

# The Application of Scanning Electron Microscopy and Energy Dispersive X-Ray Spectroscopy to Study the Morphology of Clay Minerals in Sandstones of Anambra Basin: Implications for Reservoir Quality

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**Abstract**— Clay minerals are widely distributed and are important components in sedimentary rocks. The identification of authigenic clay minerals have been a serious topic of research recently due to the impacts on reservoir quality. The goal of this study is to evaluate the presence of clay minerals in sandstones caused by the diagenetic processes and their impacts on reservoir quality using Scanning Electron Microscopy coupled with Energy Dispersive X-Ray Spectroscopy (SEM–EDX) method. The representative sandstones from Akukwa-1, Akukwa-2 and Idah-1 wells in Anambra Basin were collected from Nigeria Geological Survey Agency (NGSA) and subjected to SEM-EDX analysis. The results shows that Kaolinite occur as a pore-filling clay in AKukwa-1 and significantly impact on the porosity with fibrous illite-smectite having an impact on permeability. Chlorite coatings observed in Akukwa-2 inhibit quartz secondary overgrowth by coating the detrital grains and preserve porosity. While Chlorite platelets observed in Idah-1 occur as pore-filling clay mineral, blocking the pore spaces. This study contributes to a broader knowledge of reservoir characterization and optimization of oil and gas exploration and development strategies.

**Keywords**— Authigenic clay minerals, Clay minerals Characterization, Chlorite, fluid flow, illite, Kaolinite, Smectite, Reservoir quality, Porosity, Permeability.

## I. INTRODUCTION

Clay minerals in sandstone reservoirs play a critical role in determining reservoir quality by significantly influencing porosity, permeability, and fluid saturation (Al-Kharra'a *et al* 2023) The distribution, type, and quantity of these minerals within the reservoir matrix can alter the rock properties and complicate the interpretation of well-logging (De *et al* 2024, Ehsan and Gu 2020). Accurate characterization of clay mineral content in sandstone reservoirs is crucial for understanding mineral composition and its effects on reservoir quality (Shedid, 2018). Several analytical methods are commonly employed and these include scanning electron microscopy (SEM) for imaging clay structure and distribution. This method is instrumental in identifying how clay mineralogy affects pore structure and fluid dynamics. Diagenetic minerals are minerals that formed post-deposition of sediments but before their alteration by metamorphism (Stein, *et al* 2011). Their origin is linked to chemical and mineralogical changes in sediments (Wan *et al* 2022). These changes frequently lead to the modification of pore spaces, making diagenetic minerals a crucial factor in determining reservoir rock properties (Bjorlykke, 1988). Understanding diagenetic minerals such as

glauconite, smectite, illite, siliceous, and carbonate cement is essential in assessing the quality of the reservoir rocks. The effect of diagenetic minerals on reservoir properties has long been acknowledged (Risha *et al* 2023, Baiyegunhi *et al* 2020). Illite occurs as pore-lining and pore-filling cement, reducing the size and closing pore throats, and consequently affecting the reservoir quality (Sun *et al* 2019).

Recent studies emphasize the critical role of clay minerals in influencing the quality of sandstone reservoirs through various effects on pore structure and fluid flow. Al-Kharra'a *et al.* (2023), demonstrated that different clay types, particularly fibrous Illite and Illite platelets, impact permeability by either blocking or preserving micropore throats. Yu, *et al* (2023), showed that pore-lining chlorite coatings in the Junggar Basin enhance pore size distribution, while pore filling chlorite aggregates decrease reservoir quality. Magoba *et al* (2024), identified that diagenetic processes, particularly clay mineralization like glauconite, Illite, and smectite cementation, reduce connectivity in the Bredasdorp Basin, reinforcing the influence of clay minerals across various geological contexts. Together, these studies underscore the important effects of clay mineral type, content, and distribution on reservoir quality and hydrocarbon recovery.

Scanning Electron Microscopy (SEM) can be used to analyze the crystalline structure, surface topography, electrical behavior, and chemical composition of approximately 1m of the top part of a specimen (Vernon-Parry 2000). SEM has additional advantages due to the powerful magnification and can reach the nanometer scale (Erol, 2018) and this allows for an in-depth examination of the sample. SEM is a non-destructive analytical technique (Bonilla-Jaimes *et al* 2016), and also has a large depth of field that benefits simultaneous focus on the specimen surface, irrespective of surface roughness (Sato *et al* 1982). SEM images are formed by using various signals collected by the detectors present in the collection chamber. Each signal offers different types of imaging information for the sample (Vernon-Parry, 2000). Secondary electron imaging (SEI) is an extensively utilized imaging mode in SEM that produces images through the detection of secondary electrons (Agarwal, *et al* 2023). It provides topographic information such as surface texture, shapes and features. Backscattered electron imaging (BSEI) is generated by detecting backscattered electrons originating from the surface of the sample due to interaction with the primary

electron beam (Kejzlar, *et al* 2014). When the electron beam emitted from the gun penetrates and interacts with the volume beneath the sample surface, X-rays are generated. The deceleration of electrons as they enter the Coulomb field of the sample results in a well-established principle in physics. loses electron energy and radiates photons. In SEM analysis, similar X-ray photons are emitted, which are characteristic of the sample under investigation (Saghiri *et al* 2012). The quantification scheme is achieved by measuring the X-ray intensity. This was illustrated by Heinrich and Yakowitz in 1968 in their publication, Quantitative Electron Probe Microanalysis (Heinrich and Yakowitz 1968), which later became the standard for developing X-ray fields. At that time, X-ray absorption, determination of correction factors at the instant of electron penetration and scattering, and conversion of X-ray intensity to the relative concentration. Many problems pertaining to the electron probe field were solved with the development of energy-dispersive spectroscopy (EDX). At present, various studies have incorporated SEM-EDX for qualitative and semi-quantitative analysis in a variety of subject areas (Scimeca *et al* 2018, Duma *et al* 2022).

This research aims to characterize the sandstone reservoirs from Akukwa-1, Akukwa-2 and Idah-1 wells in Anambra Basin using SEM-EDX technique with a focus on clay mineral diagenesis, spatial variability and to determine the impact of clay minerals on porosity and permeability. This comprehensive approach seeks to enhance reservoir characterization and inform effective hydrocarbon recovery strategies, contributing to more resilient energy solutions for an increasingly industrialized world.

## II. GEOLOGICAL SETTING OF ANAMBRA BASIN

The West and Central African Rift System (WCARS) basins, which began to develop in the Early Cretaceous, include Nigeria's Anambra Basin (Abubakar, 2014). when the South Atlantic Ocean began to open up as Gondwana began to break apart (Fairhead, 1988; Benkhelil, 1989). Following the post-deformational sedimentation stage in the evolution of the Benue Trough, the basin was created, and then Santonian inversion tectonics occurred throughout the basin (Obaje, 2009; Mode *et al.*, 2016). The Anambra Basin is one of seven sedimentary basins in Nigeria, featuring a structural depression at the southwestern margin of the Lower Benue Trough. It covers an area of 40,000 km<sup>2</sup> and stretches across Nigeria's Anambra, Enugu, and Ebonyi states, and extends southwards to part of Delta state, northwards into Benue and Kogi states, and westwards to the Edo province (Akaegbobi *et al.*, 2000; Edegbai *et al.*, 2019). Geological, well/core data, gravity, magnetic and seismic modelling have shown that the Anambra Basin contains a >6 km thick sedimentary succession, representing a sequence of continental, deltaic, and marginal marine sedimentation (Agagu and Adighije, 1983; Obasi *et al.*, 2018; Dim *et al.*, 2019; Omietimi *et al.*, 2021). The basin's earliest sediments are from the Campanian epoch, and deposition persisted throughout the Late Cretaceous into the early Paleogene.

### A. Stratigraphy:

The Asu-River Group has varied lithologic units, dark grey to black colored shale, variously ferruginized, deposited in environment varying from continental through marginal marine to open marine systems (Ola-Buraimo and Akaegbobi, 2013). This is covered by Eze-Aku. The formation, which is made up mostly of black shale, is from the Late Cenomanian to Turonian periods (Ola-Buraimo, 2013a). The overlying sequence is Awgu Shale dated Coniacian (Ola-Buraimo, 2013b) marked the end of the first phase of sedimentation in Anambra Basin before the commencement of tectonic event in the Santonian. The dislocation of the depocenter into the Anambra platform resulted into the deposition of the Nkporo Shale (Nwajide, 1990). The Nkporo Group comprises of Nkporo Shale, Owelli Sandstone, and Enugu Shale dated Late Campanian (Reyment, 1965; Obi, 2001). However, study based on palynology has dated the Asata/Nkporo Shale to be Campanian-Lowest Maastrichtian age (Ola-Buraimo and Akaegbobi, 2013). Mamu Formation, which was laid during the Early Maastrichtian, covers the Nkporo Shale (Kogbe, 1989; Obi, 2000). Sandstone, siltstone, shale, and coal seams make up its composition (Kogbe, 1989). Recently, pollen and spores found in the Mamu Formation were used to determine that its age falls between the Lower and Middle Maastrichtian (Ogala *et al.*, 2009). The Mamu Formation is covered by the Maastrichtian-age Ajali sandstone (Reyment, 1965; Nwajide, 1990). The sandstone is characterized by mudstone and siltstone in nature (Kogbe, 1989), is unconsolidated, has a coarse to fine grain size, and has poor cementation. The Ajali Sandstone is overlain by diachronous Nsukka Formation (Maastrichtian- Danian) which is also known as Upper Coal Measures (Reyment, 1965); Imo Shale (Paleocene) overlies the Nsukka Formation (Nwajide, 1990) while it is successively overlain by Ameki Group, dated Eocene (Obi, 2000). This is followed by Ogwasi Asaba Formation, composed of dark grey shale and sandy shale; characterized by evidence of sediment reworking; dated Late Miocene-Pliocene (Ola-Buraimo and Akaegbobi, 2012). The most recent sediment is the Benin Formation deposited by fluvial processes is suggested to belong to Pliocene to Recent in age based on stratigraphic position (Figure 1).

## III. DATA AND METHOD

The representative sandstones from Akukwa-1, Akukwa-2 and Idah-1 wells from Anambra Basin were obtained from the Nigeria Geological Survey Agency (NGSA) and subjected to scanning electron microscopy coupled with energy dispersive spectroscopy (SEM+EDX) analysis. The smooth and fresh rock chips of samples were prepared and then mounted on the sample stub of SEM. The sandstone samples were mounted with the help of the conductive double-sided carbon solution tape. The sample stub was then mounted in the sample chamber JEOL JSM-6590LV of SEM, which is also equipped with an extra and important accessory component, Bruker of energy dispersive X-ray spectrometer (EDX) in SEM whereas in the EDX is the QUANTAX. The desired images were taken and controlled from computer to study the various morphological features and compositions of the sandstones. SEM is not just taking pictures of the morphology of the mineral, but also looking down into the pores, identify the smallest minerals, and

examine the distribution of these minerals within the pores. While Energy Dispersive X-ray spectroscopy (EDX) is an analytical technique used to analyze elements and chemical characterization of a sandstones. The measurement of chemical elements by EDX is done by analyzing the X-ray beam from

the sandstones produced by moving electrons. SEM-EDX must be operated with electron parameter settings such as high voltage, spot size, bias and beam current as well as optical parameters such as contrast and proper focus to obtain scientifically optimal image results.

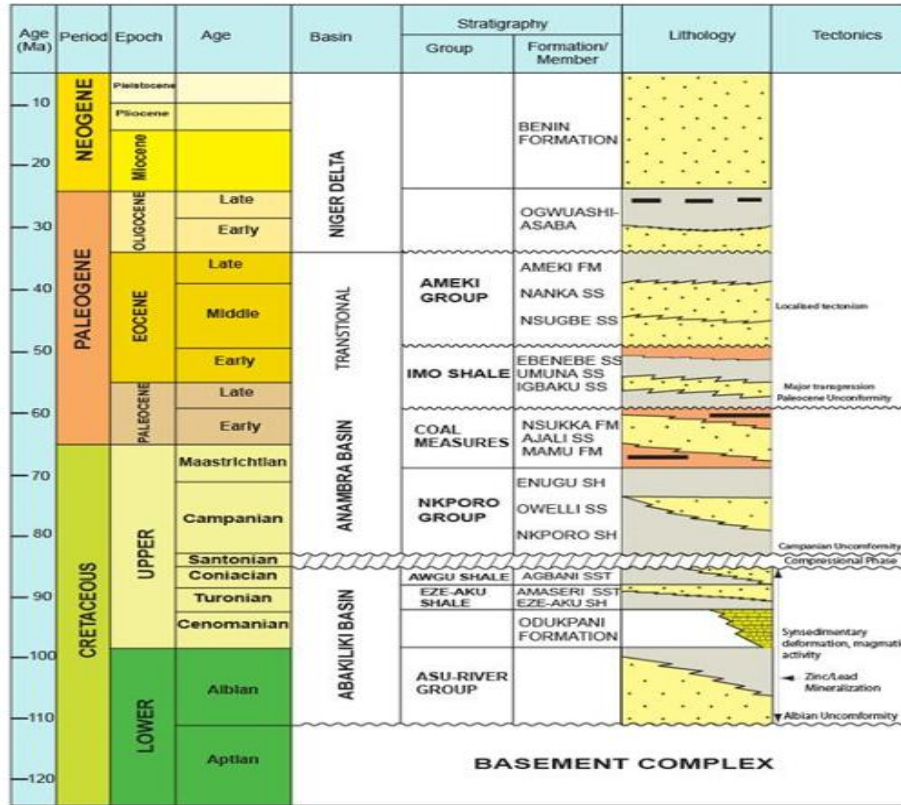


Figure 1: Stratigraphic Succession in the Anambra Basin and Outcropping Niger Delta (Ekwenye and Nichols, 2016).

IV. RESULTS AND DISCUSSION

This study analyzed SEM-EDX microphotographs to understand how different clay minerals morphologies influence the petrophysical characteristics of the sandstone reservoirs from Anambra Basin and identified the diagenetic processes affecting the pore system.

*Clay Mineral morphology and the Influence on Reservoir Quality Akukwa-1 well:*

The observation of sandstone from Akukwa-1 in SEM-EDX show a pore-filling clay mineral in Figure 2 and the EDX showing the element spectra of the clay minerals focused. SEM images indicated authigenic blocky (stacked) kaolinite books that occurs as face-to-face stacks and the existence of micropores between the detrital grain boundaries with a typical fibrous morphology of illite-smectite mixed layer clays formed during burial diagenesis (Figure 2). The stacked morphology indicates authigenic growth under relatively static conditions in closed microenvironments. The fibrous illite-smectite mixed layer clays are common intermediate products in the burial transformation of illite to smectite at increasing temperature (60-120°C) and, appear as interwoven filaments within the pore spaces and these morphologies are consistent with

diagenetically derived clay minerals formed during burial and alteration of detrital precursors (Tucker 2001; Akinlotan *et al.* 2022). The occurrence of stacked kaolinite together with fibrous illite-smectite mixed layer clays implies that the formation occurred at intermediate burial depths, under variable pH and potassium availability. The identification of microporosity aids in evaluation of overall reservoir porosity and Kaolinite which occurred as pore filling clay mineral completely or partially fills the available pore space from fluid flow and this has a severe sealing effect and may stop fluid flow in the reservoir. The fibrous illite-smectite mixed layer clays can significantly reduce permeability especially when present in pore throats and may cause formation damage during hydrocarbon production. (Tucker 2001; Akinlotan *et al.* 2022).

*Clay Mineral morphology and the Influence on Reservoir Quality in Akukwa-2 well:*

The clay morphology of sandstone from Akukwa-2 is described a chlorite mineral coating the detrital grains (arrowed) and the EDX showing the element spectra of the clay minerals focused. SEM images indicated individual chlorite platelets oriented on edge, with faces perpendicular to the detrital grain surfaces (Figure 3).

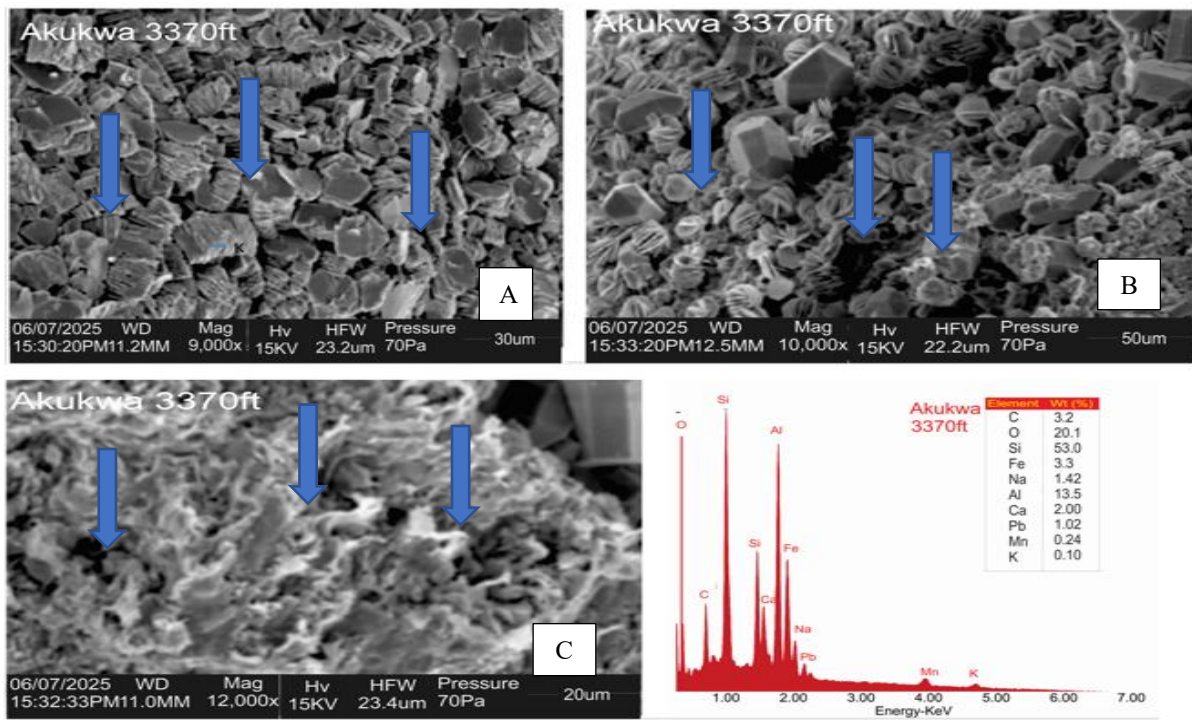


Figure 2. Microphotographs of sandstone from Akukwa-1at different magnifications (A, B and C), SEM images indicates blocky kaolinite books that occurs as face-to-face stacks and fibrous illite-smectite with the existence of micropores and the EDX element spectra taken at the areas focused in the SEM images.

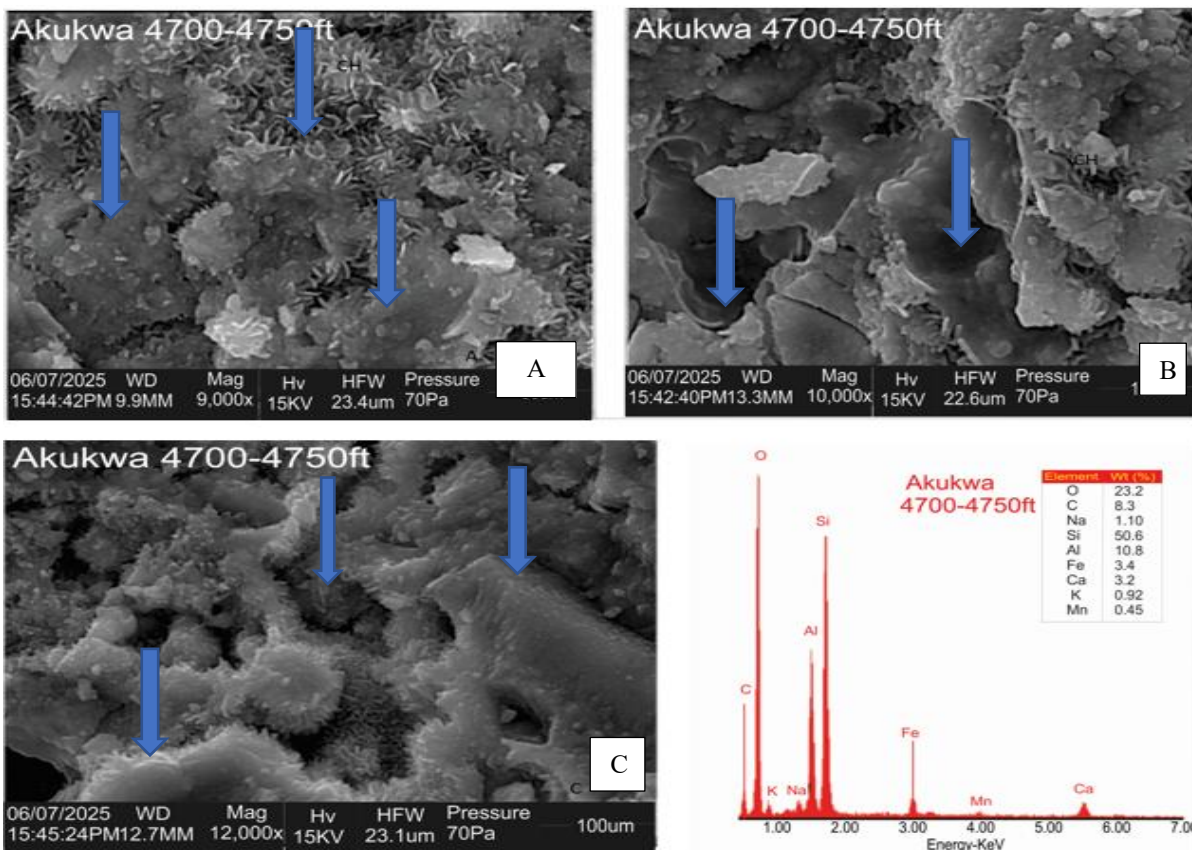


Figure 3. Microphotographs of sandstone from Akukwa-2 at different magnifications (A, B and C), SEM images indicates individual chlorite platelets oriented on edge, with faces perpendicular to the detrital grain surfaces and the EDX element spectra taken at the areas focused in the SEM images.

This type of clay morphology represents a distinct diagenetic feature with important implications for porosity preservation and cementation control in reservoir sandstones and highlights the importance of early diagenetic processes in the basin’s diagenetic evolution (Worden *et al* 2020). Chlorite coatings on detrital grains can also function as fluid flow barriers, resulting in a considerable reduction in hydrocarbon extraction and a rise in water retention. Chlorite’s influence extends to well productivity, as it contributes to clay swelling and impacts the reservoir’s response to stimulation treatments like hydraulic fracturing and acidizing. Chlorite coatings in deeper sandstone reservoirs, however, can have a stabilizing effect by preserving primary intergranular porosity from compaction and inhibiting quartz overgrowth, which reduces nucleation (Worden *et al* 2020). While this protection can enhance reservoir quality, excessive authigenic chlorite may fill reservoir space further reducing porosity.

*Clay Mineral morphology and the Influence on Reservoir Quality in Idah-1 well:*

The clay morphology of sandstone from Idah-1 is described as pore-filling chlorite mineral. SEM images indicates individual chlorite platelets exhibiting jagged or irregular edges (arrowed) coated on the detrital quartz grain (Figure 4) and the EDX showing the element spectra of the clay minerals focused. The chlorite with irregular or jagged morphology reflects moderate burial and temperatures (100-150°C) typical of intermediate diagenesis and indicates localized fluid flow events which can cause heterogeneity in diagenesis and reservoir quality (Worden *et al* 2020). The irregular or rough edges can also reduce permeability by obstructing pore throats more effectively. The chlorite in the SEM is a pore-filling clay mineral, they are normally deposited on the inner surface of the pores and the resultant effect is the restriction of fluid flow (Worden *et al* 2020). The gradual precipitation overtime will reduce the flow circumference of the pores, thereby limiting flow efficiency.

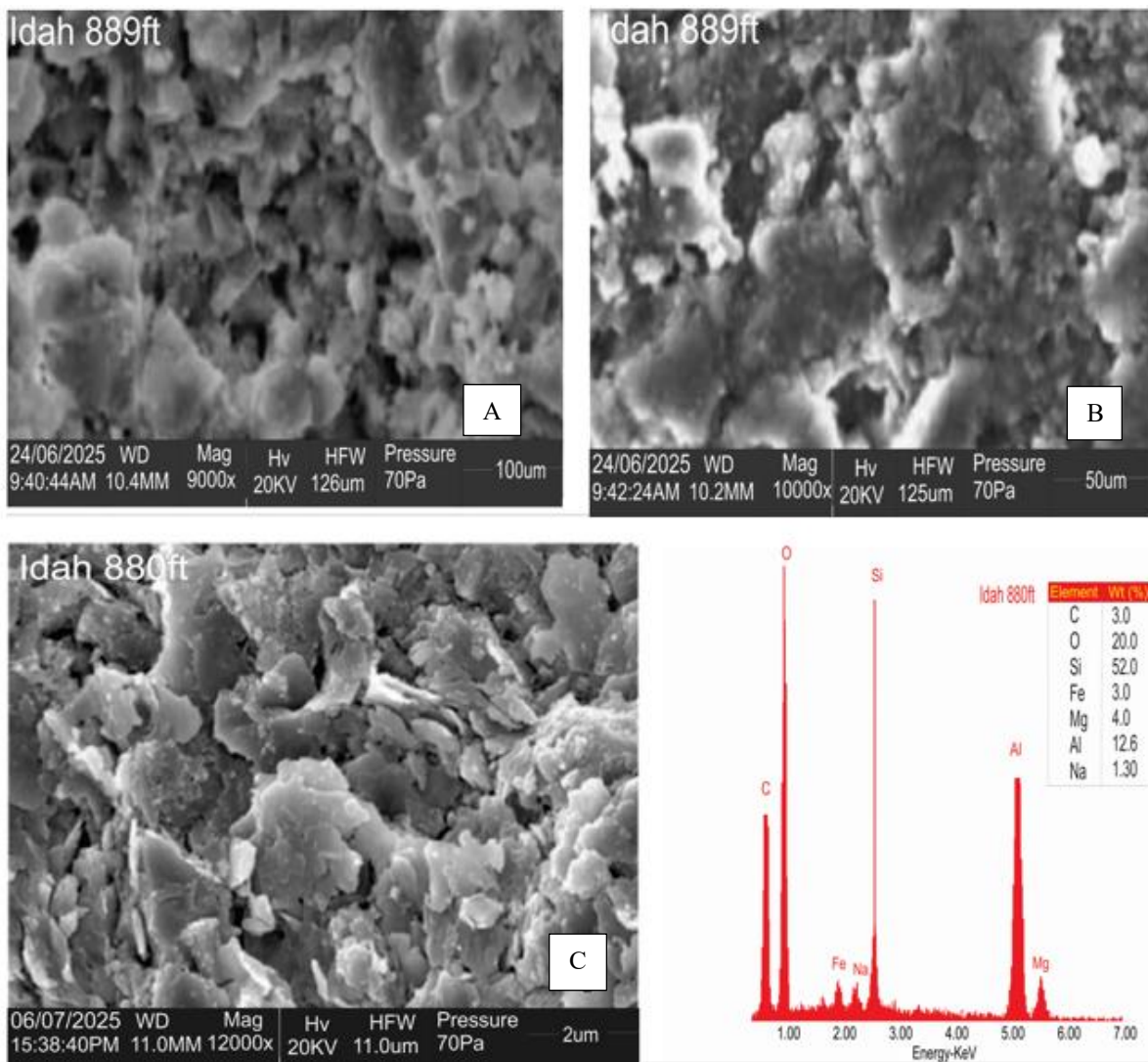


Figure 4. Microphotographs of sandstone from Idah-1 at different magnifications (A, B and C), SEM images indicates individual chlorite platelets exhibiting jagged or irregular edges (arrowed) coated on the detrital quartz grain and the EDX element spectra taken at the areas focused in the SEM images.

## V. CONCLUSIONS

SEM-EDX techniques allow for the identification of different morphologies of clay minerals and the observation of representative sandstones from Anambra Basin under the SEM-EDX confirm the presence of kaolinite, chlorite and illite-smectite mixed layer clays which significantly reduce effective porosity and permeability by contributing to pore space filling and restriction of fluid flow in the sandstone reservoirs.

Kaolinite occurs as a pore-filling clay in AKukwa-1 and significantly impact on the porosity with fibrous illite-smectite having an impact on permeability. Chlorite platelets observed in Akukwa-2 inhibit quartz secondary overgrowth by coating the detrital grains and prevents porosity loss. While the Chlorite observed in Idah-1 occur as pore-filling clay mineral and blocks the pore spaces.

These findings enhance the understanding of clay mineral distributions in sandstone reservoirs and provide valuable insights for hydrocarbon exploration and production.

*Acknowledgments:* The authors are grateful to the Nigeria Geological Survey (NGSA) for providing the sandstone samples used for the study.

*Conflicts of Interest:* The authors declare no conflicts of interest.

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