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BIO-CHEMO-PETROGRAPHICAL CHARACTERIZATION OF CENOMANIAN-TURONIAN CARBONATE DEPOSITS IN THE MIDDLE BENUE TROUGH, NIGERIA

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ABSTRACT

Recently, the Middle Benue Trough has become an area of interest in the country for the exploration activities in Ebenyi-A well which will give more insights into the subsurface potentials in the area. Several authors studied the Awgu Formation geologically, stratigraphically, petrographically, and geochemically but the petrographical and geochemical studies on the carbonate deposits to evaluate the potential reservoir quality are scarce in the literature. This study focuses on the geology, field investigation, petro-sedimentological and geochemical studies. The field investigation reveals two lithofacies of the carbonate reservoir rock namely shelly and crystalline carbonate facies. Petrographic studies show that the shelly facies are characterized by high diversity brachiopod, gastropods, shell fragments, alga materials, high CaO, and classified as biosparite on the Folk classification and wackestone/packstone to crystalline facies on the Dunham classification. Pore types in the shelly biosparmicrite microfacies are moldic porosity while the crystalline micritic microfacies is distinguished by an increased composition of grains which enhance grain-to-grain contacts and promoting interparticle porosity. The geochemical results show that the carbonates of Awgu Formation were deposited under a shallow marine environment. It also indicates that the MgO values are lower than the CaO values. The diagenetic processes considered are micritization and neomorphism. The outcome of these investigations will contribute to understanding of carbonate pore types dissolution in the deposits that will enhance identification of variable reservoir hydraulic flow units within the carbonate lithofacies for successful exploration in the Middle Benue Trough.

Keywords: Awgu Formation, Biosparite, Carbonate reservoir, Packstone, Wackestone

INTRODUCTION

Recent studies revealed large deposit of carbonates than previously estimated within the Ezeaku and Awgu Formations. However, these carbonates constitute a huge carbonate potential reservoir in Central Benue Trough petroleum system (Obaje *et al.,* 2022). This study focuses on carbonate deposits and their reservoir characterization in the Awgu Formation of the Middle Benue Trough. The carbonate rocks are generally thought to be Cenomanian-Turonian in age which is correlative with Nkalangu formation in the Lower Benue Trough and Gongila/Pindiga formation in the Upper Benue Trough Nigeria. Adopting the Folk (1959) and Dunham (1962) classifications for carbonate rocks, this study will test the hypothesis of the carbonate rock of Awgu Formation as potential reservoir rock within the petroleum system of the Middle Benue Trough. Recently, the Benue Trough has become an area of interest in the country for the exploration activities in Kolmani river 2 and Ebenyi – A wells which will give more insights into the potentials of the area. Previous studies by Obaje (1994), Obaje (1996), Obaje and Ligouis (1996), Obaje and Abaa (1996), Obaje and Hamza (1999), Obaje *et al.* (1999) and Akande *et al.* (2012) have indicated the likelihood of some potential petroleum systems in the Middle Benue Trough of Northcentral Nigeria. The carbonaceous and extremely fossiliferous shale, dark and shelly carbonate in the Albian-Santonian Asu River Group and Ezeaku Formations are thought to comprise the potential source rock in the earliest petroleum system preservation Obaje (2009). The indurated shale, sandstones and carbonates of Ezeaku Formation would compose the reservoirs, while shales of the Ezeaku Formation present as potential seal lithology. However, a recent field investigation in June 2021 revealed a significant amount of carbonate deposits within the Awgu Formation exposed at along Ribi-Jangwa road near Shankodi hamlet Obaje *et al.*(2022). However, the petrophysical characteristics and organic matter concentrations of the lithofacies is yet unknown. Also, second prospective the potential reservoir rock may be produced from the carbonates (shelly lithofacies), shales and coal interbedded with coaly shale in the Cenomanian-Santonian Ezeaku and Awgu Formations are expected to comprise the source rock in the second petroleum system. The indurated shale, sandstones and carbonates (crystalline facies) of Ezeaku Formation, sandstones and carbonates of the Awgu Formation and sandstones of the Campanian-Maastrichtian Lafia Formation would constitute the potential reservoirs, while shales and clays of the Lafia Formation will potentially act as the seal lithology for the Turonian-Maastrichtian petroleum system. For the both petroleum systems, the geographically and stratigraphically extensively deposited carbonate of the Ezeaku and Awgu Formations will present mega reservoir opportunities in which hydrocarbon migrations from the older systems through fractures, faults, dissolution tracks and structurally controlled pathways can lead to accumulations of hydrocarbon in the carbonate and constrained by stratigraphic traps. Furthermore, from earlier field observation two carbonate lithofacies within the Awgu Formation in the Middle Benue Trough were identified Obaje *et al.* (2022). This prompted the evaluation of the biostratigraphic, geochemical and petrographic parameters of the two carbonate lithofacies as a basis for characterizing the different potential carbonate deposits. Consequently, carbonate reservoirs are major reservoir rocks particularly in Asian and Arabian emirates countries such as Saudi Arabia,

Kuwait and Qatar, are thus known as the reservoir for the best oil in the world Obaje *et al.* (2020). Thus, the Benue Trough is Paleogeographically related and connected through Tethyan realm provinces of the West African rift sub-system (WARS).

Middle Benue Trough

The Middle Benue Trough which is also known as the Central Benue Trough reaches Northeast ward reported to be as far as line uniting Bashar and Mutum Biyu (Obaje, 2009). This border defines the Southern limit of the Gombe and Keri-Keri Formation whereas the earlier strata of the Upper Benue Trough undergo lateral facies shift in this location (Offodile, 1976). The Middle Benue Trough is rather little documented, especially in its Northeastern component; no precise geological maps of this portion are available but the area immediately south of Bashar was included in a photogeological map (Obaje, 2009). Maps of the Lafia-Keana-Awe region were produced by Offodile (1976) and Offodile and Reyment (1977) and of the area around Makurdi by (Nwajide, 1985). Detailed stratigraphic description of sediments in the Middle Benue Trough was published by Reyment (1965), Kogbe (1976), Offodile (1976), Petters (1982), Petters and Ekweozor (1982) and Nwajide (2013) amongst many others. The geological sequence in the Middle Benue Trough is represented in Fig. 1, Fig. 2 and Fig. 3. The Albian Asu River Group of Offodile (1976) and Nwajide (1990) encompasses the earliest marine deposits in the Middle Benue Trough (Obaje *et al.*, 2004) and (Abubakar *et al.*, 2006). It encompasses the fossiliferous Arufu, Uomba and Gboko Formations all of which are called the Albian sediments (late Aptian - early Cenomanian and older) by (Allix *et al.*, 1997) and (Brunet *et al.*, 1989). This phase is regarded to reflect slight regression Reyment and Dingle (1987) likely induced by a compressional event (Nwachukwu, 1972) and (Amajor, 1985). These are overlain by the regressive Cenomanian-Turonian Awe and Keana Formations (Murat, 1972). The late Cenomanian to early Turonian was a period of massive transgression in the Benue Trough that climaxed into possible contact between the waters of the Gulf of Guinea to the south and the Tethys Sea to the north (Zaborski, 2000). The marine facies of the Ezeaku Group and the Awgu Formation were deposited up to the Santonian overderlying the Awe and Keana Formations (Petters, 1982). During the mid-Santonian epoch, all the pre-Santonian sediments were folded and raised as a result of global plate restructuring (Guiraud & Bosworth, 1997).

The fluvio-deltaic Lafia Formation represents the only lateral facies equivalent of the post-Santonian sediments (Campanian-Maastrichtian) in the Benue Trough and which ended the sedimentation in the Middle Benue Trough, after which widespread volcanic activities took over in the Tertiary (Obaje *et al*., 2004).

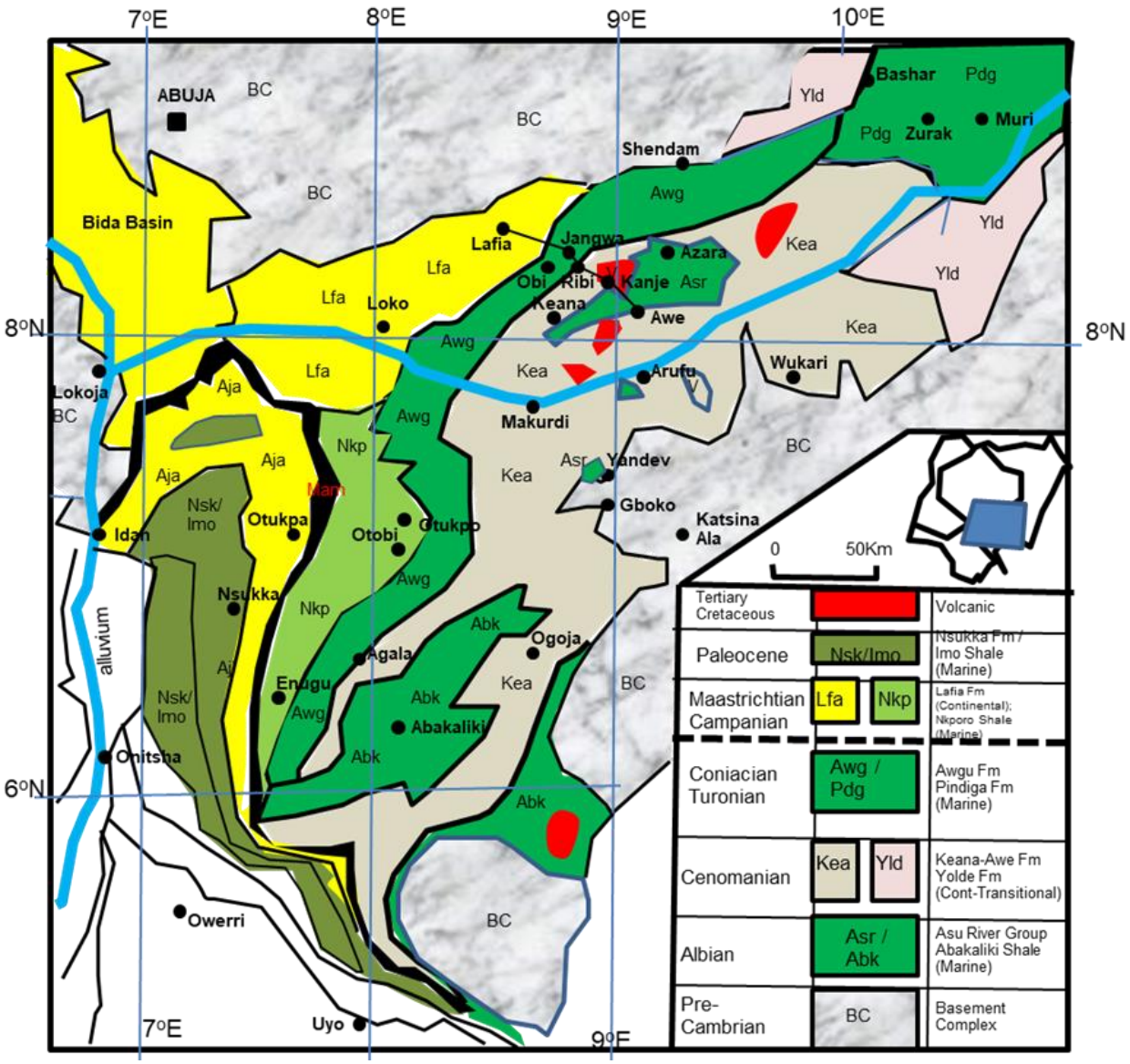

Figure 1: Geology of Benue Trough showing the studied locations (after Obaje, 2022)

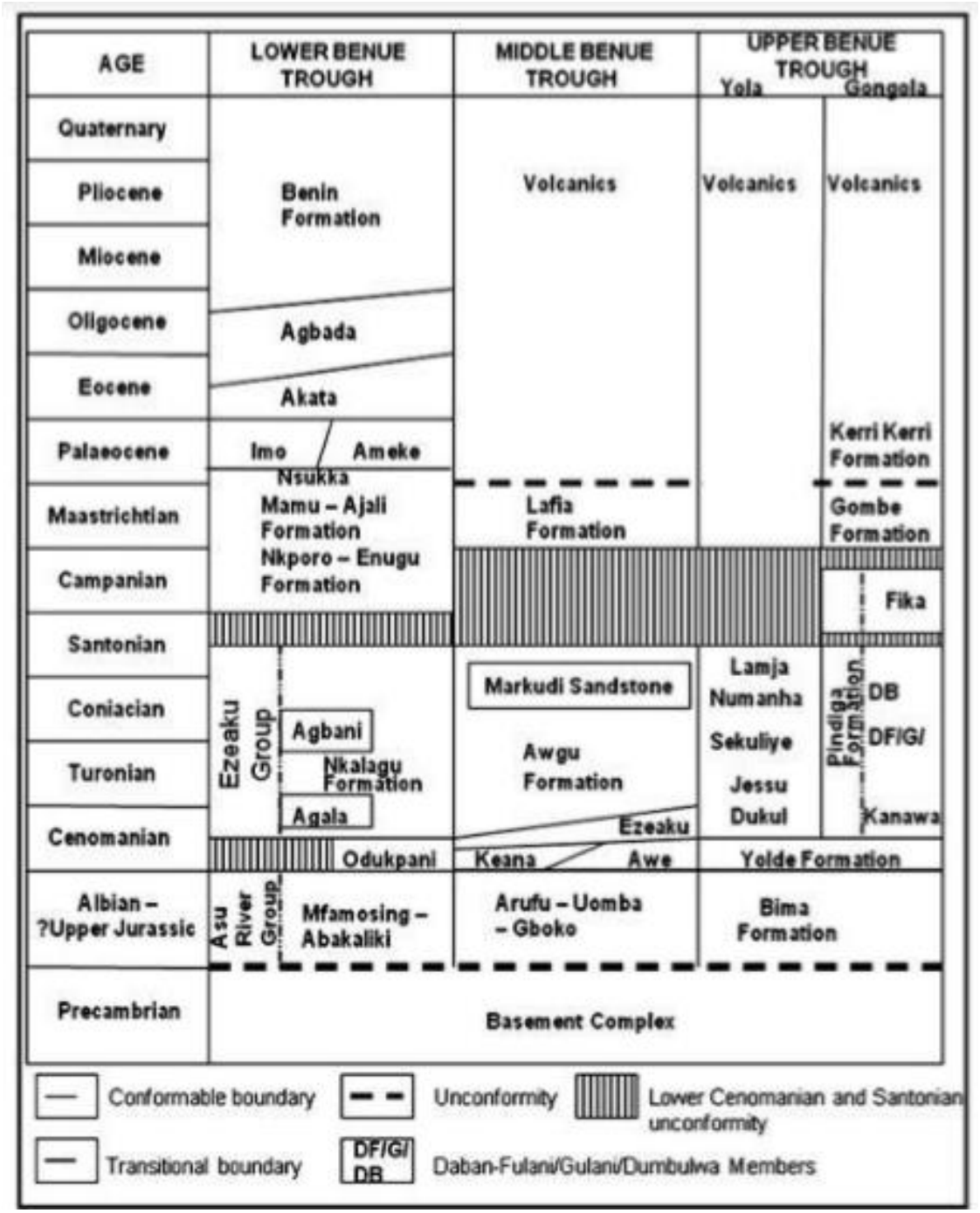

Figure 2: The stratigraphic correlation across the Benue Trough (after Guiraud, 1990)

Awgu Formation

The deposition of the Awgu Formation marks the end of marine sedimentation in this part of the Benue Trough. The formation is made up of bluish-grey to dark-black carbonaceous shales, calcareous shales, shaley limestones, limestones, sandstones, siltones, and coal seams. The major outcrop of the coal-bearing Awgu Formation is at the bank of River Dep in Shankodi, 7 km to the west of the village of Jangwa. Along the bank of this river, the coal seams can be traced laterally for about 500 m. The borehole cores of the Steel Raw Materials Exploration Agency (formerly National Steel Council) stock-piled at the Obi camp contain coal seams and coal bands at various depths within the Awgu Formation. The occurrence of low diversity arenaceous foraminifera in the Awgu Formation (Fig. 4) indicate deposition in marshy, deltaic and shallow marine conditions (Obaje, 1994). In Ribi town, from under the bridge a typical piece of the Awgu Formation is visible, consisting of shelly and crystalline carbonate rock and baked shale facies are also found along Ribi-Jangwa road, the sandstone, limestones (crystalline and shelly facies) were mapped Obaje *et al.* (2022). In the buildup of the potential petroleum systems in the Middle Benue Trough, the Awgu Formation is projected to provide a major reservoir facies congruent with the carbonate reservoir sequences of Tethyan realm paleogeographical provinces of the West African rift sub-system (WARS). The highly carbonate deposits, baked shales are highly impacted by volcano-magmatic processes in the Middle Benue Trough.

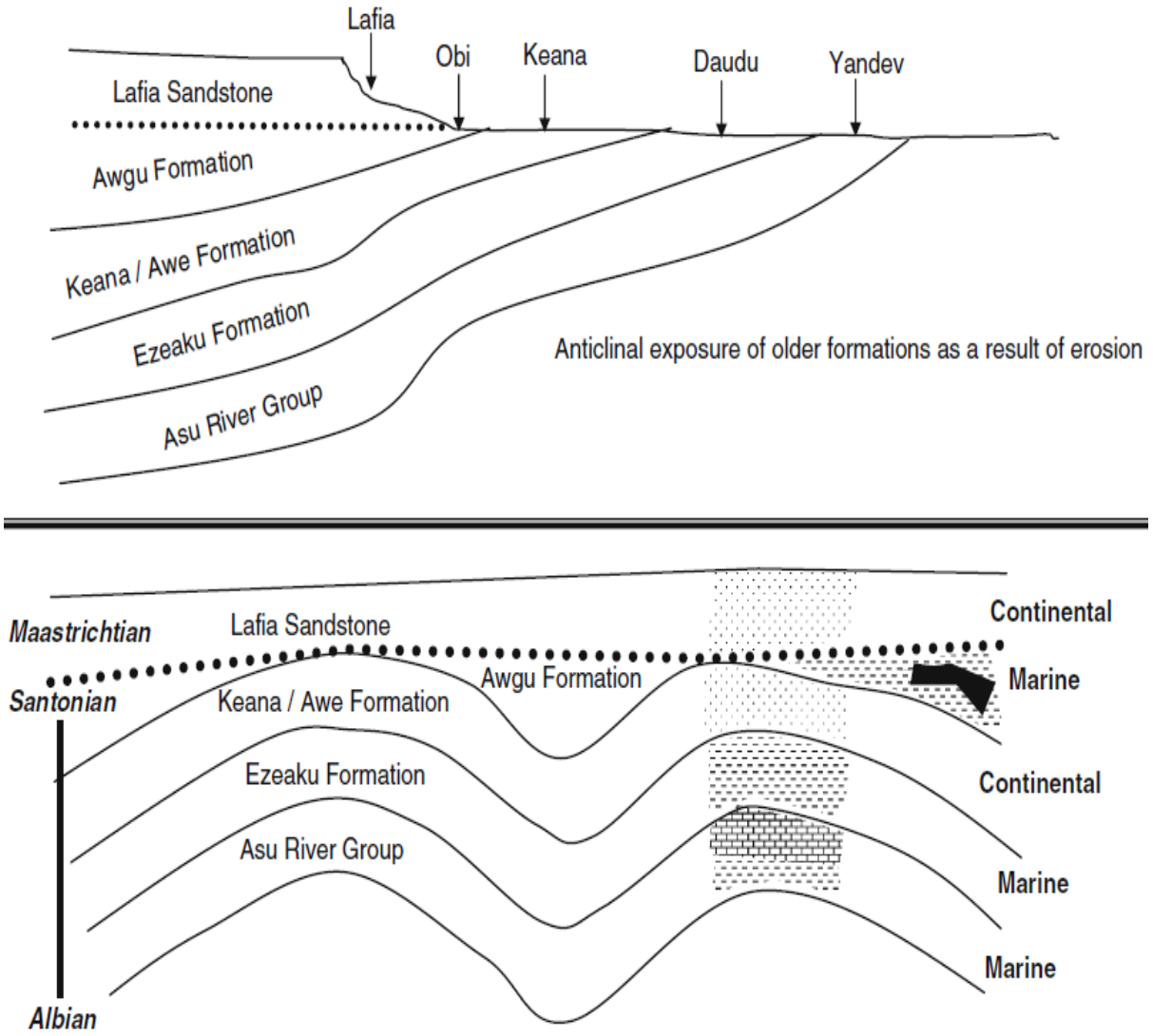

Figure 3: Stratigraphic succession in the Middle Benue Trough (after Obaje, 2009)

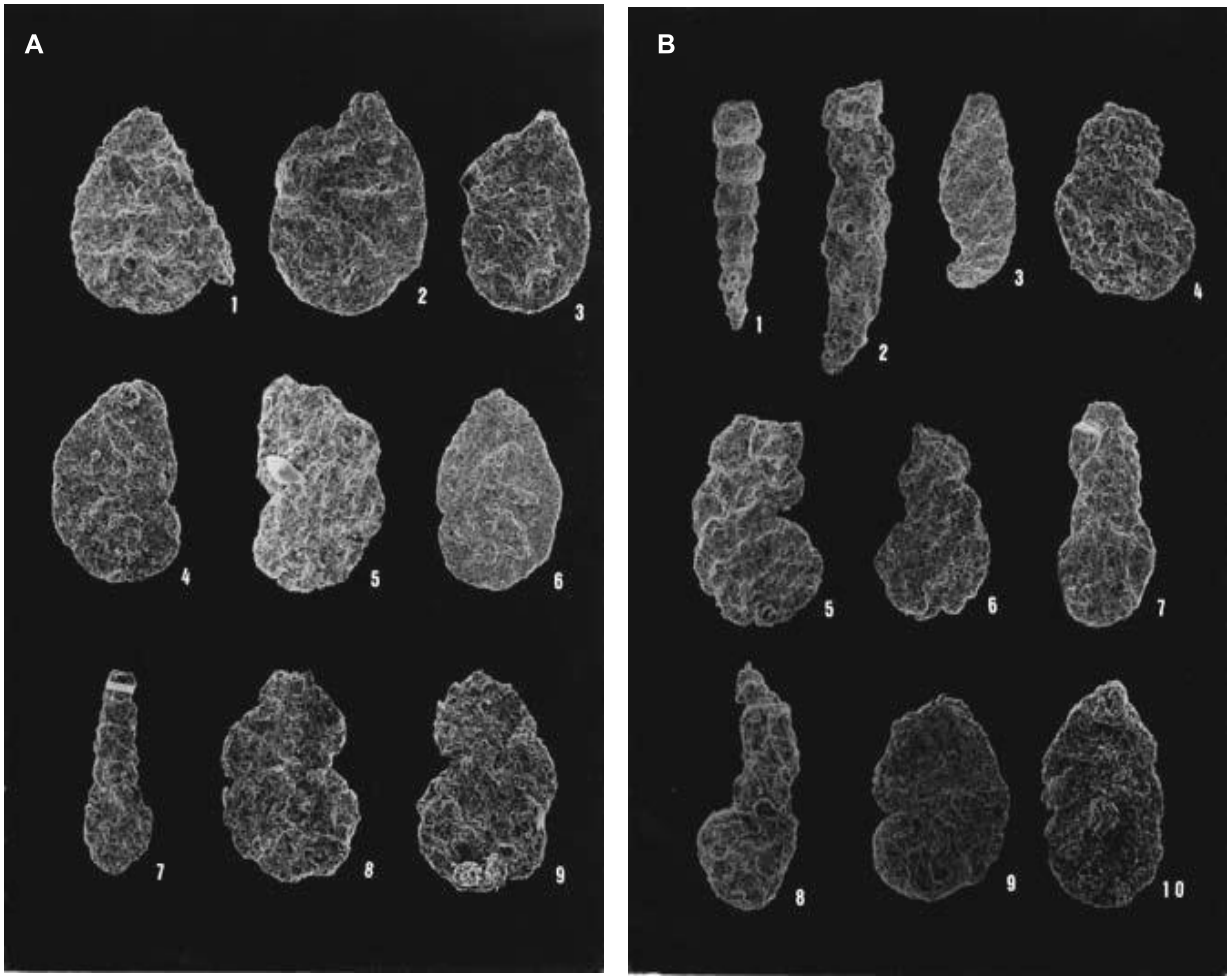

Figure 4: Arenaceous benthic foraminifera from the Turonian – Coniacian Awgu formation in the Middle Benue Trough, indicating marshy – shallow water – deltaic conditions (after Obaje, 1994)

Carbonate Sedimentology

Carbonate rocks comprise limestone, chalks and dolomites, although they form just approximately 10 percent of the Earth's surface sediments, they are of tremendous economic importance, for about 50 percent of the world's oil is held in carbonate reserves. Important carbonate reserves in the world include the Miocene Asmari Limestone of Iran, Jurassic Limestone of Saudi Arabia, and Ordovician Trenton Dolomite of Ohio. The majority of both present and ancient carbonates trace their formation to biological activity (biogenic). Several categorization systems have been established by various geologists, famous among these are those of Robert Folks of University of Texas, Robert Dunham of Shell Petroleum, and Leighton and Pendenxter of ExxonMobil. According to these workers, carbonate rocks can be classified using the following three primary principal criteria, grain types, matrix types (Folk Classification) and depositional texture (Dunham Classification). Mineralogy plays only limited role in the classification of carbonate rocks, because most carbonate rocks are essentially mono-mineralic. According to Folk (1959), carbonate rocks consist of three textural components; (1) grain, (2) matrix, and (3) cement. The cement in carbonate rocks is transparent calcite that filled the pores after the original deposition. The grains are of four different sorts; (1) shell pieces, also known as bioclast, (2) fragments of previously deposited lime called intraclasts, (3) small spherical pellets, excreta of worms (peloids), and (4) ooliths, the spheres generated by rolling lime particles down the bottom. The matrix is lime of clay particle size called micrite or lime mud.

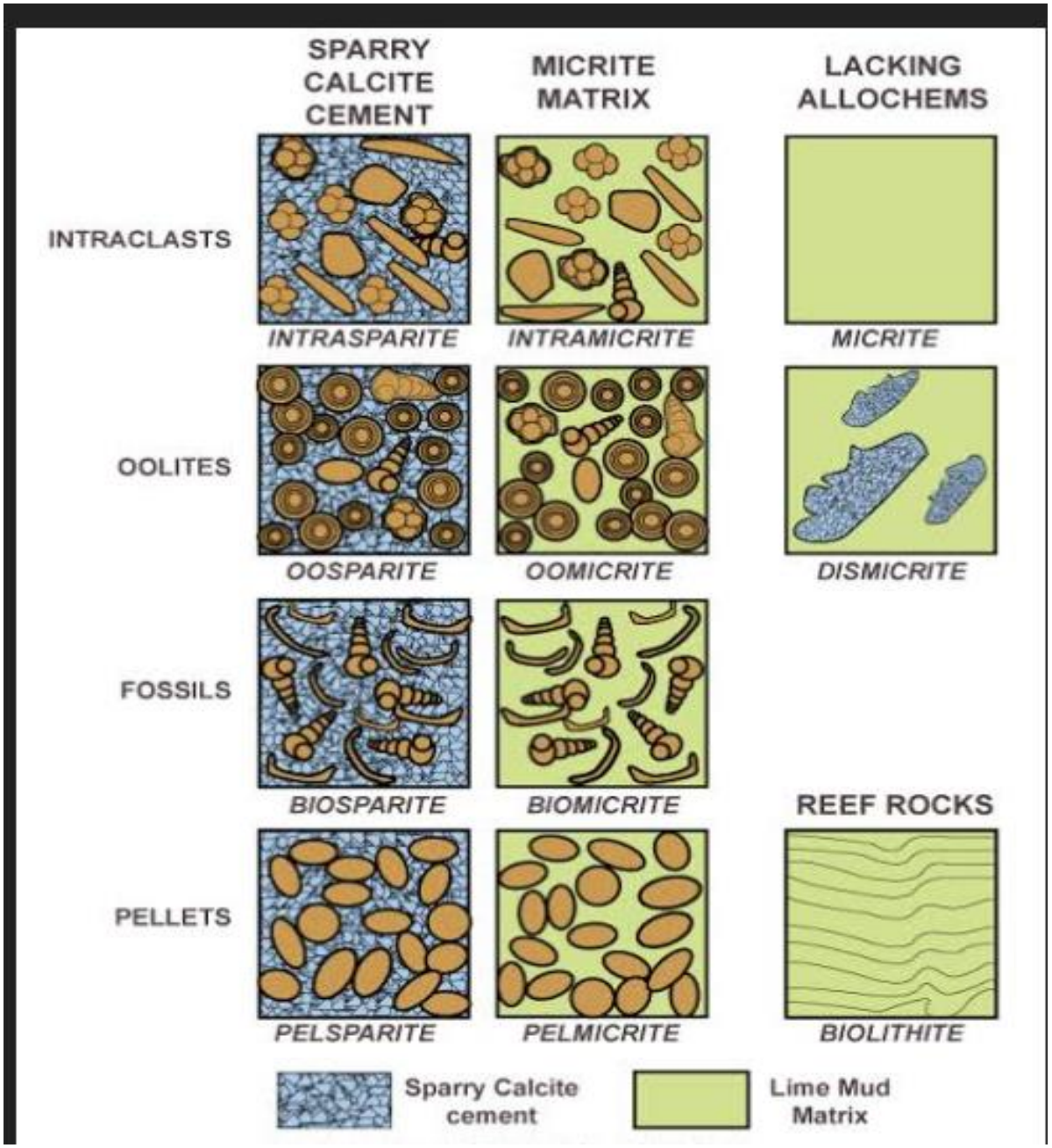

Figure 5: Schematic illustration of the basic components that form the basis for Folk (1959) classification of carbonates rocks

Classification of Carbonates Facies

Ooids**:** round or sub-spherical grains creating consecutive envelopes of carbonate commonly recrystallized to a radial structure, a sign of shallow water agitated by waves of tides. Intraclasts**:** irregular to sub-rounded particles of fine-grained carbonate formed by local contemporaneous erosion of sea-floor sediments; characteristic of regularly agitated water, but a lower energy environment than that indicated by ooliths. Pellets**:** fine-grained carbonate ejected by animals, mainly gastropods, echinoids and some bivalves. As it is often difficult to verify that pellet shaped particles of carbonate mud have a faecal origin, the term peloid is often employed.

It is known that partially cemented carbonate mud can be eroded and redeposited as peloidal sand, and that shell sand particles can be changed by burrowing organisms to create peloids. Skeletal debris**:** (prefix bio) whole or shattered and worn shell material. Micrite**:** (microcrystalline calcite) mud-sized carbonate particles generated either by inorganic precipitation or the breakdown of organic carbonate (from skeletal material), or both these processes. Sparite**:** (sparry calcite) chemically precipitated calcite gluing granules together after deposition; grains are usually larger than 100μm.

A classify description of limestones according to the Folk's scheme is derived by utilizing the prefixes for grain terms and suffixes for matrix terms; oo- for ooids; intra- for intraclasts; bio - for fossils. pel- for pellets. Dunham (1962) categorised carbonate rocks based on depositional textures, and focuses particular emphasis on the presence or lack of carbonate mud (micrite), which in the field may easily be separated from sparry cement or spaces between bigger particles.

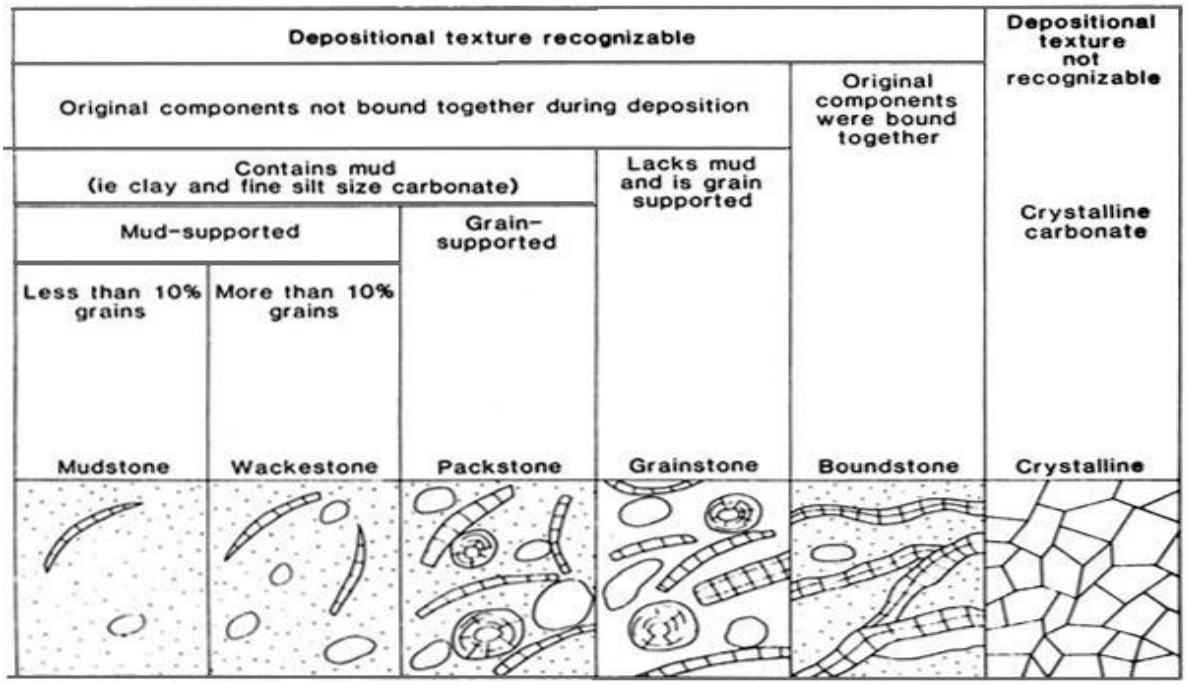

Figure 6: Textural classification of carbonate rocks according to (after Dunham, 1962)

For all sedimentary rocks, including carbonates, the less the mud or micritic content the greater the reservoir integrity. For carbonates, the highest reservoir properties, petrographically, are available in the sparry allochemical limestones (oosparite, intrasparite, biosparite, pelsparite) and in the grain-supported carbonates (packstone and grainstone).

MATERIALS AND METHODS

Field studies were carried out to identify the spatial and stratigraphic distribution of the Awgu Formation at different localities with particular focus on the exposure sections at Ribi-Jangwa road near Shankodi hamlet. About eight (8) carbonate samples were collected. Macrofossil contents and assemblages exposure as observed in the field within the Awgu Formation were documented. Portions of samples collected were subjected to thin section petrography and studied with a polarizing petrographic microscope of the Olympus model to identify the compositions on the 12 basis of the Folk and Dunham models. Geochemical studies were carried out on the carbonate to identify the paleoenvironment and provenances of the study area. The different carbonate facies identified through field studies were thereupon correlated to the petrographic and the geochemical results. In this way, attributes of those carbonates with good and poor reservoir qualities (as observed on the field) can easily be deciphered during drilling operations for hydrocarbons in the basin through the studied parameters (petrographical, foraminiferal microfossils and geochemical).

RESULTS AND DISCUSSION

From the traverses in the study area, previously unreported exposures, outcrops and sections were mapped and logged. On the road from Ribi to Jangwa, large deposits of carbonate rock of the Awgu formation comprising two lithofacies; the shelly and crystalline carbonate types which are generally whitish, brownish, granular and massive are mapped and documented. The Awgu Formation exposed at Ribi is about an 80m thick section that has been mapped and logged (Fig. 7). From the base it consists of dark shale, planar bedded, fine-grained sandstone overlain by a shale bed and sandstone bed (Fig. 7). This bed transitions upward into a dark baked shale bed, then into a coarse-grained sandstone and shale beds. These bed transit into a granular crystalline carbonate. The upper part of the section is characterized by mainly tabular cross bedding carbonate rock. A petrographic investigation of five thin sections from the Awgu Formation's carbonate rock exposure reveals variations in the abundance and morphology of constituent minerals and fossils (Fig. 8). This investigation aims to classify the carbonate rock, analyze mineralogy, textures, and composition to interpret provenance, maturity, and paleoclimate indicators. The carbonate rock predominantly comprises a high percentage of carbonate materials, with sporadic organic remnants and occasional iron patches. Quartz grains are present in the modal abundance, while micrite is abundant across all samples.

Allochem abundance ranges from 0% to 28%, while micrite range from 0% to 60% (Fig. 10). Consequently, the sections exhibit a mud-supported fabric with micrite filling the pore space between allochems or bioclasts. The micritic groundmass, composed of microcrystalline calcite, quartz, and identified clay mineral kaolinite, displays parallel laminations (laminae) with a preferred orientation, suggesting compositional variations. Brachiopod and gastropod tests align parallel to these laminations (Fig. 10). Allochem shapes vary from sub-angular to rounded, with grain sizes ranging from 4.5 to 80μm in diameter. Meanwhile, micritic groundmass particle sizes range from 0.5 to 2.0μm in diameter. The carbonate matrix consists of mud, and calcite acts as the cement (Fig. 10). These petrographic features reflect the sedimentation style leading to Awgu carbonate rock deposition, characterized by abundant micrite, megascopic shell fragments, and quartz grains within a mud and calcite cement matrix (Todd, 1968; Pettijohn, 1984). The skeletal composition, mainly calcitic, comprises sessile marine brachiopods in both brackish (hyposaline and slightly hypersaline settings). Calcite grains appear in the photomicrographs as euhedral to subhedral skeletal fragments.

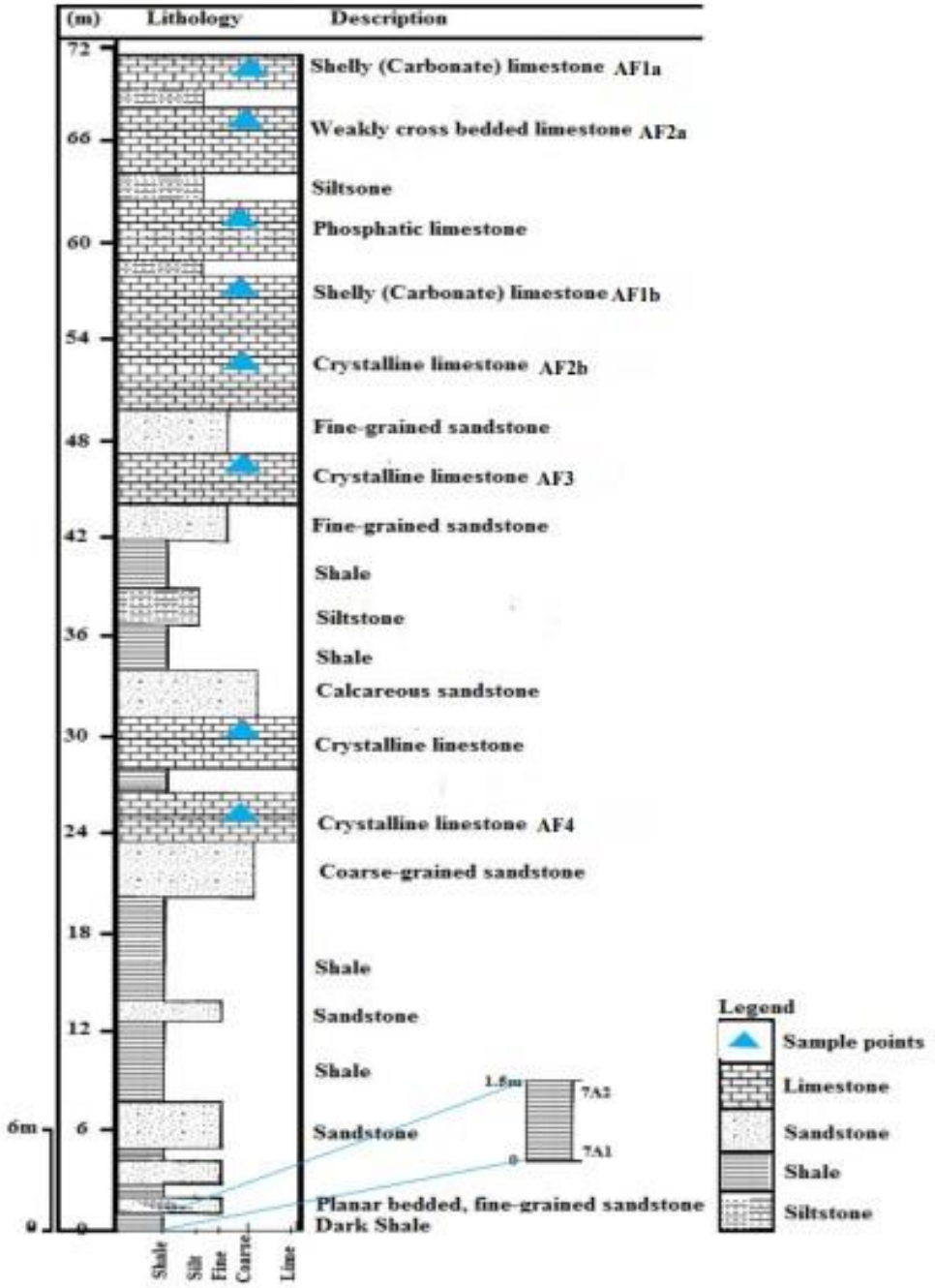

Figure 7: Lithologic log of Awgu Formation exposed at the Ribi-Jangwa road, 2 km away from Ribi

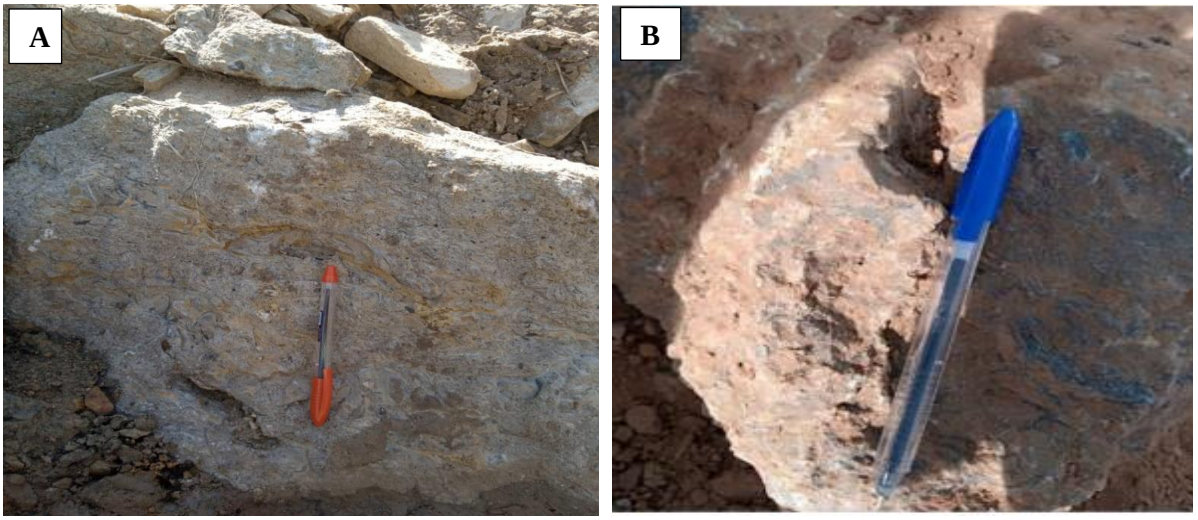

Figure 8: Outcrop photograph of shelly carbonate lithofacies, within the Awgu Formation, Middle Benue Trough

Figure 9: Field photograph of crystalline carbonate rock, formed within the Awgu Formation

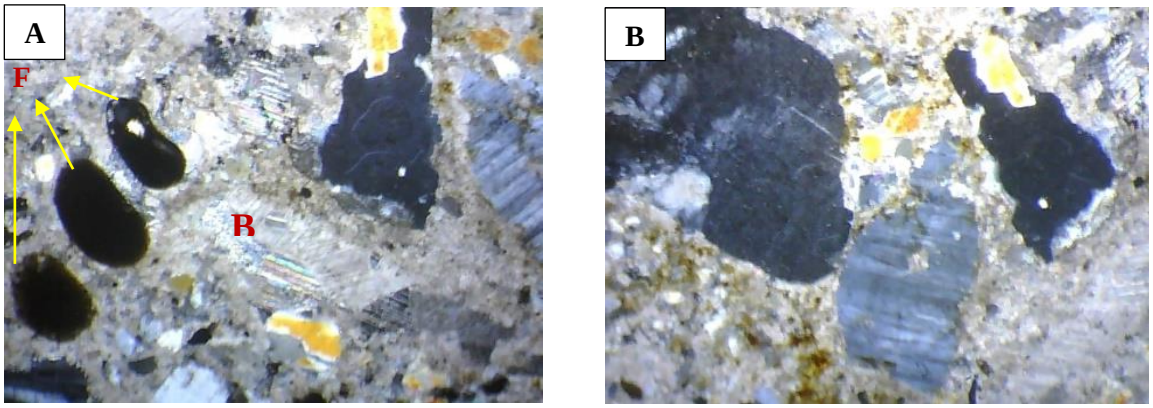

Figure 10: Thin-section petrographic analysis of the shelly facies in the Awgu Formation, classifying the carbonate as bio sparite (Folk classification) or wackestone/packstone (Dunham classification). A. Showing presence of B-Brachiopod and FP-Fecal Pellet. B. Large crystal of calcite

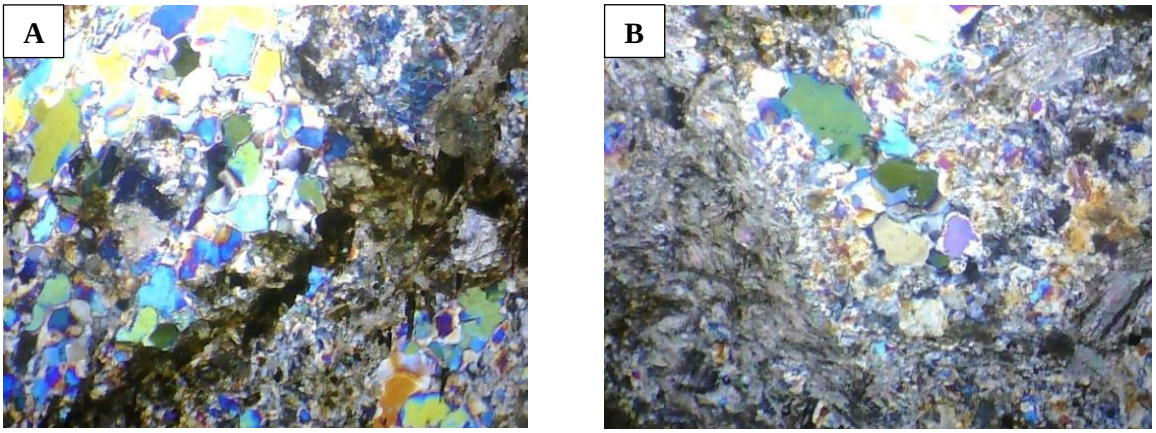

Figure 11: Thin section photomicrograph of the crystalline facies within the Awgu Formation, categorized as crystalline carbonate according to Dunham (1962) classification. A. The yellow arrow shows stylolites form during deep burial as a result of chemical pressure-solution. B. No fossil is visible about 95% of calcite crystal

Texture analysis indicates a heterogeneous composition, encompassing poorly sorted, medium-grained allochems (framework) alongside a fine-grained micritic groundmass (Fig. 11). Micro interparticle porosity exists between the micrite grains in the sections. Present as infill and matrix components, (5%). Present as matrix, clay (Kaolinite), quartz and calcite mineral laminae (95%). Neomorphism of micrite to spar, stylolites, microinterparticule porosity (Fig. 11).

Carbonate Geochemistry

These investigations indicate that the MgO values are lower than the CaO values which confirm that the carbonate is calcitic rather than dolomitic (Fig. 12). The elemental values indicated that the studied carbonate rocks are mainly from shallow marine environment. This evolution considers micritization and neomorphism as diagenetic processes, potentially involving recrystallization or mechanical degradation, these processes alter the initial depositional fabric of the deposit. Consequently, a reduction in total rock porosity has occurred, where the uppermost biosparmicrite exhibits moldic, fenestral, intraparticle, and limited interparticle porosities. The crystalline micritic microfacies is distinguished by an increased composition of grains, enhancing grain-to-grain contacts and promoting interparticle porosity (Folk, 1974).

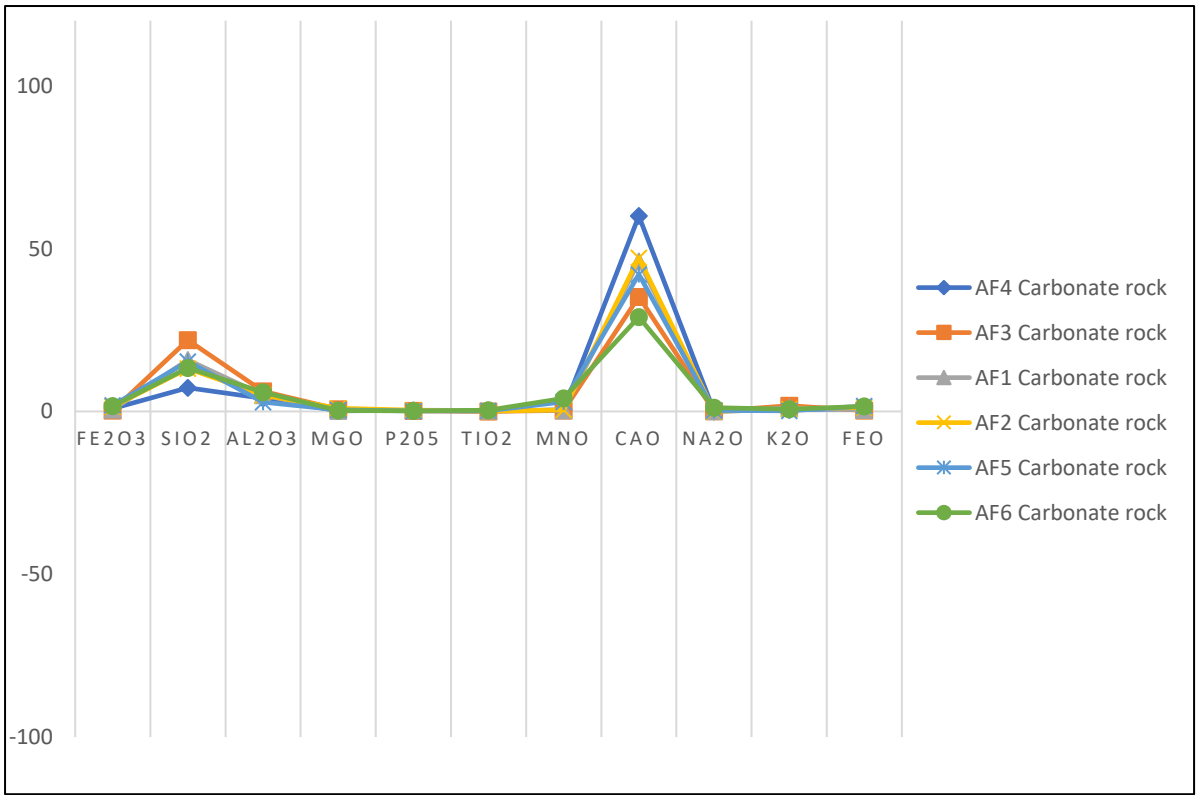

Figure 12: XRF geochemical result of the Awgu formation carbonate reservoir facies are highly rich in CaO and very poor in MgO

CONCLUSION

Earlier investigation has established the existence of some petroleum systems in the Middle Benue Trough of North central Nigeria. This work integrates field observation, Petrographic studies and geochemical investigation. The field observation reveals two major potential carbonate lithofacies namely; the shelly and crystalline carbonate facies within the Awgu Formation in the Middle Benue Trough and has gone ahead to evaluate the biostratigraphical, geochemical and petrographical parameters of the two facies. Petrographic studies show that the shelly facies are characterized by high diversity brachiopod, gastropods, shell fragments, alga materials, high CaO, and classified as biosparite on the Folk classification and wackestone/packstone to crystalline carbonate on the Dunham classification. Pore types in the shelly biosparmicrite microfacies are moldic porosity which are attributed to leaching of skeletal grains, while the crystalline micritic microfacies is distinguished by an increased composition of grains which enhance grain-to-grain contacts and promoting interparticle porosity. The geochemical results show that the carbonates of Awgu Formation were deposited under a shallow marine environment. It also indicates that the MgO values are lower than the CaO values which confirm that the carbonate is calcitic rather than dolomitic. This evolution considers micritization and neomorphism as diagenetic processes, potentially involving recrystallization or mechanical degradation, these processes alter the initial depositional fabric of the deposit. Consequently, a reduction in total rock porosity has occurred, where the uppermost biosparmicrite exhibits moldic, fenestral, intraparticle, and limited interparticle porosities. The crystalline micritic microfacies is distinguished by an increased composition of grains, enhancing grain-to-grain contacts and promoting interparticle porosity. The outcome of these investigations will contribute to the understanding of carbonate pore types and dissolution in the deposits that will enhance identification of variable reservoir hydraulic flow units within the carbonate lithofacies for successful exploration in the Middle Benue Trough.

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