

SEQUENCE STRATIGRAPHIC CHARACTERIZATION AND DEPOSITIONAL ENVIRONMENT(S) OF SEDIMENTS IN MFAMOSING AREA, CALABAR FLANK, SOUTHERN NIGERIA

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ABSTRACT

The Mfamosing Limestone of the Calabar Flank, Southern Nigeria, is one of the largest carbonate deposits in the Lower Benue Trough and provides significant information on the depositional evolution of shallow marine carbonate systems in southeastern Nigeria. Sedimentological, petrographical, paleontological and sequence stratigraphic analyses are used in this study to reconstruct the depositional environments, diagenetic evolution and stratigraphic architecture of the carbonate succession exposed within the Mfamosing area between Longitudes 8° 15'E and 8° 30'E and Latitudes 5° 00'N and 5° 15'N. Petrographic and paleontological studies revealed a high macro- and microfacies variability of the carbonate body. The diagenetic fabrics identified are dissolution, dolomitization, isopachous cementation, physical and chemical compaction, neomorphism, stylolitization and precipitation, all of which have exerted a great influence on reservoir quality. Three main lithofacies were identified: (i) bioclastic and oolitic packstone-grainstone facies with pellets and recrystallized gastropods, (ii) packstone facies with coralline algae and stromatolites, and (iii) mixed siliciclastic-carbonate facies with silt and fine sand. These facies associations are suggestive of deposition in a shallow marine nearshore environment with variable depositional energy conditions. The main types of porosity identified include interparticle, intraparticle, moldic, fenestral, framework and fracture porosities. Sequence stratigraphic analysis showed that three of the studied sections are incomplete transgressive and highstand systems tracts, while the fourth section is characterized by a complete depositional succession capped by a maximum flooding surface and subsequently by a highstand systems tract.

Keywords: depositional environments, diagenetic fabric, Mfamosing Limestone, Calabar Flank, Benue Trough.

INTRODUCTION

The Mfamosing Limestone is the biggest single carbonate deposit in the Calabar Flank of southeastern Nigeria and constitutes an essential part of the sedimentary succession of the Lower Benue Trough [1]. The formation extends for about 135 km from the Nigeria-Cameroon frontier and interfingers northwestward with the siliciclastic deposits of the Awi

Formation. Earlier studies have shown the carbonate succession to be up to 450 m thick subsurface [2]. Limestone extraction in the area has drastically reduced the exposed thickness of the limestone mass. This carbonate unit was variously referred to by earlier workers as the Odukpani Limestone [3],[4],[5] and the Ewa Limestone [6].

The Mid-Albian Mfamosing Limestone occurs within the Calabar Flank of southern Nigeria, where it developed as a shallow marine carbonate platform adjacent to the Precambrian Oban Massif. The carbonate succession exhibits considerable lithologic and facies variability associated with fluctuations in depositional energy, accommodation space, and post-depositional diagenetic processes. These characteristics make the formation suitable for sedimentological, petrographic, and sequence stratigraphic investigations (Figure 1).

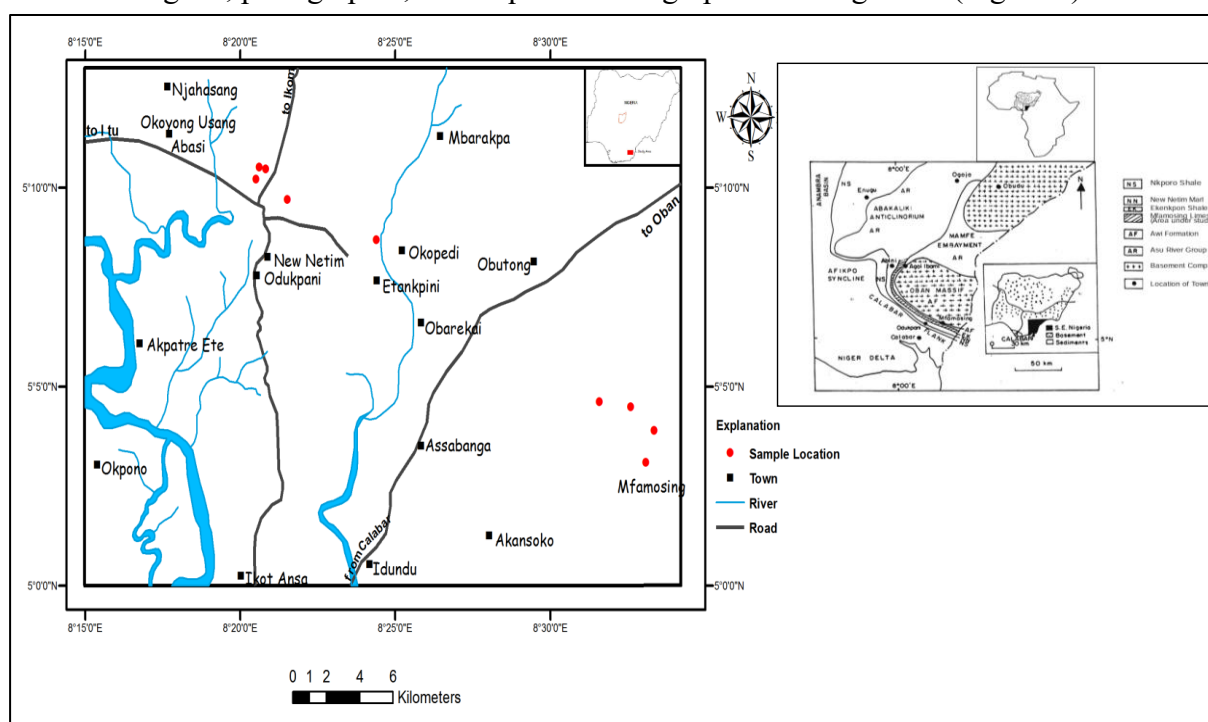


Figure 1. Location map of the study area.

The Calabar Flank has already been the subject of numerous geological and sedimentological studies, with a focus on the Mfamosing Limestone and related carbonate successions. Previous research includes Amah's petrological study of carbonate rocks in the Calabar Flank [7], Essien and Ufot's age determination and depositional interpretation of the Mfamosing Limestone [8], and Ofulume's geochemical characterization of depositional environments using fossil assemblages and microfacies analysis of the Mfamosing, Shagamu, and Gboko limestones [9]. The lithostratigraphy, microfacies succession, sequence stratigraphy, and depositional conditions of the New Netim Formation within the Calabar Flank were also examined by Essien and Edoho [10].

The carbonate succession was broadly separated into an upper slightly sandy packstone-grainstone succession and a lower algal boundstone interval interbedded with packstones and grainstones by earlier sedimentological and stratigraphic studies by Fayose [11], Nair et al. [5], Oti [12], and Petters and Reijers [2]. Together, these investigations showed that the quick

lateral and vertical facies fluctuations in the Mfamosing Limestone result in significant lithologic and palaeontologic variability [13]. The limestone sequence contains evidence of vadose, meteoric, phreatic, and subsurface diagenetic processes, according to thorough petrographic and diagenetic investigations carried out by Essien and Edet [14]. Their research also established calcite as the predominant mineralogical component of the carbonate body and showed that the Mfamosing Limestone displays diagenetic features that are mostly independent of particular microfacies types. In a similar vein, Amah's petrological research [7] substantially supported Reijers and Petters [2] earlier interpretations of the facies architecture and depositional structure of the limestone sequence. Fayose [4] and Nair [5] proposed that the Mfamosing Limestone was deposited in a high-energy shallow marine environment that was periodically disrupted by intertidal episodes based on sedimentological and facies characteristics. This resulted in a complex depositional system that included shoals, lagoons, tidal flats, and siliciclastic influences from the hinterland.

Despite earlier studies, the depositional architecture, facies variability, diagenetic evolution, and sequence stratigraphic framework of the Mfamosing Limestone remain insufficiently constrained. To better constrain the depositional environments, diagenetic processes, and reservoir potential of the carbonate succession, the current study aims to integrate sedimentological observations, petrographic analysis, facies characterization, and sequence stratigraphic interpretation.

Relatively few studies have attempted to combine diagenetic imprints with sequence stratigraphic interpretation in order to reconstruct carbonate platform evolution within the Calabar Flank, despite the fact that the works of Cratchley [15], Akpan [16],[17], and Essien and Edet [14] provided useful information regarding the age, paleoenvironment, and geochemical characteristics of the sediments. Therefore, the current study further evaluates the depositional environments, diagenetic evolution, and sequence stratigraphic framework of the Mfamosing Limestone within the Calabar Flank. Diagenetic processes such as dissolution, dolomitization, stylolitization, fracturing, and cementation significantly influenced porosity evolution and reservoir heterogeneity within the carbonate succession. Consequently, integration of sedimentological, petrographic, and sequence stratigraphic datasets provides improved understanding of facies distribution and reservoir architecture within the Mfamosing Limestone.

GEOLOGICAL SETTING OF THE STUDY AREA

Geologically, Calabar Flank is that part of Southern Nigerian sedimentary basin that is bounded by the Oban Massif to the North and the Calabar hinge line delineating the Niger Delta Basin in the South [18]. It is also separated from the Ikpe Platform to the west by a NE-SW trending fault. In the East, it extends up to the Cameroun volcanic ridge. It served as the gateway to all marine transgression into the Benue Trough and is located between two hydrocarbon provinces, the Tertiary Niger Delta and the Cretaceous Douala Basin in Cameroun [2].

Structurally, the Calabar Flank consists of basement horsts and grabens that are aligned in a NW-SE direction like other South Atlantic marginal basins in West Africa [2]. The Calabar Flank shows striking stratigraphic similarities with coeval marginal basins of the South Atlantic. They were all produced during the opening of the South Atlantic Ocean which is the first marine incursion in middle Albian that accounted for the deposition of Mfamosing

Limestone. Sedimentation started in the Calabar Flank with the deposition of fluvio-deltaic clastics of probably Aptian age on the Precambrian crystalline Basement Complex, the Oban Massif. The sediment belongs to the Awi Formation on the Precambrian Basement Complex [19]. The earliest marine transgression into the Calabar Flank and the Benue Trough occurred in the Mid-Albian times with the deposition of platform carbonate of the Mfamosing Limestone (Figure 2). This limestone unit was deposited in a variety of depositional environments [20]. It displays microfacies types ranging from algal stromatolitic boundstone to highly fossiliferous packstones.

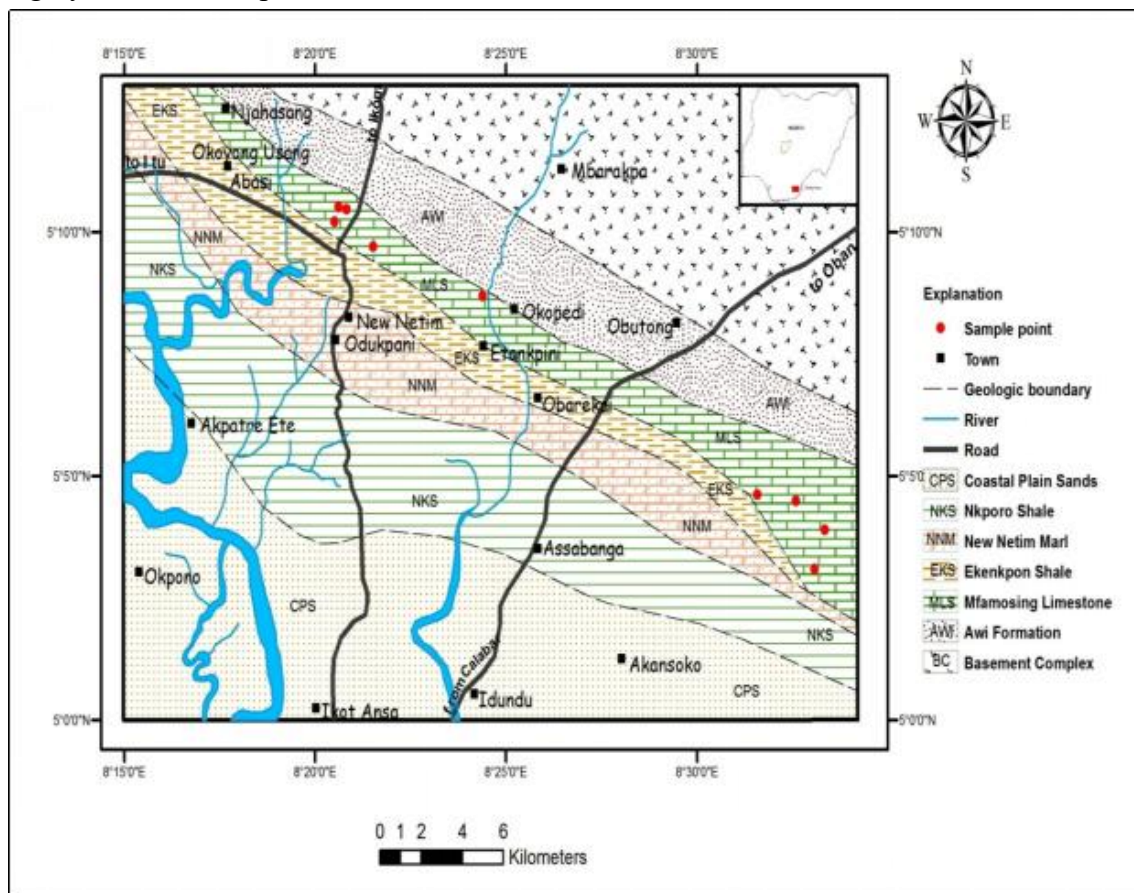


Figure 2. Geologic map of the study area.

This limestone unit is gradationally underlain by the Awi Sandstone. The Mfamosing Limestone is overlain by a thick sequence of black to gray shale unit, the Ekenkpon Shales (Nkalagu Formation) [21]. The shale unit is separated from the carbonate body by a 10cm thick hard ground. The Ekenkpon Shales (Cenomanian Turonian) are overlain by a thick marl unit, the New Netim Marl [21]. The marl unit is nodular and shally at the base and is interbedded with thin layers of shales up section. Santonian and Early Campanian deposits are absent in the Calabar Flank, this interval was marked by the period of simple uplift and non-deposition with little erosion till Late Campanian times. The new Netim Marl is unconformably overlain by carbonaceous dark gray shales of the Nkporo Formation [3]. This shale unit is interbedded with thin bands of marlstone and gypsum. The Nkporo shales were deposited during the late Campanian transgressive cycle in the Calabar Flank. Nkporo shales

appear to have been deposited in a variety of environments ranging from open marine, paralic to continental settings [22]. In the Calabar Flank, the withdrawal of the Early Maastrichtian sea was rapid, resulting in abrupt termination of the Nkporo Shale. The Nkporo Shale extends from the Calabar Flank to the Anambra Basin. The Nkporo Shale caps the Cretaceous succession in the Calabar Flank. The Nkporo Shale is overlain by a pebbly sandstone unit of the Tertiary Benin Formation (Figure 2).

METHODOLOGY

Geological mapping and detailed outcrop logging were carried out across the study area to examine lithologic relationships, sedimentary structures, textures, fossil content, and lithologic contacts within the carbonate succession. The mapping was conducted to evaluate lithologic relationships, facies distribution, sedimentary structures, and stratigraphic architecture within the carbonate succession. The lithologic relationship in the profile of the outcrops at various locations with interest in sedimentary structures, texture, color, fossils and lithologic contacts which were used to construct lithosections of the various outcrops studied. Attitude of beds (strike and dip) were measured using a compass clinometer, GPS was used to measure elevation and co-ordinates of the various outcropping section. A total of five outcrop locations were investigated and ten representative carbonate samples were collected for petrographic and sedimentological analysis. The required additional sedimentological data is provided by a facies analysis of the carbonate and siliciclastic rocks. Facies were assigned based on lithology, sedimentary structure and fossil assemblages. Thin sections were prepared to standard 30 μm thickness following conventional carbonate petrographic procedures and facies classification was based on Dunham (1962) carbonate classification scheme.

Thin Section Petrographic Analysis

Petrography is the systematic description of rocks in hand specimen and thin section. This was undertaken to determine the textural and mineralogical composition of the rock samples (limestone) as well as the various diagenetic changes which occurred. A total of ten representative carbonate samples collected from the field were analysed using thin section petrography, these samples were collected from different locations (Locations 1, 2, 3, 4 and 5). The percentages of matrix, cement, quartz, feldspar and rock fragments were ascertained.

Each thin section was observed under a flag stage petrographic microscope and visual point count of cement and matrix were estimated. Modal composition percentages were obtained using approximately 300-point visual counting per thin section under plane-polarized and cross-polarized light. Roundness and shapes of grains and grain arrangement (fabric) were also estimated. These parameters were analyzed descriptively using photo-micrographic images. The analysis was carried out at the laboratory of the Department of Geology, University of Port Harcourt, Rivers State. Standard petrographic preparation techniques, which include cutting, grinding, polishing, mounting, and staining representative carbonate samples, were used to create thin sections. Petrographic observations were carried out under plane-polarized light (PPL) and cross-polarized light (XPL) using a transmitted-light petrographic microscope at magnifications ranging from 40 $\times$ to 400 $\times$. Modal composition was estimated using visual percentage estimation and point-counting techniques involving approximately 300 counted grains per thin section. Allochems composition, matrix proportion, textural characteristics, and fossil assemblages were used to support the facies classification, which was based on Dunham's carbonate classification scheme.

Systematic Paleontology

Systematic paleontology involves the identification, classification, phylogeny, age determination, and environmental interpretation of fossils. In this work fossils were identified from thin section microscopy and an expansion of viewed body shape made for easier and further identification of species. This will aid in interpretation of depositional environment, understanding the age of sediments, biofacies analysis and will aid in the attempt to build a sequence stratigraphic framework.

Sequence Stratigraphy

The hierarchy of carbonate sequence stratigraphic geometries includes those associated with normal and forced regressions of highstand, falling stage and lowstand systems tracts; and onlapping retrogradation transgressive geometries. During forced regressions, downstepping occurs. As with clastics too, these geometries are defined by the bounding surfaces that include those formed during and/or following transgressions (TS and MFS) and those that formed during falls in sea level as regressive surfaces (SBs). Physical erosion, burrowing, boring, dissolution [23],[24], cementation may have modified these surfaces. Whatever their origin, these surfaces mark changes in the depositional regime, particularly base level, and provide a convenient means to subdivide the carbonate section.

From the perspective of sequence stratigraphy, these surfaces are used to determine the order in which strata are laid down and to define the geometries that they enclose and so interpret their depositional setting. Biostratigraphic data (both skeletal remains and ichnology) when tied to the stratal units, enables the direct comparison between shallow marine and deeper-marine carbonate sequences, their related units and the potential correlation of the carbonate cycles to relative sea-level rise and fall.

RESULTS

Lithologic Description

At Mfamosing village, the described outcrop section is light greyish in colour with fossiliferous limestone. It has a thickness of 9.38 m. The basal unit of this section is of light grey oolitic to pisolitic limestone (Figure 3a) of about 1.3 m thick which is overlain by greyish pisolitic and bioclastic limestone (Figure 3b). A second outcrop was described along Mfamosing road consisting greyish stylolitic limestone with shell fragments. It has a thickness of 10.48 m, the basal unit of this outcrop is a greyish oolitic to pisolitic limestone (Figure 3c) which is overlain by stylolitic limestone showing shell fragments. At an interval of 3.00 m to 4.10 m the outcrop is made up of oolitic, bioclast with shell fragments. The formation is fossiliferous in nature with little solution hollows, with weathered top surface. At Etankpini the described outcrop is greyish in color with stylolitic limestone, also associated with abundant shell fragments. It has a thickness of about 1.4 m, width of 2.08m. Structures found on this outcrop are sinkholes (Figure 3d). At another section described at Etankpini the outcrop is light greyish in color, showing Stylolite limestone with fossil overlain by oolitic to pisolitic limestone about 3.22 m thick with solution structures, hollows and caves as structures seen on the outcrop (Figure 3e and f).



Figure 3. Representative carbonate facies and sedimentary structures within the Mfamosing Limestone.
(a) Oolitic limestone at Mfamosing Village; (b) Bioclastic limestone with shell fragments;
(c) Solution hollows within limestone facies; (d) Sinkhole structure at Etankpini; (e) Cave structure within the carbonate succession; (f) Oolitic limestone showing solution cavities and karst features.

Thin Section Analysis

Results of thin section analysis are shown in Table 1. Slides from thin section petrography were viewed to observe percentages of mineral grains in analysed samples (Table 1). Fossil analysis of the Mfamosing Limestone from thin section yielded relative percentage of fossils present in the study area (Table 2) with its photomicrographs (Figure 4).

Table 1. Distribution of grains.

Samples/Location	Quartz (%)	Ooids (%)	Peloids (%)	Skeletal Particles (%)	Colour	Feldspar (%)
L1U1	75.0	5.0	5.0	5.0	Light Grey	2.0
L1U2	3.0	50.0	10.0	15.0	Light Grey	1.0
L2U1	10.0	10.0	0.0	25.0	Light Grey	0.0
L2U2	10.0	15.0	0.0	10.0	Light Grey	0.0
L3U1	10.0	30.0	10.0	0.0	Light Grey	0.0
L3U2	0.0	65.0	0.0	5.0	Light Grey	1.0
L4U1	20.0	30.0	0.0	25.0	Light Grey	0.0
L4U2	10.0	20.0	10.0	30.0	Light Grey	3.0
L5U1	70.0	15.0	5.0	10.0	Light Grey	0.0
L5U2	20.0	25.0	10.0	40.0	Light Grey	2.0

Table 2. Summary of petrography of Mfamosing Limestone.

Samples /Location	Algal Grains (%)	Radiolaria (%)	Gastropods (%)	Echinoids (%)	Foraminifera (%)	Pelecypods (%)	Warm Tube (%)	Brachiopods (%)	Stromatolites (%)	Feldspar (%)
L1U1	10.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	2.0
L1U2	0.0	0.0	20.0	5.0	0.0	0.0	0.0	0.0	0.0	1.0
L2U1	40.0	2.0	1.0	0.0	1.0	0.0	3.0	3.0	0.0	0.0
L2U2	60.0	1.0	0.0	0.0	0.0	3.0	10.0	0.0	0.0	0.0
L3U1	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L3U2	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
L4U1	1.0	0.0	0.0	5.0	0.0	3.0	5.0	0.0	0.0	0.0
L4U2	15.0	0.0	5.0	0.0	0.0	5.0	0.0	0.0	0.0	3.0
L5U1	5.0	0.0	0.0	0.0	2.0	1.0	0.0	5.0	2.0	0.0
L5U2	0.0	5.0	0.0	5.0	1.0	0.0	7.0	1.0	1.0	2.0

Statistical summary of petrographic constituents indicates dominance of ooids, skeletal fragments, and algal grains within the carbonate facies. The variability in allochem proportions reflects fluctuating depositional energy conditions and facies heterogeneity within the shallow marine carbonate system.

Description of Microfacies

Figure 4 (a–h) shows petrographic microfacies and diagenetic features of the Mfamosing Limestone. **Figure 4a** is characterized by a micrite-dominated carbonate rock displaying a fine-grained and relatively homogeneous texture. The matrix consists predominantly of microcrystalline calcite, within which only a few dispersed skeletal fragments are preserved. The absence of a grain-supported framework and the dominance of micrite suggest deposition under low-energy conditions, most likely within a protected lagoonal or restricted shallow marine setting [2],[27]. The overall fabric appears largely unaltered, indicating that diagenetic overprinting has been minimal.

Figure 4b exhibits a grain-supported fabric composed mainly of skeletal debris and bioclastic components. The grains are moderately sorted and show partial cementation by sparry calcite, which fills intergranular pore spaces. This textural arrangement reflects deposition under relatively higher energy conditions compared to Figure 4a. The presence of skeletal fragments and early cement suggests accumulation in a shallow marine environment influenced by moderate agitation, such as a shoal or inner shelf zone [4],[28].

Figure 4c displays a mixed microfacies consisting of both micritic matrix and allochems, including recognizable fossil fragments. The fabric is partially grain-supported, indicating intermediate energy conditions. The coexistence of micrite and skeletal material points to a setting where periods of quiet water alternated with episodes of increased energy. Such conditions are typical of semi-restricted marine environments where biological activity contributes to sediment accumulation [8],[24].

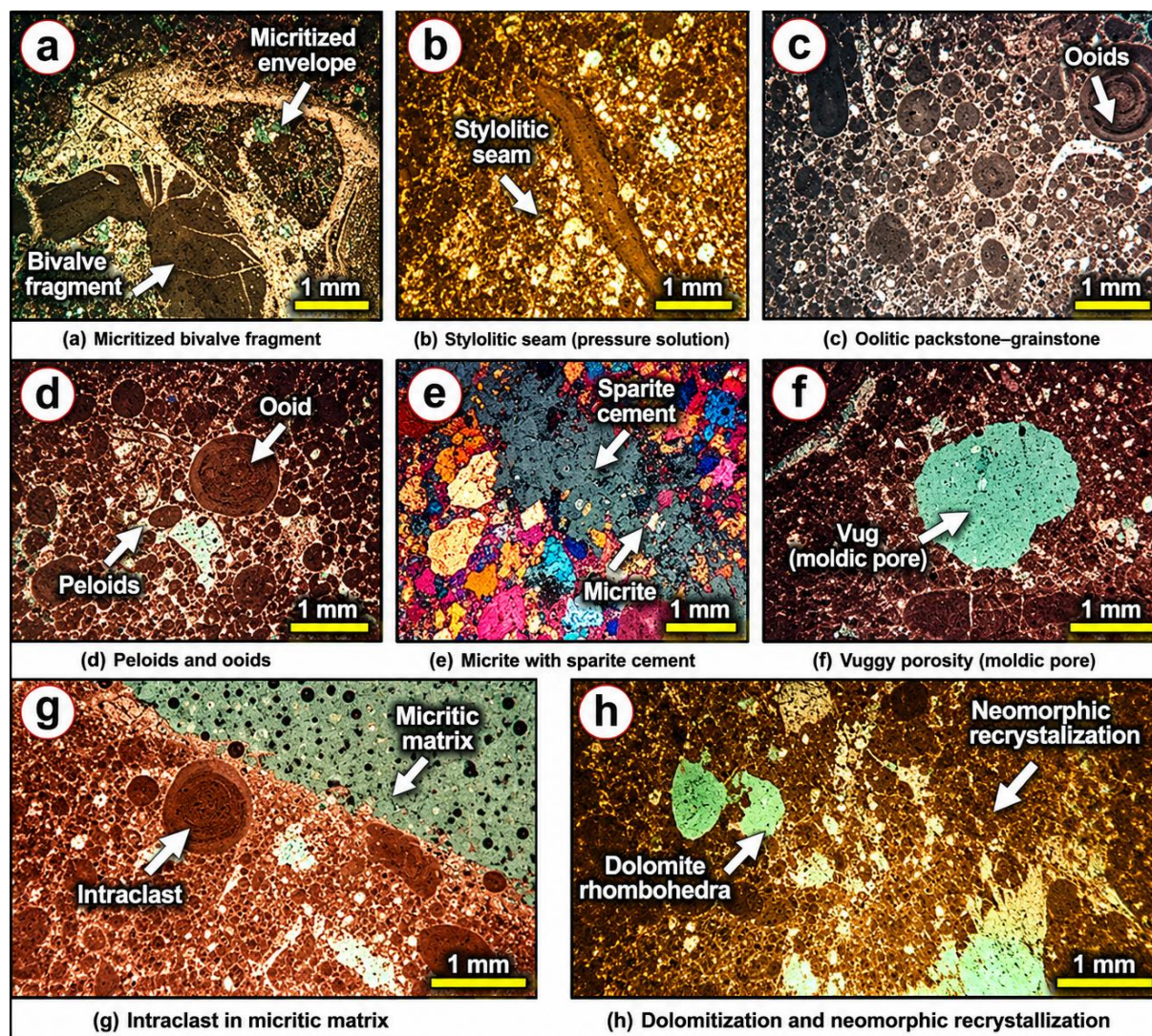


Figure 4. Typical photomicrographs of Mfamosing Limestone displaying key petrographic and diagenetic characteristics: (a) Fenestral porosity; (b) sponge spicules; (c) foraminiferal linings; (d) skeletal assemblages; (e) sparry calcite cement; (f–h) echinoderm fragments and calcareous algae. Included for petrographic interpretation are scale bars and mineral abbreviations.

Figure 4d shows an oolitic packstone microfacies dominated by well-formed ooids with distinct concentric cortices surrounding central nuclei. The ooids are moderately to well sorted and are embedded within a micritic to sparry calcite matrix. Minor skeletal fragments and peloids are also present, contributing to the overall grain-supported framework. The abundance and textural maturity of the ooids indicate deposition in a high-energy environment, such as a shallow marine shoal or carbonate platform margin, where continuous agitation promotes ooid formation [2],[27]. The preservation of ooid structures suggests that diagenetic alteration has not significantly modified the original fabric.

Figure 4e reveals evidence of diagenetic modification, particularly in the form of calcite cementation and localized dissolution features. The original depositional texture appears partially obscured due to recrystallization, resulting in a fabric that can be classified as a

modified wackestone to packstone. The development of secondary porosity through dissolution, alongside cement infill, indicates active post-depositional fluid interaction. These features reflect diagenetic processes that have altered the primary characteristics of the rock while retaining some aspects of its original depositional environment [14].

Figure 4f is distinguished by the presence of stylolites, which appear as irregular, jagged dissolution seams within the carbonate matrix. These features are formed through pressure solution during burial and are commonly associated with the concentration of insoluble residues such as clay minerals and organic matter. The occurrence of stylolites indicates significant chemical compaction, which contributes to porosity reduction and structural modification of the rock during diagenesis [27].

Figure 4g illustrates the effects of dolomitization, where original calcitic components have been partially replaced by dolomite crystals. These crystals occur as subhedral to euhedral forms distributed within the matrix. The replacement process suggests the circulation of magnesium-rich fluids during later stages of diagenesis. Dolomitization not only alters the mineralogical composition of the rock but also has implications for porosity and permeability development [27].

Figure 4h shows evidence of neomorphic recrystallization, characterized by the transformation of fine-grained carbonate material into coarser, interlocking calcite crystals. This process results in the partial to complete obliteration of original textures, although some structural features may still be faintly preserved. Neomorphism reflects a phase of mineral stabilization during diagenesis and plays a significant role in modifying the physical properties of the carbonate rock [27].

DISCUSSIONS

Diagenetic Textures

The diagenetic processes and events observed in the Mid-Albian Mfamosing Limestone were inferred from petrographic examination [28] of carbonate samples collected from four outcrop sections. The diagenetic processes on the limestone present two stages: (i) the early diagenetic process and (ii) the late diagenetic process.

- (i) The early diagenetic processes: Evidence of early stages of diagenetic processes in this carbonate body includes: Micritization, isopachous and syntaxial rim cementation, leaching, generation of cements, dissolution and neomorphism. This is found in almost all the locations visited.
- (ii) The late diagenetic processes are characterized by dolomitization and stylolitization.

Although the limestone exhibits bulk diagenetic characteristics independent of limestone microfacies type, petrographic studies reveal imprints of phreatic and submarine diagenetic environments.

Micritization: Bathurst [27] believed that micritization represents the earliest indication of diagenesis in this limestone unit. According to Essien and Edet [14], micritization in this limestone occurs as a result of boring by endolithic algae and fungi, causing widespread and wholesale destruction of all types of grain, skeletal fragments, oolites and peloids. The processes of micritization are known to occur in shallow stagnant marine phreatic zones

especially at the sediment/water interface. [29],[30],[31]. Micritization is evidenced by micritic envelopes surrounding allochems and skeletal grains as shown in Figure 4d.

Isopachous Cementation: This also represents earliest diagenetic event in the Mfamosing Limestone. It varies from very thin rim to bladed morphology, which coarsens towards the center. The first generation of cement suggests deposition in a submarine diagenetic environment. It represents early cementation in a freshwater phreatic diagenetic environment [32].

Stylolitization: The formation of stylolites, irregular planes of discontinuity between rock units due to compaction- related pressure solution. Stylolites are common features in the limestone under study. They are products of post consolidation in strata solutions [33]. Essien and Edet [14] also corroborated the findings of Petters and Reijers et al. [2], on the abundance of stylolites in the study area especially in the southern part of the study area under investigation (Mfamosing and Etankpini). In the Mfamosing Limestone stylolite occur both within the limestone units and along lithologic boundaries. Their surfaces are stained with seams of insoluble organic residues. These seams are considered to be formed as a result of intratal solution, removing the calcareous constituents and concentrating the insoluble residue. Stylolitic seams and pressure-solution features are observed in Figure 4f.

Compaction: Two phases of compaction in the Mfamosing Limestone were inferred from petrographic studies. These are the physical compaction and chemical compaction. Physical compaction involves breaking of grains and compaction of allochems while the chemical compaction is evident both as pressure solution at grain contact and multiple microcrystallite horsetail as observed in thin section.

Dolomitization: This is one of the late diagenetic events in the Mfamosing Limestone. It is observed as subhedral crystals interlocked along the cracks of the carbonate rocks affecting the original calcite crystals of both the cement and the allochems indicative of a post cementation process. Essien and Edet [14] revealed that the ions for dolomitization may have been derived from water expelled from overlying Ekenkpon Shales. Equally, magnesium released by high magnesium skeletal grains such as coralline algae during diagenesis could provide magnesium ion for dolomitization. Dolomite crystals replacing calcitic allochems are shown in Figure 4g.

Neomorphism: Folk [34] defines neomorphism as a diagenetic process whereby a mineral that has the same gross composition (ignoring changes in trace elements, isotopes, etc) merely recrystallizes to a new form crystal size, shape or orientation differing from the original. It collectively involves inversion (changing from one polymorph of a mineral to another) and recrystallization (where the original and final phases are the same mineralogically but merely differ in crystal from size, or orientation). Neomorphism is a dominant diagenetic process in the Mfamosing Limestone. In the study area, neomorphism is shown by the replacement of the original delicate fibrous structure of the carbonate skeleton (allochems) by interlocking neomorphic calcite. Neomorphic recrystallization textures are illustrated in Figure 4h.

Reservoir Quality and Exploration Implications

The recognized diagenetic processes dolomitization, dissolution, stylolitization, and cementation is crucial in altering the quality of reservoirs. Dissolution and fracturing increase permeability routes, increasing reservoir potential, whereas cementation and compaction typically decrease porosity. Stylolites and fractures indicate possible fluid migration

pathways, which are essential for the buildup of hydrocarbons. Reservoir modeling and development planning must consider the heterogeneity typical of carbonate reservoirs, which is shown by the observed vertical and lateral facies variations.

Depositional Environment

The depositional environment of the Mfamosing Limestone was interpreted from lithofacies and microfacies distributions. The main lithofacies of these carbonates observed at different outcrops were identified by a combination of variety of rocks attributes including facies, textures, fabrics, color, modal composition and diagenesis. These depositional facies types form the basis for depositional environment interpretation of the Mfamosing Limestone.

Main lithofacies identified include:

1. Packstone and grainstone with bioclasts, pellets, oolites and high spiral recrystallized gastropods,
2. Packstones with abundant coralline algae, occasionally stromatolites,
3. Mixed siliciclastic and carbonate with silt and fine sand,

although Reijers and Petters [2] identified four microfacies type as: Lime mudstones, frequently partly recrystallized into pseudosparite.

The interpretation of depositional environments based on the lithofacies and microfacies variations and successions indicate that packstone and boundstone with abundant coralline algae which is occasionally stromatolitic indicate tidal flat environment. The pseudosparitic lime mudstones and wackstones represent lagoons, behind barriers and carbonate muds, while packstones and grainstones with bioclast pellets and high spired recrystallized gastropods are indicative of bars. Laterally, the microfacies belt grade from oolitic shoals and algae patch reefs basin wards to lagoonal and tidal flat facies landwards.

In the study area Mfamosing Limestone displays diverse lithofacies and microfacies associations and is interpreted to indicate a variety of environments ranging from intertidal, lagoonal to shallow marine environment The facies succession generally indicates a shallow marine nearshore carbonate depositional system. The Mfamosing Limestone's depositional features are like those of other shallow marine carbonate systems found in the Calabar Flank and nearby marginal basins in West Africa. Reijers and Petters [2], Essien and Edet [14], and more recent carbonate sedimentological studies within tropical shallow marine carbonate platforms have documented similar facies associations, including oolitic packstones, bioclastic grainstones, and algal boundstones.

Application of Sequence Stratigraphy on Outcrops in the Study Area

Mfamosing village (Mfamosing Limestone)

The lower section starts with the deposition of coarse oncoidal packstone with abundance of bioclastic stylolites followed by a fine grained fossiliferous to bioclastic packstone which is overlain by oolitic packstone. Thus, a retrogradational TST has been identified (Figure 5).

Outcrop section at Mfamosing (along Mfamosing road)

The lower section starts with the deposition of coarse oncoidal packstone with abundance of bioclastic stylolites followed by a fine grained fossiliferous to bioclastic packstone which is overlain by oolitic packstone. Thus, a retrogradational HST has been identified (Figure 6).

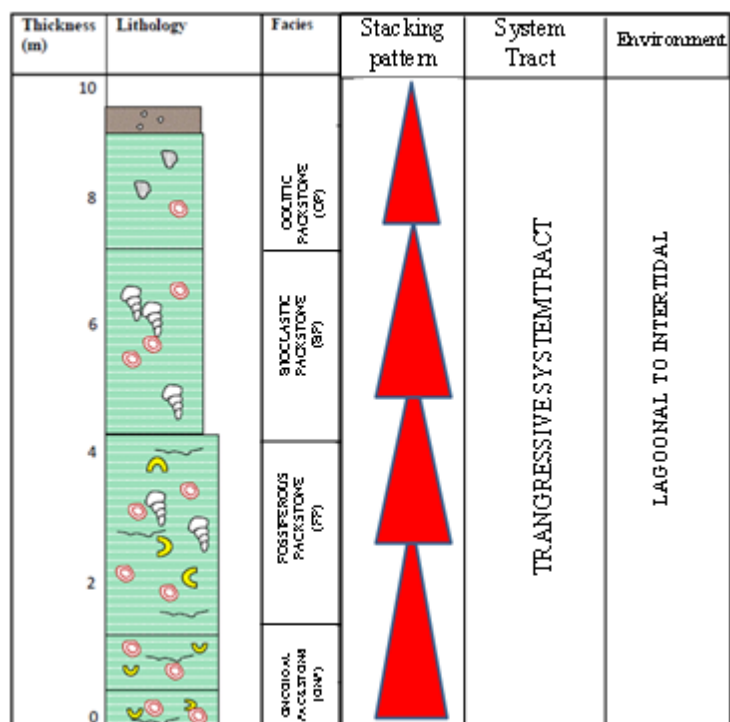


Figure 5. Lithology and sequence stratigraphic interpretation of section at Mfamosing Village.

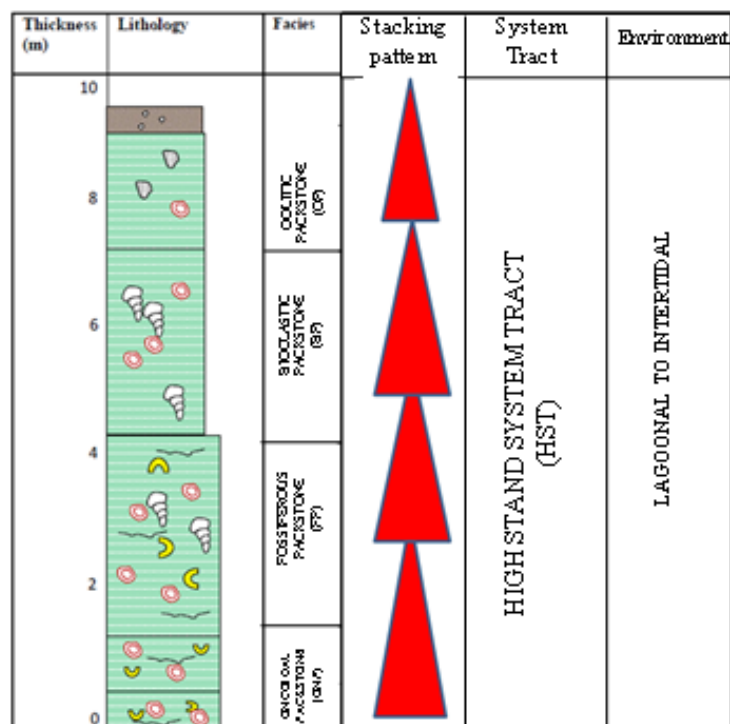


Figure 6. Lithology and sequence stratigraphic interpretation of section along Mfamosing road.

Outcrop section at Etankpini road

This section represents just one Transgressive System Tract of an aggrading stacking sequence following sea level rise (Figure 7).

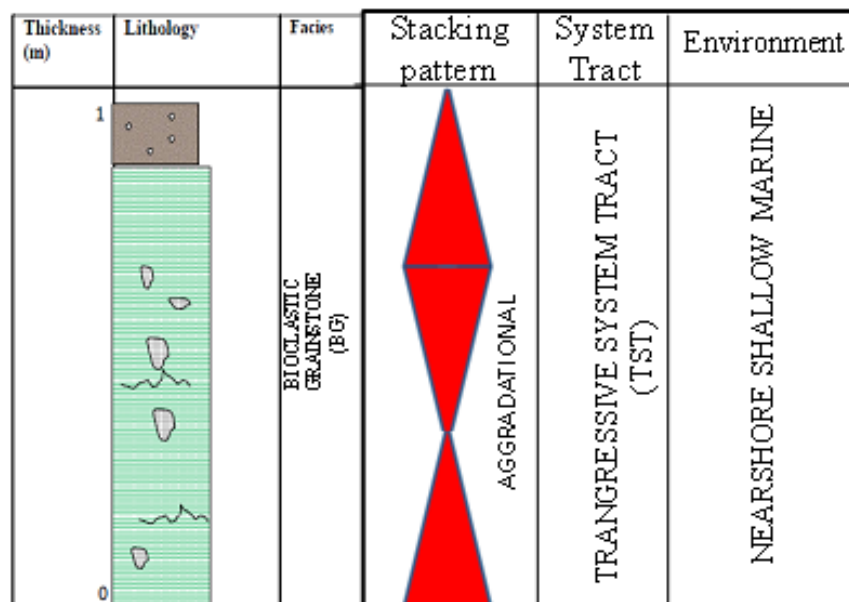


Figure 7. Lithology and sequence stratigraphic interpretation of section at Etankpini I.

Outcrop section at Etankpini

The section represents just one Transgressive System Tract of a retrograding sequence following the deposition fine oolitic packstones with pronounced fossils (Figure 8).

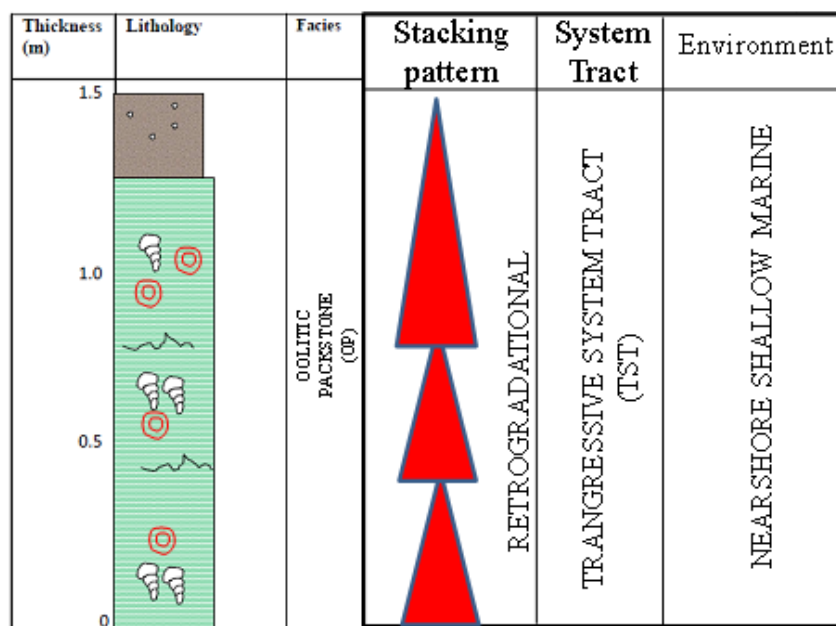


Figure 8. Lithology and sequence stratigraphic interpretation of section at Etankpini II.

Variations in relative sea-level fluctuations and accommodation space within the Calabar Flank during the Mid-Albian are reflected in the observed transgression and highstand systems tracts. While aggradational to progradational stacking patterns show decreased accommodation and relative sea-level stabilization during highstand circumstances, retrogradational stacking patterns show increasing accommodation and progressive marine transgression.

CONCLUSIONS

The study utilized an integrated sedimentological and biostratigraphic methods to characterize the limestone deposits in Mfamosing area Calabar Flank, Southern Nigeria. The study shows that the Mfamosing Limestone carbonates display diverse lithologic and microfacies associations. These facies indicate depositional environments ranging from intertidal and lagoonal settings to shallow marine carbonate systems.

Sequence stratigraphic analysis shows that three (3) outcrops represent an incomplete set of Transgressive System Tract (TST) outcrop (1 and 3), Highstand System Tract Facies in outcrop (4) and outcrop (2) as a complete succession topped by a Transgressive System Tract and a Maximum Flooding Surface followed by a Highstand System Tract.

This study demonstrates the importance of integrating lithofacies analysis, petrography, diagenetic evaluation, and sequence stratigraphy in reconstructing carbonate depositional systems within the Calabar Flank. Beyond earlier research on the Mfamosing Limestone, this work's comprehensive methodology offers more understanding of facies evolution, accommodation trends, and reservoir heterogeneity. The observed facies heterogeneity, diagenetic modifications, and sequence stratigraphic architecture significantly influenced reservoir quality within the Mfamosing Limestone. Dissolution-enhanced porosity, fracture development, and facies-controlled permeability variations indicate that the carbonate succession possesses relevant characteristics of a potential hydrocarbon reservoir analogue within the Calabar Flank.

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