

Sequence stratigraphy based on microfacies analysis: Mfamosing Limestone, Calabar Flank, Nigeria

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Abstract

Field observations and petrographic analysis allow a sequence-stratigraphic interpretation of the intensely karstified Albian Mfamosing Limestone Formation in the Calabar Flank of the south-eastern Niger Delta. Main criteria for this interpretation are the presence of siliciclastic intercalations, of prominent hardgrounds, of characteristic microfacies including stromatolites and of phreatic and vadose diagenetic patterns. These criteria enable the recognition, from bottom to top in the type section of the Mfamosing Limestone, of a late phase in the formation of a highstand systems tract and of a flooding surface followed by a lowstand systems tract in which erosional features have been developed locally. The succession is topped by a transgressive systems tract. Some of these units and key sequence-stratigraphic boundaries have been traced into other outcrops in the area. In their identification within the heavily karstified outcrops, petrography overprints and vertical sequence patterns play a significant role. A sedimentation model explains the areal differences in development. Siliciclastic shedding influenced the carbonate system. Time-equivalent carbonate bodies occur on either side of the opening South Atlantic Ocean.

Introduction

The Calabar Flank is a sedimentary basin extending from the southern margins of the igneous Oban Massif to the hinge line of the Niger Delta (Figure 1). Here sudden sediment thickening demarcates the Niger Delta Basin that formed as the latest of a series of basins in the Benue Trough, diagonally crossing Nigeria from the southwest to the northeast. Northwest-southeast trending basement structures underlie the Calabar Flank and define the Ituk High and the Iking Trough (Figures 1, 2), thus relating the Calabar Flank to the South Atlantic Cretaceous marginal basins with similar horst-and-graben structures.

The stratigraphic succession in the Calabar Flank is mostly of Cretaceous age, comprising a basal Neocomian-Aptian syn-rift fluvial sandstone, the Awi Formation, and the marine post-rift Odukpani Group of Albian and Late Cretaceous age. The Odukpani Group (Petters et al. 1995) comprises the middle Albian

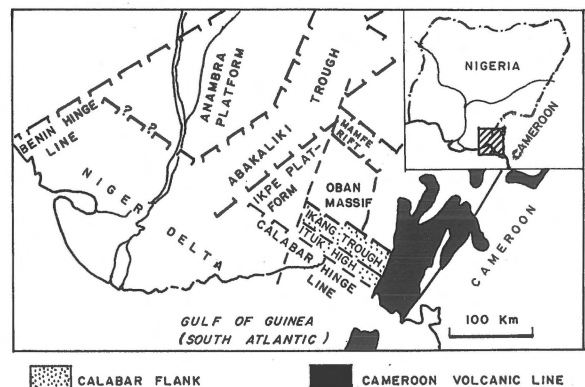


Figure 1. Tectonic setting of the Calabar Flank.

Mfamosing Limestone (Akpan 1992), the late Albian Ekenkpan Shale and the Coniacian New Netim Marl. It is unconformably covered by the Nkporo Shale. Tertiary marine shales and regressive sandstones overlie the Cretaceous succession. The total sediment thick-

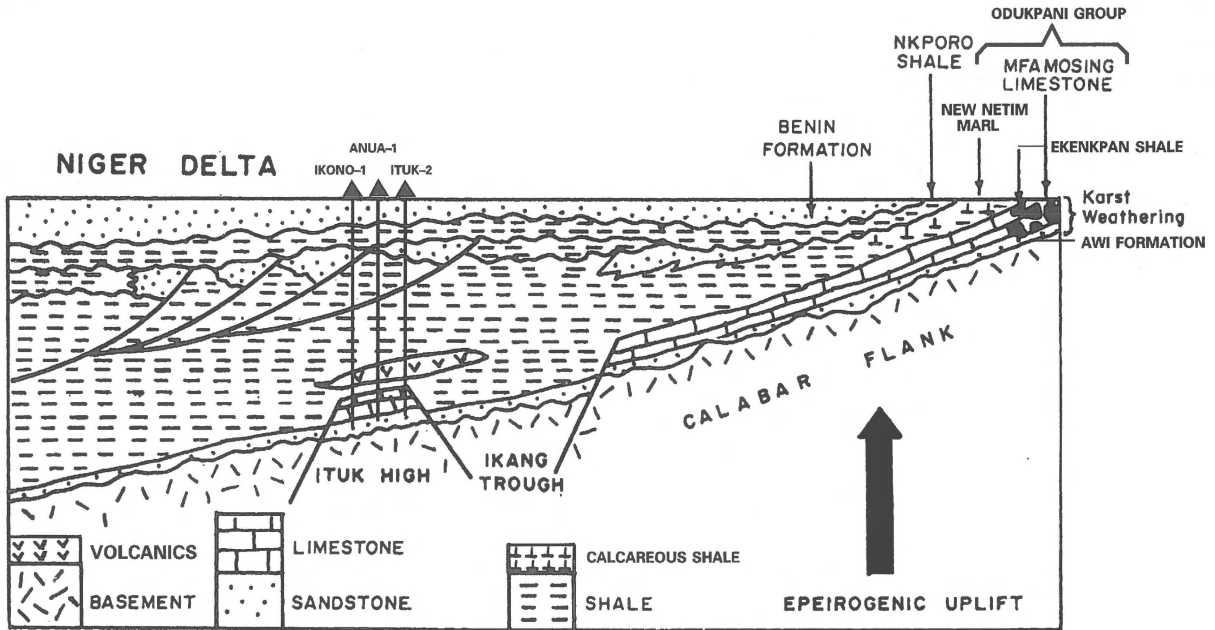


Figure 2. Schematic section across the Calabar Flank. Section shown is approximately 30 km from SW to NE. Total sediment thickness on the left is some 5000 m.

ness is over 3500 m, with a feathered edge of outcropping formations north of Calabar along the margin of the Oban basement (Figure 3).

After burial the Mfamosing Limestone Formation was exhumed during a period of epeirogenic uplift (Figure 2) associated with Neogene tectonics along the Cameroon Volcanic Line (Figure 1); subsequently the limestones were subjected to karst weathering. The tectonism produced faulting and jointing in the limestone, thereby enhancing karstification. The best outcrop locations are the Mfamosing Quarry; a locality near Etankpini village with extensive karst developments; a roadcut on the bank of the Cross River across Ikot Okpora; and Agoi Ibami on the northern border of the Oban Massif. These localities are described in this paper.

Our field study of the Mfamosing Limestone was supported by a petrographic study in the laboratory. The aim was to establish sequence-stratigraphic key boundaries and intervals in order to arrive at a useful correlation between the various outcrops and to verify and update our earlier derived sedimentation model (Reijers & Petters 1987).

Sequence stratigraphy through carbonate microfacies

Since our previous paper (Reijers & Petters 1987), sequence stratigraphy has emerged and its applications are evolving. The principles of this method will be applied to the studied outcrops of the strongly karstified Mfamosing Limestone.

Sequence stratigraphy can usefully be applied to carbonates if account is taken of their specific characteristics, especially the petrographic and diagenetic ones (James & Kendall 1992; Tucker 1993). The stacking sequence of carbonate microfacies sensitively reflects the subtle sea-level movements, and even combinations of such movements of various order. As carbonate (micro)facies follow Walther's law of facies succession and laterally grade into each other, a sudden shift basinwards (proximal over distal facies) indicates a sequence boundary, and a sudden shift landwards (distal over proximal facies) suggests a flooding surface. Generally, the latter surface is characterised by hardgrounds, borings and phreatic cements, whereas the former surface is subject to sub-aerial exposure with leaching, chalkification and vadose cementation. These surfaces define the highstand lowstand and trans-

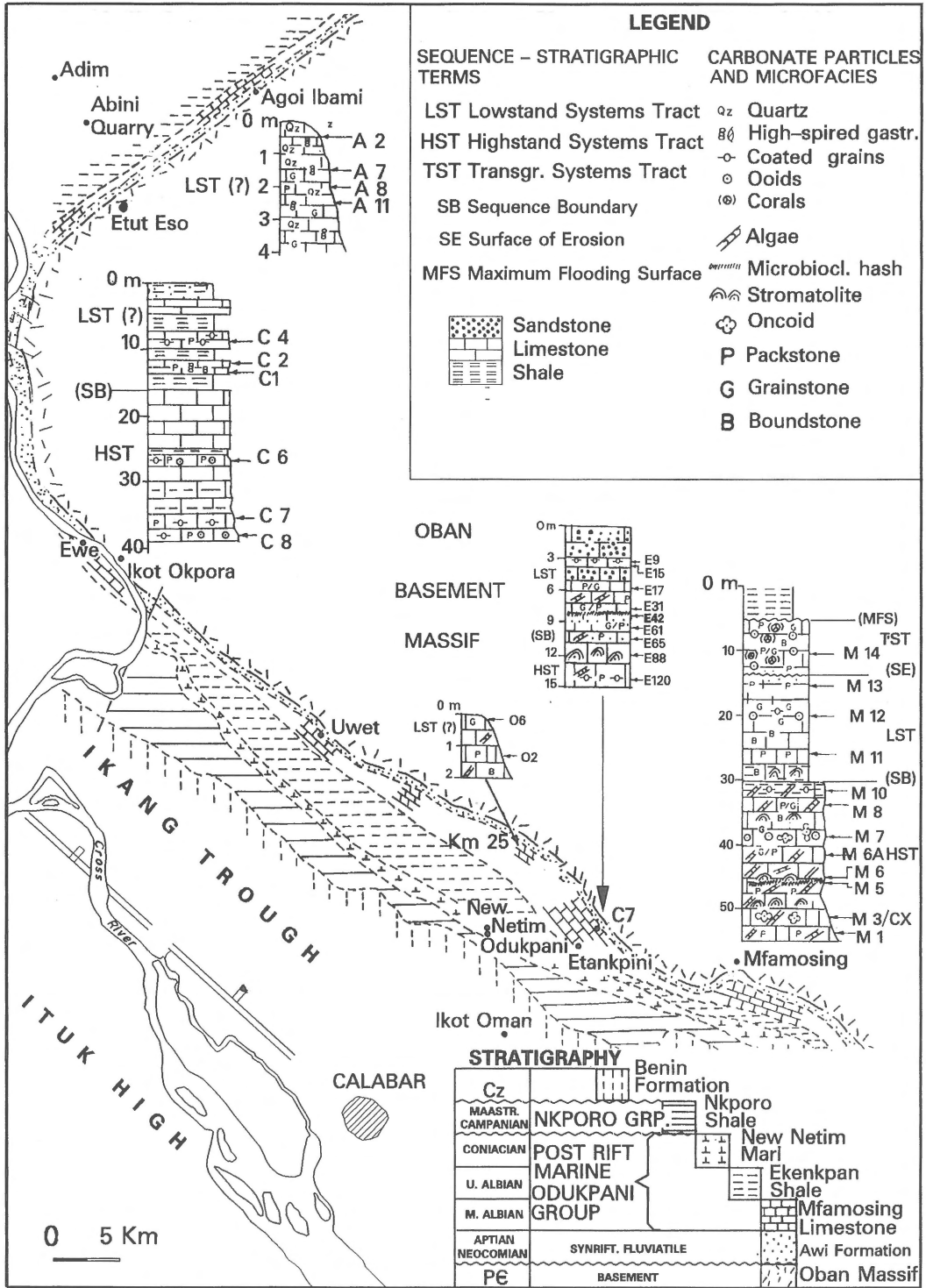


Figure 3. Outline geological map of the Calabar Flank with lithologs and sequence-stratigraphic position of the Mfamosing Limestone Formation.

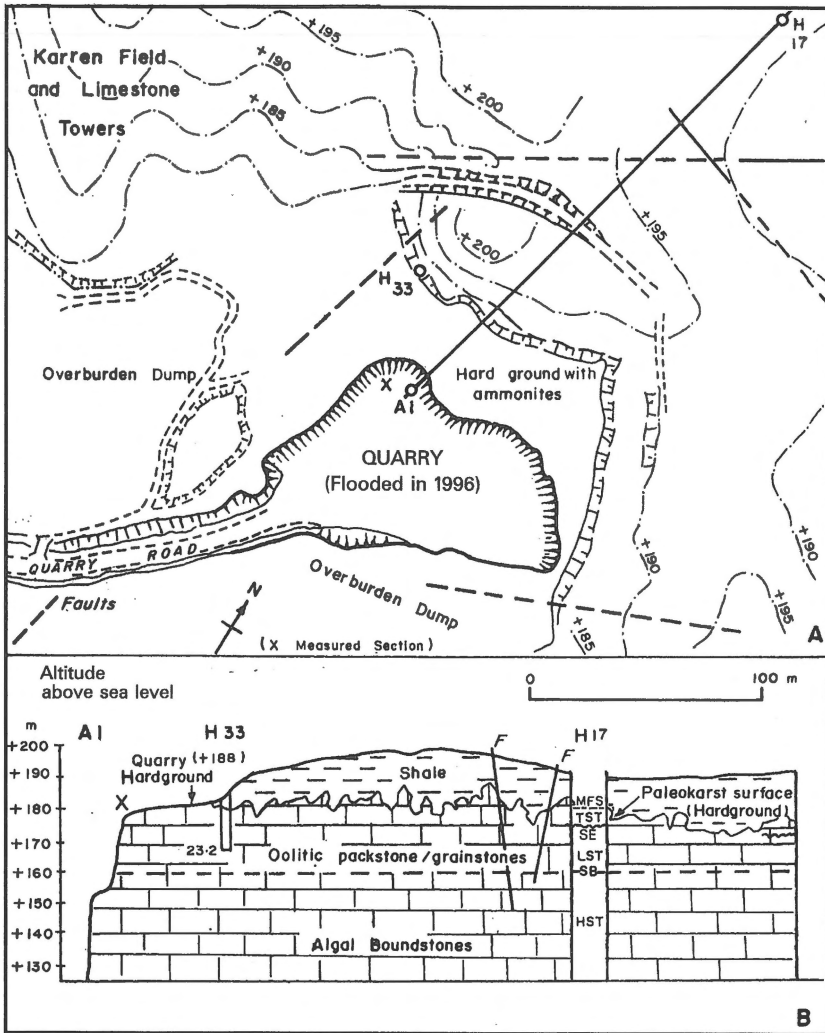


Figure 4. Mfamosing Quarry. A) Outline geological map, B) geological section. X: measured section shown in Figure 3. A1, H17 and H33 are boreholes. HST, etc. abbreviations and lithology legend as in Figure 3.

gressive systems tracts that together make up a depositional sequence.

Systems tracts are genetically related strata laterally linking contemporaneous depositional systems (Brown & Fisher 1977). They are defined by bounding surfaces, frequently of a discontinuous nature such as unconformities, onlap or downlap surfaces and condensed horizons or hardgrounds. A depositional sequence is a relatively conformable succession of genetically related strata, bounded at its top and base by sequence boundaries which are unconformities or their correlative equivalents (Mitchum 1977). Recognising depositional sequences or their component systems tracts

aided in arriving at a useful correlation template for the Mfamosing Limestone.

Petrographic analysis of the Mfamosing Limestone involved study of thin sections and of scanning electron microscope (SEM) images. To fine-tune the interpretation of the depositional environment, emphasis was placed on recognising fossil red and green algae. To recognise the bounding surfaces between systems tracts and between depositional sequences, attention was focused on (early) diagenetic features.

The four lithofacies (microfacies 1–4) earlier recognised macroscopically (Reijers & Petters 1987) were

confirmed. They occur vertically above each other but also next to each other. They are:

- 1) Packstones and grainstones with bioclasts, pellets and high-spined gastropods,
- 2) Lime mudstones, frequently partly recrystallised into pseudosparite,
- 3) Packstones with abundant coralline algae, occasionally stromatolitic,
- 4) Mixed siliciclastics and carbonates with silt and fine sand.

These microfacies can be recognised in the sections shown on Figure 3. Together these sections offer a comprehensive picture of the areal variations in microfacies distribution in the Mfamosing Limestone.

The Mfamosing Quarry

General

The abandoned Mfamosing Quarry type section has yielded fresh samples from the thickest exposed section of the Mfamosing Limestone (Figures 3, 4A, B). Now, in 1996, flooding has made the quarry poorly accessible. A number of characteristic boundaries are well exposed in the quarry profile.

Various workers (Fayose 1978; Nair et al. 1981; Reijers & Petters 1987; Oti 1990a) broadly subdivided the quarry profile into a lower algal boundstone interspersed with packstones and grainstones, and an upper, slightly sandy grainstone and packstone (Figures 3, 4B). This generalised subdivision is now further refined, based on the recognition of systems tracts in the exposure.

Petrography

The lower part of the section (samples M1–3; Figure 3) consists of packstones and occasional stromatolites with abundant coralline algae (microfacies 3). Oysters, pelecypod fragments and tiny bioclasts are preferentially dissolved and have fair microporosity (Plates 7:1, 3, 4). By contrast, oncoidal packstones with pisoids and coralline algal debris have reduced porosity. Large rhodoids with cores of thick thalli of red algae are encrusted by discontinuous laminae trapping bioclastic grains (Plates 1:3, 4). Algal, fungal and pelecypod borings are filled in. Boring pelecypods include thin-shelled smooth, and thick-shelled ribbed varieties.

The next part of the section (samples M5–10) contains fine microbioclastic packstones (Plate 2:1) with skeletal and echinoid fragments and occasional rhodoids of *Archaeolithothamnium*. Stromatolitic (rhodolithic) boundstones (Plate 3:4) with *Bacinella*, grade into packstones with fragments of algae, gastropods, echinoids and benthic foraminifera (e.g. *Marginulina*; Plate 2:2). Samples M7 and 10 are grainstones with red algae, skeletal fragments, pellets, ooids and coated grains (Plate 2:3). Amongst the algae are *Cayeuxia* and *Pianella* (*Salpingoporella*) (Plate 2:4).

Preferential chertification of oyster fragments may indicate temporary subaerial exposure under mildly lowered pH-conditions with weak silica solutions as discussed by Fairbridge (1967). Extensive micritisation and irregular drusy and blocky cements are common. Leaching and chalkification are common towards the top. Overgrowth cement and microstylolites with horsetails (Plate 2:1) suggest passage from a shallow to a deep-burial diagenetic environment. Stylolite seams across shell fragments (Plate 2:2) separate blocky cement, occluding dissolution pores, from unaltered algal fragments, and demonstrate preferential and restricted formation-water movements.

Samples M11 to 14 reflect the next packstone and grainstone microfacies with ooids, coated grains, pellets and fragments of echinoids, gastropods, ostracods, foraminifera, bryozoa and coralline algae. An intraformational hardground associated with minor siliciclastics is present between samples M13 and 14. Below this hardground the carbonates are leached. At the very top of the carbonate section another hardground occurs with a karst relief, surpassing in places 10 m (Figure 4B). It is overlain by ammonite-bearing shales.

Depositional environment

The microfacies succession indicates a shallow-marine nearshore carbonate depositional system that can be specified as follows.

The lower part of the section (M1–10) reflects stromatolitic tidal flats grading into a moderate to low-energy, shallow-marine, protected lagoon (Figure 5A) with a modest rate of addition of new accumulation space. Antecedent depositional topographic features are smoothed. The upper part of the section (M11 to 14) reflects a moderate to high-energy shallow-marine environment with bars, shoals and red-algal patch reefs concentrated in a protecting lagoonal rim. Biodegradation in the lagoon is common. Maximum interfingering of various microfacies occurs, and siliciclastic influx

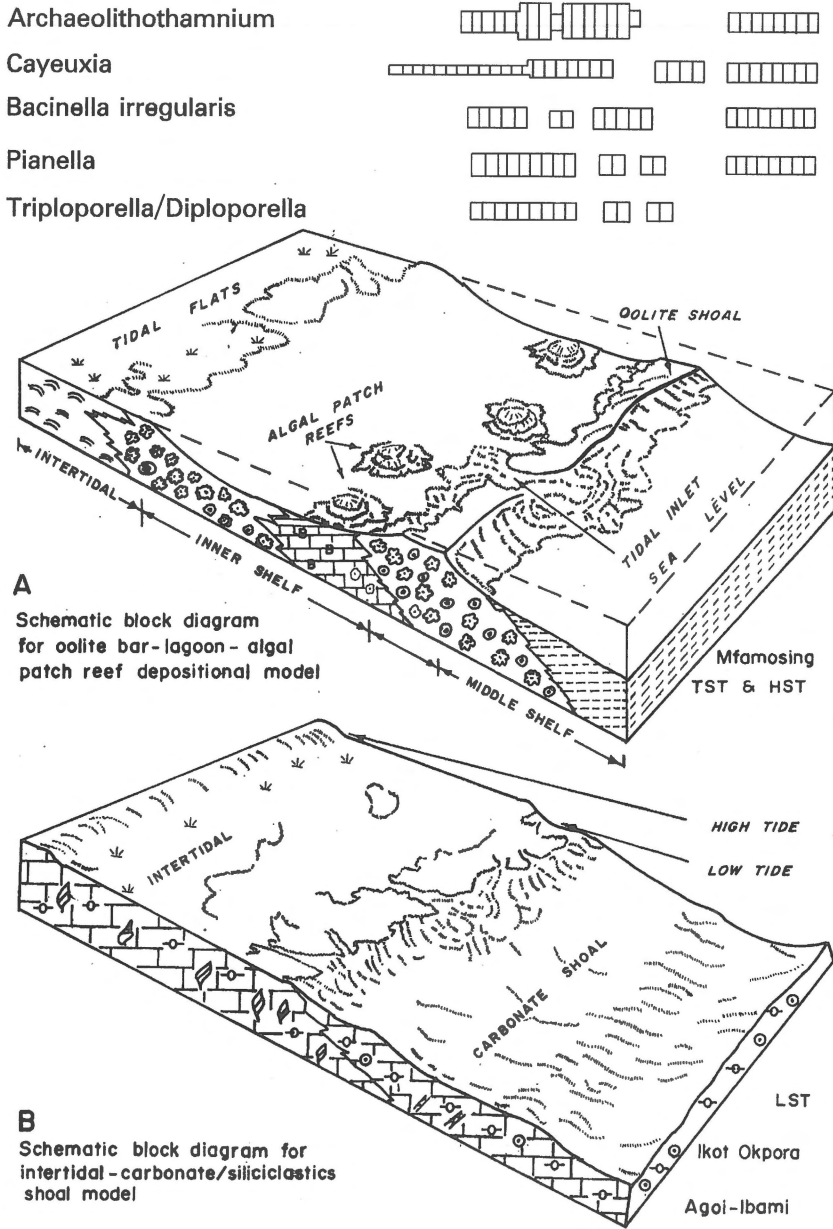


Figure 5. Facies models for the Mfamosing Limestone. A) Highstand and transgressive systems tracts. B) Lowstand systems tract. Algal zonation refers to Figure 5A. For lithology legend see Figure 3.

leads to carbonate poisoning and occasional starvation. This influx also marks the lowest eustatic sea-level stand. Occasional sub-aerial exposures mark the carbonate body.

Lagoonal conditions return when the sea level rises, as reflected by consolidation of the configuration of the pre-existent carbonate bodies that again start to build

up and become occasionally exposed, which leads to development of hardgrounds. Above such hardgrounds higher energy conditions reflect a transgressive tendency and this has given rise to renewed aggradation of high-energy rim sediments around a lagoon.

Figure 5A pictures a sedimentation model that shows retrogradation of microfacies belts in response

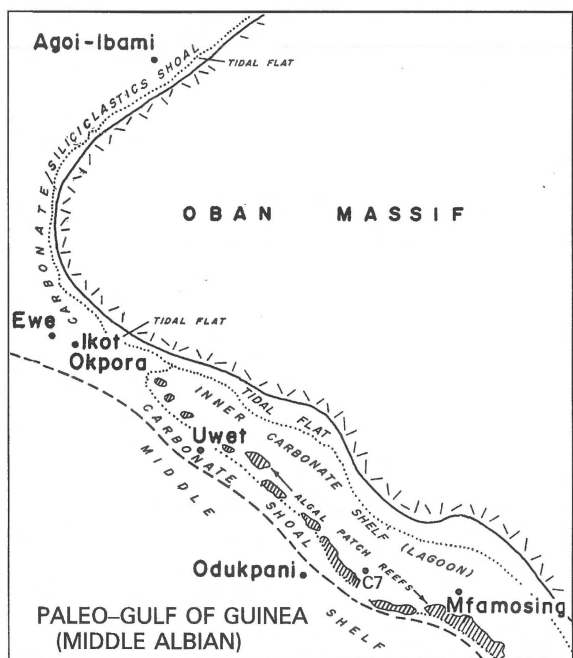


Figure 6. Paleogeographic map showing depositional patterns of facies in the Mfamosing Limestone. Compare with Figure 3 for scale.

to initial eustatic sea-level oscillation. Laterally the microfacies belts grade from oolitic shoals and algal patch reefs basinwards, to lagoonal and tidal-flat facies landwards. The phase of progradation following sea level rise is reflected in the transgressive phase which is not pictured in Figure 5A.

The algal biofacies zonation (Figure 5A) reflects the environmental preferences of the calcareous algae (Ginsburg et al. 1972) as seen in the Mfamosing Limestone, and corroborates the microfacies environmental evidence for the postulated tidal flats, lagoon and algal patch reefs. The mildly oscillating regression leading to the hardground between M5 and 6 was followed by steady transgression and associated deepening during which the highly fossiliferous oolitic grainstones higher up in the Mfamosing Limestone formed, and by deposition of the clayey siliciclastics between M10 and 11. Another hardground, between M13 and 14, was subsequently formed on top of the paleokarst, and covered by ammonite-bearing shales.

Sequence stratigraphy

In the lower algal boundstone interval (M1–10; Figures 4B, 5B) the environmental conditions trigger predominantly sideways movement of (stromatolitic) carbonates. Overall the rate of addition of new accumulation space is low. These conditions are met within a highstand systems tract (HST). At the moment that the eustatic sea-level movements turn from (late) highstand towards lowstand, a sequence boundary is formed, that is marked by clayey siliciclastics derived from an eroding hinterland.

The upper fossiliferous and oolitic packstones and grainstones (M11–13) reflect deposition under moderate to high hydraulic energy conditions. The carbonate system was areally shrunk to narrow shelves and rims that developed under less than optimum conditions, possibly locally and temporarily subaerially exposed. The eustatic curve was at its lowest position and the sediments are part of a lowstand systems tract (LST).

An intraformational hardground marks a transgressive surface of erosion and separates the LST from the topmost unit (M14). Chalkified limestones are present underneath this surface, suggesting subaerial exposure. From here upwards the sediments form part of a transgressive systems tract (TST) which ends with a maximum flooding surface, characterised by a karstic surface recognised as another hardground by Oti (1990a), which is covered by shales with ammonites (Figure 4).

Etankpini

General

Near Etankpini the Mfamosing Limestone is heavily karstified. At locality C7 (Figure 3) a core was recovered of the topmost 15 m, which provides ideal material for petrographic analysis, in addition to the field samples. Samples from that core are described from top to bottom, but the description does not cover the remainder of the section. Therefore, a datum has to be identified, to establish correlation with the other sections. The level (11 m depth) at which siliciclastics were first introduced, has been taken as that datum line.

Petrography

From 0 to 3 m a sandstone occurs with 50 to 70% moderately sorted and rounded quartz grains, subordinate

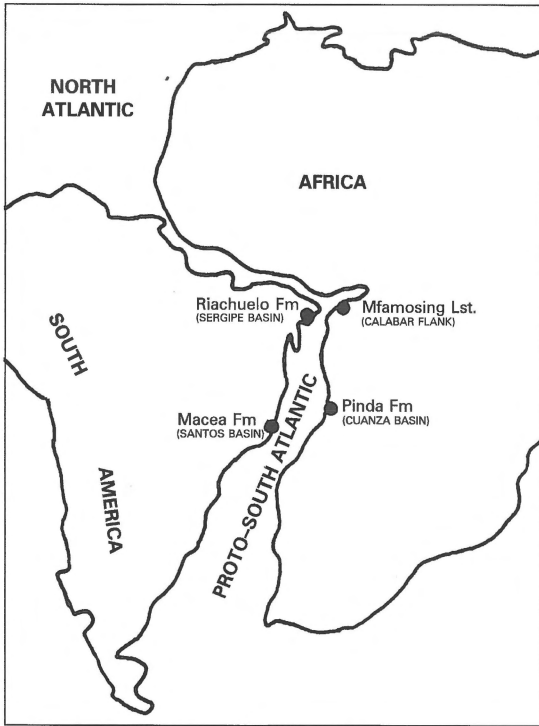


Figure 7. South Atlantic Albian carbonate platforms mentioned in the text.

feldspar and mica and usually a groundmass of micrite. The quartz content decreases downwards.

From 3 to 4 m a grainstone (sample E9) contains *Archaeolithothamnium* and *Parachaetetes/Pycnoporidium* fragments, coated grains and pellets (Plate 4:1). Limited intermixed siliciclastic sand is present. Interskeletal and intraparticle pores are filled with blocky cement and some dolomite. There is evidence of irregular drusy cement (dripstone cement).

From 4 to 6 m large amounts of siliciclastics are intermixed with grainstones and packstones.

From 6 to 11 m an interval follows, mainly composed of the packstone and grainstone microfacies, throughout intermixed with upward diminishing amounts of siliciclastics. Grainstone beds (E65) contain the algae *Pianella* (Plate 4:2), high-spined gastropods, ostracods, foraminifers, pelecypod and echinoid fragments, pellets and grapestones. They alternate with packstone beds with skeletal particles that are largely dissolved by leaching and of which the intraparticle pores are occluded by cementation at the inside, while they are strongly micritised at the outside. Plates 4:3 and 4 show such grainstones and packstones

with 5 to 10% angular, sorted quartz grains. Occasional wackestones, and pseudo-grainstones occur (Plate 5:1) with the red algae *Parachaetetes/Pycnoporidium* (Plate 5:2). Plate 5:3 shows sample E42, 8m below the top of the core, with a bed with microbioclastic hash, representing a break in the uniform grainstone and packstone microfacies persisting down to 11 m.

From 11 to 13 m siliciclastics are absent and a stromatolitic boundstone occurs with intensively bored rhodoids with diameters of some 2 cm (Plates 1:1, 2). The organic matter in the rhodoid is heavily oxidised, suggesting some temporary subaerial exposure. The oxidised iron minerals yield a faint reddish-pink colour. In places the boundstone shows skeletal particles over which the algae *Bacinellus* cf. *irregularis*, with well-developed conceptacles, forms encrustations (Plate 3:2).

From 13 to 15 m (base of the core) a pelletoidal coralline algal packstone (Plate 5:4) occurs with coated and composite grains, and *Archaeolithothamnium* and *Parachaetetes/Pycnoporidium*. There is extensive micritisation, coating, leaching and production of localised neomorphic microspar. The carbonates are pure, without admixed siliciclastics.

Depositional environment

Below the lowest occurrence of siliciclastics (the datum) algal build-ups are suggested by the abundance of stalky coralline algae and occasional stromatolites. Parts of the lagoon bottom and of the algal patch reefs were occasionally exposed to the influx of meteoric water. The lagoon bottom was covered with skeletal fragments (lime sands and silts) that result from disintegration of the thalli of Codiacea algae as *Penicillus* and *Halimeda*, and of other green algae (Milliman 1974). Skeletal fragments were first extensively micritised and subsequently converted into microbioclastic hash. This is due to biochemical corrosion by algal and fungal activity within the euphotic zone. Tidal currents rolled sand particles over the seabottom, and coated grains, pisoliths and ooids were formed, while red algae coat such particles and form rhodoids.

Above the datum line, all four groups of lithofacies alternate. This suggests a rather stable setting on which a fluctuating sea level exercised its influence. Mixed siliciclastics and carbonates (microfacies 4) re-occur a number of times, pointing to ongoing spilling of hinterland clastics into the narrow fringing carbonate shelf. Packstones and grainstones with various bioclasts (microfacies 1) and packstones with abundant

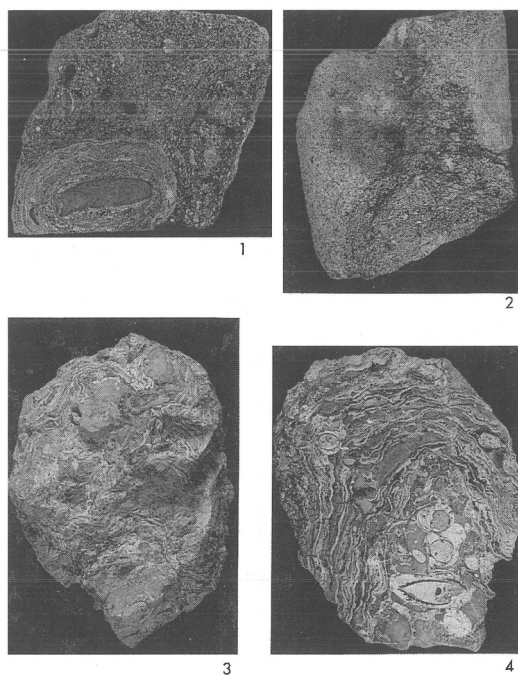


Plate 1. 1) Packstone/rudstone enclosing oncolite with fragments of *Archaeolithothamnium* (sample E88) from Etankpini corehole C7: $\times 2.5$ (polished, acid-etched obverse side of sample). A rhodoid (oncolite of red algae) some 2 cm across with as a nucleus a fragment of branching *Archaeolithothamnium* is surrounded with laminated layers trapping various grains. Oxidised iron minerals give a faint reddish-pinkish colour. The matrix of this packstone/rudstone contains red algal debris, bioclastic grains and ooids. 2) Reverse side of packstone/rudstone of Plate 1:1 shows the characteristic oncolite/rhodoid spherical weathering. 3) Reverse side of sample CX, collected close to sample M3 at base Mfamosing Quarry, with characteristically weathered oncolites, algae with thick thallus and marks of borings by pelecypods; $\times 1.5$. 4) Polished, acid-etched obverse side of sample of Plate 1:3, $\times 1.5$. This is one big rhodoid composed of thick algal thallus, which is encrusted by discontinuous laminae. The matrix is commonly chalky (Plate 7:1) with fine intraparticle porosity. Some bioclastic grains are recognisable. Algal, possibly fungal and bivalve borings are commonly filled in. At least two varieties of boring pelecypods are present: thin-shelled, smooth and thick-shelled, ribbed. The laminae commonly trap grains. Thalli of various algae are incorporated with the rhodoid (Plate 7:2). Microporosity predominates (Plates 7:3, 4) but in places it is (partly) occluded by tight streaks with blocky calcite cements (Plates 8:2, 4). Leached skeletal fragments that are usually subsequently cemented (Plates 8:1, 3) are tight spots.

coralline algae, occasionally stromatolitic (microfacies 3), constitute the bulk of the section.

The abundance of lime-mud in the groundmass (packstone), combined with a shallow-marine fauna, high-spired gastropods and coated grains indicating mild protection and occasional tidal energy, suggest that these facies formed in a protected, occasionally open, shallow-marine inner-shelf setting such as a lagoon with tidal inlets. The lagoon merged via fringing stromatolitic tidal flats (Petters 1981) with a siliciclastic hinterland, and was bounded basinwards by a series of irregular algal patch reefs (Figures 5A, 6). Overall the studied sequence is mainly transgressive. Therefore the stromatolitic tidal-flat deposits are overlain by the much thicker lagoonal packstones with patch-reef boundstones.

Sequence stratigraphy

The datum line at the first appearance of significant amounts of siliciclastics, marks the inflection point of the eustatic sea level curve, changing from a late highstand to a lowstand. Therefore, in line with the practice in the type section, the sequence boundary is placed just below this datum line and above the boundstone level with rhodoids.

The interval above the sequence boundary is characterised by varying amounts of siliciclastics. The lithology otherwise strongly resembles that of the LST in the type section. Carbonate sedimentation experienced less than optimum conditions, and regular poisoning through siliciclastic influxes.

The interval below the sequence boundary is characterised by the absence of siliciclastics and by luxuriant growth under favourable environmental conditions

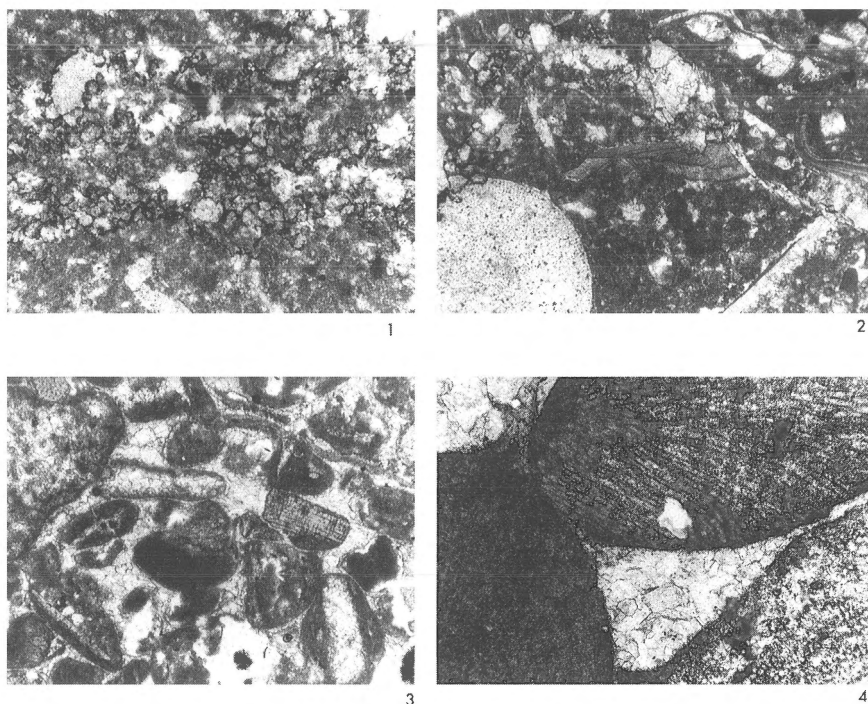


Plate 2. 1) Microbioclastic hash (packstone) containing overgrowth cement, microstylolites and horsetails suggesting deep burial following shallow burial. Sample M5, $\times 30$; Mfamosing Quarry. 2) Bioclastic packstone with echinoid fragment and benthic foraminifera (*Marginulina*) at upper right corner; micritisation and stylolites. Sample M6, $\times 60$; Mfamosing Quarry. 3) Bioclastic pelletal grainstone with micritised, partly leached and occasionally bored skeletal fragments, including fragments of *Parachaetetes/Pycnoporidium*, cemented (within inter- and intraparticle pores) with drusy and blocky cement. The diagenetic features suggest transition through surface-related, shallow and deep burial diagenetic environments. Sample M7, $\times 60$; Mfamosing Quarry. 4) Grainstone with micritised fragmented *Cayeuxia* (note radiating tubes without partitions) and *Pianella* (*Salpingoporella*) with blocky cement filling the interparticle porosity. Sample M10, $\times 60$; Mfamosing Quarry.

of stromatolitic algae in their reproductive cycle exemplified by well-developed conceptacles (Plate 3:2). Such algal stromatolites had ample possibilities to grow out sideways. They characterise the HST.

Calabar-Ikom road section at km 25

On a stream bank in a small valley, eroded through the strongly weathered limestones near kilometre post 25 on the Calabar-Ikom road, some 5 km N of the villages New Netim and Odukpani (Figure 3), an in situ boundstone is overlain by an algal packstone (Plate 3:3) with great abundances of the algae *Archaeolithothamnium*, *Triploporella/Diploporella*, *Pianella* and *Cayeuxia*. Also bioclastic grainstones occur with fragments of the same algae (Plate 3:1). Pellets, composite grains and skeletal fragments are common. Together these suggest a lagoonal setting. The isolated nature of the outcrop precludes inclusion in either the LST or the HST recognised in the other studied sections.

Cross River bank section across Ikot Okpora

General

About 40 m of fossiliferous Mfamosing Limestone is exposed on the north side of the roadcut, along the road from the ferry landing to Arochukwu on the bank of the Cross River opposite Ikot Okpora (Figure 3). Further upstream a section was studied by Oti (1990b), who divided it into a lower peloidal and extensively micritised limestone, a middle sandy part with shale intercalations and an upper limestone. The present study concentrated on the lower and middle parts.

Petrography

The lower 24 m of the section (Figure 3) are skeletal packstones and grainstones (microfacies 1). Sample C8 at the base shows skeletal fragments, ooids, coated grains and grapestones (Plate 6:1). The grainstones are extensively micritised and leached, and irregular drusy

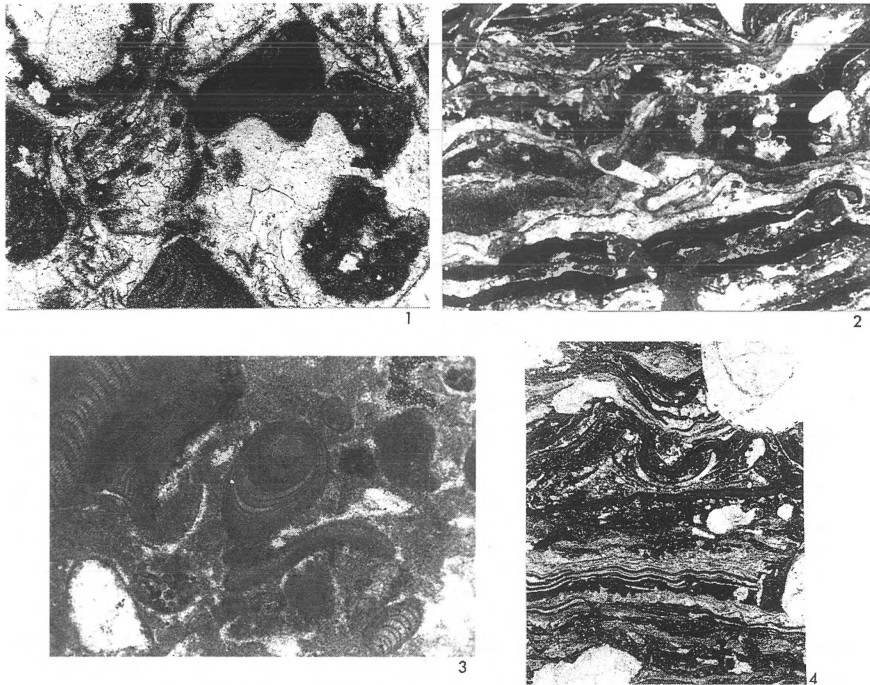


Plate 3. 1) Bioclastic grainstone containing the algae *Triplopora/Diplopora* and *Cayeuxia*; showing blocky cement. Sample O6, $\times 60$; km 25 on Calabar-Ikom road. 2) *Bacinella* red-algal boundstone showing *Bacinella cf. irregularis* with well-developed conceptacles at reproductive stage. Sample E88, $\times 15$; Etankpini, C7. 3) Red algal bioclastic packstone with *Archaeolithothamnium*, *Triplopora/Diplopora* and *Pianella*. Sample O2, $\times 60$; km 25 on Calabar-Ikom road. 4) *Bacinella* boundstone. Lower part of sample M6, $\times 15$; Mfamosing Quarry.

and blocky cement and chert developed. The packstones are largely a microbioclastic hash with pellets (sample C7; Plate 6:2). About 15 m from the base the packstone (C6) contains beds with coated grains and ooids, overlain by a 50-cm-thin shale.

The upper 16 m of the section is a limestone-and-shale unit. Packstones have abundant high-spined gastropods, many being micritised, and bryozoa, brachiopods and pellets. Dissolution of shell fragments, cement-filled pores, thin rims of cement around skeletal fragments, and geopetal structures and dripstones suggest vadose diagenesis.

Depositional environment

The lithology of the lower part of the section suggests that deposition took place in a lagoonal setting, merging landwards with a siliciclastics-shedding hinterland, and separated basinwards from the open sea by an interrupted barrier of algal patch reefs and ooid bars which formed a moderate to high-energy carbonate shoal (Figures 5B, 6).

The shaly rather than fine sandy nature of the siliciclastics admixed in the upper part of the section suggests a position more basinwards from the siliciclastic hinterland than was the case in the other described sections.

Sequence stratigraphy

In analogy with the other studied sections, the mixed carbonate-siliciclastic nature of the upper interval at Ikot Ikpora suggests that it belongs to the LST. The sequence boundary tops the thick limestone layer from which sample C6 has been taken. It is placed at the first thick siliciclastic bed. Lithologically and in terms of depositional environment, the part of the section below the sequence boundary resembles that in the other sections studied, which belong to the HST. The same interpretation is given to this interval in the present section.

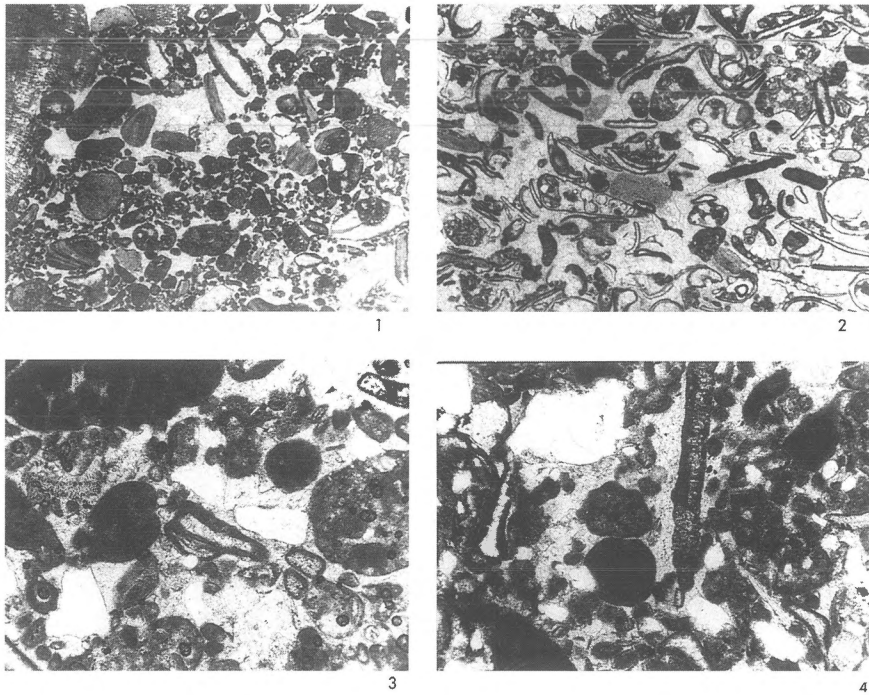


Plate 4. 1) Red-algal bioclastic grainstone with coated grains and *Archaeolithothamnium* and *Parachaetetes/Pycnoporidium*, showing leaching of skeletal fragments, dripstone cement, blocky cement and grain penetration. Sample E9, $\times 60$; Etankpini, C7. 2) Red-algal bioclastic grainstone with high-spired gastropods, micritised fragments, drusy and meniscus cement, and blocky cement. Sample E65, $\times 15$; Etankpini, C7. 3) Bioclastic grainstone/packstone with quartz, echinoid fragments and grapestones. Sample E16, $\times 60$; Etankpini, C7. 4) Sandy packstone with angular quartz, pellets, neomorphic spar patches and grain interpenetration. Sample E17, $\times 60$; Etankpini, C7.

Agoi Ibami section

General

Along the northern margin of the Oban Massif, the Mfamosing Limestone is well exposed at Agoi Ibami (Figure 3) in a 4-m-thick section which in many respects resembles the upper section of Ikot Okpora. Here, the Mfamosing 'Limestone' is more siliciclastic than along the southern perimeter of the Oban Massif.

Total carbonate content decreases from 88% in the basal part of the section to 61% in the upper part, with a corresponding increase in silica content from 12 to 39% respectively.

The carbonate part of the section is composed of the grainstone and packstone microfacies (1) with the grainstones displaying abundant skeletal fragments, mostly pelecypods, gastropods and brachiopods (sample A7; Plate 6:3). Shell fragments are micritised and leached, and irregular drusy and blocky cements formed. Plate 6:4 shows a quartz-rich packstone (sample A8) with micritised and leached skeletal frag-

ments and spotty chertification. In the upper part the packstone contains great quantities of high-spired gastropods.

Depositional environment and sequence stratigraphy

The high siliciclastic content suggests proximity to the siliciclastic hinterland area, whereas the abundance of high-spired gastropods indicates protected lagoonal conditions, possibly nearshore (Figure 6). This is in agreement with the interpretation of the other studied sections. The high content of siliciclastics suggests that the entire section belongs to the LST but it has not been possible to locate the sequence boundary in the outcrop.

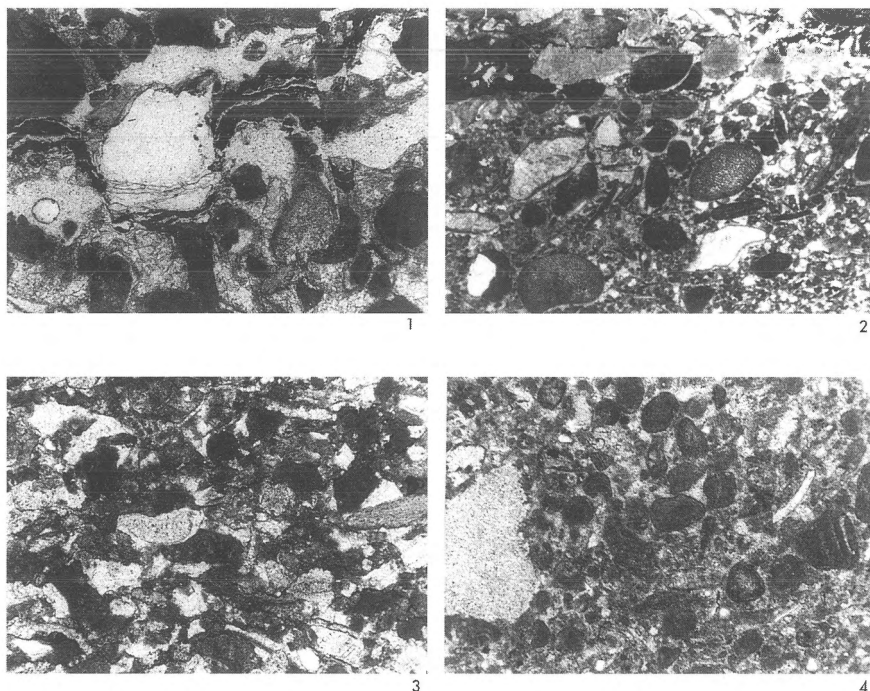


Plate 5. 1) Pelletal pseudo-grainstone with cement in intergranular pores, horsetail bundles and stylolites. Sample E15, $\times 60$; Etankpini C7. 2) Red algae, pelletal pseudo-grainstone/packstone with *Parachaetetes/Pycnoporidium* algae and echinoid fragments, minor quartz; occlusion of secondary pores by blocky cement; syntaxial overgrowth cements over echinoid fragments and stylolites. Sample E36, $\times 15$; Etankpini, C7. 3) Bioclastic packstone with pellets, echinoid fragments; syntaxial overgrowth and microstylolites. Sample E42, $\times 60$; Etankpini, C7. 4) Pelletal bioclastic red algal packstone with *Archaeolithothamnium* and *Parachaetetes/Pycnoporidium* algae, micritisation, leaching and localised neomorphic microspar. Sample E120, $\times 60$; Etankpini, C7.

Depositional model and sequence stratigraphy

General

The present study focuses on improved correlations in heavily karstified limestones. It results in an updated and expanded facies model (Figures 5A, B, 6) that captures most of the primary functions of such a model as enumerated by Walker (1992). It is regarded as a norm for purposes of comparison and as a framework or a guide for future observations. It is a predictor in new geological situations, and based on it the environments that gave rise to the facies in the model can be interpreted. To focus on the last function, it permits an explanation of the carbonate production mechanisms reflecting various stages of relative sea-level fluctuation.

The first question begging for an answer is how the various measured intervals can be correlated in the absence of a reliable biostratigraphic marker horizon. Sequence stratigraphy gives an answer. The boundaries that define sequences and systems tracts are identified

and permit setting up a correlation template. Admittedly, this method can only be applied with care, but it is potentially a way to establish genetically useful correlations.

The hardground surfaces in the Mfamosing Quarry are equated with a transgressive surface of erosion and with a maximum flooding surface respectively. The former surface is the upper boundary of the LST which has been identified within several studied sections around the Oban Massif; the latter surface occurs within the TST, which up till now has only been recognised in the type section, but which is commonly present in the subsurface (Reijers 1996 appendix B).

The highstand systems tract

The interval below the sequence boundary is interpreted as (part of) the HST. During a highstand the rate of addition of new depositional space is low and periods of deposition alternate with localised subaerial exposure during which diagenesis modifies the carbonates.

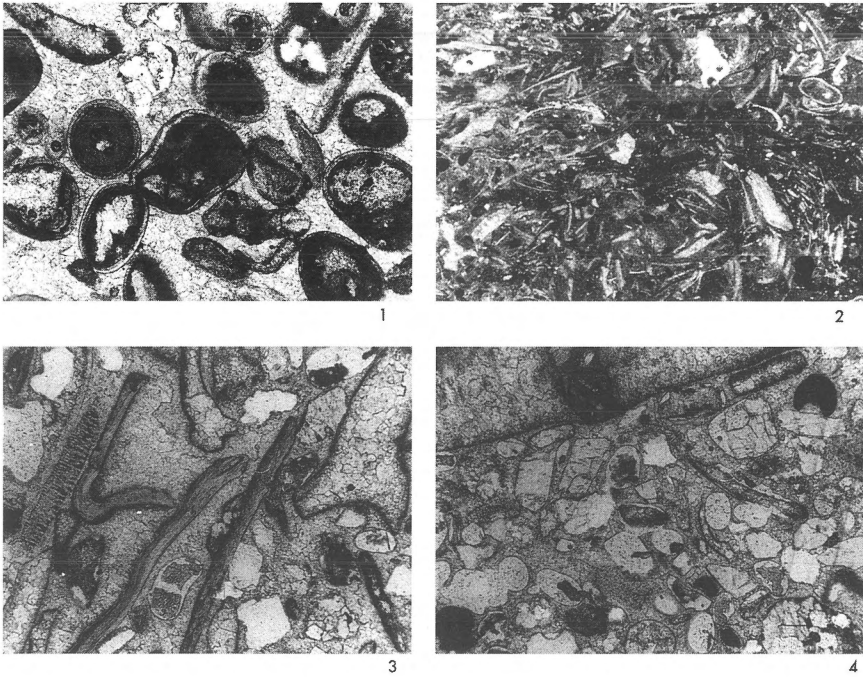


Plate 6. 1) Skeletal grainstone with coated grains and grapestones; micritisation; dog-tooth and blocky cement, and spotty chert occurrences. Sample C8, $\times 60$; Cross River bank section across Ikot Okpora. 2) Microbioclastic packstone with pellets and horsetails. Sample C7, $\times 15$; Cross River bank section across Ikot Okpora. 3) Bioclastic grainstone with quartz grains, brachiopod and pelecypod fragments; micritisation and irregular drusy and blocky cement, and chert occurrences. Sample A7; $\times 60$; Agoi Ibami. 4) Bioclastic packstone with quartz and spotty chert. Sample A8, $\times 60$; Agoi Ibami.

Carbonate production is locally confined, aggradationally filling in antecedent topography.

The carbonate platform reached its greatest areal extent during the sea-level highstand when the narrow but opening oxic ocean with its wind-driven coast-parallel circulation pattern brought maximum amounts of nutrients to nourish the benthic organisms on the platform. Distinct (micro)facies belts formed as a result of this, occupying predictable positions around the Oban Massif, in particular on the south side that faced the opening South Atlantic Ocean. Tidal-flat deposits form the landwards facies belt, and calcarenitic oolite-shoals the seawards one, with muddy lagoonal sediments and algal patch reefs in between. Sizeable amounts of calcarenites occur interbedded in lagoonal sediments, suggesting spilling-over of high-energy platform-rimming deposits, probably through tidal channels as a response to positive sea-level changes. The various units occur laterally from each other in the late HST but stack mainly aggradationally and progradationally on top of each other, depending on the amount of available accommodation space.

The lowstand systems tract

The base of the LST is the sequence boundary which is placed at the level where the first significant bed of siliciclastics enters the succession. The upper boundary occurs only in the type section, where it is an erosive surface over which transgression (of the TST) took place. The LST probably occurs everywhere around the Oban Massif. The influx of siliciclastics prevented algal build-ups, and the poorly sorted, frequently micritised or otherwise biodegraded shelly debris layers indicate environmental conditions unfavourable to prolific carbonate production, as can be expected in a shelf bordering a land area that was shedding siliciclastics during a relative fall in sea level. In contrast to the underlying HST a retrogradational stacking of facies units prevailed in the LST, reflecting diminishing accommodation space.

The transgressive systems tract

The TST has only been recognised in the type section. The transgression flooded an eroded lowstand

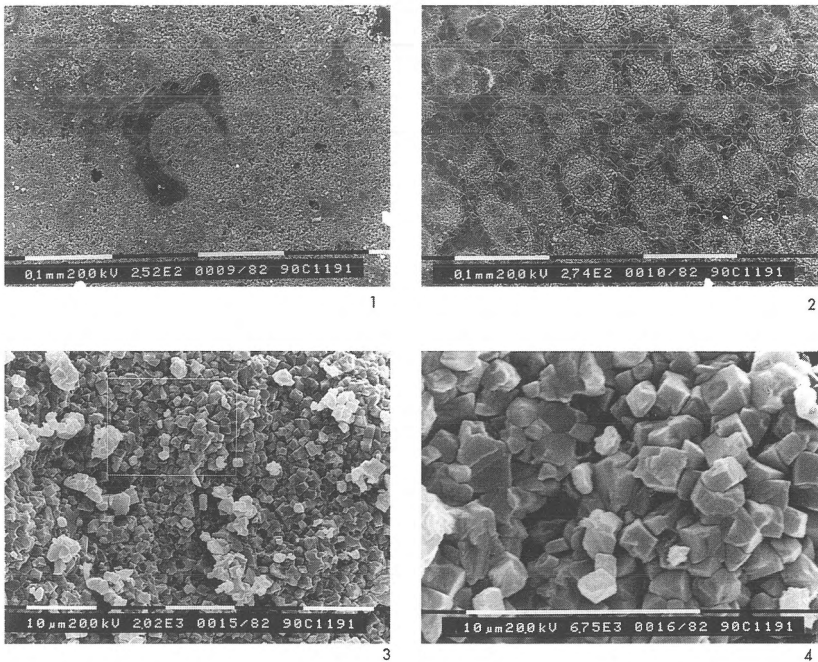


Plate 7. 1) Shell fragment in micritic matrix of acid-etched polished section through a big rhodoid. Sample CX, collected close to sample M3 at base Mfamosing Quarry. (See also Plates 1:3, 4). 2) Red algae thalli; acid-etched polished section. Sample CX. (See also Plates 1:3, 4). 3) Micrite matrix with microporosity. Aggraded micrite with planar crystal faces; fractured surface. Sample CX. 4) Detail of Plate 7:3. Micritic grains of 0.5–2 μm diameter; pores up to 2 μm diameter. Fractured surface. Sample CX.

surface marked by a hardground. Carbonate production required some starting-up time before coated grains and ooids were produced, but soon the relative rise of sea level was too great for carbonate production to keep pace with, and starvation followed, marked by another hardground and a submarine paleokarst on which a shale with ammonites was deposited. The overall stacking pattern is aggradational.

The depositional model

During deposition of the Mfamosing Limestone the study area was situated in a humid tropical belt facing the opening South Atlantic Ocean with a wind-driven sea-current directed into the Benue Trough, along the developing carbonate platform. The carbonates were deposited against a backdrop of third-order eustatic sea-level fluctuations resulting in deposition of highstand carbonates south of the Oban Massif and widespread deposition of lowstand carbonates around this massif. During deposition of the latter, a strong influx of siliciclastics took place. Only in the type section, situated closest to the opening ocean, did transgressive carbonates establish some foothold.

In an earlier study (Reijers & Petters 1987) the type section was compared with subsurface information from wells Ituk-2 and Ikpe-1, both on the Ituk High. A basin-margin carbonate platform on an overall gradually sloping substrate was postulated for the Mfamosing Limestone along the Oban Massif, and an offshore shoal or platform setting for the carbonates encountered on the Ituk High. Lack of subsurface information at that time prevented a conclusion on the continuity of the Oban-rimming carbonates into the Ituk High carbonates. A better understanding of the correlation possibilities based on sequence stratigraphy as outlined in the current paper, and additional subsurface information may lead to an answer to the question of the connection between the outcropping carbonates around the Oban Massif and those in the subsurface. This topic has been addressed in outline in appendix B of Reijers (1996), and will be further discussed in a follow-up paper.

The present study shows that south of the Oban Massif carbonate deposition was overall aggradational and took place following the model shown in Figure 5A. This model is somewhat more refined than the one published earlier. West of the Oban Massif, the outcrops

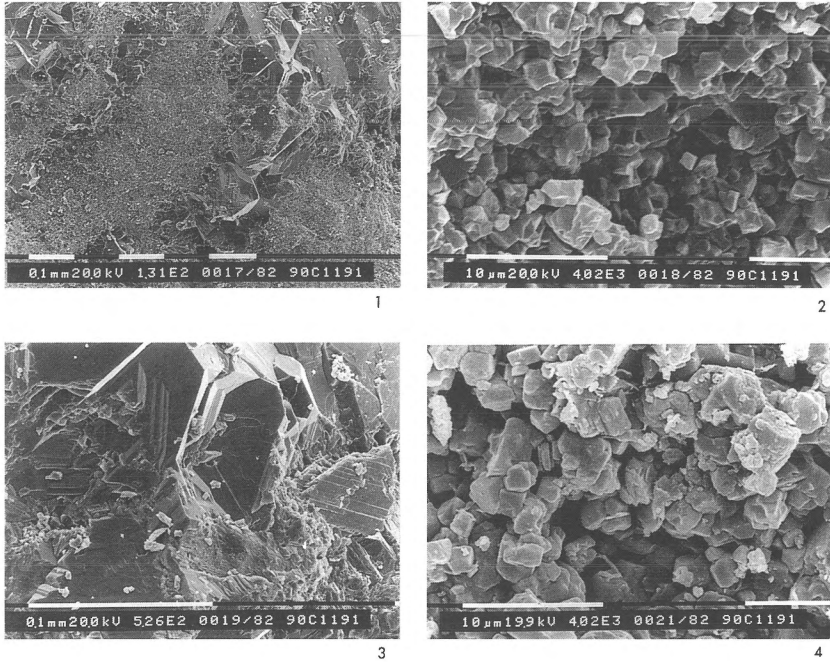


Plate 8. 1) Algae in micrite; fractured surface of sample CX. Mfamosing Quarry (See also Plates 1:3 , 4). 2) Micrite matrix, detail of Plate 8:1. Micrite grains have 0.4–3 μm diameter and interlocking, planar faces which indicates that aggradation has taken place. Pores visible are usually 1 μm and less across. 3) Detail of alga in sample CX; now replaced by blocky calcite crystals. Note cleavage trace and micropores in individual crystals. Less well-structured areas are interpreted as crystal bases of cements; micropores are visible. 4) Note irregularity of pore system; micritic often with tight interlocking contacts; also locally planar open pores. Micrite size 0.3–4 μm ; possible clays (kaolinite) present. Sample CX.

at Ikot Okpora and Agoi Ibami reflect an intertidal carbonate-shoal without a clearly defined lagoonal setting (Figures 5B, 6). There, the model only reflects the retrogradational development within the LST.

Diagenesis and sequence stratigraphy

General

Relative sea-level fluctuations of various orders control the formation of parasequences, sequences and their stacking patterns. In carbonates they also control diagenetic patterns. Products of third-order relative sea-level oscillations on a time scale of 1 to 10 Ma and with an amplitude on a one-to-ten-metre scale are the topic of this study. They have formed against a second-order relative sea-level rise within a first-order 'greenhouse' period (Veevers 1990) and result in net aggradational carbonate platforms.

Considerable amounts of rainwater flushed siliciclastics from the exposed hinterland and interfered

with the carbonate platform development. Therefore, diagenetic modifications in the carbonate body were controlled by the aggrading nature of the carbonate platform, the humid tropical climate and the associated influx of siliciclastics and meteoric water.

Diagenesis in the highstand systems tract

Towards the end of the HST deposition, sea level fell and a lens of meteoric water, developed on the exposed hinterland, was gradually driven basinwards by pore-water movements. It gave rise to some leaching features, mainly in tidal-flat algal sediments in which fine intercrystalline porosity is common (Plates 7:3, 4; 8:2, 4). Consequently chalky inter-granular porosity developed. Plates 8:1 and 3 show skeletal fragments that are partially leached and subsequently tightly cemented with blocky cement.

In the tidal-flat algal stromatolites, two types of algae and their associated micritic matrix are evident from SEM images. Structures and intraskeletal pore space in red algae have become occluded by inter-

locking blocky cement with a vaguely radial structure, suggesting aggradation or recrystallisation of the original cement (Plate 8:4). The matrix material consists of irregularly aggraded lime-mud particles, 0.4 to 4.0 μm in diameter, occasionally with interlocking structures. Porosity is patchily distributed, individual pores, up to 2 μm in diameter, may have narrow pore throats (Plate 7:4). Measured permeabilities (using minipermeameter) give extremely low values ranging from 0.02 to 0.46 md, depending on the direction in which measurements are taken.

Diagenesis in the lowstand systems tract

During LST deposition the carbonate platform was subject to variable amounts of siliciclastic influx which reduced carbonate production to a large extent. In addition, algal and fungal activity considerably biodegraded skeletal fragments through micritisation. Extensive micritisation of skeletal fragments is evident in Plates 2:2, 3; 3:1; 5:4 and 7:1.

Owing to the sea-level lowstand, parts of the lagoonal bottom were temporarily exposed, and vadose diagenetic products could form. Upon such subaerial exposure, widespread leaching took place which created considerable porosity (Plates 3:1; 4:1, 2; 7:1, 3, 4). However, much of this porosity was subsequently occluded by blocky cement during shallow burial (e.g. Plates 2:4; 3:1).

Aspects of porosity evolution are shown on the SEM images (Plates 7, 8). Well-developed stylolites are evidence of burial to depths surpassing 600 m (e.g. Plates 2:1, 2; 5:1–3).

Regional development

Marginal basins on both sides of the South Atlantic are characterised by considerable stratigraphic uniformity throughout the Late Jurassic and the Cretaceous (Lehner & de Ruiter 1977, Reyment & Dingle 1987, Petters 1991). Above a faulted crystalline basement or other substratum, the Mesozoic-Cenozoic succession comprises three distinct units: a basal non-marine pre-rift sequence, overlain by syn-rift continental siliciclastics, anoxic lacustrine shales, and locally carbonates and evaporites, that are followed by post-rift basal siliciclastics, carbonates, evaporites and shales, frequently marine and occasionally reflecting anoxic conditions.

Mid Albian carbonate bodies with facies comparable to those of the Mfamosing Limestone are the Pinda

Formation in the Cabinda enclave of Angola (Konig 1996) and porous grainstone shoals on a carbonate shelf that narrows by late Albian times further south in the Cuanza Basin which extends offshore Angola (De Klasz 1978; Clifford 1986; Figure 7). There are also the highly porous calcarenitic shoal facies of the Macea Formation in the Santos Basin, offshore of Rio de Janeiro, Brazil (Carozzi et al. 1983), and a narrow carbonate shelf with algal build-ups in the Marium Member of the Riachuelo Formation in the Sergipe-Alagoas Basin in Brazil (Ponte & Asmus 1978). In all these coeval carbonates, oolitic and oncolitic bioclastic grainstones and packstones were formed in moderate to high-energy carbonate shoals, while red-algal patch reefs formed in lagoonal settings (Dignes 1994; Koutsoukos et al. 1991). Several of these carbonates are prolific oil producers, notably the grainstone shoals in the Cuanza Basin (Clifford 1986).

This is not surprising as most of the Albian carbonates occur in juxtaposition with euxinic shales resulting from the various anoxia that occurred from the early Cretaceous to the late Aptian. These anoxia were related to basin closure to the north and to the south. Only from the early Albian onwards the Torres-Walvisbaai Ridge breached and the anoxic ocean bottom conditions changed into oxic (Mello et al. 1991; Petters & Ekweozor 1992; Petters 1991). From the exposed Mfamosing Limestones, natural oil impregnations have been reported (Reijers & Petters 1987).

Conclusions

Against the backdrop of a first-order greenhouse situation during the Cretaceous and a second-order rising sea-level during the Albian, third-order eustatic sea level fluctuations triggered deposition of carbonates around the Oban Massif in a highstand systems tract, a lowstand systems tract and a transgressive systems tract. Together they make up the heavily karstified Mfamosing Limestone Formation.

The application of sequence stratigraphy to the outcrops of this formation demonstrates the viability of this method to establish correlations. Based on these correlations a genetically useful subdivision of the formation can be made and an updated depositional model proposed. The use of petrography significantly enhances the possibility to successfully recognise the critical bounding surfaces in the formation's sequence stratigraphy which includes, from bottom to top, an HST, a sequence boundary, an LST, a transgressive

surface of erosion, a TST and a maximum flooding surface. Each of the systems tracts is present in the type section where they have been defined, and through recognition of the sequence boundary some of the systems tracts are recognised in some of the other studied outcrop sections.

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