

Unravelling the Mystery of Low Resistivity Reservoir Zonation in the Niger Delta by Integration of Mobility, Well Production Data, Mineralogical Studies and Pore Throat Distribution

David Anomneze*, Olalekan Badmus, Samuel Anikoh, Wale Obisesan, Adedeji Awujoola, Onyekachi Ihebuzor, Kingsley Akpara, Ofonmbuk Oluwaniyi, Taju Gbadamosi, Ebere Benard and Nchekwube Lazson
Seplat Energy PLC, Lagos, Nigeria

ABSTRACT

Low oil saturation within unconsolidated reservoir zones in some producing fields in the Niger Delta constitute challenge for optimal horizontal well placement. This case study is associated with relatively poor production performance from the upper zonation of heavy oil saturated reservoirs, compared to mid and lower reservoir sections. Hence, this study is aimed at understanding the relationship between low resistivity and production performance across different reservoir zones; to identify good quality reservoir intervals for optimal horizontal well placement. The integration of well logs, core, Modular-Formation Dynamic Tester (MDT), laboratory analysis and production data has helped to differentiate interval of poor-quality reservoir from good quality zones which was not possible from gamma ray and density logs alone. The techniques used for the study include insitu downhole fluid analysis, mercury injection capillary pressure measurements, thin-section analysis, X-ray diffraction and scanning electron microscopy (SEM). The results of the study reveal the presence of kaolinite clay coating on the grains, with characteristic low resistivity and low-mobility ratio for the upper reservoir zone. Also, the low resistivity interval displays bimodal pore throat distribution with a high frequency range between 10 and 100 nano-microns. In conclusion, this study has shown that the percentage of kaolinite clay mineral in unconsolidated sandstone reservoirs has direct impact on resistivity response, mobility, pore throat distribution, irreducible water saturation and production performance. The presence of kaolinite clay mineral in unconsolidated reservoir above 10% has resulted to low resistivity response, high frequency of low pore-throat below 100 nano-microns, low mobility and higher irreducible water saturation. Consequently, high fraction of kaolinite mineral will lead to increase in capillary entry-pressure, reduction in permeability and production capacity of the reservoir. Hence, the best interval for horizontal well placement in unconsolidated reservoirs should have low percentage of kaolinite clay below 10% and pore-throat diameter between 10,000 and 100,000 nano-microns.

Keywords: Low resistivity reservoir zonation, mobility, clay minerals, pore throat diameter, diagenesis, well production history, reservoir quality

INTRODUCTION

After more than six decades of exploration and development in the Niger Delta Basin, the conventional and easy-to-develop hydrocarbon reservoirs have been substantially depleted, limiting Nigeria's capacity to meet her Organization of Petroleum Exporting Countries (OPEC) production quota. This situation prompted the government to pursue an aggressive drive to increase exploration and production activities in Nigeria. Consequently, in June 2024, the Nigerian Upstream Petroleum Regulatory Commission (NUPRC) convened an industry-wide consultative workshop aimed at encouraging unique and data supported ideas that can help develop the remaining oil and gas resources in Nigeria.

From available data, a significant portion of the nation's reserves are heavy oil resources that are yet untapped due to limited development successes, technical capacity and data. There is a renewed drive by oil and gas exploration and production companies to develop these heavy oil reserves, however, the challenge of understanding the nature of these reservoirs, conceptualizing and executing successful development plans subsist. This study was undertaken in an effort to pursue the development of a heavy oil field by integrating available data, acquisition of additional data and the laboratory analysis of available cores in one of Seplat fields.

The aim of this study is to investigate (1) the relationship between mobility and reservoir quality (2) the impact of clay minerals and pore throat distribution on reservoir quality (3) and understand the combined relationship between low resistivity zones, production performance, mobility, clay mineralogy and pore throat distribution, in order to identify the zones with better reservoir quality for optimal placement of horizontal wells in unconsolidated

© Copyright 2025. Nigerian Association of Petroleum Explorationists. All rights reserved.

The authors hereby express their sincere gratitude to Seplat Energy PLC for the data used in this study and for their permission to present and publish this paper. Also, special recognition to Seplat Western Asset and Subsurface leadership team

sands.

Sandstone reservoirs often consist of clay minerals. This existence of dispersed clay minerals fill up the pore spaces of reservoir, impacting the effective porosity and permeability of the reservoirs. This has a significant effect on the reservoir quality which makes understanding, characterizing and quantifying these clay minerals crucial for optimum development and extraction of hydrocarbon resources. This is especially pertinent in unconsolidated sands whose sediments have not travelled a significant distance, leading to a low chance of plummeting all the clays that might have been transported from source. Studies by Li *et al.* (2021) have shown that depositional factors affect the strength of diagenesis, such that the strength of dissolution of clays varies between well sorted sands and poorly sorted sands, with poorly sorted sands having higher compaction index and cementation.

The case study is a field located within the Greater Ughelli depobelt of Niger Delta Basin. The reservoirs in the field have been classified into two broad sets - the shallow and deep reservoirs. The shallow reservoirs, which are the focus of this study, are characterized by relatively unconsolidated sands, with heavy oil resources, and viscosity ranging between 21cp and 100cp, The deep reservoirs are characterized by consolidated sands with light oil and gas resources and viscosity generally below 1cp. A very minor amount of heavy oil resources has been recovered, with significant volumes un-recovered. This prompted the interest to study the best development approach for our heavy oil resources by further understanding the reservoir characteristics through data integration.

Several reservoirs in the case study have been identified as having low resistivity at the top zones while the mid and lower sections have higher resistivity. These top sections are characterized by low gamma ray and low-density readings, which are ordinarily indicative of good reservoir qualities, with expected low capillarity and comparatively low irreducible water saturation. However, this contrasts with low resistivity readings recorded at those top sections (Fig 1).

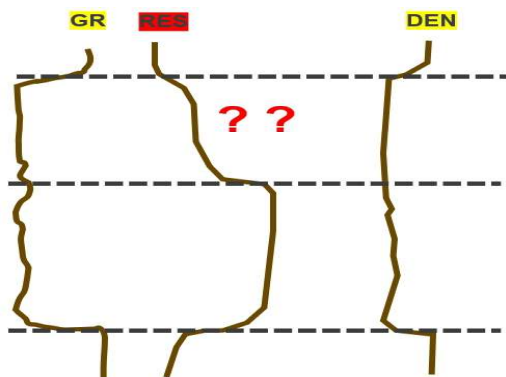


Figure 1: A cartoon illustrating low resistivity zonation peculiar to the cases of interest.

The initial assumption was that “good” reservoir quality is inferred from the gamma ray and density logs, the capillarity and oil saturation will continue to increase towards the top of the reservoir. However, following a review of the production performance of the wells preferentially completed in the different zones, it became apparent that the properties of the reservoirs at the top section are different from the properties towards the mid to lower section of the reservoirs, with peculiar log signatures. This led to the evaluation of all available data, acquisition of additional data and laboratory tests on core data from this top zone, to develop an optimal development plan for the reservoirs so affected. Examples are shown in figures 2a and 2b.

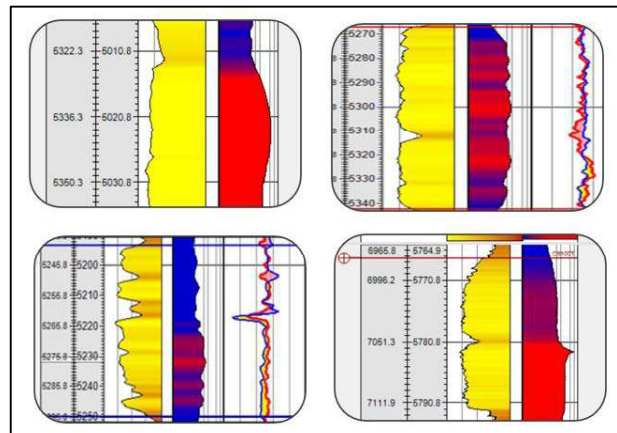


Figure 2a: Samples of reservoirs with low resistivity (second log track) at the top sections and higher resistivity at the lower section

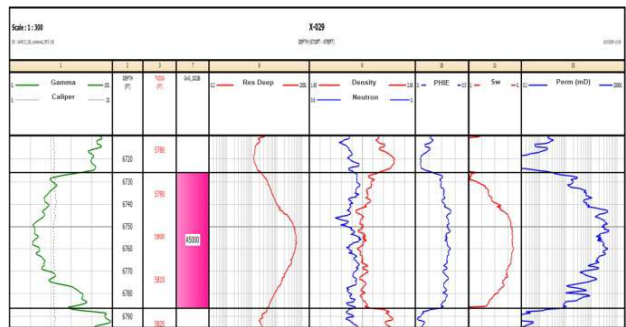


Figure 2b: Well logs interpretation of one of the peculiar cases - reservoir A5000.

DATASET AND METHODOLOGY

The following data set was utilized for the studies (Fig 3): Well logs (gamma ray, resistivity, density, porosity, permeability), production history, downhole fluid analyzer IFA (mobility data), mercury injection capillary pressure measurements (pore throats distribution and pore throat diameter) and mineralogical studies (X-ray diffraction, thin section analysis and scanning electron microscopy).

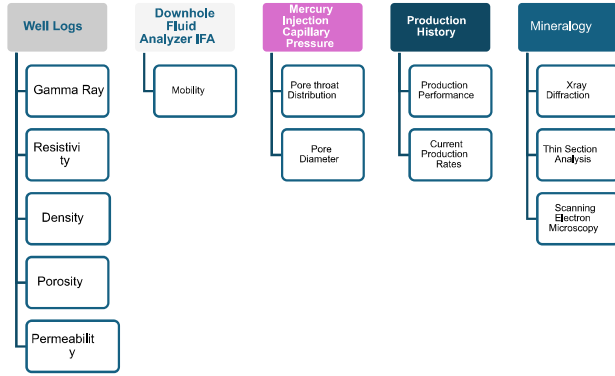


Figure 3: Data set utilized for the study.

The study reviewed the production history and performance of wells that have been completed on different zones within candidate reservoirs classified as having lower resistivity at top zone and higher resistivity at lower zones. Mobility data available for candidate reservoirs of interest were reviewed and additional mobility data was acquired on a recent 2024 well in A5 reservoir. Laboratory tests were carried out to review the mineralogical composition and pore fill using X-ray diffraction, thin section analysis and scanning electron microscopy. Thereafter, mercury injection capillary pressure measurements were carried out in a candidate reservoir using chunks of unfragmented core samples. This was done to measure the pore throat diameter and distribution within the reservoir at different zones. The integration of all the available data has provided a pointer to recommend utilizing low resistivity zonation for optimal placement of development wells.

RESULTS AND DISCUSSION

Production History: A production history of two horizontal wells (wells X-31HZ and X-33HZ) completed within one of the reservoirs was studied (Fig 4). Well X-31HZ was drilled and completed across both the top zone (lower resistivity zone) and lower zone (higher resistivity zone) of the A5 reservoir (Fig 4), while X-33HZ was drilled and completed only at the lower zone (higher resistivity zone) of the same reservoir. The performance history of the wells shows that well X-33HZ has produced about 1.1MMbbl of oil and is still producing till date, while well X-31HZ only produced about 0.5MMbbl and quit on high water cut (Fig 5a and 5b). The X-31HZ produced initially at a very high water cut of 80% and increased to over 95% water cut while well X-33HZ initially produced at less than 10% water cut with gradual and slow increase in water cut to maximum of 60%.

Mobility: The mobility of a fluid is defined as the ratio of the permeability of the formation to a fluid, divided by the fluid viscosity. Mobility is a measure of the ability of a fluid to move through interconnected pore space. Mobility

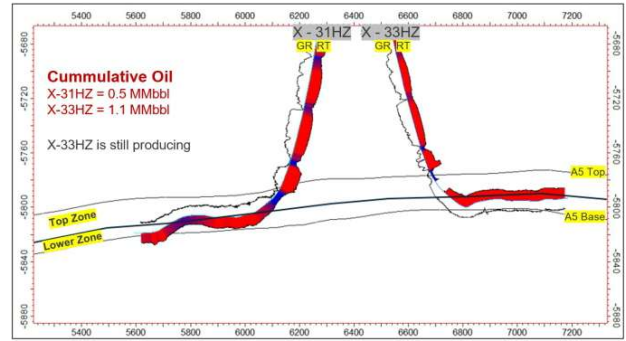


Figure 4: Cross section along wells X-31HZ and X-33HZ on A-5 reservoir.

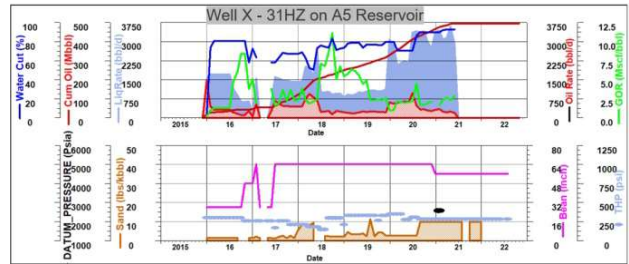


Figure 5a: Well X-31HZ production history plots on A5 reservoir.

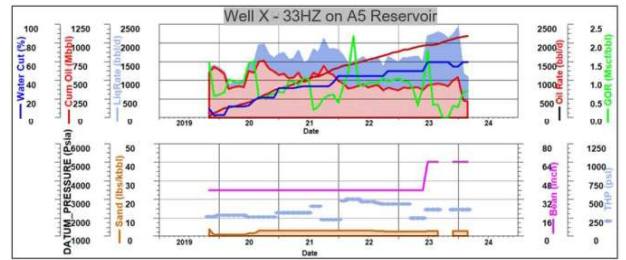


Figure 5b: Well X-33HZ production history plots on A5 reservoir.

data for candidate reservoirs with low resistivity across the top and higher resistivity within the mid to lower section were plotted on the well logs track to compare mobility values. Results from three wells show that the mobility is lower towards the top zones and higher towards the lower zones (Fig 6a, 6b and 6c). Since mobility is a function of permeability and viscosity in mD/cP, it generally shows that the permeability around the top zone is comparatively low as pore fluid viscosity was constant. Therefore, horizontal wells placed in the reservoir will have better production performance at the lower zones of the reservoirs. This fact is also evident in contrasting production performance of wells X-31HZ and X-33HZ.

This result is supported by the studies by Kampit et al. (2023) where he compared results of about seventy mobility samples acquired across 6 wells from sands in the Malay Basin, their results show that very shaly sands were very tight and had lower mobility (Fig 6d). Kampit *et al.*

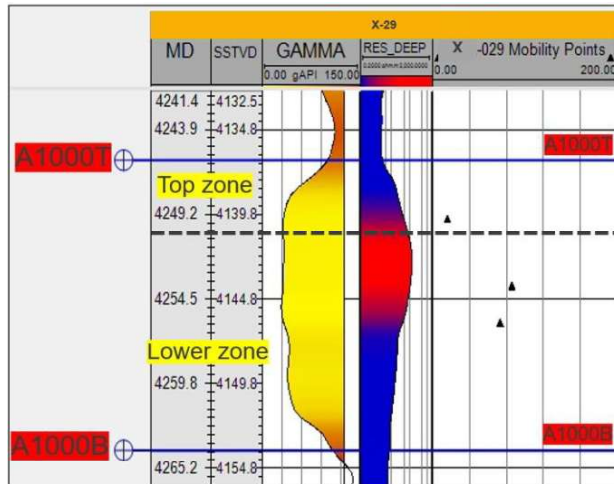


Figure 6a: Well logs and mobility data plotted to show the difference in mobility from top zone and lower zone in A1000 reservoir from well X-29.

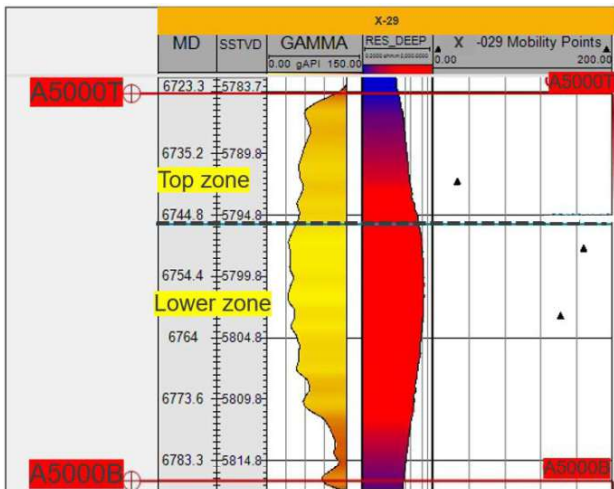


Figure 6b: Well logs and mobility data points plotted to show the difference in mobility from top zone and lower zone in A5000 reservoir from well X-29.

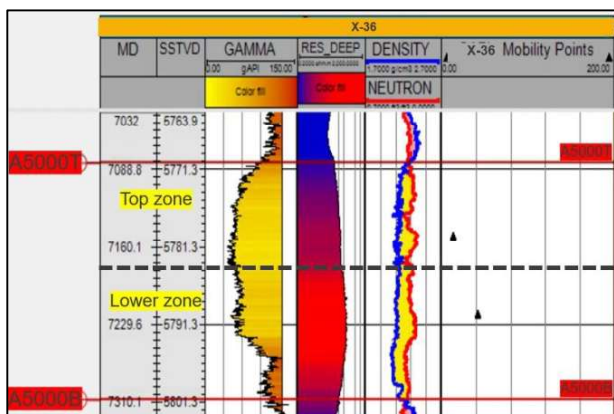


Figure 6c: Well logs and mobility data points plotted to show the difference in mobility from top zone and lower zone in A5000 reservoir from well X-36.

(2023) also deduced that there is a direct relationship between mobility and intrinsic permeability. As the sand quality increases, the both variables increases.

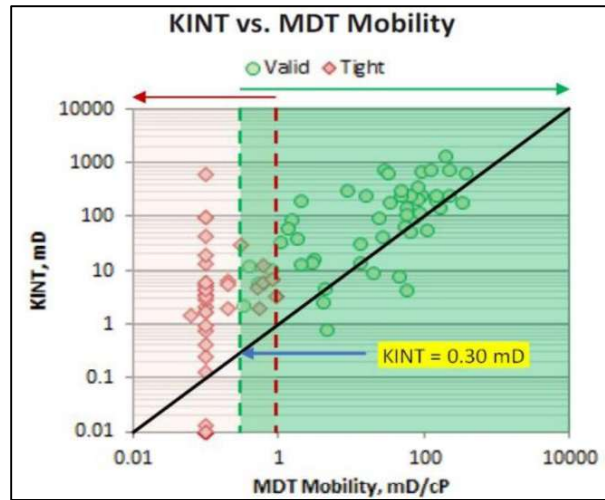


Figure 6d: Plot of intrinsic permeability against mobility with cut-off KINT for tight formations (Kampit *et al.* 2023)

Mineralogical Analysis: Three approaches of mineralogical analysis were carried out, X-ray diffraction, thin section analysis and scanning electron microscopy. This was done using core samples from reservoirs with similar resistivity issues of lower resistivity at top as compared to higher resistivity at lower units. Two candidate reservoirs with core data were utilized in carrying out the three laboratory analysis. The A3000 and A4000 reservoirs. Six sample points were taken to carry out x-ray diffraction of reservoir A3000 (Fig 7a). The sample point-1 was the only available core at the top sections. However, five samples were taken towards the base.

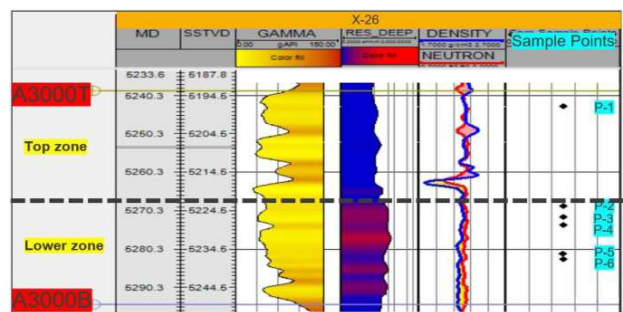


Figure 7a: Well logs and sample points for mineralogical studies of A3000 sand.

Results from the XRD analysis of A3000 sand have shown that the clay minerals range from 1.3 to 11.1% at different points (Fig 7b). The very top section has the highest percentage of clay (11.1%) while the lower zone has the lowest percentage of clay in the whole core samples. This further suggests that the reservoir can be subdivided into two zones or to three zones if the clay fractions is used to

further subdivide the reservoir. The clay minerals are kaolinite and chlorite, with Kaolinite constituting the majority of clay type, with 100% abundance at some points (sample points 1 to 5) in reservoir A3000 (Fig 7b and 7c).

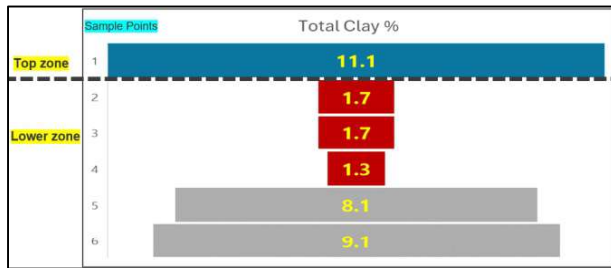


Figure 7b: Percentage clay in A3000 reservoir.

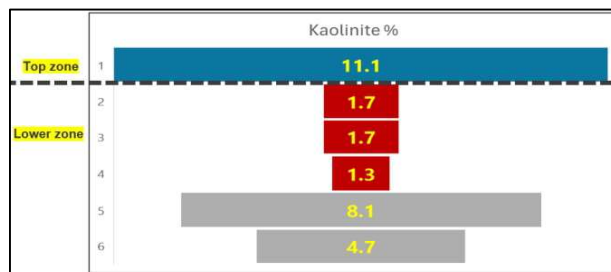


Figure 7c: Percentage Kaolinite in the A3000 reservoir.

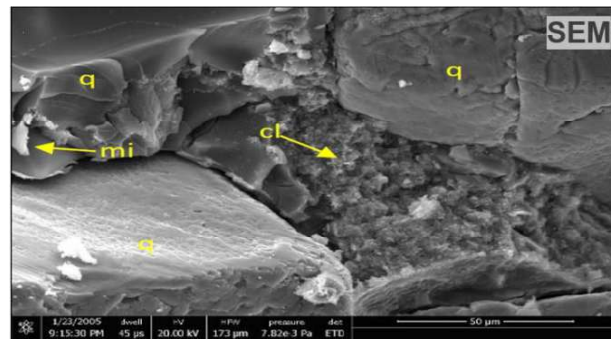


Figure 7d: Scanning electron microscopy image of A3000 reservoir.

The SEM image of the A3000 reservoir shows there are intergranular pores with clay coating and pore-filling kaolinites (Fig 7d). This clay is classified as authigenic and dispersed as seen in the thin section analysis result (Fig 7e). This shows that the more clay percentage in the reservoir will tend to strain the permeability of the reservoir. Thereby reducing the tendency of oil to flow in and out of the reservoir, which accounts for the lower mobility measured from the upper zone of the reservoir associated with higher clay fractions.

Two sample points were taken to carry out x-ray diffraction of reservoir A4000 (Fig 8a). The sample point-1 was the only available core at the top sections while one sample was taken towards the lower zone associated with higher resistivity.

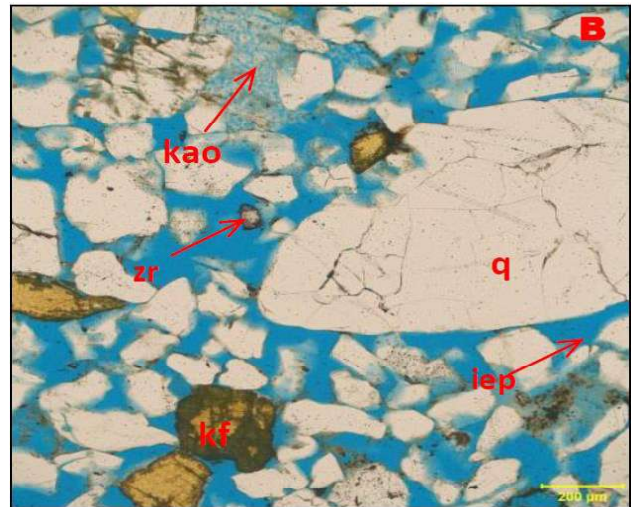


Figure 7e: Thin section analysis image of A3000 reservoir.

Results from the XRD analysis of A4000 sand show that the

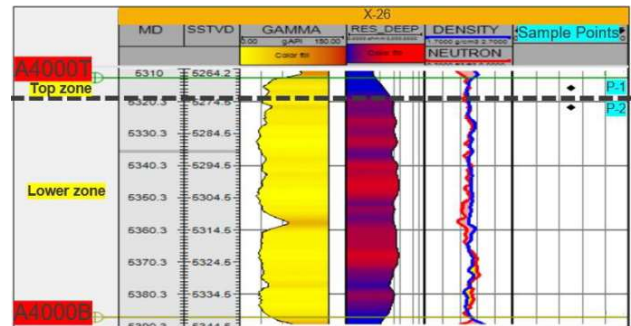


Figure 8a: Well logs and sample points for mineralogical studies of A4000 sand.

clay minerals range from 7.4 to 21% at different points (Fig 8b). The very top section had the highest percentage of clay (21%) while the lower zone had a lower percentage of 7.4%. This further suggested that the reservoir can be subdivided into two zones. The clay minerals are kaolinite and chlorite, with Kaolinite being most clay with 100% abundance at sample point 2 in reservoir A4000 (Fig 8c).

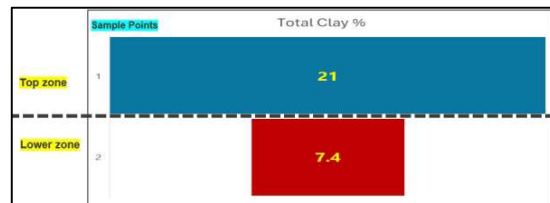


Figure 8b: Percentage clay in A4000 reservoir.

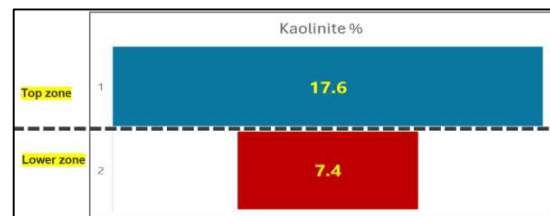


Figure 8c: Percentage kaolinite in A4000 reservoir.

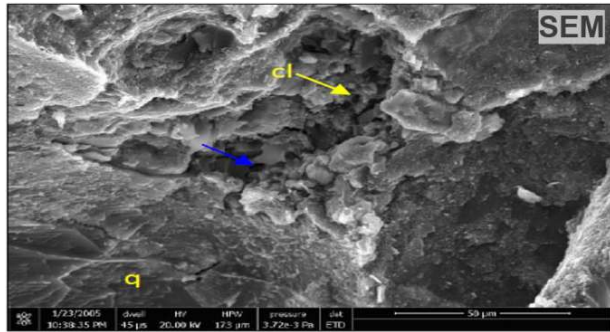


Figure 8d: Scanning electron microscopy image of A4000 reservoir.

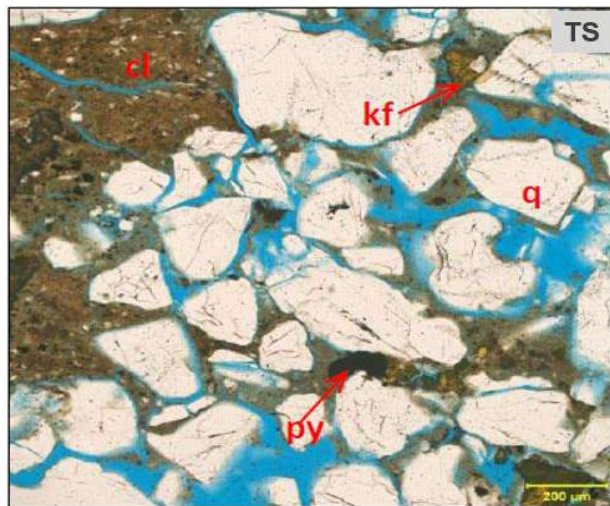


Figure 8e: Thin section analysis image of A4000 reservoir.

The SEM image of the A4000 reservoir shows there are intergranular pores with clay coating and pore-filling kaolinites (Fig 8d). This clay is classified as detrital, dispersed and authigenic as seen in the thin section analysis result (Fig 8e). This shows that the high clay percentage in the reservoir will tend to strain the permeability of the reservoir. Thereby, reducing the tendency of oil to flow in and out of the reservoir.

Pore Throat Distribution: Mercury injection capillary pressure MICP measurement was carried out to get the pore throat distribution and diameter. This enables characterization of inner rock matrix pore which is mostly not measurable in conventional porosity measurements, as it takes cognizance of the pore diameters available within a rock sample. This makes it possible to get details of micro and nano pore diameters and distribution.

In porous media, capillary pressure is the force necessary to squeeze a hydrocarbon droplet through a pore throat and is higher for smaller pore diameter. An illustration of how the MICP experiment is carried out is shown in figure 9a. It shows that as mercury is injected into a reservoir samples, the invasion first passes through the mega pores and

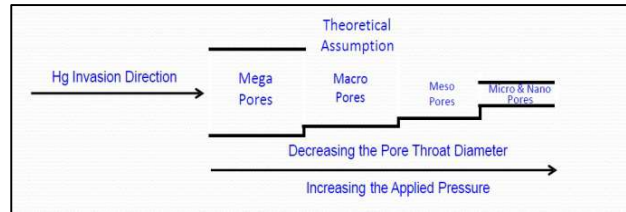


Figure 9a: Standard illustration of mercury invasion in MICP experiment.

gradually progresses into the micro and nano pores.

The relationship between capillary pressure and pore is the Young-Laplace equation shown below.

$$P_C = \frac{2\sigma \cos(\theta)}{r}$$

P_C = capillary pressure

r = pore throat radius

σ = interfacial tension

θ = contact angle

This shows that the smaller pore sizes will require very high capillary entry pressure. This was further experimented by Cuddy, 2017 in his illustration of how pore throats retain water in hydrocarbon bearing system (Fig 9b). It shows that the smallest pore holds the most water.

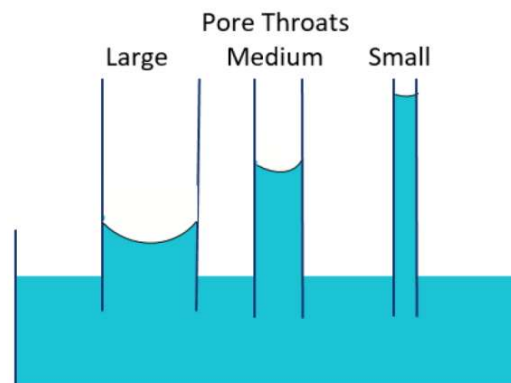


Figure 9b: Illustration of water holding capacity of pore throats, smallest pore holds the most water (Cuddy, 2017).

Studies by Kashif *et al.* (2019) have shown that the pore radius of fine-grained sediments are very low as compared to those from coarse grained sediments and the movement of reservoir fluids is mainly controlled by the capillary pressure of the rock unit.

Two sample points were utilized for the mercury injection capillary pressure measurements for one of the candidate reservoirs. This was based on available usable cores that are non-fractured (Fig 9c). Sample pt-1 is within the low resistivity zone while the Sample pt-2 is within the high resistivity zones. Pore throat distribution is bimodal with high frequency of lower pore throat diameter (10 –

100nm) at top zone (Fig 9d). Sample point 2 (lower zone) has a dominance of higher pore throat diameter of 10,000 – 100,000nm (Fig 9e) which can be classified as unimodal with less than 10% of the smallest pore throat size.

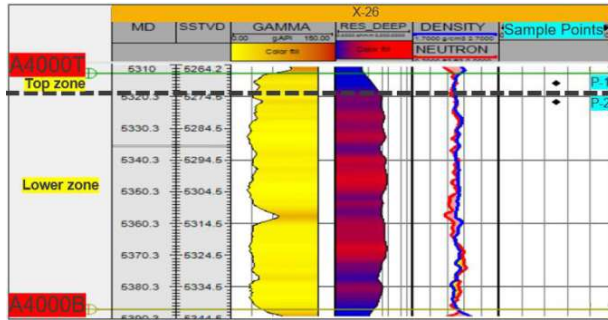


Figure 9c: Well logs and sample points for pore throat distribution of A4000 sand.

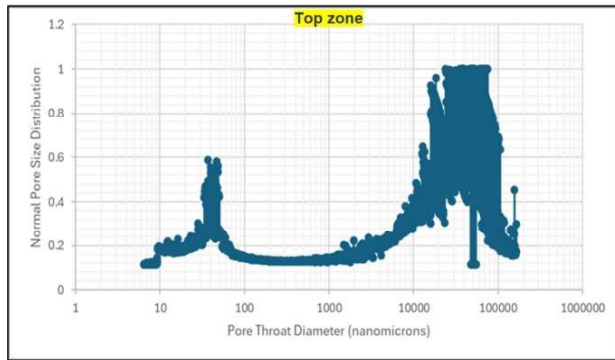


Figure 9d: A bimodal pore throat distribution from Sample point-1 (A4000 reservoir) with low pore throat diameter of 10 to 100nanomicons and high pore throat diameter cluster of 100- to 100,000nanomicons.

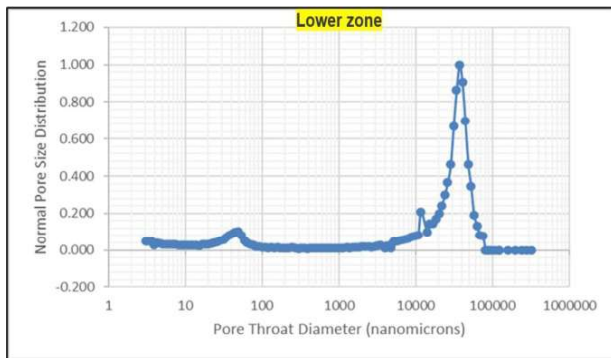


Figure 9e: A unimodal pore throat distribution from Sample point-2 (A4000 reservoir) with high pore throat diameter cluster of 10,000- to 100,000nanomicons

Outcrop Description of Kaolinite Deposits: Massive kaolinitic sandstone deposits was identified in an outcrop of Ajalli Sandstone in Enugu state. A succession of the Kaolinitic sandstone deposits is seen with increasing fractions of kaolinites towards the top of each succession as seen from the outcrop which is more whitish towards the

top of each succession. (Fig 10). This shows that in sands where kaolinites are found, there are chances of having more kaolinites associated towards the top section of each succession of sand deposits. Also, this implies that during deposition, more dirty sands with high clay contents are deposited towards the top units of each succession.

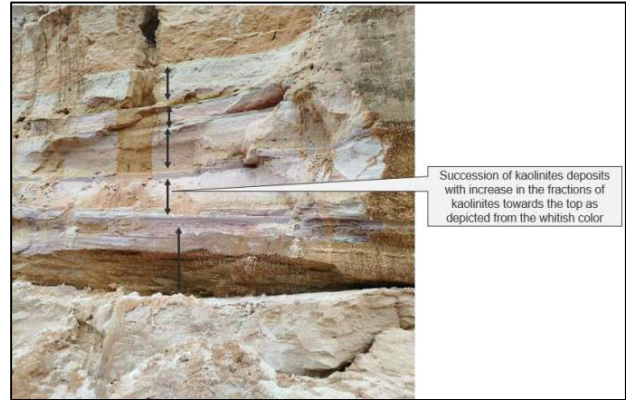


Figure 10: Outcrop of Kaolinitic sandstone deposits within the Ajalli Sandstone, Enugu state.

CONCLUSION AND RECOMMENDATIONS

Integration of production data, mobility, mineralogy and pore throat distribution has aided the subdivision of the candidate reservoirs into reservoir quality zones. The higher mobility values are associated with better reservoir quality. Kaolinite clay is the dominant clay mineral in the candidate reservoirs. Studies by Li *et al.* (2021) shows that reservoirs with less than 6% whole rock kaolinite were attributed to good quality reservoirs, however this study has shown that extending the limit to <10% will be ideal for good quality sands in Niger Delta.

This study has shown that the percentage of kaolinite clay mineral in unconsolidated sandstone reservoirs has a direct impact on resistivity response, mobility, pore throat distribution, irreducible water saturation and production performance. The presence of kaolinite clay mineral in unconsolidated reservoir above 10% has resulted in low resistivity response, high frequency of low pore-throat below 100 nano-microns, low mobility and higher irreducible water saturation. Consequently, high fraction of kaolinite clay mineral at the top zones of the candidate reservoirs led to increase in capillary entry-pressure, reduction in permeability and production capacity of the reservoir. Hence, the best zones for horizontal well placement in unconsolidated reservoirs should have a low percentage of kaolinite clay below 10% of the whole rock and pore-throat diameter between 10,000 and 100,000 nano-microns.

Recommendations: It is recommended that more core data should be acquired in more wells and reservoirs in order to have more data points for subdivision of reservoir

zones using clay mineralogy and pore throat diameter. This is pertinent in optimal placement of horizontal wells for higher recovery in unconsolidated reservoirs.

REFERENCES CITED

- Cuddy S., (2017)., Using fractals to determine a reservoir's hydrocarbon distribution. Proceedings of SPWLA 58th Annual Logging Symposium, June 17–21, 2017.
- Kampit S. J., Kamaruddin S. O., Sidek A., Rejab R., Anas Z.A., Azam M.N., (2023), Determination of petrophysical properties cutoff in heterolithic reservoirs in Malay Basin. *Journal of Technology (Sciences and Engineering)*, vol. 85(2), pp. 11-19.
- Kashif M., Cao Y., Yuan G., Asif M., Javed K., Mendez J.N., Khan D., Miruo L., (2019), Pore size distribution, their geometry and connectivity in deeply buried Paleogen Es1 sandstone reservoir, Nanpu Sag, East China. *Springer Petroleum Science Journal*, vol. 16, pp. 981-1000.
- Li J., Zhang X., Tian J., Liang Q., Cao T., (2021), Effects of deposition and diagenesis on sandstone reservoir quality: A case study of Permian sandstones formed in a braided river sedimentary system, northern Ordos Basin, Northern China. *Elsevier Journal of Asian Earth Sciences*, vol. 213, <https://doi.org/10.1016/j.jseas.2021.104745>.