



## Science Forum (Journal of Pure and Applied Sciences)

Journal Homepage: <https://atbu.edu.ng/science-forum/>



### Litho-Petro-Facies studies of the Cenomanian Awe/Keana sandstone, Middle Benue Trough, Nigeria: Implications for palaeodepositional environment and preliminary reservoir assessment

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#### ABSTRACT

*To assess the reservoir potential and distribution of the Cenomanian Awe/Keana sandstone in the Middle Benue Trough, Nigeria, this study focuses on the litho-petro-facies examination of the rock. To evaluate the facies characteristics, mineralogical composition, grain size distribution, diagenetic processes, and reservoir attributes at the microscale, field geological mapping, thin section petrography, and scanning electron microscopy (SEM) investigations were used. The study discovered two lithofacies associations in addition to nine lithofacies, including sandstone, shale, mudrock, siltstone, and heterolith facies. The glauconitic, fine-grained, and very fine-grained facies of the Awe/Keana Sandstone were further separated into arkose, subarkose, and feldspathic graywacke based on mineralogy. The subarkose falls within the craton interior margin, the arkose within the dissected arc, and the feldspathic graywacke within the recycled orogeny, with some samples exhibiting calcareous characteristics due to the presence of carbonate minerals, according to the QFL (Qt-Ft-Lt and Qm-Ft-Lt) ternary diagram. Detrital minerals such as quartz, orthoclase, microcline, plagioclase, biotite, muscovite, and clay minerals were found in the Awe/Keana Formation when the mineralogical makeup and diagenetic processes of the formation were also investigated. The primary diagenetic processes were determined to be cementation, mechanical compaction, dissolution, grain replacement, and recrystallization. Primary and secondary porosity, including primary intergranular and matrix micropores, were identified using petrographic and SEM analysis. The moderate porosity and permeability of the Awe/Keana sandstones point to their potential as advantageous hydrocarbon reservoirs, possibly requiring stimulation or fracking for the best extraction. The study also evaluated the sandstones' provenance and found that they could have originated from the crystalline basement complex rocks of the Oban and Cameroon massifs, which are found in the interior of cratons, dissected arcs, and transitional continental settings. The study's findings offer important information about reservoir quality, exploration risks, and decision-making for both academic and industrial drilling projects in the Middle Benue Trough.*

#### ARTICLE INFO

Received 12 November 2023

Received in Revised Form

14 November 2023

Accepted 15 November 2023

Published 15 January 2024

Available online 15 January 2024

#### KEYWORDS

Cenomanian,  
Diagenesis,  
Reservoir,  
Sandstone,  
Middle Benue Trough

## 1. Introduction

The West African Rift System, whose origin is cogenetic with the Early Cretaceous break-up phase of the South Atlantic Ocean, includes the multicycle Benue Trough. The Neocomian to Coniacian rift phase, the Santonian inversion phase, the Campanian to Danian sag phase, and the Thanetian to Recent passive margin phase make up the tectonostratigraphic evolution of the region. The Albian to Maastrichtian Middle Benue Trough Basin belongs to rift and inversion phases of the development of the Benue Trough, and its basin fill consists of the Asu River Group, Keana/Awe, Ezeaku, Awgu and Lafia Formations in stratigraphic order (Obaje, 2009; Fig. 1; Fig. 2). Inland basins such as Anambra, Bida, Chad, Sokoto, Southern Benue Trough, Northern Benue Trough, and my current basin of study, which is the Middle Benue Trough, have not recorded any significant exploration success due to the lack of understanding and complex geology in the basins. The inland basins are now receiving attention from the Federal Government and research to find more oil and gas. To increase the nation's exploration capacity and consequently increase the proven reserves, some exploration operations have been conducted in Nigeria's frontier basins.

However, previous studies on Nigeria have covered the southern, central, and northern Benue Trough, as documented in Offodile (1976), Benkheilil (1989), Nwajide (1990), Obaje et al. (1996), Obaje et al. (1999b), Obaje et al. (1999b), Obaje et al. (2004), Akande et al. (2012), Adamu et al. (2022), Yusuf et al. (2022), Adamu et al. (2023), and others. The majority of earlier research concentrated on information from regional studies of the Benue Trough, whereas only a few did so for the central Middle Benue Trough. These studies were mostly conducted using hydrogeological investigations, palaeontological investigations, geophysical investigations, coal resource characterization, and hydrocarbon potential assessments of a few chosen coal and shale units. It is noteworthy from the previous work that in the Central Benue region, there are certain potential petroleum system elements present within the Albian to

Maastrichtian age that cannot be ignored. These elements, such as source rocks, reservoirs, seals, and traps, have not been thoroughly investigated. In this particular study, we conducted lithofacies studies, petrographical examinations, and SEM imaging analyses to perform a preliminary assessment of the reservoir potential of the Awe/Keana sandstone in the Middle Benue Trough. The primary objective was to establish evaluation criteria for clastic material petroleum reservoir potency by focusing on detailed lithofacies analysis, mineralogical modal composition, grain size distribution, SEM image analysis, triangular plots, and diagenetic studies. This research aims to evaluate reservoir properties at the microscale, visualizing pore space distribution, pore interconnectivity, diagenesis, and overall reservoir quality.

## 2. Stratigraphy of the Middle Benue Trough

The Middle Benue Trough, also referred to as the Middle Benue Trough, extends northeastward from a boundary marked by the line connecting Bashar and Mutum Biyu (Obaje, 2009). This boundary signifies the southern limit of the Gombe and Keri-Keri Formations, while the older sediments of the Upper Benue Trough undergo facies changes in this region (Offodile, 1976). Despite some available photogeological maps and maps of specific areas, such as Lafia-Keana-Awe and Makurdi, the northeastern part of the Middle Benue Trough remains relatively poorly known with no detailed geological maps (Obaje, 2009; Obaje, 2019; Patrick et al., 2013; Offodile, 1976; Offodile and Reymont, 1977; Nwajide, 2013; Obaje et al., 2020; adamu et al., 2023).

Various researchers, including Reymont (1965), Kogbe (1976), Offodile (1976), Petters (1982), Petters and Ekweozor (1982), Nwajide (2013), and Obaje et al. (2020), have provided detailed stratigraphic descriptions of sediments in the Middle Benue Trough. Figure 4 and Figure 5 illustrate the stratigraphic succession in the region. The oldest marine deposits in the Middle Benue Trough are attributed to the Albian Asu River Group identified by Offodile (1976) and Nwajide (1990). These deposits include the

fossiliferous Arufu, Uomba, and Gboko Formations, which are considered Albian sediments (late Aptian - early Cenomanian and older) by Allix et al. (1997) and Brunet et al. (1989). This period likely represents a minor regression, possibly triggered by a compressional event (Nwachukwu, 1972; Amajor, 1985). Overlying the Albian sediments are the regressive Cenomanian-Turonian Awe and Keana Formations (Murat, 1972). During the late Cenomanian to early Turonian, a significant transgression occurred throughout the Benue Trough, potentially connecting the waters of the Gulf of Guinea to the south with the Tethys Sea to the north (Zaborski, 2000). The marine facies

of the Ezeaku Group and the Awgu Formation were deposited until the Santonian period, underlying the Awe and Keana Formations (Petters, 1982). In the mid-Santonian period, the pre-Santonian sediments underwent folding and uplift due to global plate reorganization (Guiraud and Bosworth, 1997). The sedimentation in the Middle Benue Trough concluded with the fluvial-deltaic Lafia Formation, which represents the only lateral facies equivalent to the post-Santonian sediments (Campanian-Maastrichtian) in the Benue Trough. Subsequently, extensive volcanic activity occurred during the Tertiary period (Obaje et al., 2004; adamu et al. 2023).

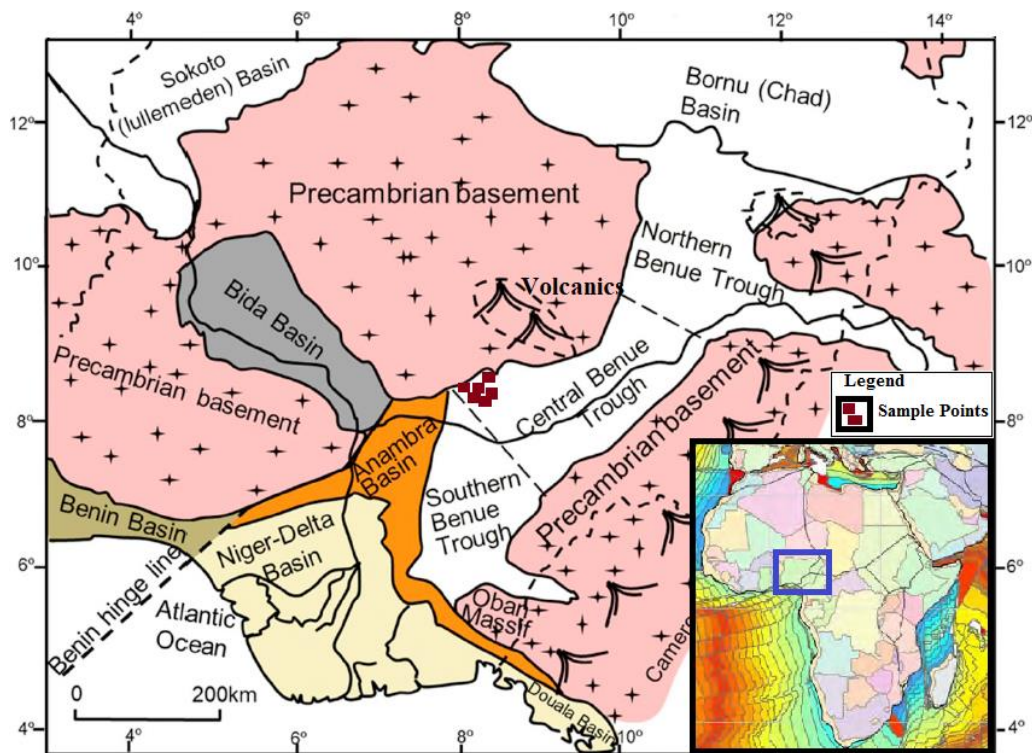


Figure 1: Map of Nigeria showing regions covered by sedimentary and basement rocks and sampling locations (adapted from Edegbai et al., 2019)

SYSTEM		STAGE/ EPOCH	NORTHERN BENUE TROUGH (Carter et al, 1963)		CENTRAL BENUE TROUGH (Ofoegbu, 1984)	SOUTHERN BENUE TROUGH (Peters & Ekweozor, 1982)		
QUATERNARY		HOLOCENE						
		PLEISTOCENE		Chad Fm				
CENOZOIC	NEO- GENE	PLIOCENE						
		MIOCENE					Benin Fm	
		OLIGOCENE					Ogwashi-Asaba Fm	
	PALEO- GENE	EOCENE					Ameki Fm/Nanka SS	
		PALEOCENE		Kerri Kerri Fm	Volcanics		Imo Sh	
		MAASTRICHTIAN		Gombe SS/ Lamja SS		Lafia Fm		Nsukka FM Ajali SS Mamu Fm
CRETACEOUS	UPPER CRETACEOUS	SENONIAN	Pindiga Formation	CAMPANIAN	Numanha Sh		Nkporo Sh/ Owe III SS/ Enugu Sh/ Afikpo SS	
				SANTONIAN				
				CONIACIAN	Fika Sh/ Sekunle Fm	Awgu Fm	Awgu Fm/ Agbani SS	Cross River Group
	MID-CRETACEOUS	TURONIAN	Gongila Fm JessuFm/ Dukul Fm	Makurdi Fm	Eze-Aku Sh/ Amasiri SS			
			CENOMANIAN	Yolde Fm	Awe/Keana Fm	Odukpani Fm/Agala SS		
			ALBIAN	Bima SS 3 Bima SS 2	Eze-Aku Sh Arufu/Uomba Fm (Asu River Group)	Awe Fm Abakaliki Sh	ASU River Grp	
		APTIAN	Bima SS1			Awi FM		
	PALEOZOIC		PRECAMBRIAN		BASEMENT COMPLEX			
	Legend		FM= Formation	SS= Sand stone	Sh =Shale	=Alluvium Deposit	=Unconformity	

Figure 2. The stratigraphic sequence of the Benue Trough of Nigeria; the red boxes indicate the coal-bearing formations (modified after Obaje, 2009)

### 3. Material and Methods

#### 3.1. Field Geological Mapping

Using 100,000 topographic base maps from Akiri Sheet 232, fieldwork was carried out over two years during the dry seasons (SW and SE). To provide the information needed for lithofacies identification and palaeoenvironmental interpretations, this entailed lithological descriptions of rock exposures and geologic mapping. The lithological characteristics of the rocks, such as lithology, composition, bed attitude, sedimentary structures, and fossil content, were used to describe them. Within the research region, the stratigraphic units were recognized. The exposures were meticulously recorded. Also highlighted were their sedimentary characteristics. A lithofacies association was formed from the identified lithofacies. Fresh samples were taken for laboratory analysis from the study region in a total quantity of 20, labelled clearly and promptly

packed in zip-lock plastic bags to be kept at room temperature.

#### 3.2. Thin section analysis

Thin-section preparation was performed on ten (10) typical samples of Awe/Keana sandstone utilizing customary laboratory precautions. Following production, a petrographic microscope was used to view and examine the thin sections. The identification of rock-forming minerals using their optical characteristics came next. This gave us an indication of the diagenetic events that had occurred because it allowed us to identify not only the constituent minerals but also the cement, matrix, average grain size, sorting, porosity, roundness, and nature of contact of these minerals. Using the roundness chart created by Pettijohn et al., the roundness was estimated (1987). Visual comparators for sorting minerals in thin sections that are based on three-dimensional distributions of spheres that are log-

normal by volume frequency were also used to estimate the sorting.

### 3.3. Scanning electron microscopy (SEM)

For SEM backscattered electron and energy dispersive investigation, six Awe/Keana Formation sandstone samples were chosen. SEM was carried out at the Central Research Laboratory of Umaru Musa Yar'adua University in Katsina, Nigeria, using a scanning electron microscope with the following specifications: PRO:X: 800-07334 Phenom World and serial number MVE01570775. To gather data on the materials' structures, surface morphology, and, in the case of nanoparticle materials, pore and fibre metric analysis as well as particle sizes.

## 4. Results and Discussion

### 4.1. Location Analysis (Field Relationship)

Between the older Asu River Group and the younger Eze-Aku Formation is the Awe/Keana Formation (Cratchley and Jones, 1965, Obaje,

### 4.2. Sandstone Facies Analysis Based on Geological Field Mapping

Consists of fine- to extremely coarse-grained, flaky, well-cemented sandstones that range in color from white to brown with red and yellow patches and are sometimes calcareous. Siliceous minerals make up the majority of cement. This unit's beds are typically tabular cross-bedded, multilayered, extremely micaceous, and current, with occasional pebbles thrown in here and there. Occasionally, shales and clays are deposited on top of it, and volcanic materials have also been introduced. In some areas, the sandstone unit grades into shale, resulting in joints that are at right angles. This facies unit commonly trends NE–SW, with a dip angle between 11°SE and 28°SE. In addition to ripple markings and faults, they frequently exhibit tabular cross-bedding, trough cross-bedding, and

graded bedding (both fining- and coarsening-upwards patterns) and are heavily jointed and folded. They are bioturbated, with Skolithos (simple straight tube), Diplocaterion (vertical u-tube with spreite), Rhizocorallium (horizontal to subhorizontal u-tube with spreite), and Trypanites (boring traces into hard substrate) present (Figs. 3-5; Table 1).

2009). The Awe Formation exposure in the study area is approximately 95 m thick. Its typical sections occur in old Awe town/Tsoho Gari, villages of Ribi and Tunga on the bank of the Benue River. The formation consists of light gray to white, light gray, flaggy, fine to coarse-grained, subangular to rounded, moderately to poorly sorted, sometimes calcareous sandstones with interbedded carbonaceous shales and clays from which brine/salt comes to the surface. The Keana Formation resulted from the Cenomanian regression, which deposited fluviadeltaic sediments characterized by cross-bedded, laminated, coarse-grained feldspathic sandstones, occasional conglomerates and bands of shales and limestone (Figs. 3-5). The fractures filled with brine/salt, chalcopyrite and quartz are derived from mineralizing solution associated with the Asu River group lead-zinc mineralization due to hydrothermal effects/origin. Interpretation: The variation in values between extremely fine and fine sands points to a change in the deposition energy. The predominance of weakly to moderately sorted values suggests deposition in an upper flow regime because they show quick fluvial deposition and minimal sediment reworking during transit (Freidman, 1967). The presence of ripple marks is thought to indicate the deposition of low-energy waves in a shallow marine environment (Walker and Plint 1992). Tabular cross-stratification is a reflection of sand wave migratory river deposition (Harms et al., 1975).



Figure 3: Exposed section of the Awe/Keana Formation (a) Heterolith, (b) intercalations of sandstone and shales (c) Intercalation of sandstone and shale sequences in old Awe town (c) Calcareous sandstone facies (d) Trough cross-bedded sandstone facies of the Awe/Keana Formation exposed in Ribi village (salt mine), (e) Conglomeratic sandstone facies of the Awe/Keana Formation exposed in Ribi village

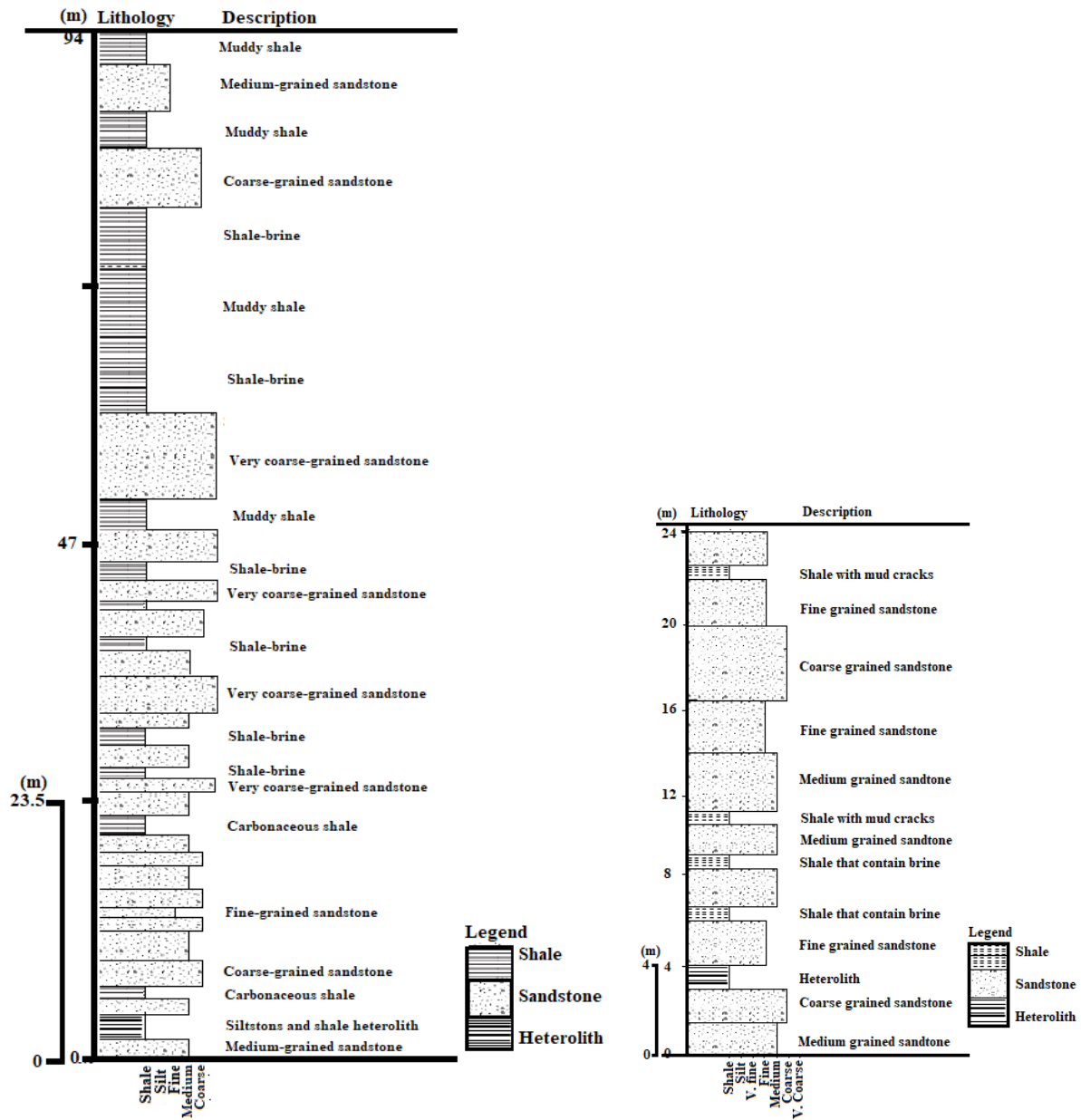


Figure 4: Lithologic log of the exposed section of the Awe/Keana Formation in the (a) southern fold limb of old Awe town and (b) northern fold limb of old Awe town

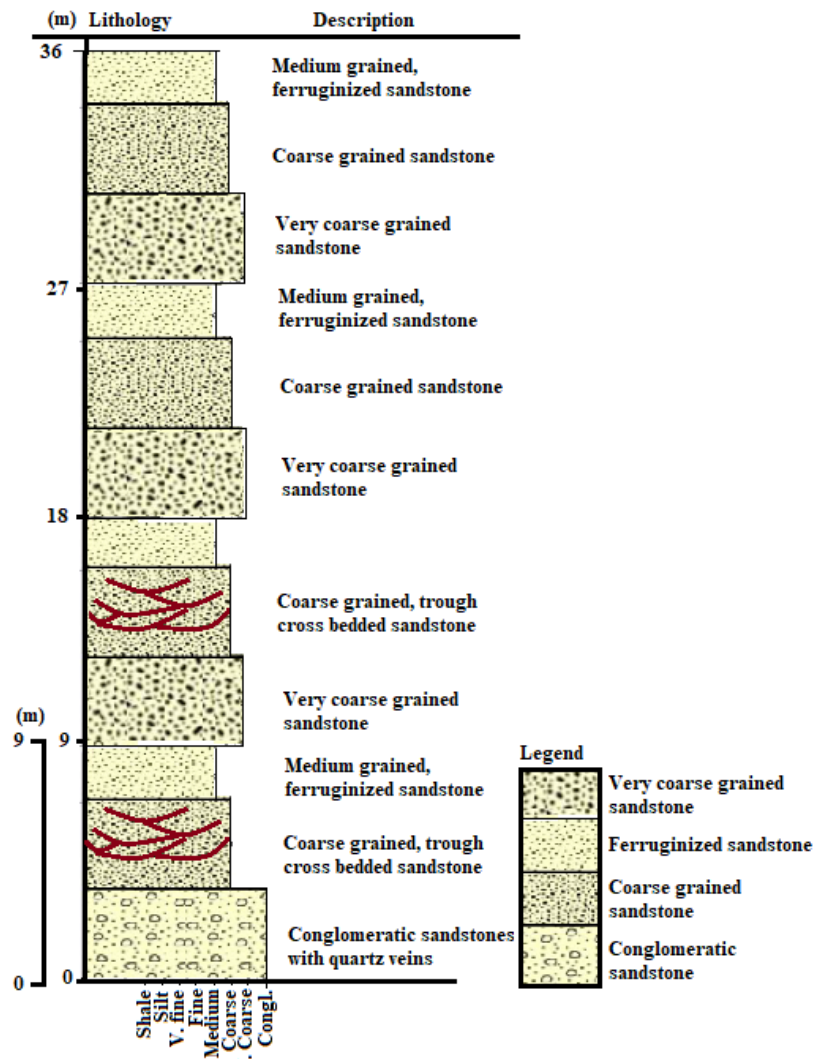


Figure 5: Lithologic log of Keana Sandstone exposed near the local salt mine at Ribi ( $8^{\circ} 22' 18.5''N$   $009^{\circ} 07' 35.4''E$ )

Trough cross beddings, which are generated by the migration of sinuous and lunate dune bedforms, are a sign of tidal action. During bedform migration, there are frequent variations in flow velocity or depth, which cause the dunes to alter and disintegrate. An erosional surface such as this one will develop when deposition picks back up. Additionally, *Skolithos*, *Diplocraterion*, and *Thalassinoides* burrows belong to the *Skolithos* ichnofacies and indicate sandy shores, intertidal flats, and marginal

marine settings. *Rhizocorallium* burrows belong to the *Cruziana* ichnofacies and indicate a sublittoral zone and marginal marine settings (Pemberton et al., 1992). As evidence that the energy of the current fluctuated at the time the sediments were deposited, the graded bedding and ripple lamination are thought to have been deposited during a relatively turbulent water phase.



Table 1: Facies distribution of the Awe/Keana sandstone in the Middle Benue Trough

Formation	Lithofacies	Sedimentary structures	Gross depositional environment
Awe/Keana	Fine to very coarse grained, flaggy, well cemented sandstones with siliceous materials constituting the bulk of the cement and ranges in color from white, grey to brown with red and yellow spots and calcareous in some areas. The beds of this unit are usually multilayered, highly micaceous.	They are bioturbated with Rhizocorallium (horizontal to subhorizontal u-tube with spreite), Diplocaterion (vertical u-tube with spreite), Skolithos (simple straight tube) and thalassenoides, Typanites (Boring traces into hard substrate) present, tabular cross-beddings, trough cross-bedding, graded bedding (both fining and coarsening upward pattern), ripple marks, fault, highly jointed and folded.	sandy shore, intertidal flats, and marginal marine settings
	Grey, fine-grained, laminated, consolidated, clayey sandstones that are micaceous and massive in places.	Well graded (finning-upward pattern), ripple mark, bioturbation structures such as Skolithos and Rhizocorallium (Horizontal to subhorizontal u-tube).	

### 4.3 Ichnofossils

Three ichnofacies were identified in the bioturbated sandstone and cross-stratified sandstone lithofacies in the Awe/keana Sandstone in the Middle Benue Trough. The lithofacies are characterized by high abundance, intermittently distributed ichnofossil assemblages dominated by Skolithos ichnofacies, Cruziana ichnofacies, and low to moderate abundance, sparsely distributed Trypanites ichnofacies. The Skolithos ichnofacies identified in Gidan Gbaagbu and Tsoho Gari villages include the Ophiomorpha, Diplocraterion, and Skolithos ichnospecies (Fig. 6a and b; 7b). Frey (1978) and Frey et al., (1978) observed that Ophiomorpha is produced by many different organisms including Callianasa, Upogebia, Axius and Thalassina. They indicate a sandy shore, intertidal flats, and marginal marine settings (Benton and Harper, 1997). The Cruziana ichnofacies in the lithofacies occur as Rhizocorallium commune (Hall, 1843) and Thalassinoides (Woodward, 1830; Ehremberg, 1944) (Fig. 6c and d) ichnospecies in Ayare and Tsoho Gari villages, respectively, while

the Trypanites ichnofacies identified in Tsoho Gari village include Trypanites ichnospecies (Fig. 7a). Trypanites are boring traces into the hard substrate. The Rhizocorallium commune are commonly horizontal to subhorizontal u-tubes with sinuous, bifurcating or planispiral spreiten burrows. The ichnospecies with occasionally scratched marginal tubes and an actively filled spreite between the tubes is identified as Rhizocorallium commune (Hall, 1843). Thalassinoides (Fig. 6d) occur in the bioturbated lithofacies at old Tsoho Gari village as a complex network of branching to interconnected burrows that extends both vertically and horizontally. The burrow walls are lined, which indicates dwelling burrows. Thalassinoides ichnospecies burrows are chiefly associated with decapod crustaceans of the infraorder Thalassinidea (Paul, 1995). The ichnospecies with vertical U-shaped burrows having a spreite between the two limbs of the tubes are identified as Diplocraterion ichnospecies, while the other species with tunnels of uniform diameters, vertical, smooth outer wall structure are Ophiomorpha and Skolithos ichnospecies. The cross-sectional

diameter varies from 1.0 to 1.50 cm, while the lengths of the shafts could be up to 32 cm in some cases. Ophiomorpha, Diplocaterion, and Skolithos ichnospecies (Skolithos ichnofacies), Rhizocorallium and Thalassinoides ichnospecies (Cruziana ichnofacies), and Trypanites ichnospecies (Trypanites ichnofacies) were identified in this study. Generally, the Awe/Keana sandstone lithofacies are characterized by fair to high bioturbations and intermittently distributed ichnofossil assemblages belonging to the Skolithos, Cruziana, and Trypanites ichnofacies. The Skolithos ichnofacies belongs to the dwelling (domichnia) and suspension feeders (fodinichnia) of Eckdale et al. (1984). The Cruziana ichnofacies

in the area belongs to fodinichnia (Permberton and Frey, 1982; Permberton and Frey, 1984). The Trypanites ichnofacies belongs to the domichnial borings of Eckdale et al. (1984). The fodinichnia (suspension feeders) are typical feeding structures representing extensive subsurface foraging by deposit-feeding organisms. They represent traces of nonvagile deposit feeders (Bromley, 1996). The domichnia are simple tubes, shafts or integrated shaft tunnels and shafts made by endobenthic suspension feeders (Frey, 1978). They represent traces developed in fully oxygenated shallow waters (Bromley, 1996).

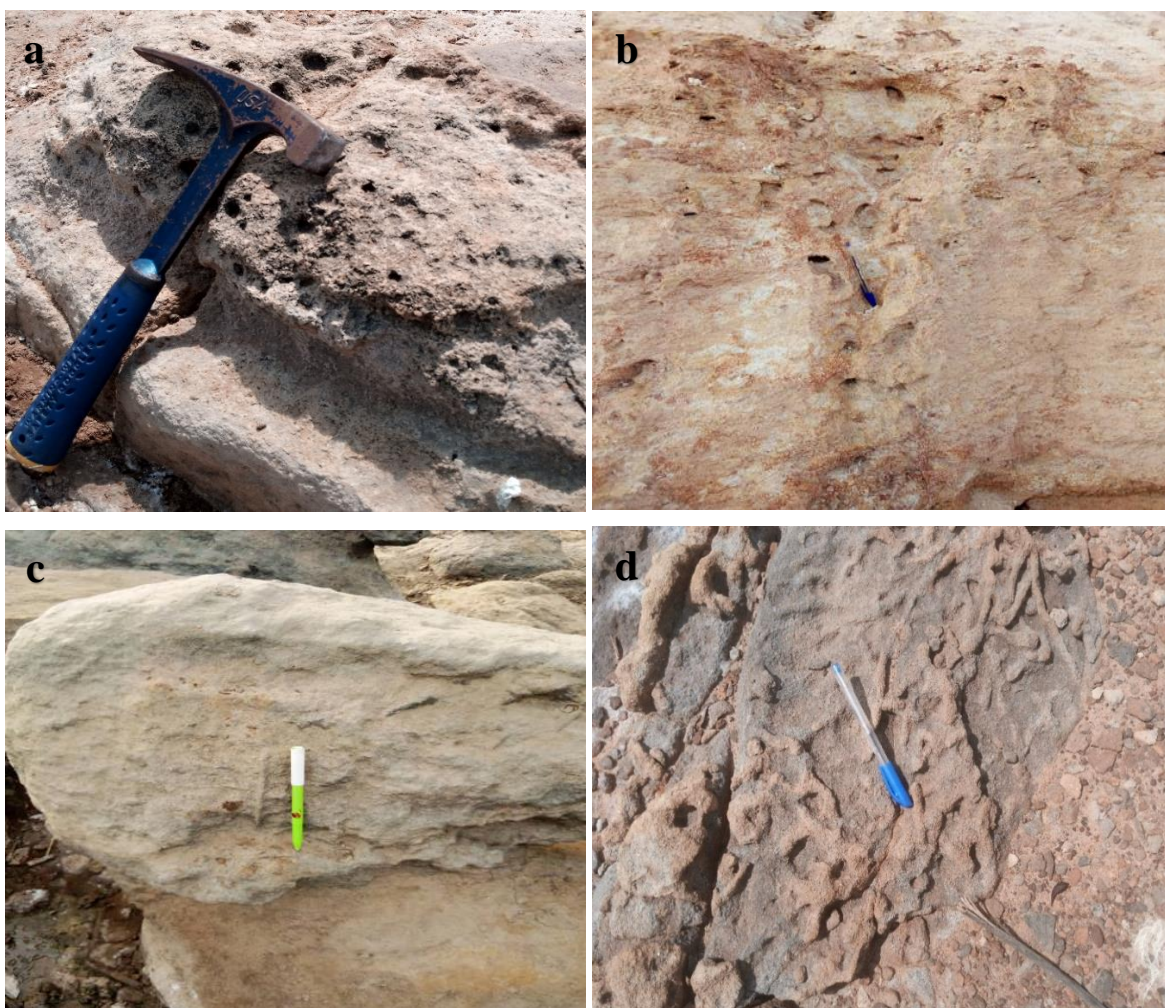


Figure 6: Bioturbation structures in sandstone facies of the Awe/Keana Formation within the study area; (a) Thalassinoides at Tsoho Gari (N080° 06' 08.0" E009° 07' 40.7"), (b) Rhizocorallium at Ayare village (N080° 03' 34.5" E009° 08' 29.9"), (c) Diplocaterion at Gidan Gbaagbu (N08°05' 28.0" E009° 04' 120.4"), (d) Skolithos at Gidan Gbaagbu (N08°05' 28.0" E009° 04' 120.4").

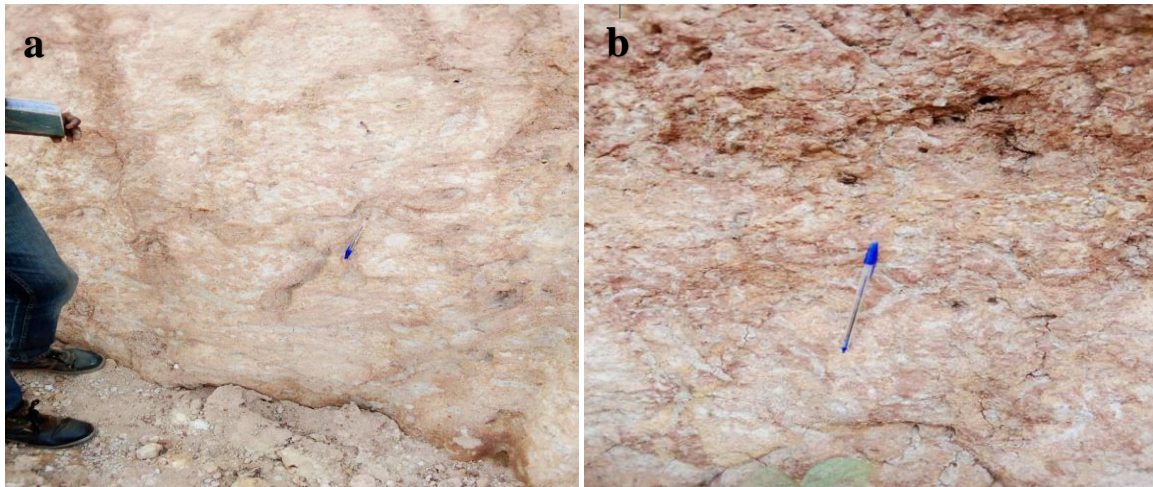


Figure 7: Bioturbation structures in sandstone facies of the Awe/Keana Formation within the study area; (a) Trypanites at Tsoho Gari (N080° 06' 08.0" E009° 07' 40.7"), (b) Skolithos at N080° 04' 21.2" E009° 07' 56.7".

#### 4.4 Sandstone subfacies description based on petrography and SEM analysis

Mineralogical compositions and textural characteristics of detrital sediments are determined by their parent rocks and diagenetic processes that exist at the time of sediment deposition and postdepositional processes after transportation of sediments from their source area to the point of deposition. As the sediments are continuously reworked, some exist as lithic fragments, and some become distinctive minerals that assist in the identification of parent rocks. Physical, chemical, and biological processes subsequently play important roles in determining the variation in mineralogical composition between parent rock and final sedimentary product. Minerals that are less resistant to physical and chemical effects are either altered or recrystallize into other minerals while the more resistant minerals become the more dominant minerals. Distance of transportation overall determines the sediment size, shape, sorting and degree of sorting. Petrographic analysis was carried out against eleven sandstone samples taken from seven sections in five different locations. Using the sandstone classification by Pettijohn (1975), the sandstone constituent of the Awe/Keana Formation is divided into three types, including arkose, subarkose, and feldspathic graywacke (Table 2; Figs. 8-12). In some sandstone samples,

carbonate minerals exhibit a fair amount, so the rocks become calcareous.

##### 1. Glauconitic sandstone subfacies

This is a bedded to massive, light, and purple-brown to gray, fine-, medium- to coarse-grained sandstone (Figs. 4 and 5). The results from the petrographic analysis show that the sandstone is composed of quartz (33.0 to 36.5%), feldspars (26.0 to 28.0%), lithic fragments (15.0 to 17.5%), muscovite mica (2.0 to 4.0%), matrix (10.5 to 11.5%), glauconite (1.0 to 1.5%), carbonates (1.0 to 1.5%), silica (1.5 to 2.0%), and authigenic clay (4.5 to 5.0%) (Table 2). Both monocrystalline (Qm) and polycrystalline quartz (Qp) are present in the studied samples; however, monocrystalline quartz is the most abundant grain (Figs. 10-12). Additionally, plagioclase feldspar is dominant with minor potassium (microcline and orthoclase) content and muscovite-type mica. Under the petrographic microscope, the sandstone is fine- to coarse-grained, matrix-supported, moderately to poorly sorted, angular, subangular to subrounded, and mineralogically and texturally immature with clay cement. Additionally, some of the plagioclase feldspars have been partially lost in solution, thereby creating secondary porosity within the rock. Where the dissolution is not total, there is the formation of sericite and kaolinite, which then doubles as cement material in some parts of the rock.

## 2. Fine-grained sandstone subfacies

This is a massive indurated, gray, yellow to brown, fine-grained sandstone (Fig. 4). The results from the petrographic analysis show that the sandstone is composed of quartz (85.0 to 86.0%), feldspars (6.0 to 6.5%), lithic fragments (0.5 to 1.5%), muscovite mica (0.0 to 0.5%), carbonates (0.5 to 1.0%), and authigenic clay (5.5 to 6.0%) (Table 2). Microscopic examination reveals that the rock is a moderately well-sorted sandstone. It is both texturally and mineralogically immature. It is composed of monocrystalline quartz and plagioclase feldspars. The plagioclase feldspars show alteration to sericite and kaolinite, with both acting as clay cement material within the contacts of the other grains in the rock.

## 3. Very fine-grained sandstone subfacies

This is a dark to gray, massive, indurated, and very fine-grained sandstone (Figs. 4 and 5). The results from the petrographic analysis show that the sandstone is composed of quartz (38.0 to 43.0%), feldspars (17.0 to 20.0%), lithic fragments (8.0 to 10.5%), muscovite mica (1.5 to 2.0%), matrix (16.0 to 28.0%), carbonates (0.5 to 1.5%), silica (0.5 to 3.0%), chlorite (0.5 to 1.5%), iron oxide (1.0 to 2.0%) and authigenic clay (1 to 5.0%) (Table 2). It is a poorly sorted, subangular to subrounded sandstone with an average matrix of 18% and contains monocrystalline quartz and abundant plagioclase feldspar grains.

## 4.5 Sandstone classification

Textural features and mineralogy are combined in the most popular and efficient methods for classifying sandstones (Dickinson et al. 1983, Baiyegunhi et al. 2017, Pettijohn, 1975, Folk, 1980, Folk, 1974). According to Raymond, 1995, Folk's classification system reveals crucial information regarding provenance, with the name of the rock revealing specifics about its composition. The link between plate tectonic settings and sandstone compositions has been successfully inferred using QFL ternary diagrams. To effectively discriminate between various plate tectonic settings and enable tectonic reconstruction of terrigenous deposits, Dickinson (1985) endorsed the use of ternary diagrams. According to Johnsson et al. (1988), when quartz is the most abundant mineral in a sample relative to the amounts of feldspar, micas, and matrix, this situation indicates the maturity of the sediments in terms of weathering and transit. The glauconitic, fine-grained, and very fine-grained sandstone facies of the Awe/Keana Formation can be classed as arkose, subarkose, and feldspathic graywacke, respectively, according to the classification system put forward by Pettijohn in 1975 (Figs. 8-12; Table 2). The ternary QFL diagram suggested by Folk, 1980 shows that 36.36% of the sandstones plot in the arkose field, 36.36% plot in the feldspathic graywacke field, and the remaining 27.27% plot in the subarkose field (Fig. 8a & b; Table 2).

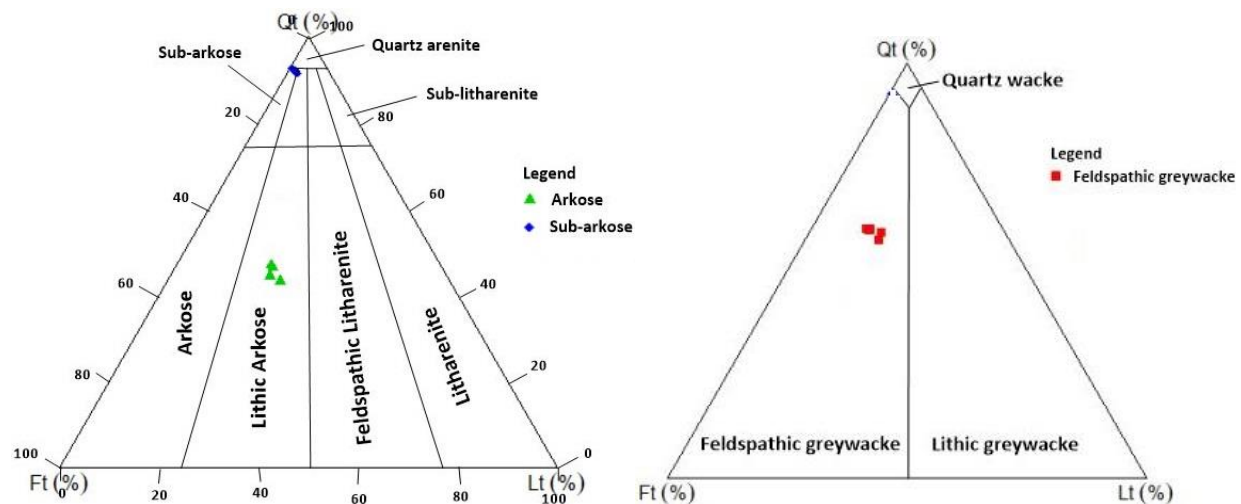


Figure 8: (a, b) Classification of the Awe/Keana Formation Sandstones (after Folk 1980)

Table 2: Modal analysis data (in %) for sandstones of the Awe/Keana Formation from the Middle Benue Trough

Sample ID	QUARTZ		FELDSPA RS		Unstable Lithic			Mica			Other Minerals					Qt (%)	Ft (%)	Lt (%)	Po	RN			
	Qm	Qp	Kf	Pl	Lv	Ls	Lm	Lg	Mu	Bi	Mt	Cl	Ch	Io	Gl	Ca	Si						
1	AK03	39.0	4.0	1.5	18.5	0.0	4.0	2.0	3.0	0.0	0.0	18.0	4.0	1.0	1.0	0.0	1.0	3.0	43	20	9.0	11.2	FG
2	AK08	35.0	3.0	1.0	17.0	0.0	6.0	4.0	0.5	2.0	0.0	28.0	1.0	0.0	2.0	0.0	0.5	0.0	38	18	10.5	10.18	FG
3	AK09	40.0	4.0	1.0	17.5	0.0	3.0	2.0	3.0	2.0	0.0	16.0	5.0	1.5	1.5	0.0	1.5	2.0	41	19.5	8.0	10.06	FG
4	AK11	37.0	2.0	2.5	14.5	0.0	5.5	4.0	0.5	1.5	0.0	25.5	3.5	0.5	2.0	0.0	0.5	0.5	39	17	10.0	10.10	FG
5	L10A	30.5	2.5	3.0	23	0.0	4.5	13	0.0	4.0	0.0	10.0	5.0	0.0	0.0	1.5	1.0	2.0	33	26	17.5	10.11	AR
6	L10B	32.5	2.5	3.0	25	0.0	3.0	12.0	0.0	2.0	0.0	10.0	5.0	0.5	0.0	1.5	1.5	1.5	35	28	16.0	10.05	AR
7	L11	31.5	5.0	1.5	25.5	0.0	3.0	11.0	1.0	2.0	0.0	11.5	4.5	0.0	0.0	1.0	1.0	1.5	36.5	27.0	15.0	9.89	AR
8	AK06	33.0	3.0	1.5	25	0.0	3.5	11.5	0.5	2.0	0.0	11.5	5.0	0.0	0.0	1.0	1.0	1.5	36.0	26.5	15.5	10.00	AR
9	AK01	84.0	1.5	0.5	5.5	0.0	0.0	1.5	0.0	0.5	0.0	0.0	5.5	0.0	0.0	0.0	1.0	0.0	85.5	6.0	1.5	9.95	SA
10	AK04	84.0	1.0	0.0	6.0	0.0	0.5	1.5	0.0	0.5	0.0	0.0	6.0	0.0	0.0	0.0	0.5	0.0	85.0	6.0	2.0	10.01	SA
11	AK12	85.0	1.0	0.5	6.0	0.0	0.0	0.5	0.0	0.5	0.0	0.0	5.5	0.0	0.0	0.0	1.0	0.0	86.0	6.5	0.5	10.21	SA
<b>Average</b>																				<b>10.16</b>			

**Explanation:****Components:**

Qm: Mono quartz Pl: Plagioclase Cl: Clay Mt: Matrix Si: Silica Ca: Carbonates Ot: Other minerals Qp: Poly quartz Lv: Volcanic rf. Ch : Chlorite Po : Porosity RN: Rock name Io : Iron oxides Kf : Potassium feldspar Ls : Sedimentary rf. Lm: Metamorphic RF. Lg: Granitic rf. Mu: Muscovite Bi: Biotite Gl: Glauconite

**Rock Name:** FG: Feldspathic graywacke AR: Arkose SA: Subarkos

The Quartzose Grains formula Qt is the total number of quartz grains. Quartz grain Qm is monocrystalline, and quartz grain Qp is polycrystalline.

Feldspar grains F = (P+K) F = total feldspar grain P = feldspar made of plagioclase K = feldspar made of potassium CUnstable

Lithic Lithics: L = Lv + LsLv stands for a volcanic or meta-volcanic lithic fragment. D = lithic piece made of sediment or metasediment. Total Lithics Lc = Extra basinal detrital lime-clasts (not included in L or Lt), Total Lithic Fragments Lt = (L+ Qp).

#### 4.6 General Features

According to Basu et al. 1975, the sediments mostly descended from a granitic source because monocryalline quartz grains predominate. Most monocryalline quartz grains, according to Dabbagh and Rogers in 1983, are thought to have broken up from the initial polycryalline quartz (quartzite or vein quartz) during high-energy or long-distance movement, particularly from magmatic and metamorphic origins. Monocryalline quartz grains are generally plutonic, hydrothermal, and recycled sedimentary in origin, whereas polycryalline quartz grains are recrystallized and stretched metamorphic kinds, according to the genetic and empirical classification of quartz types proposed by Folk, 1974. Sandstones were mostly generated from a granitic source, as evidenced by the predominance of monocryalline quartz grains in the sandstones (Basu et al. 1975). Intercryalline suturing is observed in both monocryalline and polycryalline quartz, indicating a metamorphic source location for the sandstones. Blatt and Christie, 1963 came to the conclusion that although quartz grains with undulatory extinction primarily come from metamorphic rocks, those with nonundulatory extinction are generated from nonmetamorphic rocks. As reported by (Folk, 1974; Blatt et al. 1980), polycryalline quartz grains with three or more crystals and straight to slightly curved intercryalline boundaries may have come from metamorphic and plutonic igneous rocks.

In sandstones, pristine shards of feldspar grains indicate an igneous source area, whereas altered or stained feldspar grains are often from a metamorphic source area, according to Basu et al. 1975. The sandstones contain both weathered (altered) and a few pristine feldspar grains, suggesting that they likely came from an igneous and metamorphic source area. The detrital feldspars in the sandstones of the Awe/Awe Formation are primarily plagioclase with very little microcline, as this study revealed. In the albite law, the plagioclase grains frequently exhibit twinning, while the microcline exhibits tartan (cross-hatched) twins. A low-grade metamorphic terrain and alkali-rich granites are the sources of the few microclines found in the

sandstones. Compared to the subarkose and feldspathic greywacke, the Arkosic sandstone facies include more feldspar. This is a sign that the Arkosic sandstone facies is less developed than the sandstones of the other two facies, most likely because feldspar survived because there was less chemical weathering during the period of dry climate. According to Pettijohn et al. 1987, igneous and metamorphic rocks are the primary sources of micas. The presence of muscovite in the investigated sandstones indicates that the parent rock is micaceous in composition, possibly originating from felsic igneous rocks or metamorphic rocks. Kaolinite, calcite, and chlorite, the clay minerals that have been found, may be present in the rock as detrital grains or diagenetic minerals.

The tested sandstones include a substantial proportion of rock fragments. Argillaceous sediments make up the majority of rock pieces. Most bits of sedimentary rock have undergone weathering and other alterations. Rock shards from metamorphism are visible. There are some coarser-sized granitic rock particles. Rarely detected are finer-grained components made up of opaque minerals such as magnetite and carbon. Muscovite and glauconite are also found. In contrast to coarser sandstone, which lacks it, fine sandstone exhibits a rock matrix (Figs. 10-12). Quartz and feldspar with extremely fine-grained clay minerals make up the majority of the rock matrix. The sandstones of the Awe/Keana Formation contain secondary minerals and cementing grains made up of authigenic clays, silica, iron oxides, and carbonates. Plagioclase and rock fragments are altered and weathered, largely through the mineral zoning zones, resulting in the concentration of authigenic clays. The minerals kaolinite, chloritic, and sericitic are also found in clay. Chlorite is very infrequently found, and instead of rock fragments, it forms fibrously very tiny crystals. The main causes of the presence of microcrystalline or extremely tiny irregular anhedral quartz crystals are quartz grain overgrowth and silicification of the clay mineral matrix. Siderite and other iron oxides, which act as a binder between the grain patterns, are present, and their distribution is erratic. Carbonate minerals, which developed in a

meteoric phreatic diagenetic environment, are primarily preserved as drussy mosaic anhedral calcite crystals. In certain samples, the calcite particle cementing substance was uniformly dispersed. Muscovite and glauconite are present, which points to shallow marine deposition.

#### 4.7 Tectonic setting

The petrographic study reveals that the studied sediments are characterized by higher proportions of monocrystalline quartz, smaller amounts of polycrystalline quartz, more plagioclase than K-feldspar and a minor amount of rock fragments. Many authors have successfully established the tectonic environment by the proportions of framework grains (Crook 1974; Schwab 1975; Potter 1975; Dickinson and Suczek 1979; Dickinson et al. 1983; Taylor and McLennan 1985). The QFL ternary

plots proposed by Pettijohn, 1975, Folk, 1980 have also been attempted for sandstones from the Awe/Keana Formation to unravel their tectonic settings. To assess the regional tectonic environment of source rocks (provenance), Dickinson et al.'s (1983) Qt-Ft-Lt and Qm-F-Lt triangle diagram plots are useful (Figs. 9a & b). The provenance of the Awe/Keana Formation sandstone appears to vary from the craton interior and dissected ark to the recycled orogen region, according to the plotting results in the Qt-Ft-Lt diagram (Fig. 9a). Plotting it in the Qm-F-Lt diagram (Fig. 9b), which demonstrates that the provenance of the Awe/Keana Formation spans from the craton interior, dissected ark, transitional continental to mixed environment fields, allowed for a more thorough determination.

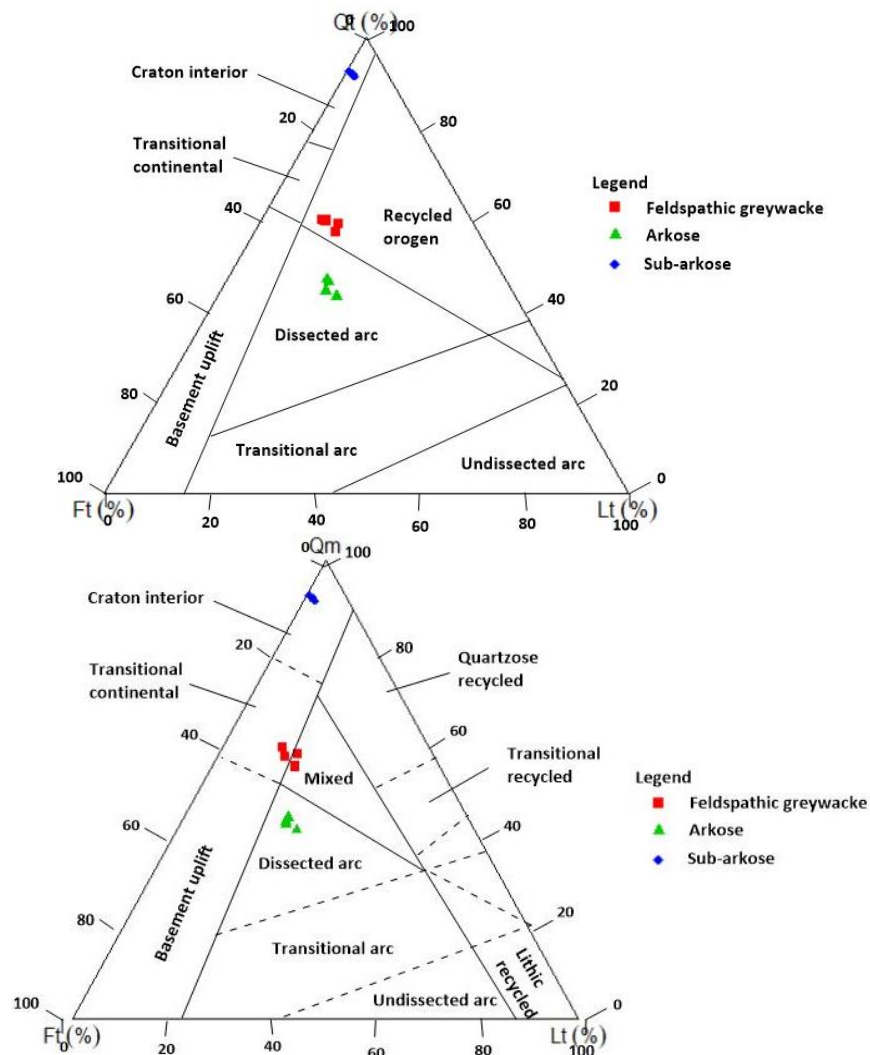


Figure 9: (a) Qt-Ft-Lt and (b) Qm-F-Lt ternary diagram relationship between sandstones of the Awe/Keana Formation and their tectonic setting (after Dickinson et al. 1983), which are located in portions that span from the craton interior, dissected ark, transitional continental up to mixed environment fields.

#### 4.8 Diagenetic Description

The Awe/Keana Formation contains detrital minerals of quartz, orthoclase, microcline, plagioclase (also known as albite), biotite, muscovite, and clay minerals (kaolinite, illite, sericite, and chlorite), according to thin section studies and SEM-EDX examinations. These minerals make up the framework of rocks, and some of them are cements. Pyrite, haematite, glauconite, and calcite are authigenic minerals that developed during diagenesis. Petrography shows that the Awe/Keana Formation sandstones are mostly calcareous sandstones. The sandstones are feldspathic graywackes, arkose and subarkose. Cementation, mechanical compaction, dissolution, grain replacement, and recrystallization are the primary diagenetic processes that have had a significant impact on the sandstones of the Awe/Keana Formation.

##### 1. Cementation

One of the most crucial processes that results in loose sediments producing cemented rock and reducing porosity is cementation. The sandstones of the Awe/Keana Formation contain four different forms of cements: quartz cement, calcite cement, feldspar cement, and authigenic clay mineral cements (Figs. 10-13).

##### a. Quartz Cementation

Quartz cement exists in the rocks as a result of precipitation of silica into the pore spaces between grains. Quartz cement occurs as both pore-filling and overgrowths in the rocks. This type of cement was formed early in the shallow marine diagenetic environment and in the early diagenetic stage. Quartz overgrowths occur as syntaxial overgrowths, growing outwardly from the detrital quartz grain surface. The overgrowths have the same optical properties as the original detrital quartz grains. In some cases, the boundaries between the detrital quartz and overgrowths are marked by clay coatings and dust lines. The result of overgrowths commonly gives the grains more euhedral crystal faces. Because silica precipitated into the pore spaces between grains, quartz cement was present in the rocks. Both pore filling and overgrowths of quartz cement can be found in the rocks. This

particular cement was created in an early stage of diagenetic development in a shallow sea environment. Syntaxial overgrowths of quartz, which develop on the surface of detrital quartz grains, are common. The optical characteristics of the overgrowths are identical to those of the original detrital quartz grains. In other circumstances, dust lines and clay coatings serve as markers to delineate the borders between detrital quartz and overgrowths. Overgrowths frequently result in grains having more euhedral crystal faces. Feldspar and mica dissolution resulted in the release of silica, which served as the silica source for the development of quartz cement and authigenic quartz. In the rocks, quartz cement can be found as fine-grained quartz (Fig. 12) and quartz overgrowths (Figs. 11 and 12). Silica precipitation in pore spaces led to the formation of quartz cements.

##### b. Calcite Cementation

Another form of cement found in the Awe/Keana Formation is calcite cementation. It mostly appears as a mineral that fills pore spaces and replaces detrital grains and the clay matrix. This may indicate precipitation at various diagenetic stages. Locally, calcite forms in pore spaces and partially or totally displaces quartz and feldspar grains, typically at their edges. The majority of the detrital grains and clay minerals (matrix) were severely damaged and replaced by calcite (Figs. 10 and 11). The replacement occasionally even reached the center of some grains. Quartz overgrowths are replaced by calcite cementation. After feldspar was dissolved, most of the secondary pores were filled with calcite.

##### c. Feldspar Cementation

A less common form of cement found in sandstones and siltstones is feldspar cement. It can be found as overgrowths around detrital K-feldspar grains and as pore-filling feldspar (Figs. 10 and 11). In a few instances, the detrital grains' original haematite rims (dust rims) are visible around the feldspar overgrowths. Feldspar overgrowths function as early diagenetic minerals and authigenic feldspar pore-filling cements. The majority of quartz overgrowths are connected to feldspar syntaxial overgrowths.



After the quartz was cemented, this cement was created.

#### d. Clay mineral cementation

Clay minerals are the most common cementing materials in the Awe/Keana Formation sandstones. These minerals act as pore lining rim cement and pore-filling matrix. Smectite and illite are the major clay minerals that act as cementing agents in rocks. These authigenic clay minerals are formed through recrystallization of a fine matrix and dissolution of K-feldspars. In addition, they may also have been formed due to modification or alteration of one kind of clay mineral to another; for instance, both smectite and kaolinite were transformed into illite. Other clay minerals that occurred as minor constituents in the rocks are sericite and chlorite. Smectite recrystallized into illite and chlorite, and kaolinite recrystallized into illite. Illite also further changed to sericite, which later recrystallized to muscovite.

#### Kaolinite clay

The most prevalent cementing components in the sandstones of the Awe/Keana Formation are clay minerals. These minerals function as the matrix that fills the pores and lines them. The two main clay minerals that serve as cementing agents in the rocks are smectite and illite. These aurigenic clay minerals are created by the dissolution of K-feldspars and the recrystallization of a fine matrix. Additionally, they might have developed as a result of the modification or change of one type of clay mineral to another, such as the transformation of smectite and kaolinite into illite. Sericite and chlorite are two more clay minerals that appear as small components in the rocks. Kaolinite recrystallized into illite, while smectite recrystallized into illite and chlorite. Illite underwent another transformation into sericite, which then recrystallized into muscovite. Kaolinite can be found as a cement or pore-lining clay matrix. Additionally, weak detrital K-feldspar and muscovite grains are frequently replaced by kaolinite clay, which also occurs naturally. Kaolinite can have an authigenic or detrital origin. While authigenic kaolinite is generated in situ in the depositional basin, detrital kaolinite is

deposited in the depositional basin by erosion and transport. The latter exhibits fibrous or euhedral crystalline shapes or booklet crystalline shapes under SEM, whereas the former exhibits erosion and transportation impacts such as angular and fractured grain forms. Clay flakes in the shape of an accordion are found as euhedral crystals in the intergranular pores, according to SEM studies (Fig. 13).

Patches of kaolinite that are somewhat large, erratic, and dispersed are known as kaolinitized intraclasts. On the other hand, muscovite can occasionally be found in thin, thread-like residues in partially kaolinitized mica. As a result, some kaolinite looks like silt-sized lithic grains or bits of detrital mud. In certain instances, the surrounding intergranular holes are filled with kaolinite patches that have been compressed and distorted between the grains. This can be an indication of a kaolinitized pseudomatrix. Feldspars that have been completely kaolinitized appear as kaolinite patches with distinct relict outlines that are comparable in size to the original detrital feldspar grains. However, detrital feldspar remains can be found in partially kaolinitized feldspars. In certain instances, the quartz overgrowths predate kaolinite because it is swallowed by it. The early diagenetic stage and uplift stage are when kaolinite was created. As a result, the development of kaolinite is caused by the presence of altered K-feldspar and muscovite, which act as sources of silica and aluminum.

#### Illite Clay

Illite clay develops as the lining and pore filling of clay minerals. A partial to complete modification or recrystallization of kaolinite and smectite is hence likely what caused it to form. It also appears as booklets and vermicular stacked platelets that mimic kaolinite (Fig. 13). Illitization normally takes place after kaolinite and smectite have precipitated and calls for an input of potassium at a higher temperature. Kaolinite decomposition is not always followed by illitization, and kaolinite does not always dissolve when illitic cements form, although illitic clays are frequently linked to kaolinite decomposition (Hurst and Irwin, 1982). Particularly when it is

created as a result of the dissolution of kaolinite, illite frequently retains the morphology of its forerunners. The presentation and alteration of smectite/kaolinite and other labile detrital minerals, which are quickly altered and need alkaline (illite) and acidic (kaolinite) pore fluid, are essential for the autigenesis of illite clay. Illite typically develops during shallow burial diagenesis at higher temperatures. At temperatures between 55 and 200°C, smectite turned into illite (Hurst and Irwin, 1982). Smectite transforms into illite as the temperature rises, beginning with the formation of individual illite pellets on smectite for nucleation (Fig. 13). Illite grows from the surfaces of the observed smectite, giving it a honeycomb shape and curved flake or platy box-work shapes, which causes mixed illite–smectite layers to occur. Illite changed from illite to sericite as the temperature rose. Sericite is then transformed into muscovite. Illite must grow in a medium with a high potassium (K), silica (Si), and aluminum (Al) content (pore fluid and space). Illite or illite–smectite mixed layers only arise when smectite clay minerals undergo transformation or conversion during a shallow burial diagenetic process at elevated temperatures between 90°C and 130°C (Pollastro, 1985).

### Smectite Clay

Smectite occurs as grain coatings and microcrystalline matrix aggregates (Fig. 13). SEM examinations revealed that smectite clay has a cornflake-shaped texture and sometimes appears to have honeycomb morphology (Fig. 13). In some cases, illite grows from the surface of the cornflake-shaped smectite or forms mixed illite–smectite interlayers. The smectite flakes also recrystallized into pelletic and fibrous illite. Smectite can be transformed to illite through the process of illitization. Smectite can contain substantial amounts of Fe and Mg. Thus, the destruction of smectite layers during illitization can release significant amounts of these elements, depending on the initial composition of the rock. According to Pollastro (1985), it is necessary to increase the amount of tetrahedral Al<sup>3+</sup> and to add K<sup>+</sup> to the interlayer region to convert smectite to illite. The transition from smectite to illite in the examined samples is not

constant. Al-rich strata are more prone to illitization than Fe- and Mg-containing strata. Smectite may change to chlorite during uplift-related diagenesis as a result of weathering, dissolution, and oxidation. It might also accelerate the weathering, decomposition, and breakdown of minerals and rocks.

### 2. Compaction

Mechanical compaction began to affect the soft sediment during the early phases of diagenesis under oxidizing pore fluids when it was buried by overloaded deposits. The compaction is more severe the higher the overburden. In sedimentary rocks, the pressure from the overburden causes the bed to narrow, the grains to pack more tightly, and the porosity to decrease. During their progressive burial, the sandstones of the Awe/Keana Formation experienced moderate to extreme physical and chemical compression. The shift in grain contacts, with lengthy, concavo-convex, and sutured contacts of adjacent framework grains, is indicative of this (Fig. 13).

From noncontact to point contacts, to long contacts, and finally to concavo-convex contacts, the grain contact patterns gradually evolved. The concavo-convex connections are stitched at a later stage. Some of the grains, particularly the feldspar and muscovite grains, were fractured as a result of the overburden that compacted the sediments (Fig. 13). Some of the muscovite grains had totally distorted shapes. Mica flakes occasionally show signs of cracking or bending (Fig. 13). In the samples under investigation, long connections are frequent, and their presence indicates a moderate level of compaction (Fig. 13). Additionally, concavo-convex and sutured contacts, which are both related to deep burial diagenesis, are frequent. Progressive burial caused increased compaction and porosity loss through grain rotation or sliding, which ultimately caused resistant minerals to fracture. This led to pressure dissolution, a type of deformation where minerals dissolve into an aqueous pore fluid at grain-to-grain contacts (boundaries) in regions of relatively high stress. Occasionally, pressure dissolution results in the deformation of quartz and muscovite grains. Some of the siliciclastic sandstones contain stylolite

formations. Although fractures are typically rare, when they do occur, they are typically small fractures on detrital quartz grains. Additionally, burial compaction is indicated by grain fracture in the rocks.

### 3. Dissolution

In general, dissolution entails the removal of all or a portion of previously present minerals in solution, leaving pore holes in the rocks (Boggs, 2009). It serves as a source of silica for quartz overgrowths and quartz cement. Some mineral grain boundaries were dissolved as a result of high temperature and deep burial (Fig. 13). Some kaolinite and albite grains were found to have developed as a result of the dissolution of weak detrital K-feldspars, according to SEM and petrographic studies. Additionally, the release of silica from the dissolution of feldspars and micas created a source of silica for the emergence of authigenic quartz. Authigenic quartz was more likely to occur as feldspar dissolved and was replaced by illite.

### 4. Mineral Replacement

Mineral replacement includes the simultaneous in-place precipitation of two different minerals, while one mineral dissolves. New minerals may gradually replace the host or current minerals during this dissolution and reprecipitation throughout time. The fact that replacement is a reasonably frequent diagenetic activity in the rocks of the Awe/Keana Formation may be because K-feldspars are susceptible to change during burial diagenesis. Some minerals become weak and unstable when the temperature rises as a result of increased burial depth; as a result, these minerals are replaced by more stable minerals in a new diagenetic environment. The detected mineral substitutions in the investigated rocks include albitization, kaolinitization/illitization, and calcite replacing quartz, feldspar, and the clay matrix.

#### a. Replacement with Calcite

Mineral replacement includes the simultaneous in-place precipitation of two different minerals, while one mineral dissolves. New minerals may gradually replace the host or current minerals during this dissolution and reprecipitation

throughout time. The fact that replacement is a reasonably frequent diagenetic activity in the rocks of the Awe/Keana Formation may be because K-feldspars are susceptible to change during burial diagenesis. Some minerals become weak and unstable when the temperature rises as a result of increased burial depth; as a result, these minerals are replaced by more stable minerals in a new diagenetic environment. The detected mineral substitutions in the investigated rocks include albitization, kaolinitization/illitization, and calcite replacing quartz, feldspar, and the clay matrix.

#### b. Replacement with Albite

The K- or Ca-feldspar framework grains were either partially or completely replaced by albite in the rocks of the Awe/Keana Formation. Albitization of K- and Ca-feldspar is one of the major diagenetic changes during burial diagenesis. Albite replaced the K-feldspar mineral grains, although in some cases, albite grains precipitated out after partial dissolution.

#### c. Authigenic Clay Minerals

Kaolinite and sericite are two more often changed forms of K-feldspar (Fig. 13). Sericite grains can be found on the entire feldspar grain or dispersed as tiny flakes along cleavage planes. The matrix and framework grains of K-feldspar and muscovite are partially to totally replaced, according to SEM observations, by fibrous kaolinite. Occasionally, sericite took the place of some feldspar grains.

### 5. Recrystallization

The Awe/Keana Formation rocks frequently experience mineral recrystallization. Recrystallization is the process of altering the size or shape of crystals made of a certain mineral without altering the material's mineralogy or chemical makeup. Microgranular and fine minerals can become coarse textures as temperature and pressure rise with burial depth. Existing minerals can also change in size but maintain their chemical makeup. However, some minerals that already exist may undergo a complete transformation or convert into a new mineral. The altered silica or silicate minerals in the rocks were discovered by petrographic and

SEM examinations to be feldspars, quartz, muscovite, chlorite, sericite, and muscovite. Illite developed from kaolinite in terms of clay minerals. Illite further transformed into sericite (Fig. 13) and muscovite as the temperature rose. The mica underwent additional alteration to become kaolinite, typically near the edges or along the boundary, as seen in Fig. 13. Fine matrix materials were transformed to create several quartz cements. Detrital grains, such as quartz and feldspar, were also seen to progressively change and grow in size as crystals. Progressive recrystallization results in larger crystalline grains, which tends to result in less pore interconnectivity and less pore space between the grains.

#### 4.9 Diagenetic Stages

Early diagenesis, burial diagenesis, and uplift-related diagenesis are the three stages of the diagenetic features seen in the sandstones of the Awe/Keana Formation. The earliest diagenetic event occurred soon after deposition, and the most recent event occurred until the present. The term "early diagenesis" refers to all activities that took place at or near the surface of the sediment, where the depositional environment predominantly controls the chemistry of the interstitial water (Chapelle, 1993). According to Burley and Worden (2003), during this stage, the influence of the original depositional pore water predominates and includes bacterially mediated redox reactions in marine environments. At shallow burial, the early diagenetic realm may only reach a few meters below the sediment surface, yet the depositional system will still have an impact. Diagenesis that occurs during burial, immediately following the cementation of the sediments and before they are freed from the influence of the depositional environment to undergo metamorphism, is referred to as burial diagenesis. On the other hand, elevated and exhumed rocks experience uplift-related diagenesis. These rocks have been exposed to surface (meteoric) water influx that is unrelated to the host sediments' depositional environment. Because the rocks are in contact with low salinity, high oxygen, and high carbon dioxide-charged fluids, uplift-related diagenesis differs from burial diagenesis. Despite the fluids' low ionic strength,

they can nonetheless cause substantial geochemical alterations, including the transformation of feldspar into clay minerals (often kaolinite) and the oxidation of ferric minerals.

#### 1. Early Diagenetic Stage

Early diagenesis refers to all the transformations that the sandstones of the Awe/Keana Formation underwent before becoming solidified hard rock. Early diagenesis is primarily influenced by time temperature history, fundamental mineralogy and fabric, pore water geochemistry, and the presence of petroleum-related fluids (such as oil and shale gas). Early diagenetic processes that have been observed include the precipitation of authigenic clay minerals, modest quartz and haematite coating development, pyrite production, and lithification.

Early in the diagenetic process, little quartz cementation caused by the remobilization of biogenic silica and compaction begins to develop. Quartz syntaxial overgrowths, however, occur between 70 and 80°C at depths of several kilometers, well after most compaction and outside the range of early diagenesis. In actuality, a large portion of the quartz and feldspar cements are supplied through grain compaction and dissolution. According to Lewin (1971), the early appearance of quartz cements in marine sandstones and mudstones may indicate that biogenic siliceous creatures began to decompose soon after the sediments were produced. Cementation very immediately started, and distinct forms of cement started to precipitate. The clay matrix is one of the earliest minerals to precipitate from the pore spaces between framework detrital grains. The second category of cements produced in the Awe/Keana Formation includes autigenic smectite and kaolinite cements. The third category of cements includes haematite, quartz, and feldspar cements. The Awe/Keana sandstones mostly contain the clay minerals kaolinite and illite. In reality, grain compaction and dissolution supply a significant amount of quartz and feldspar cements. In marine sandstones and mudstones, the early emergence of quartz cements may suggest that biogenic siliceous organisms started

to degrade soon after the sediments were created, according to Lewin (1971). Almost quickly, cementation began, and different types of cement began to precipitate. One of the first minerals to form in the pore spaces between framework detrital grains was the clay matrix. Authigenic smectite and kaolinite cements are included in the second type of cement formed in the Awe/Keana Formation. Hematite, quartz, and feldspar cements are included in the third category of cements. The clay minerals kaolinite and illite are the most common minerals found in the Awe/Keana sandstones.

This indicates that the pore water rich in iron oxide during early diagenesis was responsible for the creation of these grain coatings. Since the chemistry of the interstitial waters was predominantly controlled by the depositional environment, as shown by Schmidt and McDonald (1979a, 1979b), oxidizing conditions in the interstitial waters must have prevailed at this time to permit the synthesis of iron cement. Another clay mineral that precipitates in the early diagenetic stage is glauconite. Glauconite precipitation must have taken place in the presence of pore fluids containing Si, Fe, Al, and K near the boundary between reducing and oxidizing zones in muddy sediments (Harder, 1980). One of the elements influencing the precipitation of glauconite is the silica content. The Awe/Keana Formation sandstones have a low organic material content because of this. This might be what caused the low levels of glauconite in the examined sandstones. The cementation and mechanical compaction of the soft sediments led to their lithification. Increased burial depth and overburden pressure lead to compaction, which entails dewatering and closer grain packing. In conclusion, matrix and cement precipitation, authigenic mineral formation, compaction, and mild cementation were the characteristics of the early diagenetic processes.

## 2. Burial Diagenetic Stage

All the alterations that may occur to rocks following consolidation but prior to metamorphism are referred to as burial diagenesis. Increased temperature and pressure, as well as a change in the composition of the pore

water, are the key factors influencing diagenesis in the burial diagenetic stage (Boggs and Kingsley, 2006). These elements cause both chemical and mineral changes that tend to bring the sediments into equilibrium with the diagenetic environment, such as mineral replacement, mineral dissolution, and the precipitation of new cements, as well as physical changes (such as compaction and porosity loss). Pore fluids underwent additional modifications or changes as a result of clay mineral interactions with deeper burial. In addition, unstable grain breakdown occurred. Without taking into account the impact of organic materials, diagenesis in the buried diagenetic environment is incomplete (Boggs, 2009). In response to organicoorganic interactions, carbonates (such as calcite cements) and some silicate minerals (such as feldspar) may both dissolve. Cementation, physical and chemical compaction, dissolution, recrystallization, precipitation, and replacement of minerals (i.e., albitization, sericitization, and chloritization), pressure-resolution, grain-deformation, and fracturing are the diagenetic processes that took place in the burial diagenetic stage. Due to the rise in overburden pressure during burial diagenesis, the Awe/Keana sandstones continue to be compacted. This resulted in a loss of some pore spaces and an increase in the tightness of grain packing. Likewise, the partial dissolution of silicate grains and recrystallization of fine minerals were caused by the rise in temperature and pressure brought on by compression.

The subsequent burial diagenetic alterations are dominated by quartz and feldspar overgrowths, mineral replacement, and clay mineral alteration (i.e., kaolinite to illite or sericite, sericite to chlorite, etc.). The replacement of K- and Ca-feldspars, notably the K-feldspars, results in the formation of albite and illite. Some K-feldspars are replaced by calcite, and as a byproduct, authigenic quartz is released. Unstable detrital grains allow cations to enter pore water, which causes calcite cements to form in the pore space or take the place of detrital grains and matrix. The creation of the calcareous character that is typically attributed to the sandstones of the Awe/Keana creation was caused by some of the calcium carbonate ions moving towards a center

in pore-solution within the sandstones. These calcareous natures are typically connected to the original depositional environment, such as sea sediments, and they may also be connected to later diagenesis because of pore water leaching and evaporation (caliche). The potash feldspar lattice can be destroyed by solutions high in  $\text{Ca}^{2+}$  and  $\text{CO}_3^{2-}$  ions, presumably by forcing the silica tetrahedral units into solution in a high pH burial environment (Dapples, 1967). Mineral replacement in the rocks of the Awe/Keana sandstone was not limited to K-feldspars. Quartz grains and the clay matrix underwent partial replacement as well. The crystalline structures of minerals containing  $\text{Ca}^{2+}$  ions, which occupy less interstitial space and allow the remaining space to be filled by the precipitated carbonate, can be linked to the precipitation of calcite inside clay minerals (Dapples, 1967).

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result of additional compression. Furthermore, excessive compression caused muscovite flakes to bend and distort. When the muscovite grains, detrital feldspar, and rock pieces were also fragmented, secondary porosity was produced.

### 3. Uplift-Related Diagenetic Stage

Rocks from the marine Awe/Keana Formation are uplifted and exposed to an influx of surface water, resulting in an uplift-related diagenetic environment. According to Hurst and Irwin (1982), unless marine deposits are raised and exposed to weathering, they are never invaded by significant amounts of meteoric or surface waters. The uplift-related diagenetic stage is typically characterized by oxidizing and meteoric pore fluids, as well as lower temperatures and pressures. In the uplift-related diagenetic stage, mineral assemblages that were initially produced under high pressure and temperature become unstable. Unstable minerals may change or dissolve as a result. Furthermore, additional diagenesis may occur in the initial detrital mineral assemblages. The Awe/Keana Formation rocks underwent diagenesis at a depth below the Earth's surface, but they were still in the area of meteoric water circulation. Uplift and weathering processes caused it to continue at the surface. At the time of uplift, the rocks were exposed to acidic rainwater, which caused previously created carbonate cements to dissolve (decementation), increasing porosity. Most experts agree that kaolinization, particularly the kaolinization of sandstones, depends on the freshwater flushing of sediments (Bjorlykke et al. 1979). Additionally, pore space was generated by the partial dissolution and leaching of calcite and kaolinite. To summarize, grain fracturing, dissolution, and chloritization were the main characteristics of the uplift-associated diagenetic processes.

#### 4.10 Diagenetic Sequence

The sandstones of the Awe/Keana Formation include a succession of diagenetic modifications that are connected to one another and can be considered to be a diagenetic route. Table 3 lists the diagenetic pathways and mechanisms that led to the production of various minerals in the rocks of the Awe/Keana Formation.

Table 3: Diagenetic events and pathway of the Awe/Keana Formation in the study area

Diagenetic Events	→		
	Early Diagenesis	Burial Diagenesis	Uplift-related Diagenesis
Clay matrix	██████████		
Kaolinite	██████████		
Point contact	██████████		
Physical compaction	████████████████████		
Planar contact	████████████████████		
Calcite cementation	████████████████████		
Quartz cementation	████████████████████		
Authigenic minerals		██████████	
Hematite cement		██████████	
Quartz overgrowth		████████████████████	
Illitization		████████████████████	
Sericite		████████████████████	
Calcite replacement			████████████████████
Albitization			████████████████████
Muscovite alteration			████████████████████
Concave-convex contac			████████████████████
Suture contact			████████████████████
Chemical compaction			████████████████████
Chlorite			██
Grain fracturing			██
Dissolution			██

#### 4.11 Implications of Diagenesis for Reservoir Quality

The link between porosity and permeability, which can take several forms, determines the quality of a reservoir. Two essential characteristics of sedimentary rocks, porosity and permeability, are regulated to some extent by the textural features of grain size, shape, packing, and arrangement. By regulating the flow of fluids through rocks, they also play a very important part in the diagenesis of sediments.

Minerals dissolve, cement, and undergo authigenesis as a result of fluid flowing within the rock. The Awe/Keana sandstones showed both primary and secondary porosity upon petrographic and SEM analysis. The pore space that was present in the sediment immediately following deposition and before diagenetic alteration is known as primary porosity. It is composed of microporosity (matrix micropores) and intergranular porosity (pore space between grains). Diagenesis may result in a change in the

kinds of pores, such as when authigenic clay minerals precipitate in pores and cause the pore mouths to narrow.

Diagenetic activities that either decrease or increase porosity and permeability have a significant impact on the reservoir quality of the Awe/Keana sandstones. The cementation of calcite, quartz, feldspar, clays, and iron oxide as well as compaction are the two most significant diagenetic processes in the sandstones of Awe/Keana. Principal intergranular and matrix micropores are the principal porosities that have been found. Point and line contacts are created as overburden compacts the sediments.

Primary porosity loss from compaction was caused by progressive burial, as shown by the lengthy and sutured contact between nearby clastic grains. Due to modifications in grain contacts, primary intergranular porosity and pore radii were decreased. In some samples, the carbonate cement lessened or stopped further compaction, which led to the clastic grains being

packed closely together. The retention of porosity was also greatly aided by authigenic kaolinite and iron oxide. The primary porosity was reduced by kaolinite and mixed layer clays, yet porosity might form and be preserved between kaolinite crystals (Figs. 10 – 13).

Generally, the matrix pores are quite small in size, perhaps as a result of the significant amount of illite minerals present. The rocks did, however, contain a few rather large and elongated pores (Fig. 13). The maintenance of primary porosity in the rocks may be hampered by the presence of quartz cements because they are known to be damaging to primary porosity. Some samples have detrital quartz grains coated with quartz overgrowth, which reduces pore radii and, as a result, porosity and permeability.

Some overgrowths are surrounded by chlorite rims, which preserve the ineffective matrix microporosity. Patches of calcite cement can be seen in the sandstones, and they partially fill the intergranular pores (Fig. 13). A result of severe compaction and cementation is a reduction in the number of primary intergranular pores. The same mechanism that produced the wackes epimatrix, a matrix made up of clays that form during diagenesis (authigenic), occasionally from the alteration of feldspars, also removed the majority of the main pores.

The rocks did have a modest degree of secondary porosity, however. In the course of burial diagenesis, pore fluids formed pore spaces for subsequent cementation by preferentially destroying less stable minerals or clastic grains. Secondary porosity was also produced during a different episode of dissolution that took place during uplift-related diagenesis and entailed the partial removal or dissolution of previously built carbonate cements.

The secondary intragranular, dissolution, and fractured pores that have been found in the rocks are secondary porosities. The dissolution of feldspar grains that were unstable, the breakdown of clay minerals created by altering the pseudomatrix, and the dissolution of carbonate materials (such as calcite cement) all led to secondary intragranular and dissolution pores. On the other hand, structural stresses and differential compaction are responsible for the broken pores. As burial depth increases, some of the detrital feldspar and muscovite grains are broken, most likely as a result of compaction.

Overcompaction, which in certain cases led to a loss in porosity, is another factor that fractures indicate. Regarding reservoir quality, compaction and cementation first reduced porosity, which was later increased by the dissolution of calcite cement and unstable minerals (decementation). A fair-medium potential (moderate) reservoir quality results from the majority of the secondary pores being very small and isolated, which results in relatively low porosity and permeability.

The Awe/Keana sandstones are ideal hydrocarbon producers due to their medium porosity and permeability, which at best would require stimulation or fracking. Figure 10-13 and Table 2 provide a summary of the petrophysical characteristics the authors measured for the Awe/Keana sandstones. For the outcropped sandstone samples from the Awe/Keana Formation, the average measured thin section and SEM porosity is (= 10.16%). The actual or true porosity of the rocks in the field may be significantly larger than the observed or measured thin section porosity because the Awe/Keana sandstone outcrops have developed fractures, splits, and faults.



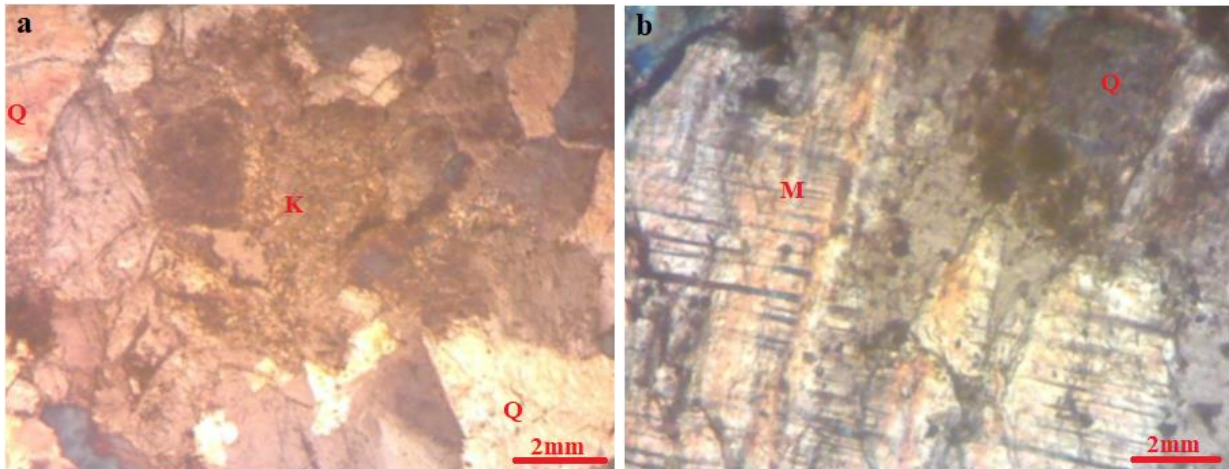


Figure 10: Photomicrographs of arkosic sandstone of the Awe Formation (a) under PPL and (b) under XPL (Mag x40). K: Kaolinite, M: Microcline; Qz: Quartz

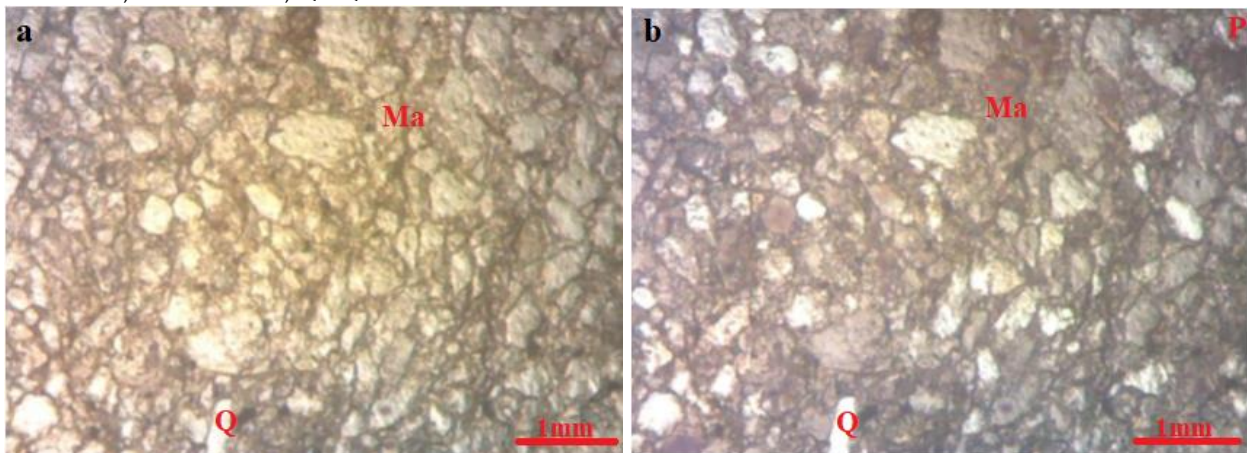


Figure 11: Photomicrographs of feldspathic graywacke sandstone of the Awe Formation (a) under PPL and (b) under XPL (Mag x40) Q: Quartz, Ma: Matrix, P: Plagioclase Feldspar

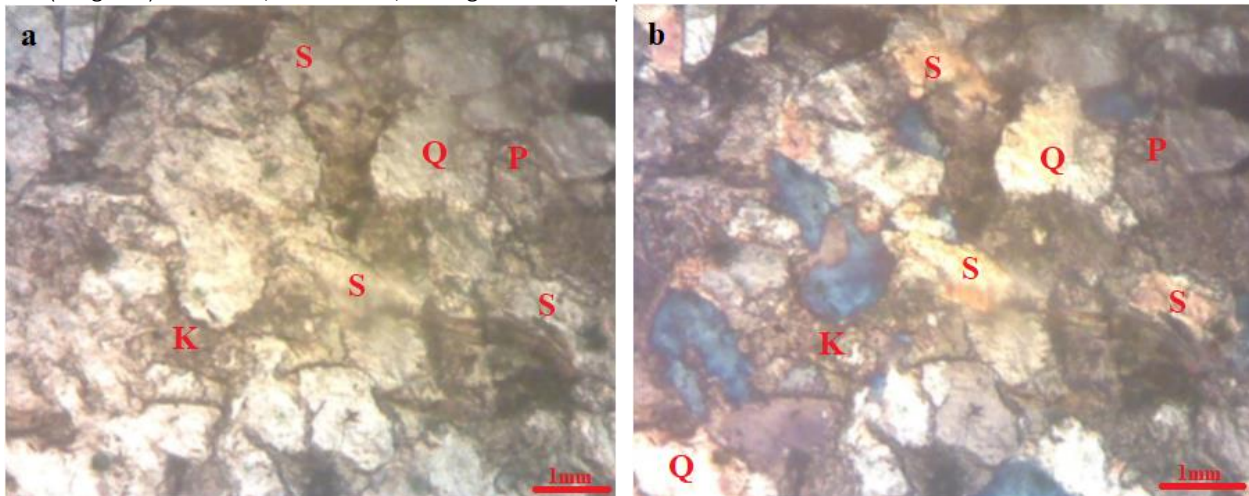
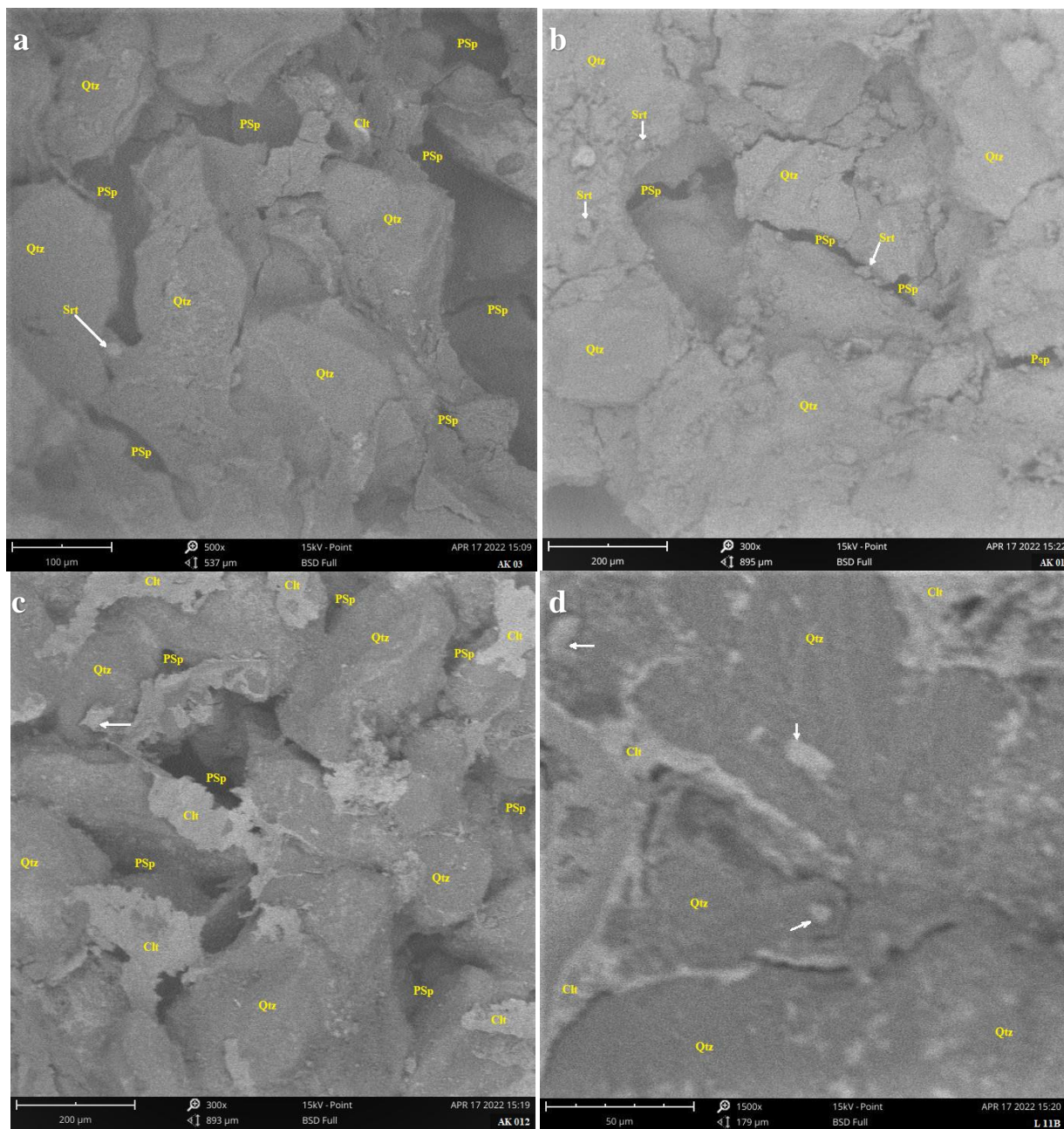


Figure 12: Photomicrographs of a subarkose sandstone of Keana Sandstone (a) under PPL and (b) under XPL (Mag x40) Q: Quartz, S: Sericite, K: Kaolinite, P: Plagioclase Feldspar



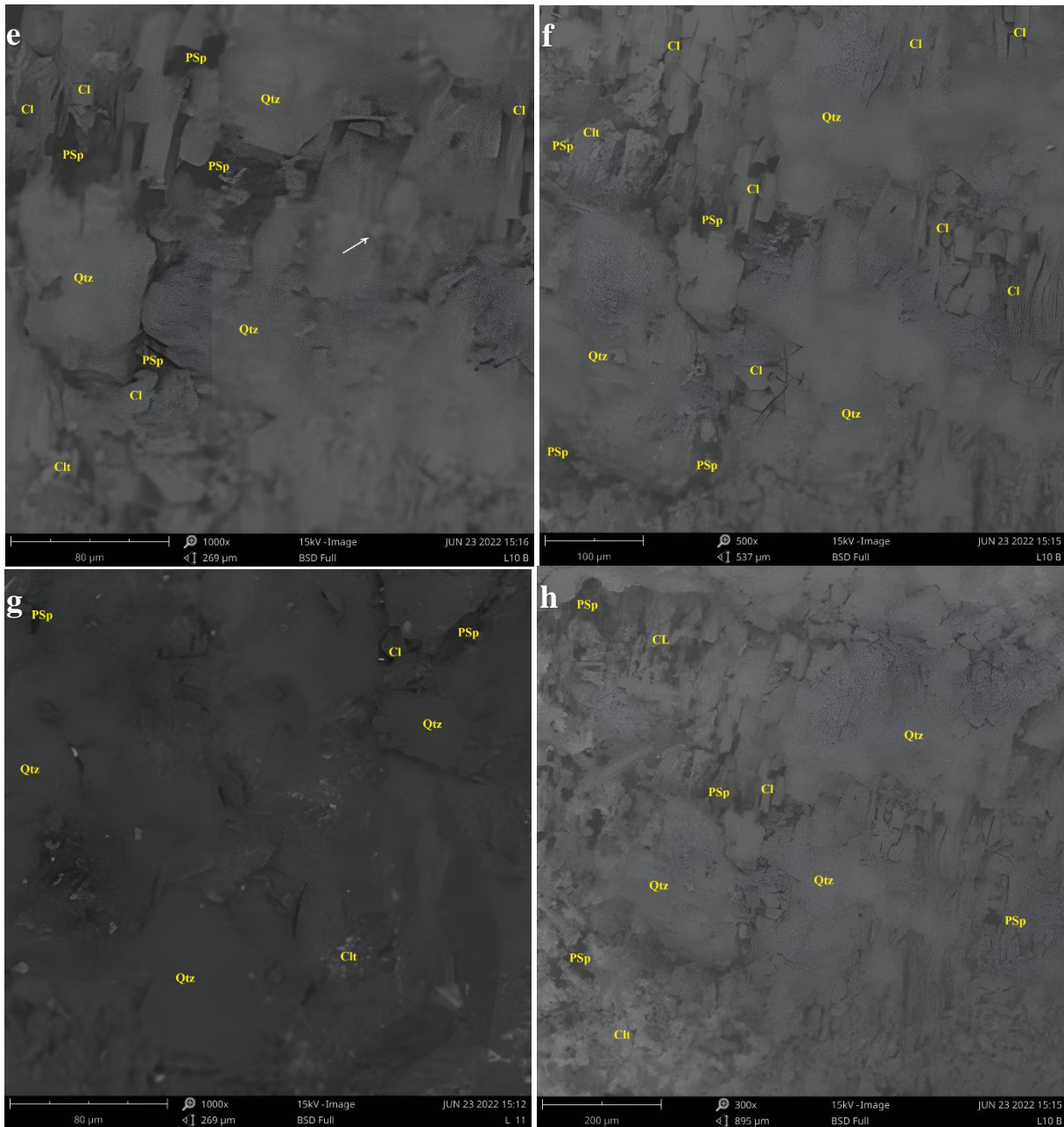


Figure 13: SEM micrograph diagenesis and reservoir quality alteration (a) pore space (PSp) distribution within quartz grains (Qtz) (b) shows fragments of authigenic siderite clogging pore spaces indicated by the white arrows (c, e, f, g, h, i) pore spaces (PSp), quartz grain (Qtz) and calcite cements (Clt) obliterating pore spaces by clogging intergranular pore connectivity

## 5 Conclusions

This study conducted a comprehensive evaluation of the reservoir potential of the Awe/Keana Formation in the middle Benue Trough using facies studies, petrographical examinations, SEM imaging geochemical analyses, and diagenetic studies. The analysis

revealed the presence of diverse lithofacies and lithofacies associations, including sandstone, shale, mudrock, siltstone, and heterolith facies. The sandstones were further classified into glauconitic, fine-grained, and very fine-grained facies, corresponding to arkose, subarkose, and feldspathic graywacke classifications based on

their mineralogical composition. The QFL ternary diagram demonstrates the distribution of sandstones within different fields, such as arkose, feldspathic graywacke, and subarkose, with some samples exhibiting calcareous characteristics due to carbonate minerals.

The study also provided insights into the diagenetic processes that have influenced the Awe/Keana Formation, including cementation, compaction, dissolution, grain replacement, and recrystallization. Petrographic and SEM examination identified both primary and secondary porosity in the sandstones, with primary intergranular and matrix micro pores observed. The medium porosity and permeability of the Awe/Keana sandstones indicate their potential as favorable reservoirs for hydrocarbons, although stimulation or fracking might be necessary for optimal extraction. Furthermore, the provenance analysis using plotting techniques suggested that the sediment source of the Awe/Keana Formation varied from the craton interior to dissected ark and transitional continental to mixed environments, which probably came from the crystalline basement complex rocks of the Oban and Cameroon massifs. These findings contribute valuable information for future exploration strategies, risk mitigation, and decision-making regarding scientific and commercial drilling activities in the Middle Benue Trough.

### Acknowledgements

This paper is based on part of a Ph.D. thesis under the supervision of N. G. Obaje, J. A. Adeoye, and R. G. Oladimeji of IBB University, Lapai. The first author thanks the management of Prince Abubakar Audu University (Kogi State University) Anyigba, the Tertiary Education Trust Fund and the Nigerian National Petroleum Corporation through the office of the NNPC Chair in Basinal Studies, Ibrahim Badamasi Babangida University, Lapai, Nigeria.

**Declaration of Competing Interest:** We have nothing to declare.

### References

- Adamu L.M., Obaje, N.G., Bomai, A., Zanna, M., Adeoye, J.A., & Oladimeji, G.R. (2022). Multivariate Geo-Chemo Statistical Characterization of Potential Source Rocks in the Middle Benue Trough, Nigeria. *83rd EAGE Annual Conference & Exhibition*, Jun 2022, p.1 – 5. DOI: <https://doi.org/10.3997/2214-4609.202210199>
- Adamu, M.L., Obaje, G. N., Adeoye, A. J., Oladimeji, G. R. and Yusuf. I. (2023). Trans-Saharan seaway connection between the South Atlantic and the Tethys Sea during the Coniacian-Turonian: Evidence from bibliographical synthesis, field mapping, and seismic interpretation. *Geosystems and Geoenvironment*, 3 (2024) 100243.
- Akande, S. O., Egenhoff, S. O., Obaje, N. G., Ojo, O. J., Adekeye, O. A., & Erdtmann, B. D. (2012). Hydrocarbon potential of Cretaceous sediments in the Lower and Middle Benue Trough, Nigeria: Insights from new source rock facies evaluation. *J. Afr. Earth Sci.*, 64: 34–47.
- Allix, P., Grosdidier, E., Jardine, S., Legoux, O., & Popoff, M. (1997). "Decouverte d'Aptien Supérieur à'Albien Inférieur par Microfossiles dans la Série Détritique Cretace du Fosse de la Benoue (Nigeria)," In: H. Gebhardt, Ed., *Journal Paper, Cenomanian to Turonian Foraminifera from Ashaka (NE Nigeria): Quantitative Analysis and Palaeoenvironmental Interpretation. Cretaceous Research*, 18(1), 17-36. <http://dx.doi.org/10.1006/cres.1996.0047>
- Amajor, L.C. (1985). The Stratigraphy of the Bima Sandstone Formation in the Middle Benue Trough. *Bull. Geol. Sur. Nig.*, 32, 1-87.
- Baiyegunhi, C., Liu, K., & Gwavava, O. (2017). Diagenesis and reservoir properties of the Permian Ecca Group sandstones and mudrocks in the Eastern Cape Province, South Africa. *Minerals*, 7(6), 88.

- Basu, A., Young, S. W., Suttner, L. J., James, W. C., & Mack, G. H. (1975). Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation. *Journal of Sedimentary Research*, 45(4), 873-882.
- Benkhelil, J. (1989). The origin and evaluation of the cretaceous Benue Trough (Nigeria). *J. Afr. Earth Sci.*, 8, 251-282.
- Benton, M. J. and Harper, D. A. T. (1997). *Basic Palaeontology*. Addison Wesley Longman, Harlow, Essex, 342pp.
- Bromley, R. G. (1996). *Trace fossils: biology, taphonomy and application*. Chapman and Hall, London, p 361.
- Brunet, M., Dejax, J., Brillanceau, A., Congleton, J., Downs, W., Dupéron-Laudoueneix, M., Eisenmann, V., Flanagan, K., Flynn, L., Heinz, E., Hell, J., Jacobs, L., Je-henne, Y., Ndjeng, E., Mouchelin, G., & Pilbeam, D. (1989). "Mise en évidence d'une Sédimentation Précoce d'Age Barremien dans le Fossé de la Bénoué en Afrique Occidentale (Bassin de Mayo Oulo Léré, Cameroun)," In: J. Benkhelil, M. Guiraud, J. F. Posard and L. Saugy, Eds., *The Bornu— Benue Trough, the Niger Delta and its Offshore: Tectono-Sedimentary Reconstruction during the Cretaceous and Tertiary from Geophysical Data and Geology*, In: C. A. Kogbe, Ed., 2nd Edition, *Geology of Nigeria, Rock View Nigeria Limited., Jos*, pp. 277-309.
- Bjørlykke, K., Elvekhøi, B. A., & Malm, A. O. (1979). Diagenesis in Mesozoic sandstones from Spitsbergen and the North Sea—a comparison. *Geologische Rundschau*, 68, 1152-1171.
- Blatt, H., Middleton, G.V. and Murray, R.C., 1980. *Origin of Sedimentary Rocks*, 2<sup>nd</sup> Edition, Prentice-Hall Inc., New Jersey
- Blatt, H., & Christie, J. M. (1963). Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks. *Journal of Sedimentary Research*, 33(3), 559-579.
- Boggs, S. (2009). *Petrology of sedimentary rocks*. Cambridge university press.
- Boggs, S., & Krinsley, D. (2006). *Application of cathodoluminescence imaging to the study of sedimentary rocks*. Cambridge University Press.
- Chapelle F. H. (1993) *Groundwater Microbiology and Geochemistry*. Wiley.
- Cratchley, C. R., & Jones, G. P. (1965). An interpretation of the geology and gravity anomalies of the Benue valley, Nigeria. *Overseas Geol. Sur. Geophys. paper*, 1, 1-26.
- Crook, K.A.W., 1974. Lithogenesis and Geotectonics: the significance of compositional variation in flysch arenites (graywackes). In: Dott, R.H., Shaver, R.H. (Eds.), *Modern and Ancient Geosynclinal Sedimentation*, 19. Society for Sedimentary Geology (SEPM) Special Publication, pp. 304–310.
- Dabbagh, M. E., & Rogers, J. J. (1983). Depositional environments and tectonic significance of the Wajid Sandstone of southern Saudi Arabia. *Journal of African Earth Sciences* (1983), 1(1), 47-57.
- Dapples, E. T. (1967). Diagenesis of sandstones. In *Developments in sedimentology* (Vol. 8, pp. 91-125). Elsevier.
- Dickinson, W.R., 1985. Interpreting detrital modes of greywacke and arkose. *J. Sediment. Petrol.* 40, 695–707.
- Dickinson, W. R., & Suczek, C. A. (1979). Plate tectonics and sandstone compositions. *Aapg Bulletin*, 63(12), 2164-2182.
- Dickinson, W. R., Beard, L. S., Brakenridge, G. R., Erjavec, J. L., Ferguson, R. C., Inman, K. F., ... & Ryberg, P. T. (1983). Provenance of North American Phanerozoic sandstones in relation to tectonic setting. *Geological Society of America Bulletin*, 94(2), 222-235.
- Eckdale, A. A, Bromley R. G. and Pemberton S. G. (1984). Shallow marine terrigenous environments. In *Ichnology. Trace fossils in Sedimentology and Stratigraphy*. SEPM Short Course, 15, 185–198.

- Edegbai, A.J., Schwark, L., & Oboh-Ikuenobe, F.E. (2019). A review of the latest Cenomanian to Maastrichtian geological evolution of Nigeria and its stratigraphic and paleogeographic implications. *J. Afr. Earth Sci.*, 150, 823–837.
- Ehremberg, K. (1944). Ergänzende Bemerkungen zuden seinerzeit aus dem Miozaan von Burgschleinitz beschrieben Gangkernen und Bauten dekapoder Krebse. *Palaontologische Zeitschrift*, Berlin, 23, 345-359.
- Falconer, J.D., 1911. The Geology and Geography of Northern Nigeria. Macmillan, London, p. 135.
- Guiraud, R., & Bosworth, W. (1997). Senonian Basin Inversion and Rejuvenation of Rifting in Africa and Arabia: Synthesis and implications to Plate-scale Tectonics. *Tectonophysics*, 282(1-4), 39-82. [http://dx.doi.org/10.1016/S0040-1951\(97\)00212-6](http://dx.doi.org/10.1016/S0040-1951(97)00212-6)
- Hall, J. (1843). Geology of New York. Part 4. Comprising the Survey of the Fourth Geological District (525 pp.). Albany: Carroll and Cook.
- Harder, H., 1980. Synthesis of glauconite at surface temperatures. *Clays Clay Miner.* 28, 217–222.
- Harms, J. C., Southard, J. B., Spearing, D. R., & Walker, R. G. (1975). Stratification Produced by Migrating Bedforms: In *Depositional Environments as Interpreted from Primary Sedimentary Structures and Stratification Sequences*. S.E.P.M. Short Course No. 2, P.120.
- Hurst, A., & Irwin, H. (1982). Geological modelling of clay diagenesis in sandstones. *Clay minerals*, 17(1), 5-22.
- Frey, R. W. (1978). Behavioral and ecological implications of trace fossils. In: Basan PB (ed) Trace fossil concepts. *Miscellanea University of Kansas Press*, Kansas, pp 177–245.
- Frey, R. W., Howard, J. D. and Pryor WA (1978). Ophiomorpha: its morphologic, taxonomic, and environmental significance. *Palaeogeography Palaeoclimatology Palaeoecology*, 23, 199–229.
- Folk, R. L. (1980). *Petrology of sedimentary rocks*. Hemphill publishing company.
- Folk, R. L. (1974). The natural history of crystalline calcium carbonate; effect of magnesium content and salinity. *Journal of Sedimentary Research*, 44(1), 40-53.
- Friedman, G. M. (1967). Dynamic processes and statistical parameters compared for size frequency distribution of Beach and River sands. *Journal of Sedimentary Petrology*, 37, 327–354.
- Johnsson, M. J., Stallard, R. F., & Meade, R. H. (1988). First-cycle quartz arenites in the Orinoco River basin, Venezuela and Colombia. *The Journal of Geology*, 96(3), 263-277.
- Kogbe, C. A. (1976). "Palaeogeographic History of Nigeria from Albian Times," In: C. A. Kogbe, Ed., *Geology of Nigeria*, Elisabethan Publishing Co., Lagos, pp. 237-252.
- Lewin, I. P. 1971. Use of Servo Mechanisms for Volume Change Measurement and KO Consolidation. *Géotechnique*, 21(3), 259-262. <https://doi.org/10.1680/geot.1971.21.3.259>
- Murat, R.C. (1972). Stratigraphy and paleogeography of the Cretaceous and lower tertiary in southern Nigeria. In: Dessauvage, T.F.J., Whiteman, A.J. (Eds.), *African Geology*. University of Ibadan Press, Nigeria, pp. 251–266.
- Nwajide, C. S. (1990). Sedimentation and palaeogeography of the Middle Benue Trough, Nigeria. In: Ofoegbu CO (ed) *The Benue trough structure and evolution*. Vieweg, Braunschweig, pp 19–38.
- Nwajide, C.S. (2013). *Stratigraphy and Sedimentology of the Benue Trough, Nigeria*. Elsevier.
- Nwachukwu, S.O. (1972). The tectonic evolution of the southern portion of the Benue Trough, Nigeria. *J. Min. Geol.*, 11, 45-55.
- Obaje, N.G., Ligouis, B., & Abaa, S.I. (1994). Petrographic composition and depositional environments of Cretaceous coals and coal measures in the Middle Benue Trough of Nigeria. *Int. J. Coal Geol.*, 26, 233–260.

- Obaje, N. G., Funtua, I.I., Ligouis, B., & Abaa, S.I. (1996). "Maceral Associations, Organic Maturation and Coal-derived Hydrocarbon Potential in the Cretaceous Awgu Formation, Middle Benue Trough, Nigeria". *J. Afr. Sci.*, 23, 89-94.
- Obaje, N. G., Umar, U. M., Aweda, A. K., & Ozoji, T. M. (2020). Nigerian Cretaceous Coal Deposits and their Petroleum Source Rock Characteristics. *Int. J. Pet. Gas Expl. Man.*, 4(1), 1-14.
- Obaje, N. G., Ulu, O. K. and Petters, S. W. (1999a). 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 (1999b) Economic geology of Nigerian coals resources—a brief review. *African Geosciences Review*, 6, 71-82.
- Obaje, N. G. (2009). *Geology and Mineral Resources of Nigeria* (p. 240). Springer Verlag, Heidelberg, Berlin, New York.
- Obaje, N. G. (2019). *Update on Geology and Mineral Resources of Nigeria* (p. 240). Springer Verlag, Heidelberg, Berlin, New York.
- Offodile, M. E. (1976). *The geology of the Middle Benue, Nigeria*. Palaentological Institute, University Uppsala, Special Publication, 4, 1-166.
- Offodile, M.E. & Reyment, R.A. (1977). "Stratigraphy of the Keana-Awe area of the Middle Benue Region of Nigeria". *Bull. Geological Institutions University Uppsala (N. S.)*, 7, 37-66.
- Patrick, N.O, Fadele, S.I, & Adegoke, I. (2013). Stratigraphic report of the middle benue trough, Nigeria: Insights from petrographic and structural evaluation of abuni and environs part of late albian-cenomanian awe and keana formations. *Pacific J. Sci. & Techn.*, 14, 557-570. <http://www.akamaiuniversity.us/PJST.htm>
- Paul M. M. (1995). Thalassinoides and the enigma of Early Palaeozoic open-framework burrow systems. *PALAIOS*. 10(1), 58-74.
- Pemberton S. G. and Frey R. W. (1982). Trace fossil nomenclature and the Planolites-Palaeophycus dilemma. *J Palaeontol.*, 56, 843-881.
- Pemberton S. G. and Frey R. W. (1984). Ichnology of storm influenced shallow marine sequence, Cardium Formation (Upper Cretaceous) at Seebe, Alberta. In: Stolt DF, Glass DJ (eds) *The Mesozoic of middle North America*. CSPG special publications, Canada, pp 281-304.
- Pemberton, S. G., MacEachern, J. A., & Frey, R. W. (1992). Trace fossil facies models: environmental and allostratigraphic significance. In: Walker, R. G., & James, N. (Eds.), *Facies Models: Response to Sea Level Change*. St. John's, Newfoundland, Geological Association of Canada, pp. 47-72.
- Petters, S.W. (1982). Stratigraphy of the Cretaceous and Lower Tertiary rocks of northeastern Nigeria. *Bull. Geol. Sur. Nig.*, 45, 1-120.
- Petters, S.W., & Ekweozor, C.M. (1982). Petroleum geology of the Benue Trough and South-Eastern Chad Basin, Nigeria. *AAPG Bull.*, 66, 1141-1149.
- Pettijohn, F. J., Potter, P. E., Siever, R., Pettijohn, F. J., Potter, P. E., & Siever, R. (1987). Introduction and source materials. *Sand and sandstone*, 1-21.
- Pettijohn, F. J. (1975). *Sedimentary rocks* (Vol. 3, p. 628). New York: Harper & Row.
- Pollastro, R. M. (1985). Mineralogical and morphological evidence for the formation of illite at the expense of illite/smectite. *Clays and Clay Minerals*, 33, 265-274.
- Potter, P.E., 1978. Petrology and chemistry of modern big river sands. *J. Geol.* 86, 423-449.
- Reyment, R.A. (1965). Stratigraphy and paleontology of the Upper Cretaceous sediments of the Benue Valley, Nigeria. *Bull. British Museum (Natural History)*, 10(2), 95-148.
- Schmidt, V., & McDonald, D. A. (1979a). The role of secondary porosity in the course of sandstone diagenesis. Aspects of Diagenesis, Peter A. Scholle, Paul R. Schluger. <https://doi.org/10.2110/pec.79.26.0175>

- Schmidt, V., & McDonald, D. A. (1979b). Texture and recognition of secondary porosity in sandstones. The Society of Economic Paleontologists (SEPM) Special Publication, 26, 209-225
- Schwab, F. L. 1975. Framework mineralogy and chemical composition of continental margin-type sandstone. *Geology*, 3, 487-90
- Walker, R. G., & Plint, A. G. (1992). Wave- and storm-dominated shallow marine system. In: Walker, R. G., James, N. P. (Eds.), *Facies Models: Response to Sea Level Change*. Geological Association of Canada, St. John's, P. 219–238.
- Worden, R.H., Burley, S.D., 2003. Sandstone diagenesis: from sand to stone. In: Burley, S.D., Worden, R.H. (Eds.), *Clastic Diagenesis: Recent and Ancient*. International Association of Sedimentologists, vol. 4. Blackwells, Oxford, pp. 3–44.
- Woodward, S. (1830). A synoptic table of British Organic remains. London & Norwich, 50pp.
- Yusuf, I., Obaje, N. G., Adeoye, J. A., Adamu, L. M. and Yusuf, T.U. (2022). Geology, Reservoir Diagenesis and Quality of Albian -Cenomanian Keana/Awe Potential Reservoir Sandstone in Middle Benue Trough, Nigeria. *Lapai Journal of Science and Technology*, 8(1), 16-31.
- Zaborski, P.M. (2000). Tectonic and Palaeogeographic Evolution of the Benue Trough and Its Surroundings. In: B.C. Schreiber, and A.J. Redmond (Eds.), *The Benue Trough Structure and Evolution*. G