



Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

**GEOLOGY, RESERVOIR DIAGENESIS AND QUALITY OF ALBIAN -  
CENOMANIAN KEANA /AWE POTENTIAL RESERVOIR SANDSTONE IN  
MIDDLE BENUE TROUGH, NIGERIA**

**<sup>1</sup>\*Yusuf, I., <sup>1,2</sup>Obaje, N. G., <sup>1</sup>Adeoye, J. A., <sup>3</sup>Adamu, L. M. and <sup>4</sup>Yusuf, T.U.**

<sup>1</sup>Department of Geology & Mining, Ibrahim Badamasi Babangida University, Lapai,  
Niger State, Nigeria

<sup>2</sup>NNPC Professorial Chair in Basinal Studies

<sup>3</sup>Department of Earth Sciences, Kogi State University, Anyigba, Kogi State, Nigeria

<sup>4</sup>Department of Physics, Ibrahim Badamasi Babangida University, Lapai, Niger State,  
Nigeria

**\*Correspondence:** ishaq.yusuf@yahoo.com; 08036317988

**ABSTRACT**

The Keana/Awe formations constitute important reservoirs across the Middle Benue Trough, North-central, Nigeria. Ongoing 3D seismic data acquisition in search of hydrocarbon deposits in the Middle Benue Trough has necessitated the need to enhance geological and geophysical data to minimize exploration risk. In this study, surface outcrops were mapped and described to determine depositional environment and further subjected to petrographic description, petrographic image analysis (PIA) and scanning electron microscopy (SEM) to evaluate reservoir quality of the sandstone formation. Geological field mapping reveals light gray to white, fine to coarse-grained, sub angular to rounded, moderately to poorly sorted sandstones which are calcareous at some sites and bioturbated with vertical and horizontal worm (*Rhizocorallium*, *Diplocaterion*, and *Skolithos*) burrows at other locations. It exhibits structures such as graded bedding; fining and coarsening upward pattern at Old Awe/Tsoho-Gari, Trough cross-bedding at Tunga, Ribi and Tsoho-Gari. At Gidan Barenyi-Tsoho Guaria road and Tsoho Gari, an observed high-low angle and directional tabular cross-bedding, Ripple marks at Abuni and sinistral sense of fault movement of 10 cm at Tsoho-Gari, joints around Old Awe/Tsoho Gari, Gidan Osande - Gara road and fold generally trending NW- SE with fold plunge direction of 145° and plunge amount of 064° as observed at Tsoho Gari. All these are inferred to influence of tides in a shallow marine which supports fluvio-deltaic depositional environments. Results from integration of petrography, petrographic image analysis (PIA), and SEM analysis highlights reservoir diagenesis processes of a mechanical grain compaction and cementation; calcite and siderite are main authigenic minerals resulting in reduction and obliteration of intergranular pore spaces ranking the Keana/Awe reservoir



## Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

---

sandstone a moderate reservoir quality grade formation with porosity of  $\phi = 10.91\%$  and calcite cement of 33% composition.

**Keywords:** Reservoir, Sandstone, *Rhizocorallium*, *Diplocaterion*, *Skolithos*

### INTRODUCTION

Ongoing 3D seismic survey in search of hydrocarbon deposits in the Middle Benue Trough has necessitated the need for new surface information to minimize exploration risk as frontier basins are synonymous to both exploration success and failure. The Middle Benue Trough is amongst the Nigerian frontier inland basins with no exploratory well drilled into her stratigraphy till date as recorded in the Nigeria's sector of the Chad basin, Anambra, Dahomey and Upper Benue Trough basins. Benue Trough of Nigeria is a rifted basin in central West Africa that extends NNE-SSW for about 800 km in length and 150 km in width. The trough is arbitrarily subdivided into a lower, middle and upper portion (Figure 1), No concrete line of subdivision can be drawn to demarcate the individual portion, but major localities (towns, settlements) that are constitute the depocentre of the different portions have been well documented (Nwajide, 1990; Idowu and Ekweozor, 1993; Obaje *et al.*, 1999; and Obaje 2019). It contains up to 6000 m of Cretaceous - Tertiary sediments of which those predating the mid-Santonian have been compressionally folded, faulted and uplifted in several places. From recent exploration field geological mapping conducted by the Nigerian National Petroleum Corporation Professorial Chair team as the Nigerian National Petroleum Corporation (NNPC) proposed testing the basin. (Obaje *et al.*, 2021), concluded that the intercalated sandstones in all the pre-Santonian formations and the widespread sandstones of the Keana-Awe Formation can provide potential reservoirs within the basin. These studies intend to evaluate the potential reservoir properties at microscale to visualize pore space distribution, pore interconnectivity, diagenesis and general reservoir quality to potentially evaluate exploration risk as it impacts of fluid flow and transmissivity within the reservoir rock through petrographic and microscopic point of analysis to compliment ongoing geophysical subsurface data

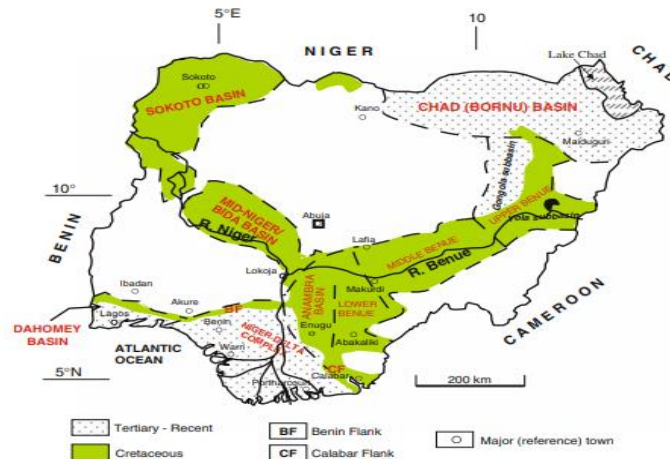


Fig 1: Map of Nigeria showing the Middle Benue Trough amongst other Sedimentary Basins (after Obaje, 2019)

### Sedimentological and Stratigraphy of the Middle Benue Trough

In Middle Benue Trough, around Obi/Lafia area, six (6) Upper Cretaceous lithogenic formations comprise the stratigraphic succession (Figure 2). This succession is made up of Albian Arufu, Uomba and Gboko Formations, generally referred to as the Asu River Group (Offodile, 1976; Nwajide, 1990; Obaje, 2019). These are overlain by the Cenomanian Turonian Keana and Awe Formation and Cenomanian – Turonian Ezeaku Formation. The Ezeaku Formation is contaminant with the Konshisha River Group and the Wadata Limestone in the Makurdi area. The Late Turonian – Early Santonian coal bearing Agwu Formation lies on conformably on Ezeaku Formation. In the Makurdi area, the Makurdi Sandstone interfingers with the Awgu Formation. The mid-Santonian was a period of folding throughout the Benue Trough. The post-folding Campano-Maastrichtian Lafia Formation ended the sedimentation in the Middle Benue Trough, after which widespread volcanic activities took over in the Tertiary (Figure 2).

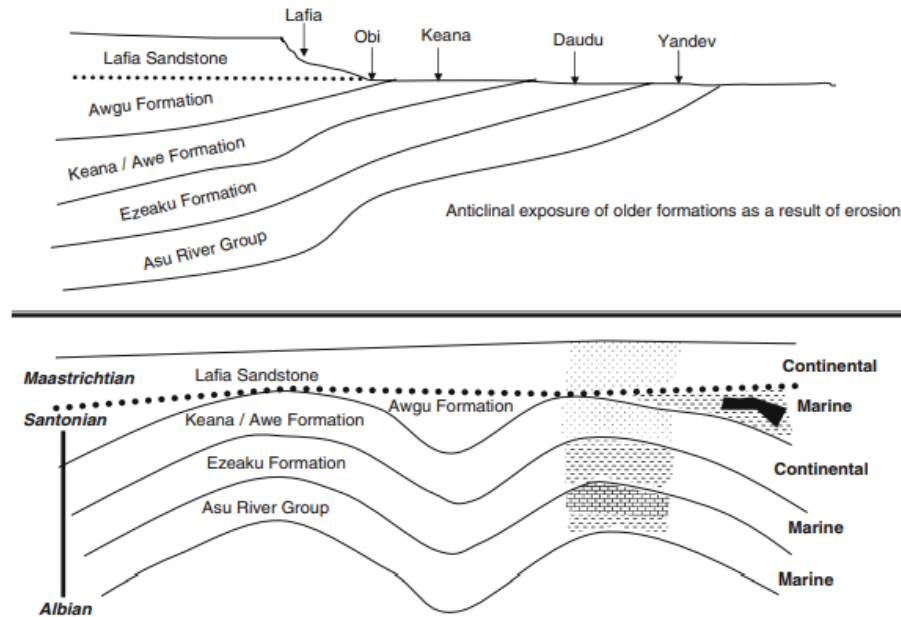


Fig 2: Stratigraphic successions in the Middle Benue Trough (after Obaje, 2019)

## MATERIALS AND METHODS

Investigation includes field mapping and description of the Keana-Awe formation, collection of twenty (2) rock samples followed by a petrographic thin sectioning for sedimentological grain assemblage descriptions (grain size and shape), petrographic image analysis (PIA) for pore space, matrix and grain mass quantification. Scanning electron microscopy imagery (SEM) is use to visualize pore attribute geometry as effected by the mineral diagenetic alterations and burial compaction.

## RESULTS AND DISCUSSION

### Field Mapping and Descriptions

The rocks were carefully described, logged and sampled for the purpose of this report and other laboratory studies. Below is the summary of the location of the potential Awe and Keana sandstone formations visited in the Middle Benue Trough:



## Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

---

### **Keana/Awe Formation**

The Keana-Awe formations are lateral equivalents overlying the Asu River Group with type sections in Awe and Keana respectively. They are transition beds of Late Albian to Early Cenomanian regression dominated by fluvio-deltaic sandstones with interbeds of shales and claystones. The fieldwork findings are described below.

- i. *Localities/coordinates*: Outcrops were mapped, logged and sampled along stream channels of Awe/Tsoho town (N08°06'01.9", E009°07'47.6"), Tsoho-Gari (N08°06'08.0", E009°07'40.7"), Tunga (N08°00'03.4" E009°19'41.5") and Gidan Barenyi-Tsoho Guaria road (N080° 05' 36.3" E009° 06' 21.0").
- ii. *Lithofacies Description*: The rock types are dominantly coarse-grained feldspathic sandstones, conglomerates, shales, mud rock, and siltstone (Fig. 3).
  - Sandstones: Consist light gray to white, fine to coarse-grained, sub angular to rounded, moderately to poorly sorted sandstones which are calcareous in some locations` (Fig 3a). They are bioturbated with vertical and horizontal worm burrows (Fig 3c).
  - Shale: Grey to milky white, laminated, and fissile with white bands of limestones. This rock unit generally trends in NE-SW direction with dip of 26° E – 36° E. It's about 16 m thick at old Awe (type locality).
  - Mudrock: Massive, light brown to light-gray rock.
  - Siltstone: It is light to dark gray, micaceous, bedded and baked
- iii. *Structures*: There are a lot of interesting features which are both tectonically and post depositional induced in this formation as described below.
  - Graded bedding: typical of sandstones with both fining and coarsening upward pattern observed at Old Awe/Tsoho-Gari.
  - Trough cross-bedding: Common on the sandstone with azimuth trends of 170° and 002° at Tunga, 169o at Ribí and 150°, 002°, 176° at Tsoho-Gari.



## Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

---

- Tabular cross-bedding: High-low angle and directional tabular cross-bedding observed on the sandstones at Gidan Barenyi-Tsoho Guaria road (N080° 05' 36.3" E009° 06' 21.0" 142m) and Tsoho Gari.
- Ripple marks: On the sandstones observed at Abuni (N08°11'30.7" E009°03'07.1" 137 and N08°11'25.7" E009°02'52.4" 148m).
- Fault: Sinistral sense of movement of 10cm at Tsoho-Gari (N080 06' 08.0" E0090 07'40.7" 105m).
- Joint: At Old Awe/Tsoho Gari trends 050°, 051°, 062°, 150°, 146°, 028°, 108°, and Gidan Osande - Gara road 078°, 044°, 077°, 154°, 151°, 122°.
- Fold: The general trend of the fold is NW- SE with fold plunge direction of 145° and plunge amount of 064° as observed at Tsoho Gari (N08°06' 08.0" E009° 07' 40.7" 105m).
- Bioturbation: A post depositional structure observed at Old Awe/Tsoho Gari consisting *Rhizocorallium* (horizontal to subhorizontal u-tube with *spreite*), *Diplocaterion* (vertical u-tube with *spreite*), *Skolithos* (simple straight tube) are rounded burrows and Typanites (Boring traces into hard substrate).

From field description, observation reveals graded bedding which are inferences of a typical river setting with ripple, tabular and trough cross bedding structures. These features all point towards actions of the rivers as well as the influence of tides in a shallow marine which however supports the fluvio-deltaic depositional environments of the earlier authors.



Fig. 3: Outcrops of Awe Sandstone with different bedding structures A. Massively bedded calcareous coarse grained sandstone exposed at Old Awe village, B. Trough cross-bedded poorly sorted coarse grained sandstone exposed at Ribi village (salt mine), C. Trough cross-bedded, feldspathic, fine grained sandstone exposed at Tunga village. D. Laminated Sandstone facies of Awe/Keana Formation exposed in Ribi village

### **Petrography and Petrographic Image Analysis (PIA)**

Petrographic description reveals a poly crystalline medium to coarse grain of quartz and calcite grain minerals (Fig 4). The calcite minerals are poly crystalline, angular to sub-angular in size and shape. While quartz aggregates vary from medium to coarse grains and generally poorly sorted grains. Minerals grains of quartz, calcite and feldspar exhibit



## Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

---

intergranular compaction indicated by suturing joining as result of pressure-solution during early burial compaction. It also shows minor occurrence of pore filling siderite (in dark-brown) and feldspar dissolution that lead to the development of a secondary pore space depicted by red arrows (Fig 4c). The sandstone composes of high calcitic cements that may have result from precipitation of calcium oxide to calcium carbonate during burial and diagenetic alteration, thereby obliterating most of the primary intergranular pore spaces. Initial porosity in the sample is reduce to 10.91% (Fig 4b) with quartz grain composition of about 53.43%, feldspar of 2.66% composition and calcite cement of 33% substituting for matrix content. The effect of the calcite cement is wholly noticeable in the field due to the very massive nature and resistance to breaking during the sample collection. Petrographically, the Awe/Keana sandstone heavily calcified as a result of it high composition of calcite mineral at about 33 % and thus destroys intergranular pore space and reduction of it reservoir potential.

### **Diagenesis of the Awe/Keana Sandstone formation**

The diagenetic study of the Awe/Keana comprised following major diagenetic processes examined on macroscopic scale in the field and microscopic scale. This evaluation is of utmost importance in case of the Awe/Keana sandstone formation, because the diagenetic processes may either impede fluid flow (Yusuf and Padmanabhan, 2019) or it may provide selective passageways for the lateral migration (Yusuf & Padmanabhan, 2019) of fluids as diagenetic processes have influential control on the subsurface fluids dynamic and subsurface porosity distribution. Petrographic and SEM studies reveals several diagenetic processes mainly compaction, cementation, and moderate dissolution had affected the Awe/Keana sandstone formation. Massive lithification and resistance to breakage in the field (calcitic-cementation) is a visible diagenetic process that has been noted on macroscopic level in the field (Fig. 3). All the diagenetic features in the sample are shown in Figs. 4 and 5 respectively.





## Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

---

### **Cementation**

The cementation is distributed diagenetic event in the Awe/Keana sandstone (Fig. 4 & 5). The identified cement types and cement fabric in the sandstone is mainly blocky calcite cement (Fig.4). This type of blocky cement is well developed and occupying the intergranular pore space (Fig. 4c & d). This type of cement is established during the meteoric-phreatic diagenesis (Khalifa et al. 2009; Abu-El Ghar et al. 2015). In meteoric-phreatic zone, the intergranular pores are predominantly filled with water where cementation is more uniform with crystal growth (Fig. 5c & d) that produces larger crystal size of blocky calcite cement (Tucker and Wright 1990).

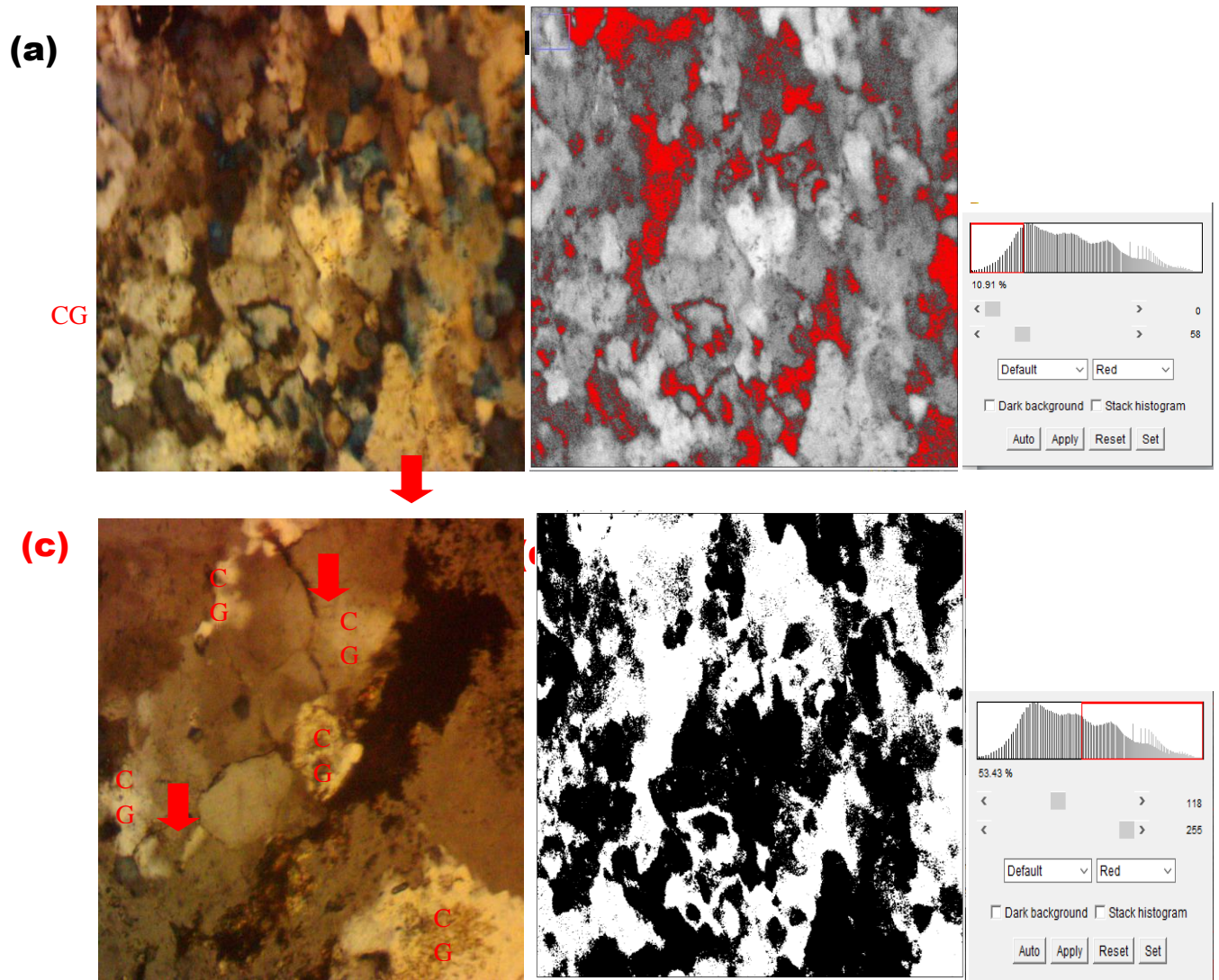


Fig 4: Thin section of Awe sandstone (a) poly crystals of calcite grains (CG) intermixed with sub-rounded to rounded mono crystalline quartz grains (b) Threshold imaging of pore spaces covered in *red* of about 10.91% porosity (c) calcite grain in suturing with quartz, feldspar grain and suspected siderite (dark-brown) pore-filling carbonate mineral (d) Threshold image mapping of poly crystalline quartz grains covered in black colour of about 53.43%, while masses in *white* colour are poly crystalline calcite cement at 33% respectively.



## Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

---

### **Compaction**

The compaction process affected the Awe/Keana formation after deposition that led to physical and chemical reorganizations and variations in the bulk volume of sediments. More visible type of compaction in the field at macro scale (Fig.3) and microscopic level is the mechanical compaction (Fig. 4 and 5). Mechanical compaction is much more evident and noted in the studied samples.

The order of the practical features of mechanical compaction includes closer packing of grains, close grain contacts and decrease of primary intergranular porosity (Figs. 4a, c & 5a & b; Mahboubi et al. 2010). The grains have been squeezed because of burial or tectonic load that results in closer packing of sediments (Fig. 5a & b). However, when the brittle or ductile strength of the grains are exceeding, then breaking of grains and fracturing take place (Fig. 5b). It also decreases porosity and substantial reduction of sediment thickness (lithification) occurs through closer packing and sediments squeezing (Vincent *et al.*, 2007). It is challenging to infer whether grain fractures may occur at shallow burial or uplift in deep burial realm of sediments.

### **Impact of diagenesis on reservoir quality**

From petrophysical evaluation, diagenetic process is the key controlling factor on the reservoir quality that plays both constructive and destructive role upon the pore volume distribution and pore-wall alteration in potential reservoir rock (Taghavi *et al.*, 2006; Tavakoli et al., 2011; Abuseda et al., 2015). The heterogeneities in the petrophysical properties caused by the diagenetic processes have reflective impact on the reservoir quality of the Awe/Keana sandstone. These diagenetic processes are mainly two types in order to show their impact on reservoir quality of the Awe/Keana formation

### **Diagenetic processes**

The cementation in the reservoir sandstone is the main diagenetic mechanism that reduces pore spaces and volume distribution (porosity) (Fig. 4 & 5). The key porosity impeding cements precipitated in the early diagenetic phase of the reservoir sandstone where intergranular pore



## Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

---

spaces filled by the calcite cements and diminishing the reservoir potentiality. The impact of cementation on reservoir porosity is very obvious by its reduction to 10.91%. The sandstone that has more than 30% calcite cement and later diagenetic blocky calcite cement filled intergranular pore space where cement minimizes flow pathways pore related attributes including pore size and pore throats in this way reduces reservoir quality of the Keana/Awe reservoir sandstone formation (Fig. 4; Westphal et al. 2004).

The mechanical compaction due to overburden pressure as sediments undergoes burial that have result in closer packing, sutured contacts and tight/packed rock pattern formation within the sandstone (Fig. 4c). These features obliterate all intergranular pore spaces or either completely diminished pore throats or decrease pore size. Thus, all shown features of mechanical compaction reduce the reservoir quality of the reservoir sandstone.

### **Reservoir Quality**

Diagenesis as it effects the Awe/Keana potential reservoir sandstone focusing on primarily on changes in porosity and permeability distribution and potential. Porosity and permeability are initially controlled by depositional condition of the sediments, but subsequently altered through diagenesis. It can observe generally that the grains are experiences compaction and mineral alterations at micrometer scale (Fig. 5).

At this scale, the medium angular to sub-angular grains are moderately sorted and randomly diagenetic alter mineral that have potential effect on intergranular pore space. Primary intergranular pore spaces are filled by authigenic carbonate minerals; calcite and siderite thereby obliterating intergranular pore space (Fig 5c-d) as a pore-filling mineral.

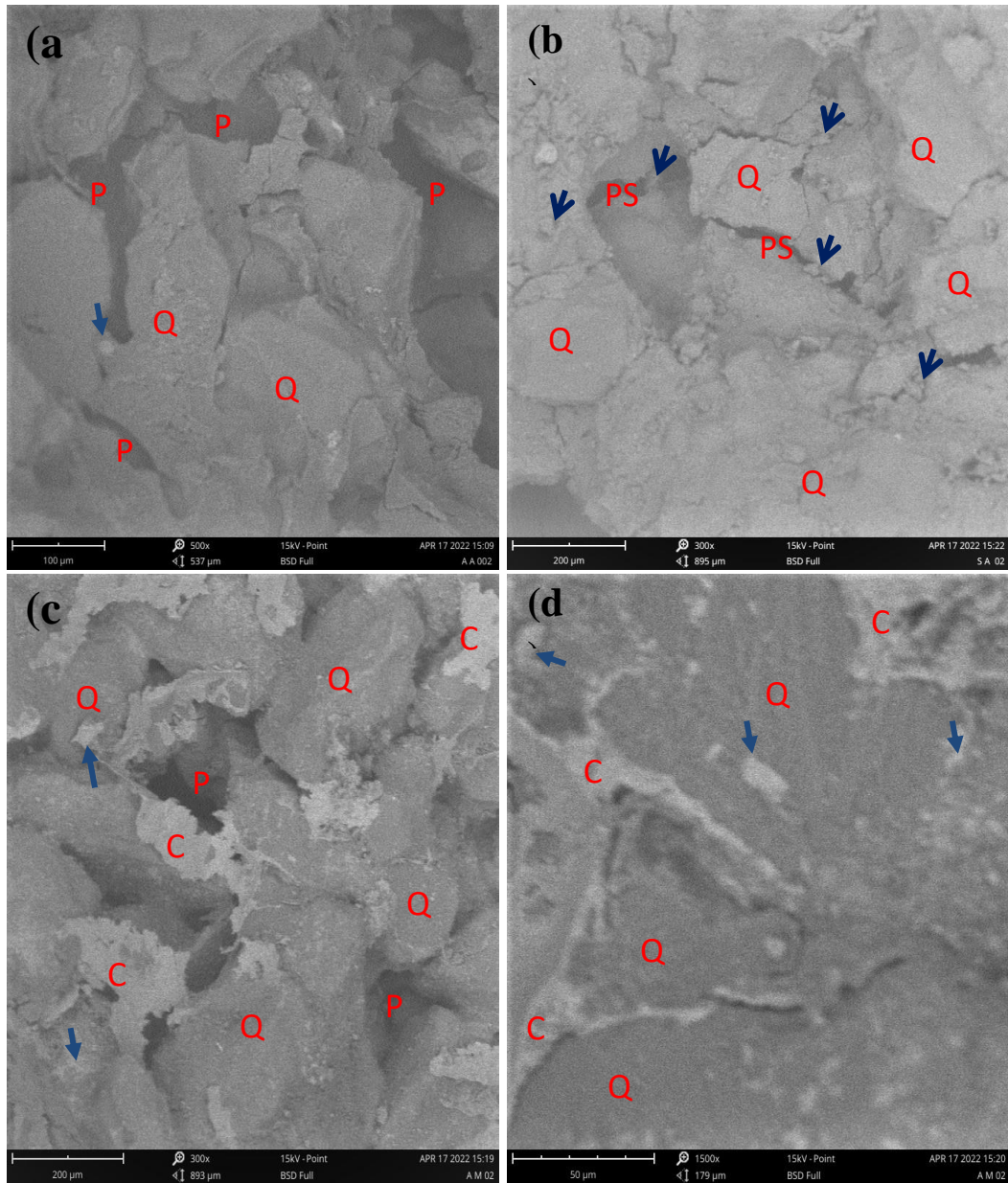


Fig 5: SEM Micrographs diagenesis and reservoir quality alteration (a) pore space (PS) distribution within quartz medium to coarse grains (QG) (b) shows fragments of authigenic siderite clogging pore spaces depicted in dark-blue arrows (c) pore spaces (PS), quartz grain (QG) and calcite cements (CC) obliterating pore spaces by clogging intergranular pore connectivity (d) Calcite cements fully clogging



## Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

---

It effects the distribution and interconnectivity of potential effective pore space (porosity) that are the major parameter in fluid storage and transmitivity in a reservoir rock. The randomly disperse (Fig 5) authigenic siderite within pore wall potentially alters pore tortuosity resulting from the effect of their roughness impacted on the pore-walls. This will potentially contribute to lower the ease of fluid transmitivity (permeability) within the reservoir rock or into the future wellbore in the basin. In general, intergranular pore-filling of pore space, pore throats by carbonate cement and alteration of pore walls by fine grained siderite destroys pore interconnectivity and invariably will have negative potential on effective porosity distribution and permeability of the reservoir rock.

### CONCLUSION

The Keana/Awe formations surface outcrop samples were map, log and subjected to petrographic description, petrographic image analysis (PIA) and scanning electron microscopy (SEM) to describe their reservoir quality. Geological field mapping reveals the formation as a light gray to white, fine to coarse-grained, sub angular to rounded, moderately to poorly sorted sandstones which are calcareous at some sites and bioturbated with vertical and horizontal worm (*Rhizocorallium*, *Diplocaterion*, and *Skolitho*) burrows at other locations. Interesting sedimentary structures such as graded bedding, Trough cross-bedding, tabular cross-bedding, ripple marks, sinistral sense of fault and general fold that trend NW- SE are observed in the field. These observations made infer the influence of tides in a shallow marine which also supports the fluvio-deltaic depositional environments as documented by earlier workers. Results from integration of Petrography and SEM analysis highlights observation mechanical grain compaction and carbonate cementation; calcite and siderite are mainly present as authigenic minerals by reduction and obliteration of intergranular pore spaces through diagenetic processes of precipitation, cementation and pore-filling. Petrographic image analysis (PIA), indicate a moderate reservoir quality for



## Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

the Awe/Keana potential reservoir sandstone formation with porosity ( $\phi = 10.91\%$ ) and calcite cement of 33%.

### ACKNOWLEDGEMENT

The Nigeria National Petroleum Corporation (NNPC) is gratefully acknowledged for providing the funds for this project through the Professorial Chair endowment at the IBB University, Lapai, Nigeria

### REFERENCES

- Abu-El Ghar, M. S., Khalifa, M. and Hussein, A. (2015) Carbonate diagenesis of the mixed clastic-carbonate Galala Formation, North Eastern Desert. *Egypt. Arab J Geosci.*, 8,2551–2565.
- Idowu, J. O. and Ekweozor, C. M. (1993) Petroleum potential of Cretaceous shales in the Upper Benue Trough, *Nigeria. J Petrol Geol.*, 21,105–118.
- Khalifa, M., Kumon, F. and Yoshida, K. (2009) Calcareous duricrust, Al Qasim Province, Saudi Arabia: occurrence and origin. *Q Int* 209,163–174.
- Mahboubi, A., Moussavi-Harami, R., Carpenter, S. J., Aghaei, A. and Collins, L. B. (2010) Petrographical and geochemical evidences for paragenetic sequence interpretation of diagenesis in mixed siliciclastic-carbonate sediments: mozduran Formation (Upper Jurassic), south of Agh-Darband, NE Iran. *Carbonates Evaporites* 25,231–246
- Nwajide, C. S. (1990) Sedimentation and paleogeography of the Central Benue Trough, Nigeria. In: Ofoegbu CO (ed) *The Benue trough structure and evolution*. Vieweg, Braunschweig, pp 19–38.
- Offodile, M. E. (1976) *The geology of the Middle Benue, Nigeria*. Palaentological Institute, University Uppsala, Special Publication 4,1–166.
- Obaje, N. G., Ulu, O. K. and Petters, S. W. (1999). Biostratigraphic and geochemical controls of hydrocarbon prospects in the Benue Trough and Anambra Basin, Nigeria. *NAPE Bull* 14:18–54
- Obaje NG, Abaa SI, Najime T, Suh CE (1999) Economic geology of Nigerian coals resources—a brief review. *Afr Geosci Rev* 6,71–82.
- Obaje, N. G. (2009). *Geology and Mineral Resources of Nigeria* (p. 240). Springer Verlag, Heidelberg, Berlin, New York.



## Lapai Journal of Science and Technology, Vol. 8, No. 1 (2022)

---

- Obaje, N. G. (2019). Update on Geology and Mineral Resources of Nigeria (p. 240). Springer Verlag, Heidelberg, Berlin, New York.
- Tucker, M. E. and Wright, V. P. (1990) Carbonate sedimentology. Blackwells Scientific Publications, Oxford
- Taghavi, A. A., Mørk, A. and Emadi, M. A. (2006) Sequence stratigraphically controlled diagenesis governs reservoir quality in the carbonate Dehluran Field, southwest Iran. *Petrol Geosci.*, 12,115–126.
- Tavakoli, V., Rahimpour-Bonab, H. and Esraflī-Dizaji, B. (2011) Diagenetic controlled reservoir quality of South Pars gas field, an integrated approach. *Comptes Rendus Geosci.*, 343,55–71.
- Vincent, B., Emmanuel, L., Houel, P. and Loreau, J. P. (2007) Geodynamic control on carbonate diagenesis: petrographic and isotopic investigation of the Upper Jurassic formations of the Paris Basin (France). *Sediment Geol.*, 197,267–289.
- Westphal, H., Eberli, G. P., Smith, L. B., Grammer, G. M. and Kislak J (2004) Reservoir characterization of the Mississippian Madison Formation, Wind River basin, Wyoming. *AAPG Bull*, 88,405–432.
- Yusuf, I. and Padmanabhan, E. (2019) Delineation of reservoir lateral continuity for flow zones in wells using cluster analysis: Case of West Baram Delta, offshore-Sarawak. *International Journal of Advanced and Applied Science*, 6, 20-32.
- Yusuf, I. and Padmanabhan, E. (2019) Impact of rock fabric on flow unit characteristics in selected reservoir sandstones from West Baram Delta Offshore, Sarawak. *Journal of Petroleum and Exploration*, 3,1-16.