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Stratigraphic Appraisal and Diagenetic History of the Paleocene Ozuabam Limestone in the Afikpo Basin, Southeastern Nigeria

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Abstract

The Imo Formation (Paleocene), about 500 m thick cropping out around Umuahia and Okigwe areas, is predominantly clayey shale, mudstone, shale, limestone and sandstone. The formation is exposed at Ozuabam in the Afikpo Basin, southeastern Nigeria. Field investigations, petrology, diagenesis and geochemical analyses were undertaken to evaluate the microfacies characteristics of the carbonates, their depositional dynamics and environmental milieus. They are composed of a 22-m thick alternation of black glauconitic shale and carbonates. Bedded, coarse bioclastic facies overly poorly bedded finer lithology of the unit. Calcimetric analysis permits the differentiation of the carbonates into limestone (>90%$CaCO_3$), marly limestone (65-90% $CaCO_3$) and marl (35-65% $CaCO_3$). The limestone is bioclastic grainstone - packstone, composed of fragmented shells of pauperized and low faunal diversity. The underlying silty and marly mosaic facies, with impoverished organic communities, are essentially wackstone-mudstone. Geochemically and mineralogically, the finer carbonates are more siliceous and dolomitic, respectively. Dolomitization was contemporaneous and related to stylolitization and Mg^{2+} absorption from illite in the illitic and glauconitic shale interbedding units suggestive of a restricted depositional environment for the carbonates. Early diagenetic imprints included glauconitizaton, fragmentation and micritization while pseudo sparitization, pore cementation and dolomitization represent late diagenesis. The fragmented shells indicate energetic depositional process and correspond to facies 2 and 7 of the carbonate microfacies typifying skeletal sand shoal of lagoon fore slope while the marly facies constitute microfacies 9 and 11 and support deposition within a lagoon shelf.

Keywords: *Microfacies; Diagenesis;, Geochemistry; Limestone; Afikpo Basin.*

1. Introduction

The Afikpo basin occurs as a synclinal depression in the eastern flank of Abakaliki Anticlinorium. It is found in the southern extreme of the Anambra Basin [1-3]. The basin is one of the most geologically important inland sedimentary basins in Nigeria. The Paleogene sedimentary outcrops in the Afikpo basin contains the Late Maastrichtian-Paleocene Nsukka Formation, Paleocene Imo Formation, Eocene Ameki Group and Eocene-Oligocene Ogwashi-Asaba Formation. The Nsukka and Imo Formations represent the beginning of a Paleocene transgression in the basin [4]. Limestone facies alternate with shale and sandstone beds in most of the southeastern Nigerian sedimentary basin. Thus, Mgbo limestone (Mid. Albian), Ebonyi Limestone (Late Albian-Cenomanian), Nkalagu (Turonian) and Ogugu (Coniacian) Limestones occur in the Abakiliki Basin [5], Ozuabam Limestone (Paleocene) occurs in Afikpo Basin, while the Eocene Ameki Formation has limestone beds at Bende and Ameke axis.

Limestone studies in southeastern Nigeria included carbonate facies analyses [5], several biostratigraphic and paleontological studies [3,6-9]. Opatola *et al.* [10] integrated petrographic, microfacies and geochemical information in order to determine the environment of deposition of the Nkalagu Limestone in the Southern Benue Trough. The study suggested deposition in shallow, sub-tidal environments. Okoro and Igwe [2] conducted sequence stratigraphic analysis utilizing palynological biofacies and lithofacies data from outcrops of the Afikpo Basin. There were found to be four third-order depositional sequences that were unconformity-bounded. The sequences range from coastal and shallow marine shelf settings to tidally impacted bay head delta and central estuarine environments. Onyekuru *et al.* [3] utilized lithofacies and biofacies information obtained from three outcrop segments of Nkporo and Mamu Formations in the Afikpo basin for stratigraphy and paleoenvironmental studies. The study recognized two incomplete depositional sequences and play components which are fundamental in basin wide correlation

Integration of field, petrographic, diagenetic and geochemical studies have been employed in the present study to appraise the stratigraphy and diagenetic processes and microfacies classification of the Ozuabam Limestone. The facies classification is based on paleontological and sedimentological criteria identifiable in thin sections- the allochems, matrix, cement and fabrics. Ozuabam lies within Latitude 5^0 36′ 0″ and 5^0 38′ 0″ N and Longitudes 7^0 45′ 0′′ and 7^0 48′0″ E in Arochukwu Local Government Area, about 70 km east of Umuahia in the Afikpo Basin southeastern Nigeria. The basin is bounded to the north-west by the Abakaliki Anticlinorium (Abakaliki Uplift) and to the south-east by the Oban Massif (Figure 1).

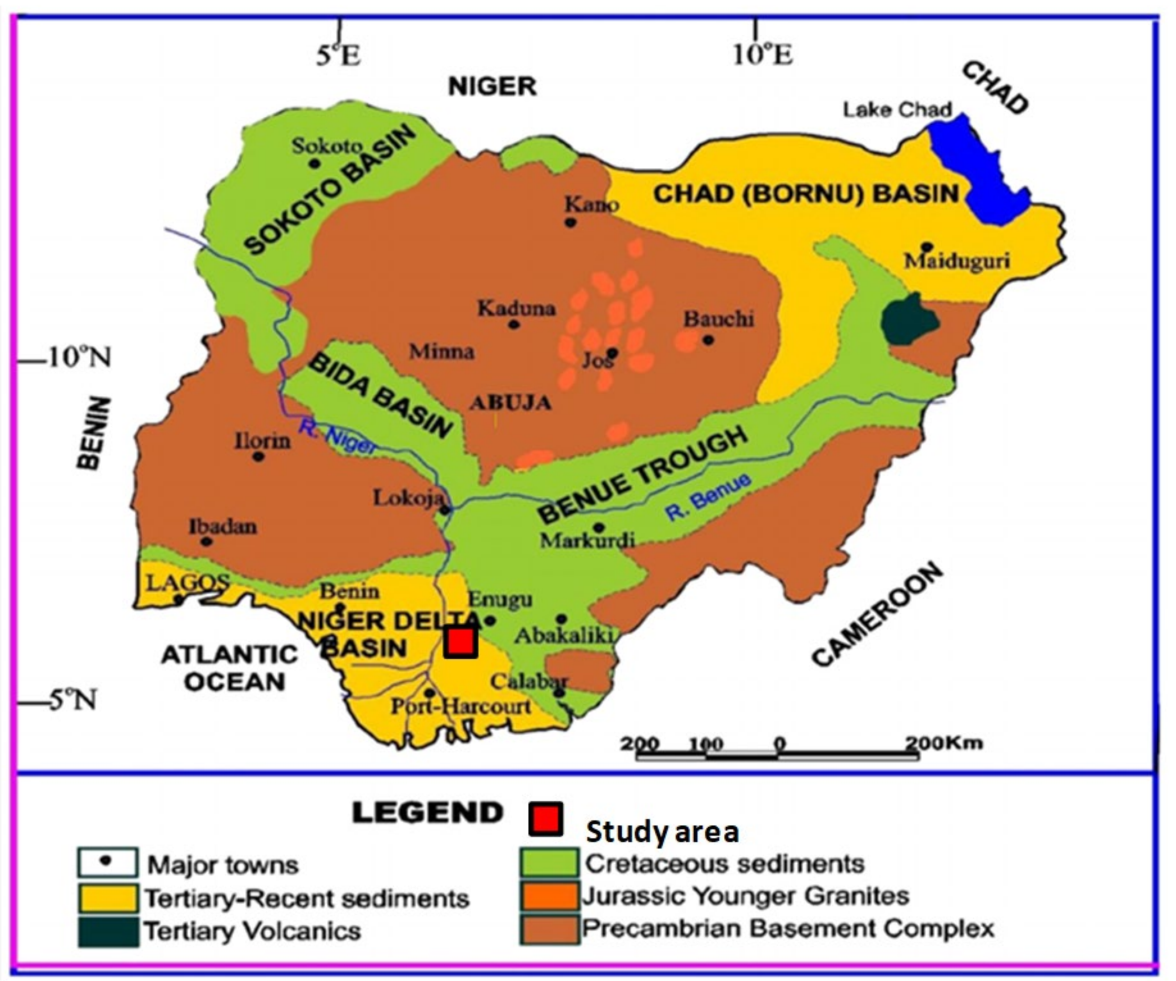


Figure 1. Map of Nigeria showing location of study area (modified from Obaje [4]).

2. Geology of the Afikpo Basin

The Afikpo Basin resulted from the Santonian crustal deformation during the flexural inversion of the Abakiliki Trough into the Abakiliki Anticlinorium (Uplift) and the conversion of the Anambra and Ikpe Platforms into the Anambra and Afikpo Basins respectively (Figure 2). The latter basins were filled with detritus eroded from the Abakaliki Anticlinorium [11-12]. The Nkporo Formation [13] with its intertongues of the Afikpo Sandstone form the initial deposition and the beginning of the third Cretaceous marine depositional cycle in southeastern Nigeria following the above conversion. The formation is unconformably disposed on the folded beds of the Abakaliki-Benue Trough and underlying the Coal Measures Group of Umeji [14]. The latter include the sandstone/shale lithology of the Mamu, Ajali and Nsukka Formations [14-15], which are overlain by the Paleocene Imo Formation and succeeded by the Eocene Ameke and the Oligocene Ogwashi Formations in southeastern Nigeria. Sedimentation in the Afikpo Basin continued throughout the Campanian to the Oligocene (Figure 3).

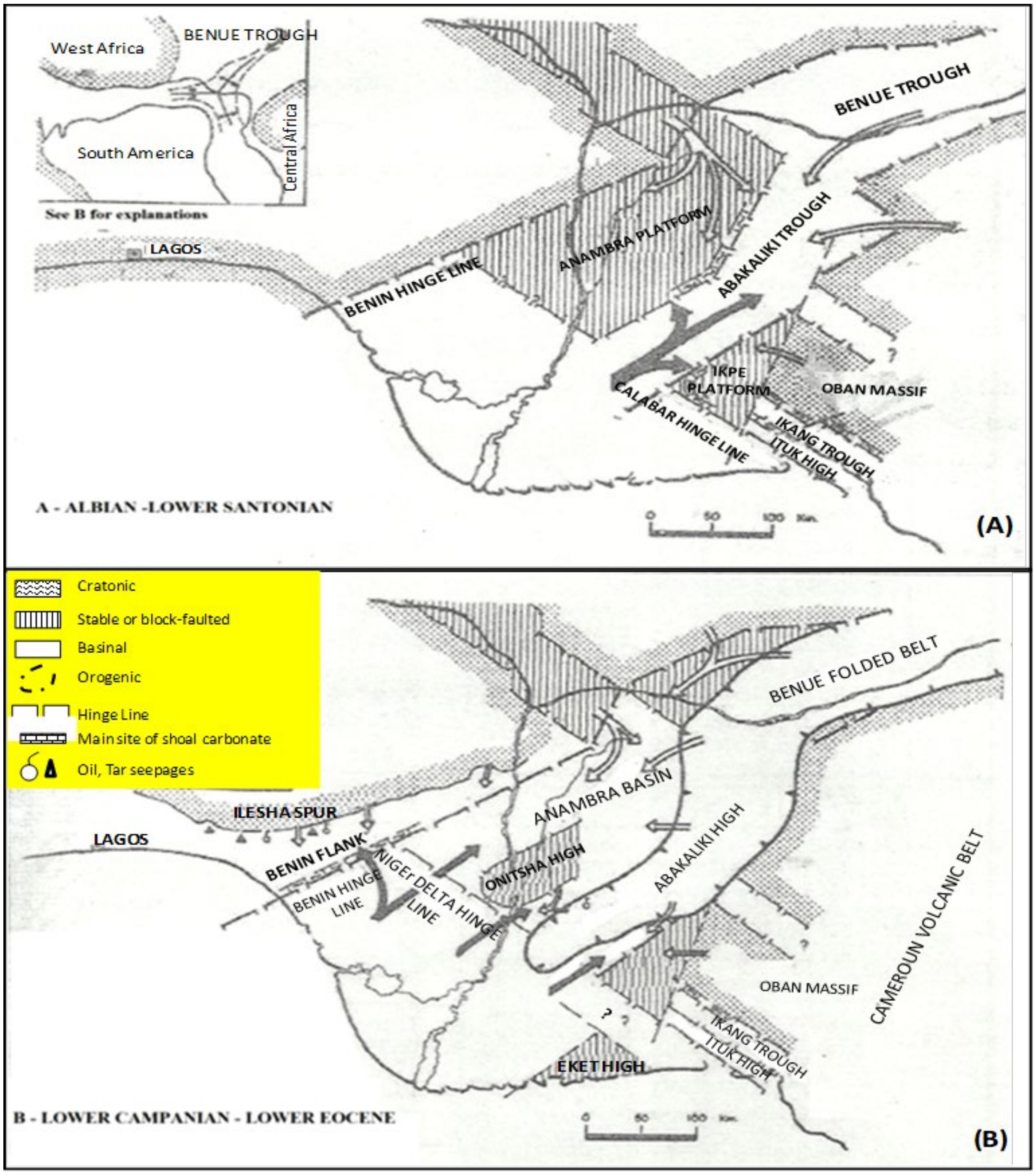


Figure 2. (A) Tectonic evolution of the Southern Benue Trough (Albian to Lower Santonian) culminating in the formation of the Anambra and Ikpe platform. (B) The Santonian crustal deformation resulting in the flexural inversion of the Abakaliki Trough into the Abakaliki Anticlinorium and the conversion of the Anambra and Ikpe Platform into the Anambra and Afikpo Basins [11].

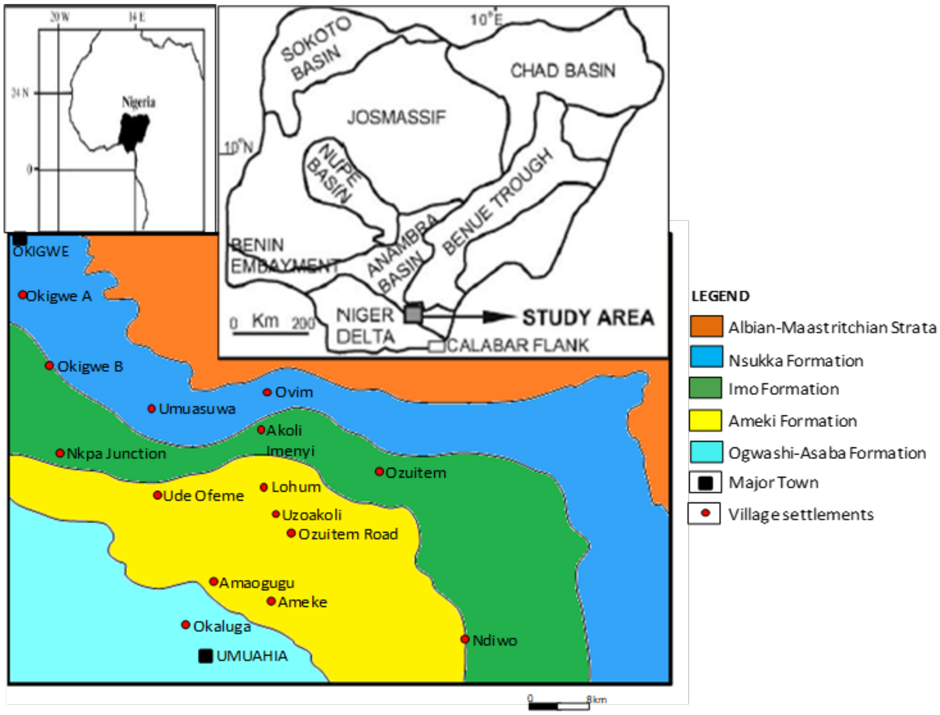


Figure 3. Early Cretaceous-Tertiary stratigraphy of Southeastern Nigeria: (a) Map showing the regional stratigraphic succession in the Afikpo Basin in relation to Ozuabam area [12].

AGE		ABAKALIKI-ANAMBRA BASIN	AFIKPO BASIN
m.y 30	Oligocene	Ogwashi-Asaba Formation	Ogwashi-Asaba Formation
54.9	Eocene	Ameki/nanka Formation/Nsugbe Sandstone (Ameki Group)	Ameki Formation
65	palaeocene	Imo Formation Nsukka Formation	Imo Formation Nsukka Formation
73	Maastrichtian	Ajali Formation Mamu Formation	Ajali Formation Mamu Formation
83	Campanian	Nkporo Owelli Formation/Enugu Shale	Nkporo Shale/Afikpo Sandstone
87.5	Santonian	Agbani Sandstone/Awgu Shale	Non-deposition/erosion
88.5	Coniacian		
	Turonian	Eze Aku Group	Eze Aku Group (incl. Amaesiri Sandstone)
93 100	Cenomanian-Albian	Asu River Group	Asu River Group
119	Aptian Barrenian Hauterivian	Unamed Unit	
	Cambrian	BASEMENT COMPLEX	

Figure 3. Early Cretaceous-Tertiary stratigraphy of Southeastern Nigeria: (b) Correlation chart for Early Cretaceous-Tertiary strata in Southeastern Nigeria (Modified from Nwajide [15]).

The regional stratigraphic succession in the Afikpo Basin in relation to Ozuabam area has been given by Obo-Ikuenobe *et al*. [12] and is illustrated herein in Figure 3 while the geological map of the study area is shown in Figure 4. The Nkporo Formation in the Afikpo Basin is a lateral equivalent of the Enugu Formation in the Anambra Basin [15-16]. Its Campanian- Maastrichtian age was confirmed with *Syncolporites Lisamaesubtilis* and *auriculisdittosp* [16]. It consists of dark grey, often friable shale with occasional thin beds of limestone. The Mamu Formation (Lower Coal Measures) overlies the Nkporo Formation) and consists of fresh water and low salinity sandstone, sandy shale, mudstone with coal seams at several horizons [17]. It is overlain by the Ajali Sandstone which consists of coarse- medium cross-bedded sandstone with thin bands of purple-stained clay and shale. The sandstone is thick, friable poorly sorted, typically white with some iron stains. A marked banding of coarse facies and fine layers are displayed. The grains are sub- rounded with sparse cement of white clay. The deposit varies in thickness from 100-1000 m across the Afikpo Basin. Good exposures with vertical and lateral facies changes occur at Igbere in the Afikpo Basin.

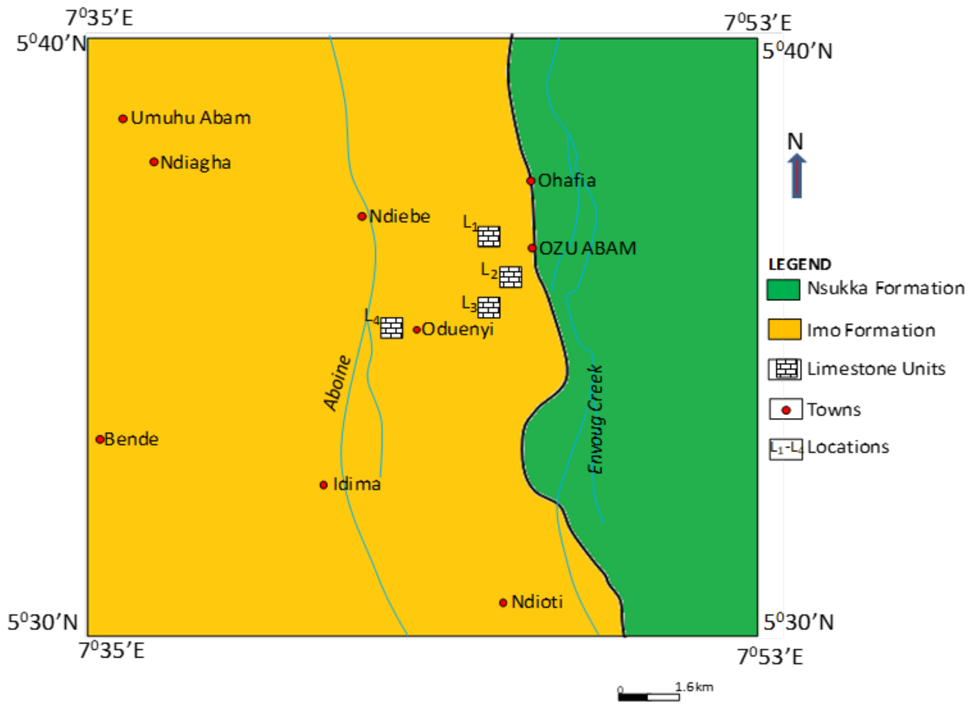


Figure 4. Geologic map of the study area.

The Nsukka Formation (Danian) also known as the Upper Coal Measures [17] is conformably disposed on the Ajali Formation. Like the Mamu Formation it consists of alternating succession of shale and sandstone with sandy shale and some coal seams [17].

The Imo Formation developed as thick clayey shale consisting of blue – grey shale, thin bands of calcareous sandstone, marl, limestone and some lateral sandstone facies which, depending on the outcrop location, has been differently named the Umuna Sandstone, Ebenebe and Igbabu Sandstones, respectively [6,18]. The formation contains ostracodes, foraminifera and molluscs [6]. The basal limestone units also contain microfauna [19]. It is laterally equivalent to the fossiliferous Ewekoro Formation in the western Nigeria [20].

3. Materials and methods

The field occurrence of the Ozuabam limestone was established by close-pace traversing to produce the geological map of the area (Figure 4) and by describing the limestone lithological variations. An approximate estimate of its thickness was determined along traverses across the investigated area. The limestone beds were sampled and measured at convenient intervals. Samples of limestone bed and the associated shale were collected for further analyses. The major control of the sampling was the availability of suitable outcrops (Figure 4). Numerous samples were collected at permissible intervals of about 1.5 m along profiles. The mapping indicated a broad disposition of the limestone while the detailed interval sampling and descriptions revealed lithological variations on bed-to-bed basis. Ten representative limestone samples including oriented samples with the top and bottom marked and the attitude of the outcrop measured were prepared for microfacies and geochemical analyses. Some samples of the interbedding shale were also geochemically analyzed for the major oxides. The analyses and thin sections were done in the Laboratories of the Nigerian Geological Survey Agency (NGSA), Kaduna, Nigeria.

Microfacies analyses were based on the work of Wilson [21] and Flugel [22] while Folk [23] and Dunham's [24] classification schemes were employed to establish the limestone types.

Sand for geochemical analyses were milled to pass through 100 mesh British standard sieve. Gravimetric methods were used to determine insoluble matter, pure silica, combined oxides, calcium and magnesium oxides as described by Jeffry *et al.* [25].

One gram of each prepared sample was digested with HCl and HNO_3 in the ratio of 3:1 (30mL: 10mL). Ten ml of HF was added for the complete digestion of SiO_2. The reaction of the carbonate sample with excess HCl to produce carbon dioxide was utilized to ascertain the carbonate levels of the limestone (This is equivalent to calcimetric determination of percentage of carbonate and CO_2).

Figure 5. Outcrop of limestone at Ozuabam.

Atomic absorption spectrometer (AAS) was used to determine the elemental composition of the limestone and shale samples while loss on ignition (LOI) was determined gravimetrically by igniting milled samples in a furnace. Four limestone outcrops of various sizes occur at Ozuabam but one outcrop was sufficiently thick and continuous for appraisal. The others were more or less boulders. The selected unit which consisted of limestone- shale succession was approximately 22 m thick with sharp limestone-shale boundaries (Figure 5). The shale is generally grey to black and cumulatively thicker than the limestone. It is glauconitic which latter also occurs in the limestone.

The limestone is divisible into a lower and an upper lithological unit. The lower is about 13.5 m thick and composed essentially of limestone with interbedded thin shale of 0.8 m thick. The upper unit which is 8.5 m thick is composed of alternations of shale which could be up to 1.8 m thick and limestone beds up to about 1.0 m average thickness.

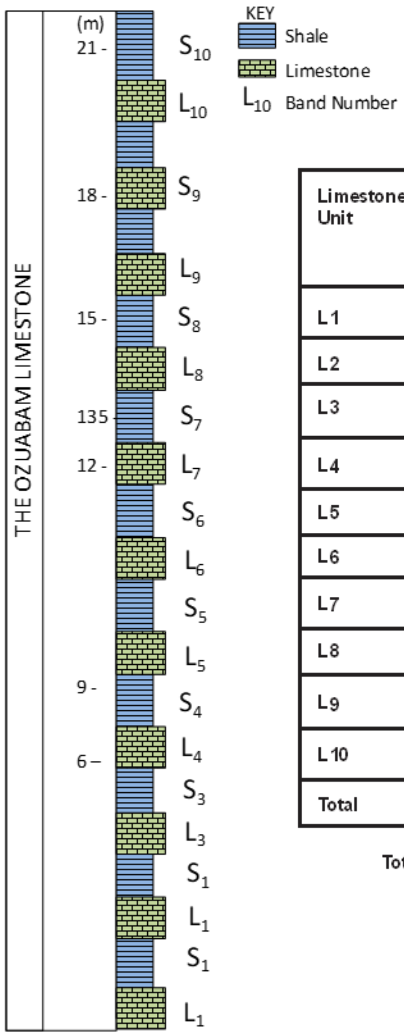
The basal unit of the section is represented by a medium-grained grey, bedded, fossiliferous limestone succession with upward grain grading from L_1 – L_7. Lithological unit- 8(L_8)- is medium – grained with fining upwards size from L_8 - L_{10} (Figure 6).

4. Results and discussion

4.1. Microfacies

Microfacies classification studies, assignation to facies zones (FZ) and standard microfacies (SMF) types were based on the classification schemes of Dunham [24], Folk [23], Wilson [21] and Flugel [22] and adopted by Nair *et al.* [26], Enu and Adegoke [27], Ojo [28], Agumanu [5] and Nwachukwu [18].

Four major microfacies types were distinguished from thin sections made from the profile at Ozuabam. They were biomicrite (wackestone), sandy bioclastic wackestone, packstone and packstone- grainstone.



Limestone Unit	Thickness (m)
L 1	1.4
L2	1
L3	1.1
L4	0.7
L5	0.64
L6	0.64
L7	0.91
L8	0.55
L9	1.13
L 10	0.8
Total	8.75 m

Shale Unit	Thickness (m)
S1	2.13
S2	1.7
S3	1.43
S4	0.8
S5	0.7
S6	1
S7	1.1
S8	1.4
S9	1.7
S10	1.1
Total	13.01 m

Total thickness = 21.76 m (approx. 22m)

Figure 6. Lithostratigraphic log of the Ozuabam limestone.

***Biomicrite (Wackestone)*:** The wackestone is composed of allochems consisting of unabraded, randomly oriented skeletal grains, supported by matrix- admixture of carbonate and siliclastic mud, non-skeletal grains, matrix and cement. The allochems are polymictic-skeletal grains among which are both whole and fragmented pelecypod and gastropod shells, and microfaunas such as ostracodes. They are mainly matrix-supported. Smaller skeletal and non-skeletal grains are contained in whorls of gastropod (Figure 7c-e). The allochems are between 20 and 50% of the constitution of the limestone.

The non-skeletal grains are quartz, feldspar and micrite which occur in inter-granular spaces and intra- skeletal pores. The quartz is subrounded and varies in size from 250-500µ. It occurs freely within the micritic medium.

There is cementation of molluscan shells embedded inmicrite with extraclasts of quartz, feldspar and molluscan space fillers- algae, shell outlines, voids- diagenetic vugs- with both epitaxial and syntaxial rim cement (Figure 7k and i).

Sandy bioclasticwackestone: This microfacies is represented by greyish limestone composed of pelecypods, gastropods, ostracodes and other microfaunas as allochems and quartz as extraclasts with micritic and calcite cement. The constituent parts are buried in brown coloured sandy micrite (Figure 7e). Mineralogical conversion of aragonite-calcite probably has taken place in the fragments of bioclasts such that several of the boundaries between fossils and adjacent voids are occasionally obliterated or delimited by critter. This type of conversion according to Dodd [29] is Type II or Type III solution deposition conversion [27]. The quartz grains are essentially subangular to subrounded and well sorted. Some algae are also present. The vugs are surrounded by epitaxial calcite cement of different sizes, included in several thin sections are grains of glauconite (Figure 7a)

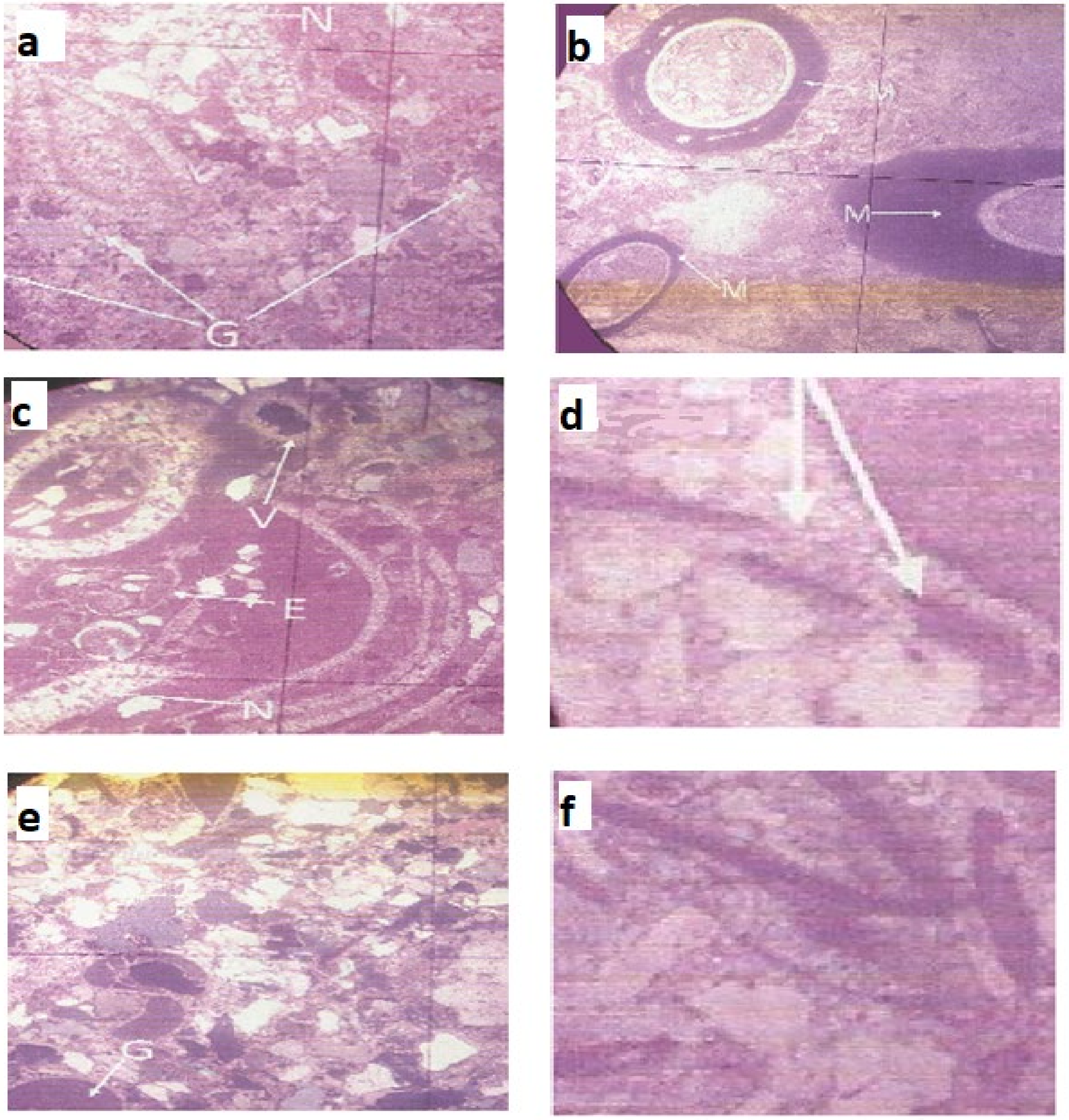


Figure 7. Thin section profiles of Ozuabam Limestone: **a.** Bioclastic packstone (note neomorphic cementation of fossil outline and several grains of glauconite (G); **b.** Bioclastic Packstone-Grainstone with micrite enveloped echinoid spinel (M). (Note boring of micrite rind; endolithic organisms to produce secondary porosity; **c.** Biomicrite: matrix-supported smaller skeletal and non-skeletal grains are contained in whorls of gastropods; **d.** Micritic envelopes continuous with both vadose and phreatic cement (Arrows point to area of vadose and phreatic cement continuity); **e.** Sandy bioclastic Wackstone: Contains pelecypods, gastropods, as allochems and quartz and feldspar as extraclasts with epitaxial cement and intensely micritized shell space (G); **f.** Fractured micritic rinds to bring both the critter and primary pore cement together.

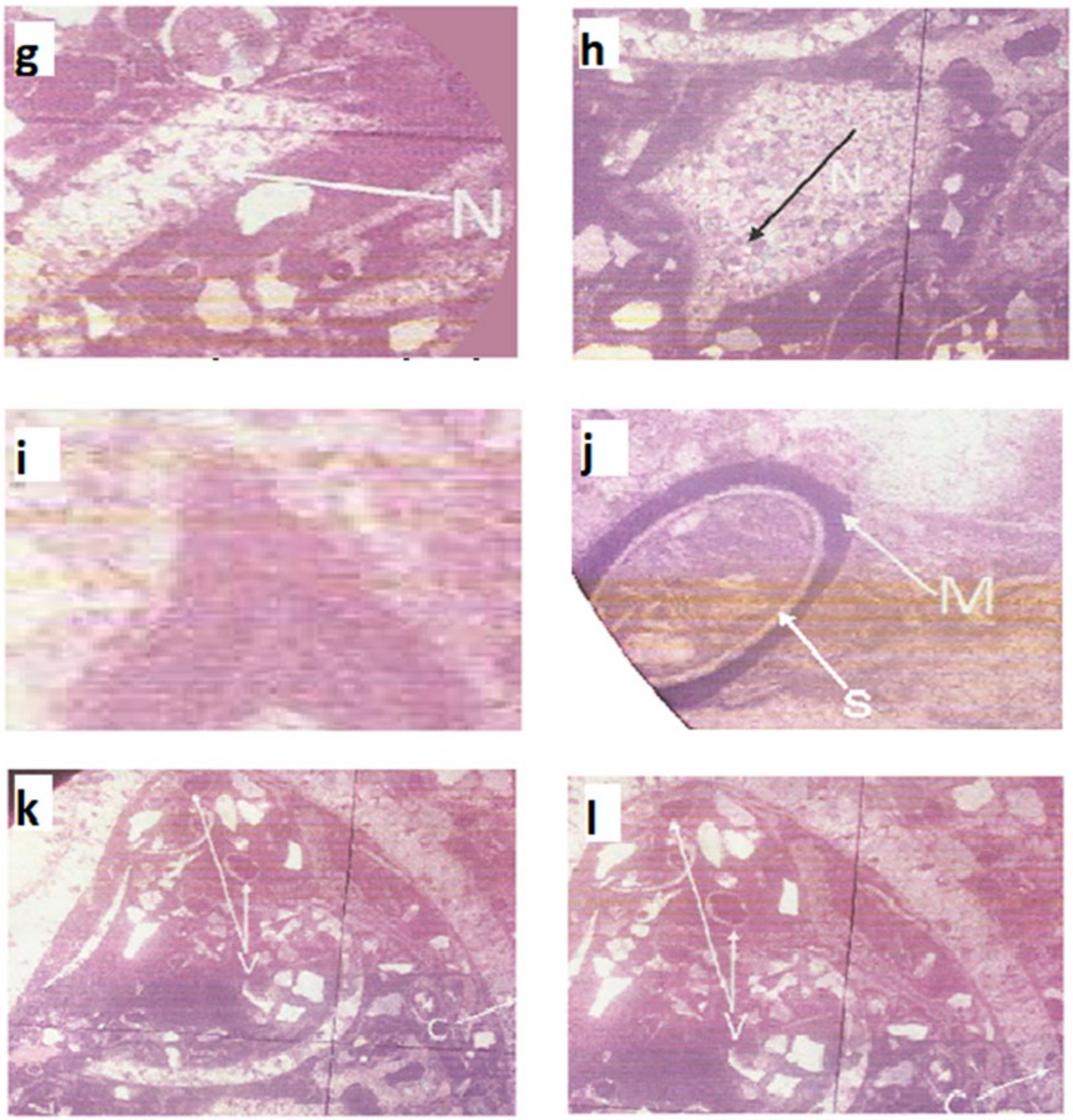


Figure 7. Thin section profiles of Ozuabam Limestone (continues): **g.** Pseudosparitization (aggrading neomorphism) demonstrated by whole sale replacement of shell by calcite. Gastropod shell at the top is replaced by equant calcite. **h**. Neomorphic crystallization exhibiting neomorphic aggregation: arrows is in the direction of crystal size increase. **i.** Cementation preceded by isopachous mucilage with paridiotopic, equiangular texture of meteoric vadose origin. Pore cement increases outwards from isopachous layer to fills space. **j.** Syntaxial cement (S) develops on micrite foundation (M) suggestive of primary or secondary pore space. **k.** Cementation of molluscan shells embedded in micrite with extraclasts-quartz, feldspar-algae voids, diagenetic vugs with epitaxial and syntaxial rim cement. **l.** Diagenetic vugs (V) surrounded by epitaxial cement

Packstonemicrofacies: Thepackstone consists of allochems (20-50%), extraclasts (25-30%), micrite (5-10%), sparite (25-50%). The skeletal grains are mainly fragmented pelecypods, gastropods, some ostracodes and limited foraminifera. The bioclastic grains are often sub-rouded, moderately sorted and both grain- and poorly micrite-supported. They are generally cemented by sparite and pseudospar and with callianasid burrows.

Bioclastic packstone is often associated with whole or fragmented mollusks, echinoids and microfaunas including ostracode and algae and worm burrows. The bioclasts and extraclasts-quartz and feldspar- are both grain- and matrix-supported.

Packstone- grainstone: This microfacies is often associated with whole or fragmented mollusk, echinoids and microfaunas including mainly ostracode and algae; poorly preservedweathered, reworked or oxidized- few radial ooids also occur. The ooid in association with borings, encrustations of sessile organisms are probably product of hardground [30-31]. The echinoid spines are enveloped by thick micrite rinds which latter rind is much exaggerated in diagonal sections (Figure 7b). Borings of the rinds by endolithic organisms produced secondary porosity which latter was reduced by pore cement. The rinds have both thicker syntaxial and thinner epitaxial cement. The latter is in sharp contact with the interparticle pore cement. The cement is probably reworked by indeterminate biota some of which are epitaxially cemented.

4.2. Environment of depositions

The differentiation of the Ozuabam carbonate microfacies from bioclastic grainstone (biosprite) to wackestone (biomicrite) is a factor of the carbonate production, particulate size, transportation and hydrodynamic conditions operating in Ozuabam depositional area [32]. The field observations, stratigraphic and microfacies analyses, diagenesis, geochemistry and other components of the limestone have provided clues for interpreting the environmental milieu of the depositional area. Our stratigraphic analyses above have indicated a shallow marine depositional setting for the Paleocene Imo Formation in which the Ozuabam limestone occurs as detailed bellow.

The rhythmically alternating glauconitic shale-limestone sequence (Figure 6), suggests instability of shallow shelf platform in which clastics were supplied at low sedimentation rate from adjacent topographic heights or due to oscillations in deposition and/or production of both fine argillaceous and organochemical materials [33-34].

Glauconite occurs both in several thin sections and the shale thus confirming shallow marine depositional environment for the limestone [34]. Glauconite also occurs in neo-formed calcite crystal from shells and intra-micrite cement. It is used to designate the Fe- rich pelletal micas of marine origin [35]. Like illite it is K-deficient with small tetrahedral substitution. It is used with illite in the carbonate to absorb Mg^{2+} from the shale and environment for the conversion of calcite to dolomite [36].

The relatively high content of MgO in the limestone reflects the extent of dolomitization as a characteristic feature of marine depositional environment.

Based on mud-bioclastic ratio, the limestone is divisible into three facies zones of Flugel [22]: Z 2 and 7 and standard microfacies (SMF) 8, 9 and 10. The three major grain/matrix relationships are wackestone, packstone and packstone- grainstone.

Wackestone microfacies: The wackestone consists of both lithic and bioclastic materials. The former is sandy with both whole and fragmented bioclasts. It typifies a restricted sand-shoal or muddy/sandy deposit impoverished of faunas and with sediments suggesting low-energy, shallow water biota. This probably reflects the inner muddy interior of a lagoon with both pauperized biota and lithic influx [37]. It represents Facies Zones (FZ) 2 and 7 and Standard Microfacies (SMF) Type 8 of Flugel [22] and Wilson [21].

Packstone microfacies: The packstone is typical of shell carbonate facies which ranges in colour from light to dark gray; these together with marl component, the stenohaline forms ("normal marine faunas"), mollusks, a few foraminifera among others suggest middle shelf environment for the packstone. It belongs to FZ 2 and 7 of SMF 10 of Wilson [21] and Flugel [22]. The presence of few macrofossils- gastropods, bivalves-and scarce microfaunas has similarly been suggested by Akaegbobi *et al.* [38] as indicative of shallow marine shelf lagoon environment of deposition.

Packstone- grainstone: The individual grains in the packstone- grainstoneare strongly cemented together thus, making identification difficult (Figure 7g). Usually the allochems are poorly compacted, suggesting that cementation occurred soon after deposition, and the occurrences of coated bioclasts were probably typical of depositions during storm events in supratidal beach ridges [39]. It is more probable that the reworked or oxidized ooids are part of oolitic shoal surface and surface of smaller oolitic sand bodies reworked by daily exchanges of currents at the lagoon inlet [31]. As Smith and Mason [40] have indicated, the presence of radial-fibrous laminae implies ooid formation in relatively quiet area. Nevertheless, their association with whole or fragmented mollusks suggests occasional strong current influx with coarse materials. Cementation probably was caused by percolation of sea water below the surface of sediment to proceed under vadose conditions [39].

4.3. Diagenetic history

The data accruing from this study permit a possible reconstruction of the diagenetic history of the Ozuabam limestone. The various stages of diagenetic processes in the deposit are herein discussed. The first diagenetic imprint on the Ozuabam limestone was the precipitation of authigenic glauconite in pore spaces and neo-formed calcite crystal. According to Erlich *et al.* [41] glauconite usually occurs with mixed clays in near shore marine and deep marine environments, in high, middle or low latitudes [5]; therefore, its occurrence in the Ozuabam limestone is normal especially when there is a proven evidence of its presence in the deposit as indicated on Figure 7a. Dasgupta *et al.* [42] have shown that glauconite forms rapidly after deposition even while the sediments are still within the sediment–seawater interface. Chronologically, other diagenetic features revealed in the Ozuabam limestone included micritization, cementation, compaction (fragmentation) stylolitization, dissolution, replacement, neomorphism, dolomitization.

Micritization: The formation of micrite which is an aspect of early marine diagenesis [26,43] is the next stage of diagenesis recorded from the Ozuabam limestone. Microcrystalline calcium carbonates- non-descript, brownish space-filling or framework envelope occurs severally in the Ozuabam limestone. According to Bathurst [30] and Flugel [22] it forms as centripetal replacement not as centrifugal accretion and is a ubiquitous occurrence among wackestone and packstone facies of the Ozuabam limestone. The formation of micrite predates the development of isopachous cement which latter often develops next to mirite rinds and grows as pore cement.

Micrite is the very fine–grained matrix of carbonate grains. Micrite envelopes are common features of limestone from all parts of geological column. Apart from being a centripetal replacement or mucilage envelope which Sibley and Murray [44] suggested had an average composition of 96% aragonite and 4% calcite, it occurs as lime mud fillers in bioclastic bores and chambers such as ostracodes, gastropods, bivalves, foraminifera. In such cases the contact between shell and micrite is sharp [44]. The rinds are more pronounced in diagonal crinoid columnar or as micrite in echinoderm skeletons. In several sections they are bored by endolithic organism and filled with pore cement (Figure 7b). They are seen as intensely micritised shell space or whorls, (Figure 7c). Framework voids are filled by fine- to coarse- grained biomicrites or biosparite, which implies locally variable energy conditions (Figure 7d) [45]. The critter moulds which are defined by micritic envelopes are usually continuous with both vadose and phreatic cement (Figure 7e) while some of the former are replaced by microspar [28]. Micrite envelopes recorded from the Ozuabam limestone appear to be outcome of automicritization in view of the *in-situ* development of micro-bioclastic carbonates [26,30].

***Compaction (Fragmentation)*:** Compaction is said to occur early in digenetic history of carbonate as it commences immediately after deposition and increases with increased overburden pressure. It occurs as soon as accumulation of skeletal grains in muddy matrix of siliclastic and carbonate grains commence [28]. It manifests in the limestone in several textural features for example, skeletal fragmentation and fracturing of micritic rinds (Figure 7f). These last two phenomena are dependent on the grain-mud ratio because fragmentation would hardly show in mud-supported medium. The finer material (mud) present in samples tends to cushion the effect of compaction as the stress is sheared among the innumerable mud particles [46]. The rupturing of critter (micritic envelope) was probably caused by force of crystallization with the consequent formation of microthrust shown by some skeletal grain. Such fracturing brings both the critter and primary pore cements together.

***Neomorpic cement*:** Neomorphic cement occurs as part of several bioclastic fillers-micrite. Neomophic replacement of micrite by calcite occurs in the Ozuabam limestone and exhibits neomorphic aggradation where crystal size increase from the centre outwards Figure 7g and Figure 7h. Such replacement calcites are Folk's [47] pseudospar. Pseudosparitization is demonstrable in whole sale replacement of micrite by calcite, or shell replacement by calcite which latter Bathurst [30] considers as aggrading neomorphism. This is inclusive of the diagenetic alteration of micrite to sparry calcite *in situ,* without the intermediate formation of visible porosity. The observation by Longman [36] is probably the mechanism of conversion in our study: the thick alternating beds of marine shale with limestone facilitate the neomorphism of micrite to microspar. Furthermore, because the formation of pseudospar is closely associated with weathered zones and stylolitization [36], interstitial fluid movement through the micrite flushed out the Mg^{2+} ion for the calcite development and consequently, the formation of microspar.

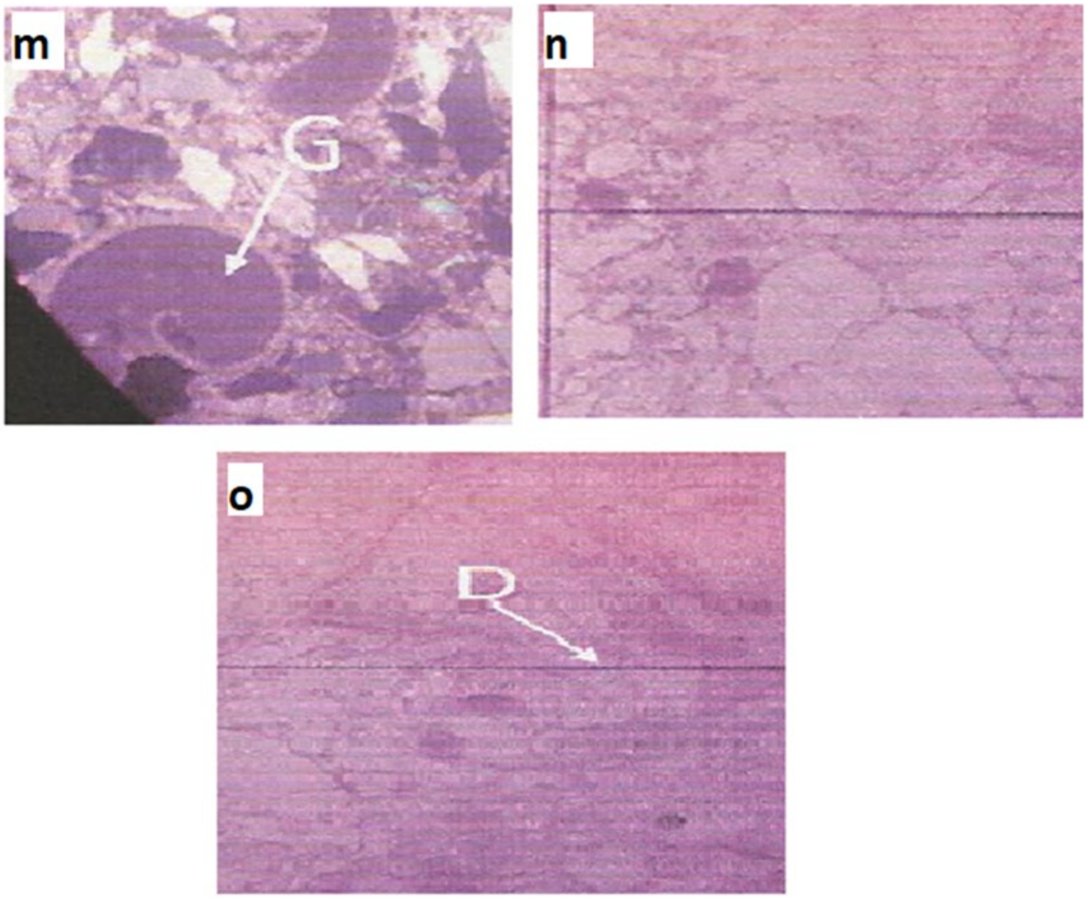


Figure 7. Thin section profiles of Ozuabam Limestone (continues): **m**. Micrite cement as geopetal void fillers, mud fossil grains and grain-sheltered mud patches (note the epitaxial cement on gastropods (G)). **n**. Anastomosing (interconnecting network) of stylolite with non-discript brownish, clayey or insoluble seams, pulerisation and automicritization as a result of granulation during stylilization. **o.** Stylolization recognized as irregular wormy dark traces. Dolomite rhomb is indicated by arrow.

Cementation: Bioclastic grains in Ozuabam limestone have the most common cement - coarse equant cement (Figure 7i) usually with hypidiotopic, xenotopic or poikilotopic texture [48]. Such cements according to Nair *et al.* [26] are found in the meteoric phreatic environment as pore filling phase in carbonate deposits. The cements are usually preceded by athinisopachous micron-size calcite with panidiotopic, equigranular texture of meteoric vadose origin. The isopachous morphology (isopachous fringe calcite [26] with remnants of fibrous texture constitute the first-generation cement of littoral origin in Ozuabam limestone. In some cases, the isopachous layer is composed of small, usually equant calcite crystals which develop on the foundation of shell fragment. Cement could develop on both sides of the micritic envelope as illustrated by Talbot [49] suggesting the existence of void spaces as both mouldic and primary interstitial porosity [46]. Despite the foundation of micritic coating syntaxial cement also develops (Figure 7j and figure 7k) [30]. Among this type of cementation is the sparry calcite which occurs in the limestone as a precipitation from solution unto free surface causing the outward growth of crystalline material which adheres to the surface [49]. The pore space occupied by the crystal is either primary or secondary. The former includes interparticle or intraparticle space, mouldic and vuggy pores (Figure 7l) and small discontinuous fractures [50]. The intraparticle spaces are mainly bioclastic pores – pelecypod and ostracode valves or gastropod spaces (Figure 7m).

Stylolitization: Stylolites are recognized as irregular planes of discontinuity between two rock units which appear to be interlocked or mutually interpenetrating along a very uneven surface. They are characterized by the concentration of relatively insoluble constituent of the enclosing rock. Stylolite is a pressure dissolution surface [51] pressure solution, microstylolite, pitted pebble, wavy clay seam or residual seams in carbonate. There are both aggregate and intergranular stylolites. Geometrically, Park and Schot [51] has defined simple or primitive stylolite, sutured stylolite, down-peak or up-peak type and sharp-peak type (tapered or pointed). Stylolite occurs in a few thin sections of the Ozuabam Limestone mainly as a consequence of crushing and hence, is related to overburden pressure as there are no tension gashes which are common in tectonic stylolite [5].

In relation to bedding plane, the Ozuabam limestone is affected by both irregular anastomosing (interconnecting network) and vertical stylolite (Figure 7n). Horizontal, vertical, and incined stylolite are present with the inclined stylolite predominating in the limestone. Thus, morphologically, simple or primitive wave-like sutured types and sharp-peaked types as defined by Park and Schot [51] are present in the limestone. The peaks are filled with non-descript brownish seam materials like clay or insoluble seams. An overburden pressure of between 600 and 900 m was probably the main cause of pressure solution. This depth appears to be a threshold figure as little is certain about the depth at which pressure dissolution can begin [52]. The quantity of rock dissolved was probably insufficient in view of the less than 1mm size of the stylolite [26] as the microstylolite seams are generally less than 0.1mm thick; suture amplitudes are usually less than 0.1mm. Choukroune [53] called these types of fractures tension gashes and stated that they were related to the same stress conditions that formed the stylolite. Nelson [54] redefined "tension gashes" as excellent fractures and concurred with Choukroune's theory of origin. Nelson [55] further suggested that the pattern of stylolite with extension fractures are similar to the stress patterns produced in laboratory triaxial compression and extension tests and are, therefore, of probable tectonic origin.

Solution: Some of the sections contain vugs which probably are associated with secondary porosity. Further evidences for dissolution include collapsed micritic envelope, filling of shell walls with clear sparry calcite where crystal sizes increase toward the centre from the wall. Stylolitization is caused by pressure solution or chemical compaction. The mechanism leads to pulverization and micritization which phenomenon has been described as 'pressure-conditioned transformational communition [46].

Automicritization: Automicritization is evident in grain granulation during stylolitization, and also in borings by endolithic organisms to form algal dust or algal micrite. Micrite cement, muddy matrix of siliclastic and carbonate grains occur as geopetal void fillers, mud infillig of fossil grains and grain-sheltered mud patches.

Dolomitization: Dolomitization in the Ozuabam limestone occurs in association with stylolite. The euhedra are small dolomite rhombs with cloudy appearance in association with wavy stylolites, (Figure 7o) suggestive of influence of pressure solution in its development [56]. The cloudiness probably is suggestive of replacement dolomite which in this case is fabric destructive with non-mimetic replacement of allochems (e.g. fossil fragments, ooids, peloids [56]. It occurs in association with the extraclasts-quartz, feldspar and micrite. There is a preference for dolomitization of the stylolitized fine-grained carbonates than the tightly packed areas. As observed by Petters [8] in the Ewekoro Formation, southwestern Nigeria, the crushed areas were more susceptible to dolomitization because of the porosity. The stylolite became zone of fluid migration to the fine-grained zones to aid dolomitization. This is because stylolite acts as a "fracture" framework controlling fluid migration, dolomitization and hydrocarbon entrapment [50]. As occurred in the Bromide Formation, south-central Oklahoma [36], by acting as Mg^{2+} and K^{+}

ion sump, the illite and glauconite present in the shale interbeds adsorb Mg^{2+} into the carbonates to facilitate dolomite formation. Occasional dolomite rhombs occur along pressure dissolution seams. The occurrence of dolomite in such circumstances has been related to interstitial porosity and subsurface fluid. Often dolomite occurs closer to stylolite planes than in the compact areas. This could be due to lower solubility of dolomite than calcite and/or Mg^{2+} supplied by water passing along stylolite reams [26]. The dolomite rhomb is not cross-cut by stylolite suggesting that void-filling dolomite post-dates pressure dissolution [56].

4.4. Geochemistry

Geochemically, the percentages of major oxides of the Ozuabam limestone are described as follows: CaO which ranges between 31.69% and 53.56% constitutes the major oxide in the limestone. The MgO is between 0.40% and 10.62%. In accordance with Pettijohn's [57] classification, the limestone includes high calcium limestone 1.1% MgO), magnesian limestone (1.1-2.1% MgO) and dolomitic limestone (2.1-10.82% MgO).

The relationship between CaO and MgO is given on Figure 8, thus, only one sample with 95.58% total carbonate qualifies as pure limestone. The CaO is 32%-54% while MgO is between 0.4% and 10.6% and are inversely related. According to Bathurst [30] the inverse relationship is due to the inhibiting effect of Mg^{2+} on Ca^{2+}.

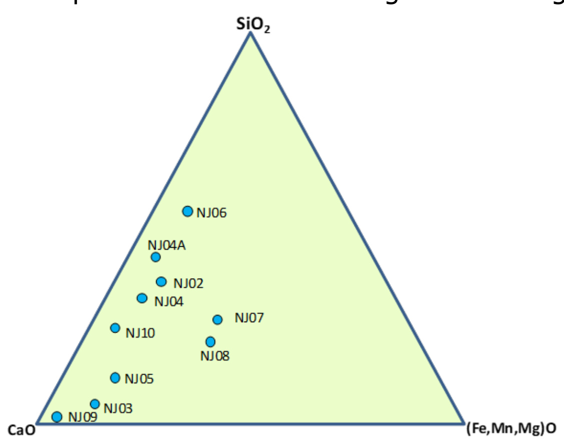


Figure 8. SiO_2, CaO and MgO - (Fe, Mn, Mg) O ternary plot.

Lippmann [58] accounted for the inhibiting effect of $Mg2^{+}$ on calcite growth as follows: the reluctance of Ca^{2+} to grow in the presence of Mg^{2+} was related to differences in standard free energies of formation (ΔF^{O}) of the hydrated Ca^{2+} and Mg^{2+}. The ΔF^{O} of hydrated Ca^{2+} is -428 Kcal./mole and that for Mg^{2+} -501Kcal./mole. As the hydrated Ca^{2+} and Mg^{2+} gather at the surface of a crystal Ca^{2+} is more easily released from the water dipole and joins with CO_3^{2-} to construct the least soluble lattice which is calcite. If the activity of Mg^{2+} in the solution is high enough the lattice so built is magnesian-calcite because the Mg^{2+} hydrate is adsorbed on the surface of the nucleus. The growth of lattice nucleus is prevented by the obstructive adsorption of hydrated Mg^{2+}.

Other oxides are Fe_2O_3 (0.80-1.60%), Al_2O_3 (0-13.58%), SiO2 (1.81-34.36%). Ozuabam limestone shows significant SiO_2 and Al_2O_3 content indicative of non-carbonate detritus in the deposit (Figure 9) [38]. Consequently, there is an inverse relationship between carbonate and silica. This strong inverse relationship occurs because SiO_2 dilutes other elements; therefore, as SiO_2 increases, all other elements decrease [59]. SiO_2, CaO and MgO - (Fe,Mn, Mg) O - ternary plot also shows such an inverse relationship between CaO and SiO_2 (Figure 10). Total Carbonate diminution in the presence of silica appears to have resulted from the introduction of silica mineralizing fluid into the carbonates [60-61]. The shale beds with a high percentage of silica (> 66%); alternating with the carbonate provide a plausible source of adsorbed silica fluid.

Limestone in relation with TiO_2 and P_2O_5: The limestone is low both in P_2O_5 and TiO_2. The concentration of TiO_2 ranged from traces (TR) -0.2 with an average of 0.05 while P_2O_5occured only in traces (TR). Davou and Ashano [62] accounted for such low values by the marked difference in their ionic potentials (IP). Precipitation of Ca (IP: 2.0) and Mg (IP: 3.0) on the one hand, and Ti (IP: 5.9) and Mn (IP:6.7) on the other in a sedimentary milieu is a probability [63]. Consequently, the elements with similar IP precipitated together during sedimentation. Therefore, the respective depletion of one of these elements from the system will be accompanied by the depletion of others. Hence, Mn, Ti and P will not be expected in Ca and Mg-rich carbonates. Ti, Mn and P will not co-precipitate with Ca and Mg because of differences in their ionic potentials [63].

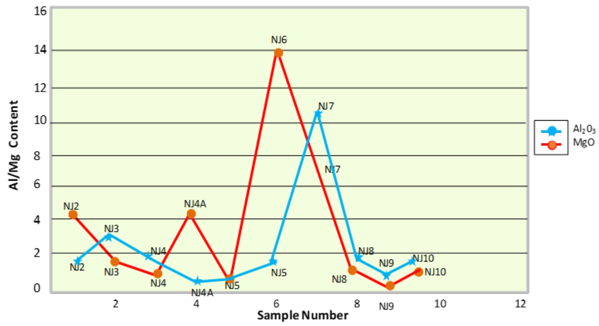


Figure 9. Aluminum-magnesium relationship in the study area.

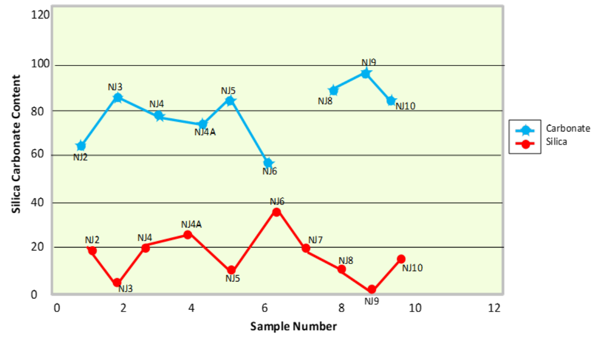


Figure 10. Carbonate-silica relationship in the study area

Limestone in relation with *Na_2O and K_2O*: The Na_2O and K_2O concentrations in Ozuabam limestone were in the ranges of 0.09-0.1 and 0.01-0.24 respectively, suggestive of shallow "saline" depositional environment for the limestone [62,64]. The presence of stenohaline organisms, molluscs, echinoids and some foraminifera on the one hand and glauconite on the other confirms shallow marine environment of deposition for the limestone [5,34,65-67].

5. Conclusions

The Ozuabam limestone is of the Paleocene Imo Formation in the Afikpo Basin, southeastern Nigeria. The limestone is a 22-m thick alternation of limestone (> 90% $CaCO_3$), marly limestone (65-90% $CaCO_3$) and marl (35-65% $CaCO_3$) on the one hand and glauconitic-illitic shale on the other. The limestone facies are characterized by bioclastic packstone- grainstone, packstone and bio-lithic wackestone of carbonate facies 2 and 7, 9 and 11 respectively. Deposition occurred as rhythmic alternations of organochemical (carbonate) and fine argillaceous materials in an oscillatory regime. The environment, probably a lagoon, was restricted with pauperized biota.

Early diagenetic processes are demonstrable in glauconitization, micritization and compression. Micritic envelopes or micritic rinds occur mainly on the bioclasts. More advanced diagenesis suggests an overburden threshold pressure of between 600 and 900m and consequent non- tectonic stylolitization. The latter was essentially irregular anastomosing and vertical stylolite with non – descript brownish insoluble seams. Cementation included neomorphism of micritic areas and pseudospiritization of shells; coarse hypidiotopic, xenotopic or poikilotopicpore-filling or sparry calcite cement of meteoric-phreatic environment; and thin mucilage or isopachous fringe calcite with panitopic, equigranular texture of vadose origin as the first-generation littoral cement associating with Ozuabam limestone.

Dolomitization is associated with wavy stylolite arising from overburden pressure. The crushed areas were more susceptible to dolomitization because of porosity. The stylolite acted as a" fracture" framework which controlled fluid migration and dolomitization. By acting as Mg^{2+} and K^+ ion sump, the illite and glauconite present in the interbedding shale adsorbed Mg^{2+} into the carbonates to facilitate dolomite formation.

Geochemically, the most abundant oxide is CaO followed by MgO. The Ozuobam limestone includes high calcium limestone (1.1% MgO); magnesian limestone (1.1-2.1% MgO); and dolomitic limestone (2.1-10.8% MgO). MgO is inversely related to CaO due to the inhibiting effect of Mg^{2+} on Ca^{2+}. Silica (SiO_2) and Al_2O_3 occur significantly because of the introduction of non-carbonate detritus into the deposit. There is carbonate diminution in the presence of silica because of the introduction of silica mineralizing fluid from the alternating glauconitic/Illitic shale with the limestone.

The ionic potentials(IP) of Ti^{4+}(5.9), Mn^{4+}(6.7), Si^{4+}(9.7) and P^{5+} (14.0) on the one hand and Ca^{2+}(2.0) and Mg^{2+}(3.0) on the other, are markedly different; therefore, CaO and MgO-rich limestone will be low in TiO_2 and P_2O_5. The presence of Na_2O and K_2O confers marine condition on the environment of deposition.

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