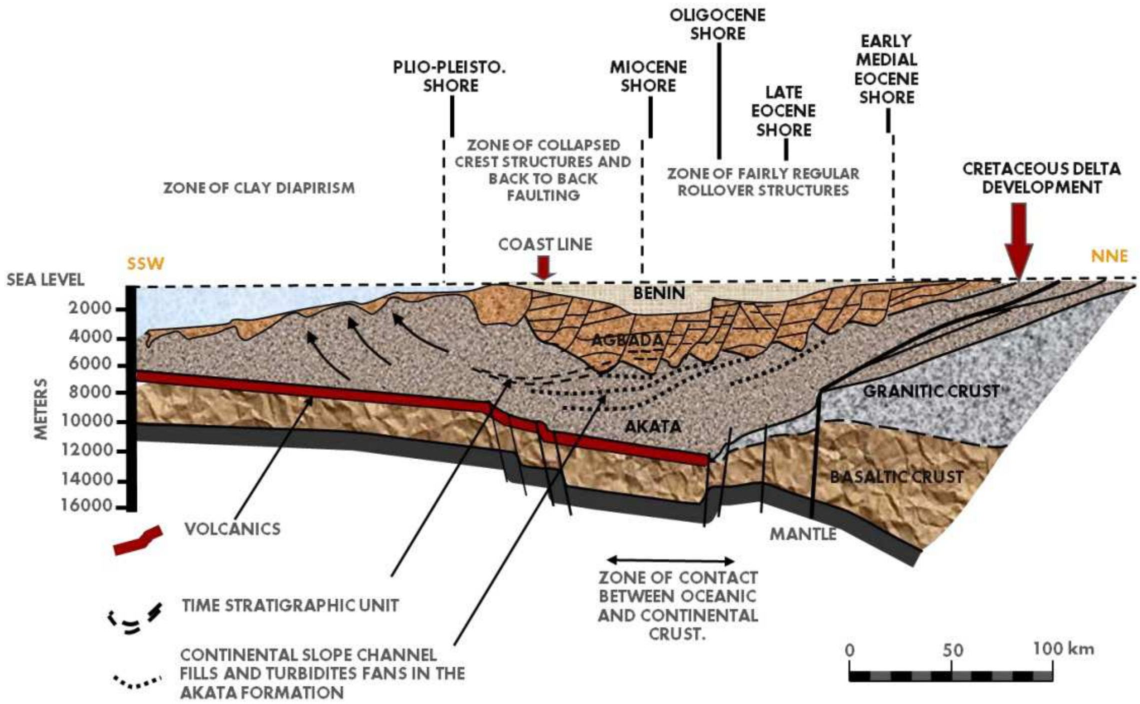


Fig. 3: Generalized dip section of the Niger Delta Basin (Doust and Omotsola 1990; Aigbadon et al., 2019).

Delta Basin (Tuttle, 1999). The Agbada Formation is underlain by dominantly over-pressured marine shale deposits of Akata Formation with a thickness of about 6000m (Short and Stauble, 1967; Evamy et al. 1978). The Niger Delta Basin consists of five depobelts namely; Northern Delta, Greater Ughelli, Central Swamp, and Coastal Swamp, and Offshore Depobelts respectively (Weber, 1971).

Materials and Methodology

This study adopted a range of tools and procedures. The techniques include cores descriptions, well logs, X-ray Diffraction (XRD), thin-section petrography, core permeametric, and petrophysical analyses. The composition, texture, and mineralogy of rocks are determined from the thin sections photomicrographs using Leica polarizing microscope.The data obtained helped to identify and quantify the mineral morphology and abundances, and clay fractions. The composition and petrological characteristics of the sandstone reservoirs are determined from thin sections to evaluate the effect of diagenesis; compaction and cementation in the reservoirs across the studied wells to ascertain pore characteristics and pore throats, the type of authigenic clay minerals from core data, and thin sections. The interpretations and integration followed the methodology of Davies et.al (1997) and Bouma sequence (1962) approach.

Results and Discussion

Depositional Environments of the Reservoirs Using Core Data Descriptions and Gamma-Ray Log Motifs

The earlier depositional environmental interpretations on the core samples and well log data from Usani Field by Aigbadon et al. (2017a) and Aigbadon et al. (2019) were at variance, hence, the re-interpretation by this study. A careful and detail descriptions of core data in this study reveals that reservoirs A, A2, A3, and A4 across the four wells in Usani Field are characterized by brownish medium- coarse-grained, discontinuous,and laminated sandstones disrupted by bioturbation with planar cross-bedded structures and capped by mudstone (Fig. 4). Log motif from the gamma-ray log shows a right bow shape with irregular/ serrated trending patterns. These reservoirs represent a storm-dominated shelf depositional environment (Fig. 5). These reservoirs are been truncated at the base and top by shale/mudstone. Core data reveals that reservoirs B,B2, B3, and B4 across the four wells are characterized by brownish medium- coarse-grained massive with faint indistinct cross beddings and moderately sorted (Fig. 4). The medium-grained sandstones consist of disrupted slump structures and bioturbation as well as thin mudstone laminations at the lower part of the reservoirs. Log motif from the gamma-ray log shows symmetrical shapes suggesting an offshore bar (worked) depositional setting (Fig. 5). These reservoirs are been bounded at the base and top by shale/mudstone. Core data reveals that reservoirs C, C2, C3, and C4 are characterized by an alternation of sandstone with planar cross-beds and thin mudstone laminations (Fig. 4). The sandstones are fine to medium-grained, burrows, and well sorted. The mudstone laminations have been disrupted by burrowing and bioturbation. Log motif from the gamma-ray log shows symmetrical shapes suggesting an offshore regressive bar depositional environment (Fig. 5).These reservoirs are been truncated at the base and top by shale/mudstone.

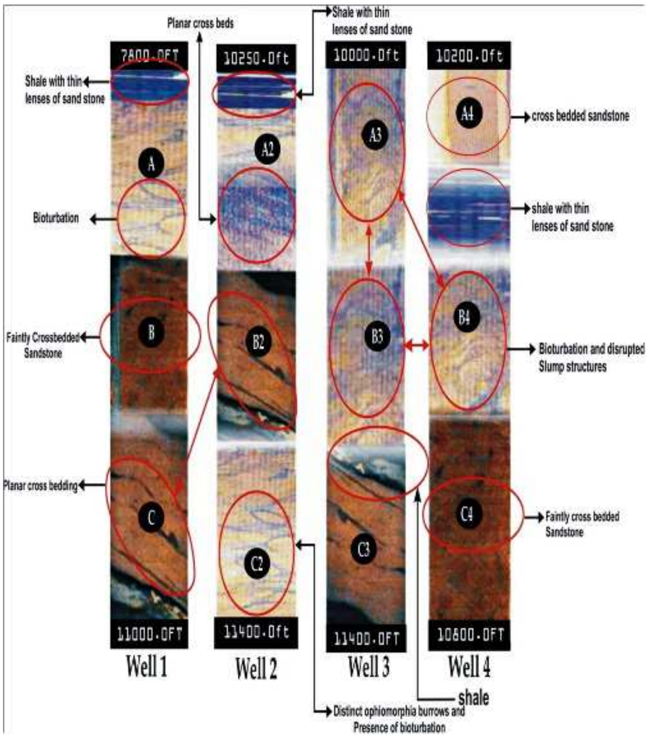


Fig. 4: Core samples for the wells showing sedimentary facies (core samples used by Aigbadon et al., 2017a; b).

Effects of Diagenesis on Hydrocarbon Reservoir Quantity and Quality of the Usani Field

Table 1 shows the result of the XRD analysis carried out on core samples from the Usani Field. It shows a cation exchange capacity (CEC) which is a measure of the amount of smectitic layers within the clay fraction of the bulk samples.The values range from 1.60 - 8.40 meq/100g with quartz and kaolinite as main

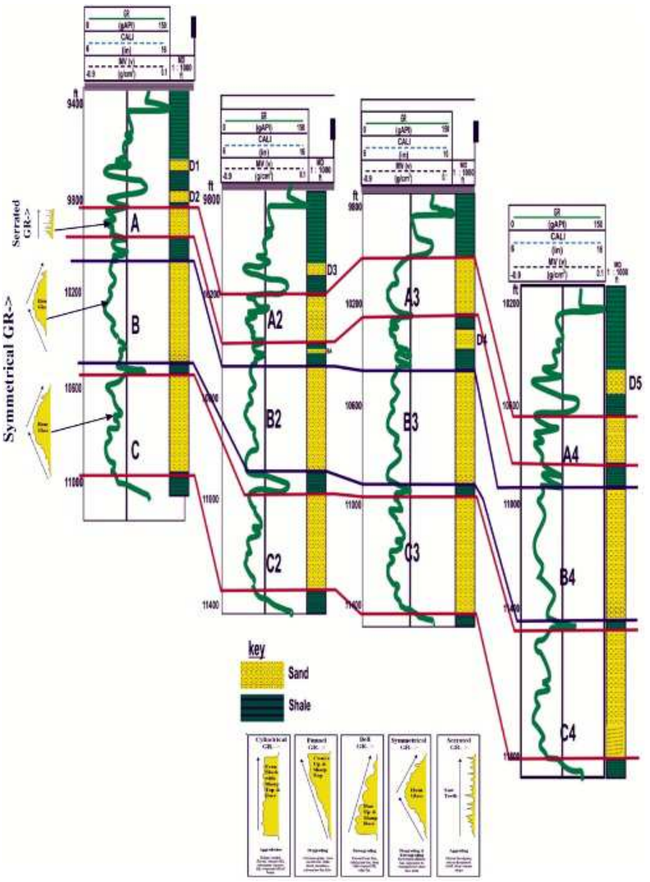


Fig. 5: Correlation in well 1, 2, 3, and 4 in NW-SE direction (Aigbadon et al. 2017a; b) and interpretation of depositional environments from log motif using the log pattern of Cant (1992).

mineralogical components and minor traces of muscovite-illite, feldspar, kaolinite, and hematiteat different depths in reservoirs A, B, and C in well-1, 2.10 – 8.30 meq/100g with quartz as main mineralogical component and minor traces of muscovite-illite, feldspar, and kaolinite in at different depths reservoirs A2, B2, and C2 in well-2, 2.00 – 8.30 meq/100g with quartz and kaolinite as main mineralogical components and minor traces of muscovite-illite at different depths in reservoirs A3, B3 and C3 in well-3, and 1.60 – 8.30 meq/100g with quartz and kaolinite as main mineralogical components and minor traces of muscovite-illite, and feldspars at different depths in reservoirs A4, B4 and C4 in well-4. It further reveals a cation exchange capacity value ranging from 2.00 - 8.40 meq/100g with quartz and kaolinite as main mineralogical components and minor traces of muscovite-illite, feldspar, and hematite in reservoirs A, A2, A3, and A4 across the well,2.10 - 8.30 meq/100g with quartz as main mineralogical components and minor traces of feldspar and kaolinite in reservoirs B, B2, B3, and B4 across the wells and 1.60 - 8.10 meq/100g in reservoirs C,C2, C3 and C4 across the wells. The high values of CEC indicate high clay contents or matrix; coupled with the presence of minerals of kaolinite (Fig. 6a), siderite, feldspar, illite-smectite (Fig. 6b), and muscovite-illite (Fig. 6c) and opaque mineral (Fig. 6d) at the reservoirs intervals. The low values of CEC indicate low clay contents or matrix; coupled with the occurrence of kaolinite, siderite, feldspar, illite-smectite, and illite at some of the reservoirs intervals. The core porosity from core porosity tests (Table 2) value ranges from 30-35% in well-1, 24-28% in well-2, 21-23% in well-3, and 19-20% in well-4.

Table 1: Cation exchange capacity and Mineralogical components in Usani reservoirs

Reservoirs	CEC Meq/100g	Main components	Traces
A	8.30	Quartz with the presence of kaolinite, illite, smectite/ /mixed layer	Muscovite- illite, hematite
B	2.30	Quartz	Feldspars, kaolinite
C	1.60	Quartz and Kaolinite	Muscovite- illite,
A2	8.40	Quartz, kaolinite, illite/ mixed layer	Muscovite- illite
B2	2.10	Quartz	Feldspar, kaolinite
C2	8.10	Quartz, kaolinite,	Feldspar, kaolinite
A3	8.30	Quartz with the presence of kaolinite, illite, pyrite smectite / mixed layer	Muscovite- illite, Hematite
B3	8.28	Quartz with the presence of kaolinite	Feldspar, kaolinite
C3	2.00	Quartz and Kaolinite	Feldspar, pyrite
A4	2.00	Quartz	Muscovite-illite, hematite
B4	8.30	Quartz with the presence of kaolinite, smectite/ mixed layer	Feldspar Kaolinite
C4	1.60	Quartz, kaolinite	Feldspars

(Table 2). It further reveals a porosity value ranging from 20- 21% in reservoirs A, A2, A3, and A4 across the four wells, a value of 23-35% in reservoirs B, B2, B3, and B4 across the wells, and a value of 22-32% in

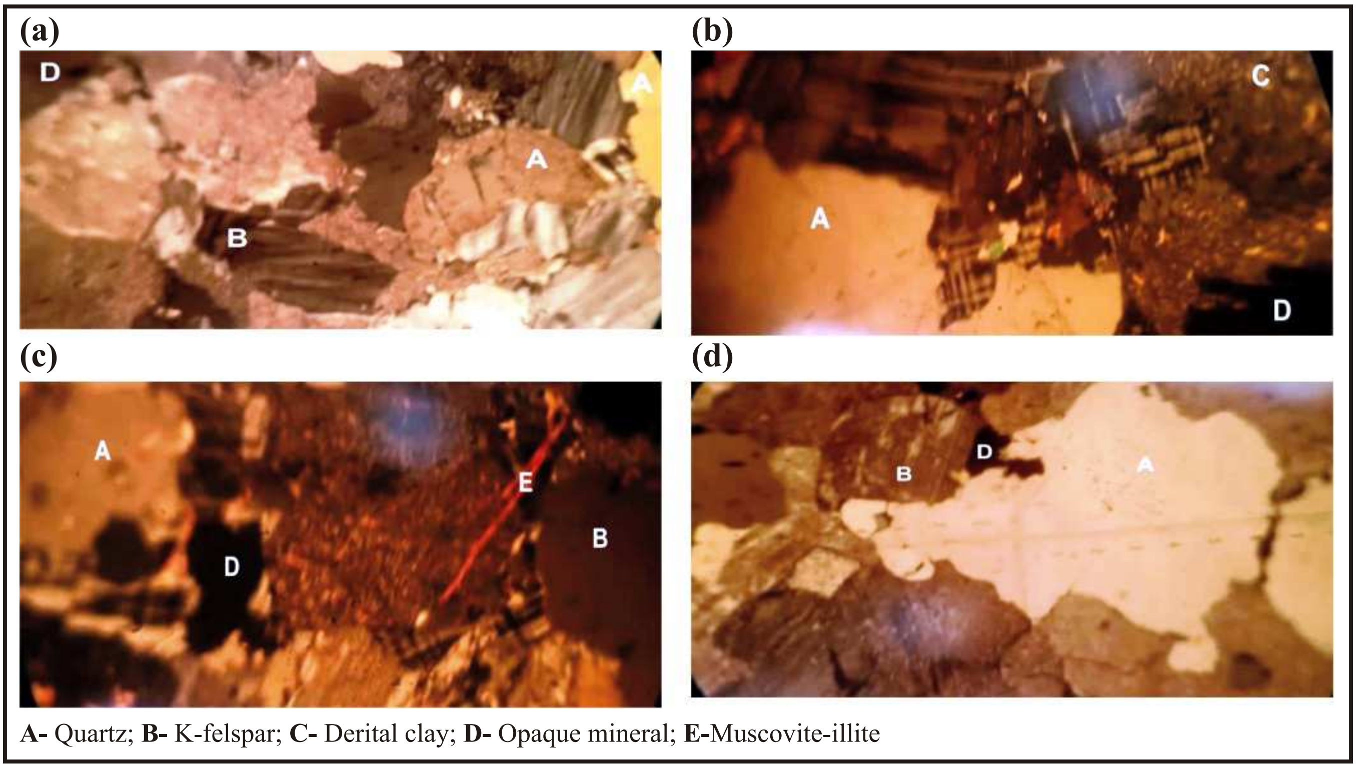


Fig.6a: Photomicrographs of (a) A2 showing the presence of kaolinite in well 2 (b) B3 showing illite-smectite mixed layer in well 3 (c) B2 showing the presence of muscovite- illite in well 2 (d) B2 showing the presence of opaque mineral in well.

Table 2: showing the porosity and permeability values.

S/N	Reservoirs	Core porosity (%)	Permeability (mD)
1	B	35	454.7
2	C	32	452.5
3	B2	30	425.5
4	C3	28	450.2
5	C4	25	440.4
6	B3	24	438.5
7	B4	23	438.4
8	C2	22	245.7
9	A	21	242.5
10	A2	20	240.5
11	A3	21	242.5
12	A4	20	241.5

reservoirs C, C2, C3, and C4 across the wells. The permeability from core permeametric tests for reservoirs A, A2, A3, and A4 value ranges from 240.5-242.5 mD in wells 1 -4; reservoirs permeability of B, B2, B3, and B4 across the wells ranges 438.5-454.7mD; and reservoirs C, C2, C3, and C4 have permeability of 240.5-242.5mD across the wells (Table 2). It further reveals that the reservoirs B, C, B2, C3, and C4 still possess good porosity and permeability even at deeper burial because the sandstones are textural maturity and also possess low content of derital clay materials. The plots of core porosity versus permeability (fig.7) show a positive relationship between porosity and permeability of the Usani sandstone reservoirs with respect to depth and depositional facies across the wells (Figs. 4 - 6). At shallow depths, more of illite, illite-smectite is in abundance. The unstable illite, illite-smectite minerals respond faster to diagenetic changes such as mechanical compaction and cementation which reduces the primary porosities in reservoirs A, A2, C2, A3, B4 within a depth range of 9400ft to 11800ft at a temperature range of 98°C to 110°C in the wells. At a deeper depth, the value of CEC decreases with more abundance of kaolinites with a high rate of compaction and cementation within the primary porosity of the Usani sandstone reservoirs which result in blockage of the pore throat within the reservoirs. The high amount of illite-smectite distribution within the shallow depth could be attributed to the contact with the meteoric water relative to sea-level fall. It makes the sandstones respond to diagenetic changes faster. Major mineral components as revealed from the thin sections are quartz, rock fragments, and feldspar with some traces of pyrite and hematite coatings. The mineral grains are typically quartz arenites (Fig. 8) composing of monocrystalline and polycrystalline quartz grains. The medium to coarse-grained, cross-bedded sandstones with shale/clay drapes in reservoirs A, A2, A3, A4, B4, C2, and C3 show the polycrystalline quartz grains with lines of demarcation and a high level of pink and light brown colours interferences containing little fluid, and that the pore throats of the reservoirs are well interconnected in reservoirs B, C, B2, C3, and C4 (figs.9).

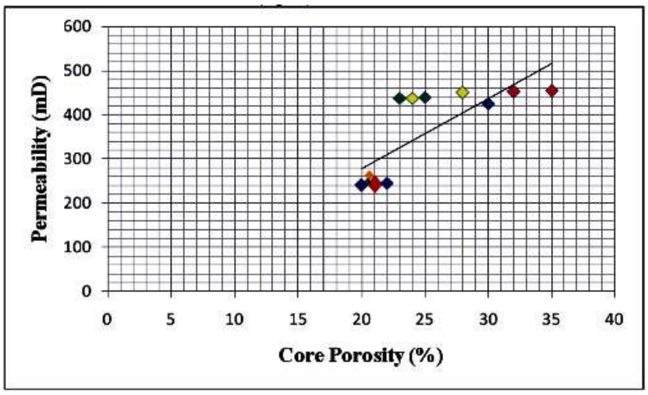


Fig. 7: Plot of core porosity against permeability of Usani sandstone reservoirs in the wells.

The red colours indicate plots for well 1, the blue indicates plots for well 2, the yellow indicates plots for well 3 and the green indicates plots for well 4 for the reservoirs across the wells in the field.

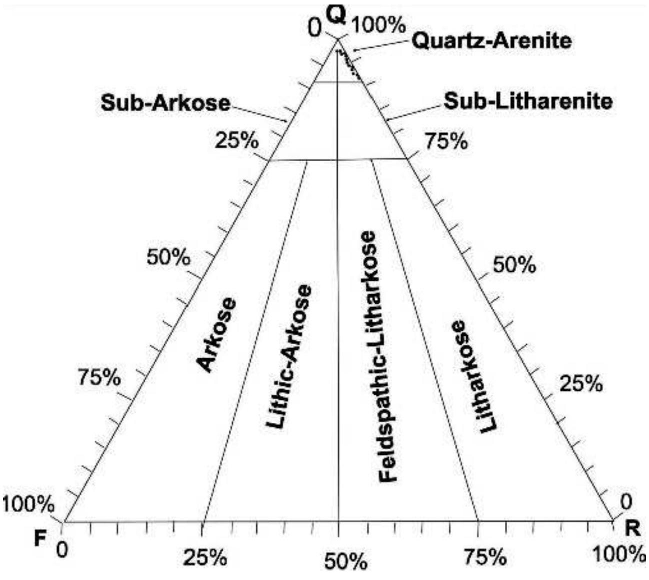


Fig. 8: Ternary diagram for the composition of Cenozoic Usani sandstone (After Folk 1980 classification).

These automatically reduce the quantity of hydrocarbon produced in affected reservoirs within the wells. The presence of sulfur contents from the pyrites affects the quality of hydrocarbon produced too. The thin section analysis also supported the compaction and cementation including quartz and hematite cement coatings of the sandstones within the field (Fig 9a-e). The quartz cement also precipitated as a result of clay mineral transformation such as smectite to illite and mixed-layer illite – smectite due increase in depth of sediment burial at 9800ft -11,400ft at a temperature of 90°C – 110°C in the Usani Field. This is shown in the reaction:

$$\underset{\text{K-feldspar}}{KAlSi_3O8} + \underset{\text{authigenic Kaolinite}}{Al2Si_2O_5(OH)_4} = \underset{\text{Authigenic Illite- Smectite}}{KAl_3Si_3O_{10} + 4SiO_2} + \underset{\text{water}}{H_2O}$$

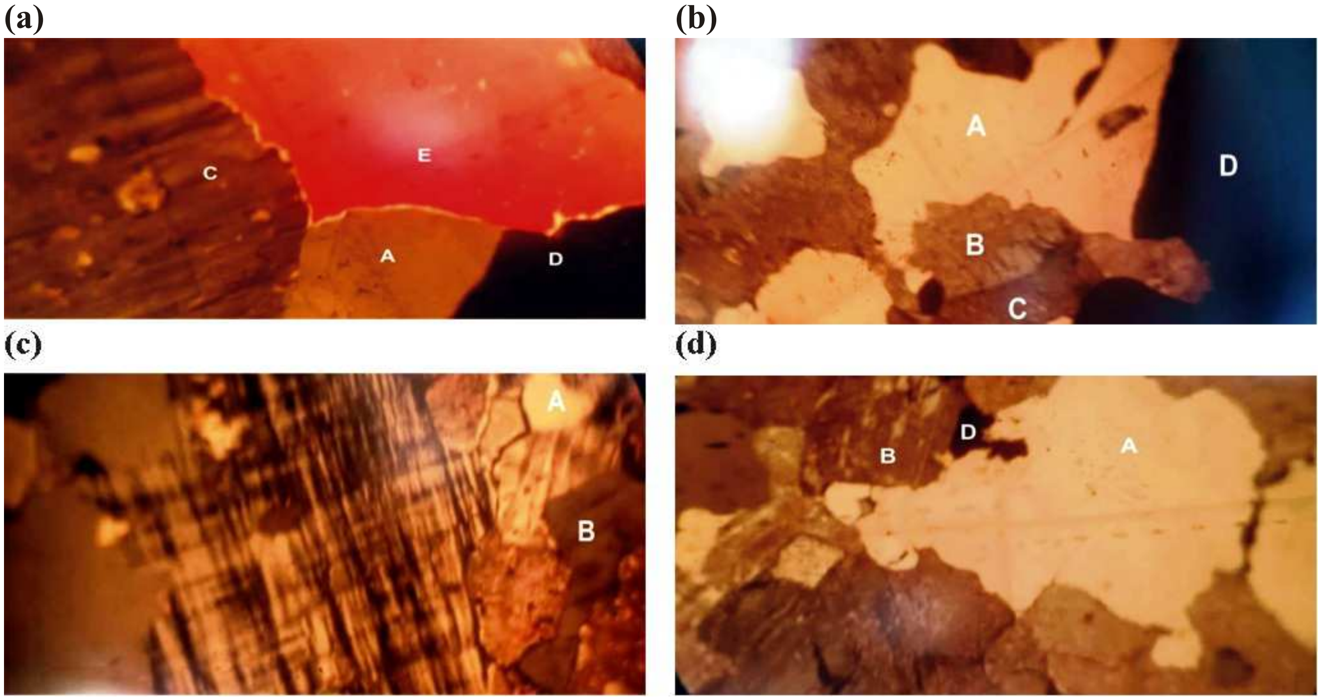
which is in line with the equation of reaction proposed by (Worden and Morad, 2003; Yu, Yu et al., 2018).The illite-smectite and kaolinitic distributions are thought to be stratigraphically and thermally controlled at geothermal – pressure regime within the field. Reservoirs pores that contain kaolinite at greater depth are very important because of kaolinitilization of K-Feldspar at reservoirs interval within a closed system; which depicts little or no presences of mixed layer illite-smectite clay within a depth range from 9800ft-11400ft in the field. It provides the reason for variation in reservoir quality as depth increases with the burial of sediments in the Usani offshore field.

Conclusion

Reservoir quantity and quality of the four wells from the Usani field, Niger delta were assessed using data from geochemical(XRD) analysis, gamma-ray log suites, thin section, porosity, and permeability. Gamma-ray log suites and core samples descriptions show that the reservoirs are made up of fine, medium to coarse sandstone lithofacies capped by mudstone and shale lithofacies of different depositional settings ranging from the storm-dominated shelf, offshore bar to offshore regressive bar depositional environments. The XRD and thin section data show that the dominating mineral is quartz with the presence of feldspar, illite-smectite, siderite, and traces of hematite, pyrites minerals. The high cation exchange capacity values indicate high clay contents or matrix, coupled with the presence of kaolinite, siderite, feldspar, illite-smectite, illite in reservoirs A, A2, C2, A3, B4 at a depth range of 9400 to 11800ft within a temperature range of 98-110°C in the across wells in the field. These characteristics were responsible for faster response to diagenetic modifications such as compaction and cementation that resulted in variation and reduction of the primary porosity of Usani sandstone reservoirs as the depth of burial increases. The presence of sulphur contents from the pyritic coatings reduces the quality of hydrocarbon in the studied field in terms of the global ranking.

Recommendations

I recommend further sedimentological analysis and the



A- Quartz; **B-** K-felspar; **C-** Derital clay; **D-** Opaque mineral; **E-**Muscovite-illite

Figs. 9a-d: Photomicrographs showing (a) effect of compaction and cementation (detrital clay) in reservoir C2 in well 2 (b) effects of compaction and cementation (detrital clay) in reservoir B4 in well 4(c) effect of compaction and cementation (quartz overgrowth and leaching) in reservoir B2. (d) The effect of compaction with quartz over-growth in reservoir B in well 1.

used of Scanning Electron Microscope (SEM) revealed the pore structures and the reservoir architectures of the sandstone reservoirs in the study area.

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