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Lithofacies, Palynology and Facies Association: Keys to Paleogeographical Interpretation of the Enugu and the Mamu Formations of Southeastern Nigeria

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Abstract
The lithofacies, palynological assemblages and facies association have been employed in the interpretation of depositional setting, paleogeography and age of the Enugu and the Mamu Formations of the Anambra Basin, southeastern Nigeria. Palynological analysis yielded index sporomorphs and marine dinoflagellates typical of the Late Campanian to Early Maastrichtian for the Enugu Formation and Early- Mid Maastrichtian for the Mamu Formation. The coarsening upwards characteristics of the lithofacies and the general decrease to the absence of marine dinoflagellates coupled with an increase in the abundance of sporomorphs from the Enugu Formation into the Mamu Formation suggest shallowing of the sea. There is also a gradation from transgressive to regressive facies association. Late Campanian marine transgression deposited the basal part of the Enugu Formation. Seaward advancement of the shoreline commenced during the Early Maastrichtian in the Enugu Formation and continued into the Mid Maastrichtian in the Mamu Formation.

Key words: Paleogeography, Sporomorph, Lithofacies, Dinoflagellate, Transgression, Regression

1. Introduction

This study examines part of the sedimentary units of the Late Cretaceous Anambra Basin exposed (near flyover, 200 m away from NNPC Filling Station along Enugu- Port Harcourt expressway and opposite Onyeama mine, along Enugu- Onitsha expressway) in the Enugu Area, southeastern Nigeria (Figures 1b, 3 and 4). Simpson, (1954), Reyment, (1965), Nwajide and Reijers, (1996), Nwajide, (2005), Ojo *et al*., (2009) and Adeigbe and Salufu, (2009) have studied the Enugu and the Mamu Formations with respect to their lithostratigraphy, age relations, biostratigraphy, sequence stratigraphy, coal geology and petroleum geology. This study has integrated both the lithofacies, palynology and facies association in the reconstruction of the paleogeography of the Campanian- Maastrichtian in the Enugu and the Mamu Formations in the Anambra Basin, southeastern Nigeria. Index palynomorphs were used for the inference of the ages of the formations.

2. Regional Tectonic and Stratigraphic Setting

The origin of the Anambra Basin is intimately related to the development of the Benue Rift. The Benue Rift was installed as the failed arm of a trilate fracture (rift) system, during the breakup of the Gondwana supercontinent and the opening up of the southern Atlantic and Indian Oceans in the Jurassic (Burke *et al*., 1972; Olade, 1975; Benkhlil, 1982, 1989; Hoque and Nwajide, 1984; Fairhead, 1988). The initial synrift sedimentation in the embryonic trough occurred during the Aptian to early Albian and comprised of alluvial fans and lacustrine sediments of the Mamfe Formation in the southern Benue Trough. Two cycles of marine transgressions and regressions from the middle Albian to the Coniacian filled this ancestral trough with mudrocks, sandstones and limestones with an estimated thickness of 3,500m (Murat, 1972; Hoque, 1977). These sediments belong to the Asu River Group (Albian), the Odukpani Formation (Cenomanian), the Ezeaku Group (Turonian) and the Awgu Shale (Coniacian). During the Santonian, epeirogenic tectonics, these sediments underwent folding and uplifted into the Abakaliki- Benue Anticlinorium (Murat, 1972) with simultaneous subsidence of the Anambra Basin and the Afikpo Sub- basins to the northwest and southeast of the folded belt respectively (Murat, 1972; Burke, 1972; Obi, 2000; Mode and Onuoha, 2001). The Abakaliki Anticlinorium later served as a sediment dispersal centre from which sediments were shifted into the Anambra Basin and Afikpo Syncline. The Oban Masif, southwestern Nigeria basement craton and the Cameroon basement complex also served as sources for the sediments of the Anambra Basin (Hoque and Ezepue, 1977; Amajor, 1987; Nwajide and Reijers, 1996). Table 1 is the summarized stratigraphy of the Benue Trough and the Anambra Basin.

After the installation of the Anambra Basin following the Santonian epeirogeny, the Campanian- early Maastrichtian transgression deposited the Nkporo Group (i.e the Enugu Formation, Owelli Sandstone, Nkporo

Shale, Afikpo Sandstone, Otobi Sandstone and Lafia Sandstone) as the basal unit of the basin, unconformably overlying the Awgu Formation. This was followed by the Maastrichtian regressive event during which the coal measures (ie the Mamu, Ajali and Nsukka Formations) were deposited. Figure1 is the geologic map of the southeastern Nigeria indicating the study area.

3. Methods and Materials

Selected exposures of the Enugu and the Mamu Formations in the Enugu area were studied and logged (Figures 2- 5). Fresh samples of shales and heteroliths collected from the outcrops (bottom to top) were analyzed for palynomorphs using the maceration technique. The samples were digested for 24 hrs in 40% HF to remove silica, sieve washed with water, oxidized for 30 minutes in 70% HNO_3, rinsed in 2 % NaOH and centrifuged.

The aliquots were dispersed with polyvinyl alcohol, dried and then mounted in Canada balsam. The palynomorphs were studied using the binocular microscope.

4. Result and Interpretations

4.1The Enugu Formation

4.1.1 The Lithofacies and Palynological Assemblages

1. The grey to dark shale facies (A)

The lithofacies consists of thick shale which is commonly grey to dark in colour and was deposited at the basal part of the studied outcrops (Figure 2a). The shale is interbedded with thin beds of fine sandstones. Parallel laminations, growth fault and sparse horizontal burrows of *Thalassinoides isp.* were found on the shale. Weathering on this unit is producing a yellowish earthy coloration suggestive of a mineral pyrite. The presence of pyrite depicts anoxic conditions as in open marine setting.

Palynological analysis of samples from this unit (E9 and E11 in Figure 3) yielded relatively higher diversity but low abundance of marine dinoflagellate cysts compared with the overlying lithofacies. The dinoflagellate assemblages include; *Senegalinium bicavatum, Homotryblium tenuispinosum, Phelodinium* sp., *Phanthanoperidinium* sp., *Polysphaeridium* sp., *Impletosphaeridium* sp. and *Spiniferites ramosus* among others. The assemblage is typical of shallow to open marine depositional setting (Muller, 1959; Sargeant *et* al., 1987; Oloto, 1992; Carvaliho, 2004; Torricelli *et al*., 2005; Johan, 2010). However, sporomorphs and fresh water algae were also recovered from the unit.

2. The heterolithic facies (B)

The unit overlies (A) and consists of alternation of shales and fine sandstones (Figure 2b) in which the thickness of the sandstone beds increases upwards (i.e the sandstones become thicker upwards). The shales are grayish in colour, indurated and laminated. The fine sandstones display wavy laminations. Burrows of *Planolites, Teichichnus, Skolithos* and nodular concretions occur in this unit.

Palynological analysis of samples from this facies (E5 and E6 in Figure 3) yielded fewer marine dinoflagellates which include; *Exochosphaeridium* sp., *Areoligera* sp., *Cordosphaeridium* sp., *Spiniferites ramosus, Cometodinium* sp., *Cyclonephelium* sp. *Miltordia* among others. Sporomorph assemblage is dominated by *Cyathidites minor, Constructipollenites ineffectus, Longapertites marginatus, Cyathidites australis* and *Retidiporites magdalenensis*. *Botryococcus* and *Pediastrum* are the fresh water algae. The assemblage recovered indicates a range from coastal swamp and shallow to open marine depositional setting.

4.1.2 Facies Associations of the Enugu Formation

Based on the lithofacies and the palynomorphs, the association identified in this formation include; the transgressive facies association that consists of dark grey to black shales and the heterolithic facies of shallow to open marine. The facies association is rich in marine dinoflagellates.

4.2 The Mamu Formation

4.2.1 Lithofacies and palynological assemblages

The lithofacies and the palynological assemblages of the Mamu Formation

1. The wave ripple laminated fine sandstone facies (C)

This facies consists of wave ripple and laminated fine sandstone (whitish in colour), alternated with thin beds of shale and coal. The shale bed is grayish in colour and laminated. *Skolithos* and *Ophiomorpha* were found on the sandstone bed. The facies is at the base of the outcrop.

Palynological analysis of the shale sample from this facies unit (MB1 in Figure 5) yielded abundant and diverse kinds of sporomorphs dominated by *Cyathidites minor, Cyathidites australis, Constructipollenites ineffectus, Longapertites marginatus, Proxapertites operculatus Echitriporites trianguliformis Deltoidospora* sp. and *Retidiporites magdalenensis*. Others include; *Longapertites vandeenburgi, Cingulatisporites ornatus, Monocolpopollenites sphaeroidites, Spinizonocolpites echinatus, Distaverrusporites simplex, Ariadnaesporites nigeriensis, Foveotrilete margaritae* among others. Marine dinoflagellates were not recovered except an acritarch (*Leisphaeridia*). The facies constitutes the shoreface/littoral deposits

2. The heterolithic facies (D)

This consists of sandy shale and shaly sandstone that coarsens upwards (i.e becomes sandier upwards). Sporomorphs constitute over 98% of the palynomorphs (MB2 – MB4 in Figure 5) and were dominated by *Cyathidites minor, Constructipollenites ineffectus, Longapertites marginatus, Proxapertites operculatus, Cyathidites australis, Retidiporites magdalenesis, Monocolpites marginatus, Deltoidospora* sp. and *Rugulatisporites caperatus.* Some others are *Echitriporites trianguliformis, Longapertites vandeenburgi, Monocolpopollenites sphaeroidites, Cingulatisporites ornatus* and *Syncolporites marginatus.* No marine dinoflagellate was recovered except an acritarch (Leiosphaeridia). The unit constitutes the lagoonal and coastal swamp deposits.

3. Laminated fine sandstone and mudstone facies (E)
This facies consists of alternation of mud laminated fine sandstone and mudstone (upper part of Figure 4a). The mudstone becomes thicker upwards. Sedimentary structures include flaser bedding and parallel laminations. This unit is from tidal flat environment (possibly mixed flat).

2.2.2 Facies association of the Mamu Formation
The regressive facies association was identified in the Mamu Formation based on the lithofacies and palynomorphs. The association is dominated by sporomorphs and with very little to no marine dinoflagellates and constitutes the facies association of the distributaries channel, tidal marsh and coastal swamp environments.

5. Paleogeography

The depositional environment suggested by the lithofacies succession, associations and the palynological assemblages of the Late Campanian- Mid Maastrichtian in the Anambra Basin of southeastern Nigeria include; transgressive (marine) to regressive depositional setting.

The lithofacies stacking pattern (coarsening upwards) characteristics displayed by the section from the base towards the top suggests deltaic progradation (shoaling upwards) during active deltaic growth (Ojo *et al*., 2009). Deltas are known to be sites where sediments build outwards from the coast. The landward depositional environments move seawards over more marine/ lacustrine deposits. Thus the general succession grades upwards from open marine shale into shallow marine, delta front/ distributary to coastal/ tidal marsh facies.

The successive decrease in the marine dinoflagellate species diversity from the basal facies (A) into the heterolithic facies (B) in the Enugu Formation is also an indication of shoreline progradation (Huan and Habib, 1996). The larger number of dinoflagellate species in the basal shallow to open marine shale facies (A) represents a transgressive event. The onset of regression is evidenced from the heterolithic (facies B) of coastal swamp environment in which the marine dinoflagellates are very few and sporomorphs constitute up to 90% of the palynomorphs. The relatively higher abundance of terrestrial- derived sporomorphs and absence of marine dinoflagellates in the Mamu Formation (tidal marsh/ distributary channel and coastal swamp facies associations) is suggestive of a regression and thus shallowing of the sea.

The paleogeography of the Late Campanian- Mid Maastrichtian in the Anambra Basin of southeastern Nigeria is summarized in Figures 6 and 7.

6. Age Determination

The following stratigraphically important palynomorphs were recovered from the outcrops studied
6.1 Sporomorphs (Figure 8)
1. *Syncolporites usame* (Upper Campanian) Adebayo and Ojo, (2004)
2. *Syncolporites sphaeroidites* (Upper Campanian) Adebayo and Ojo, (2004)

3. *Syndemicolpites typicus* (Upper Campanian- Early Maastrichtian)
4. *Proteacidites longispinosus* (Upper Campanian- Mid Maastrichtian)
5. *Triolites* sp. (Upper Campanian-Early Maastrichtian)
6. *Retitricolpites* sp. (Upper Campanian- Early Maastrichtian)
7. *Zlivisporis blanensis* (Campanian- Maastrichtian) Adebayo and Ojo, (2004)
8. *Laevigatosporites* sp. (Early Maastrichtian)
9. *Periretisyncolpites magnosagenatus* (Upper Campanian- Early Maastrichtian)
10. *Auriculopollenites reticulatus* (Upper Campanian-Early Maastrichtian)
11. *Buttinea andreevi* (Upper Campanian- Maastrichtian) Atta-Peters and Salami, (2004)
12. *Psilamonocolpite medius* (Upper Campanian)
13. *Mauritidites lehmanii* (Upper Campanian- Early Maastrichtian)
14. *Proxapertites marginatus* (Early Maastrichtian)
15. *Scabratisporites simpliformis* (Early Maastrichtian)
16. *Ariadnaesporites spinosa* (Early- Mid Maastrichtian)
17. *Mauritidites crassienus* (Early Maastrichtian)
18. *Margocolporites* sp. (Early Maastrichtian)
19. *Ladaktipollis* sp. (Early Maastrichtian)
20. *Spinizonocolpites echinatus* (Maastrichtian) Atta-Peters and Salami, (2004)
21. *Spinizonocolpites baculatus* (Maastrichtian) Adebayo and Ojo, (2004)
22. *Spinizonocolpites kotchiensis* (Maastrichtian) Adebayo and Ojo, (2004)
23. *Psilatricolporites* sp. (Early Maastrichtian)
24. *Arecipites* sp. (Early Maastrichtian)
25. *Hexaporotricolporites emelianovi* (Early Maastrichtian)
26. *Foveomonocolpites bauchiensis* (Early Maastrichtian)
27. *Psilastephanocolporites* sp. (Early Maastrichtian)
28. *Aquilapollenites* sp. (Upper Campanian- Early Maastrichtian)
29. *Ariadnaesporites nigeriensis* (Upper Campanian- Early Maastrichtian)
30. *Tricomonosulcites* sp. (Early Maastrichtian)
31. *Monocolpites marginatus* (Early Maastrichtian) Edet and Nyong, (2003)
32. *Tubistephanocolpites cylindricus* (Early Maastrichtian)
33. *Proteacidites sigalli* (Early Maastrichtian)
34. *Psilamonocolpites marginatus* (Early- Mid Maastrichtian)
35. *Retitrilete* sp. (Early Maastrichtian)
36. *Ariadnaesporites spinosa* (Early- Mid Maastrichtian)

Other stratigraphically important ones that are long ranging in this study include

37. *Echitriporites trianguliformis* (Campanian- Maastrichtian) Atta- Peters and Salami, (2004).
38. *Proxapertites operculatus* (Maastrichtian) Atta- Peters and Salami, (2004).
39. *Longapertites marginatus* (Campanian- Maastrichtian) Atta- Peters and Salami, (2004)
40. *Foveotrilete margaritae* (Maastrichtian) Atta- Peters and Salami, (2004); Oloto, (1994).
41. *Cingulatisporites ornatus* (Campanian- Maastrichtian) Adebayo and Ojo, (2004)
42. *Monocolpopollenites* sp. (Maastrichtian) Adebayo and Ojo, (2004)

6.2 Marine Dinoflagellates (Figure 9)

The index marine dinoflagellates recovered include;

1. *Senegalinium bicavatum* (Upper Campanian) Umeji, (2006)
2. *Homotryblium tenuispinosum* (Upper Campanian)
3. *Impletosphaeridium* sp. (Upper Campanian)
4. *Phanthanoperidinium* sp. (Upper Campanian)
5. *Polysphaeridium* sp. (Upper Campanian)
6. *Phelodinium* sp. (Upper Campanian) Umeji, (2006)
7. *Areoligera* sp. (Upper Campanian- Early Maastrichtian)
8. *Eocladopsis* sp. (Upper Campanian- Early Maastrichtian)
9. *Coronifera oceanica* (Early Maastrichtian)
10. *Spiniferites ramosus* (Upper Campanian- Mid Maastrichtian)
11. *Cyclonephelium* sp. (Early Maastrichtian)

6.3 Age of the Enugu Formation

Based on the palynomorphs below, a Late Campanian to Early Maastrichtian age is proposed for the Enugu Formation in the Anambra Basin (Figures 8 and 9). The palynomorphs (both sporomorphs and marine dinoflagellates) typical of Late Campanian and early Maastrichtian were recovered. These include; *Buttinia andreevi, Zlivisporis blanensis, Syncolporites usame, Proteacidites longispinosus, Syncolporites sphaeroidites, Auriculopollenites reticulates, Syndemicolpites typicus, Laevigatosporites, Psilamonocolpites medius, Aquilapollenites, Mauritidites lehmanii, Mauritidites crassienus, Periretisyncolpites magnosagenatus, Arecipites* sp., *Triolite* sp., *Retitricolpite* sp., *Margocolpites* sp., *Ladktipollis* sp., *Psilatricolporites* sp., *Senegalinium bicavatum, Homotryblium tenuispinosum, Phelodinium* sp., *Phanthanoperidinium* sp., *Polysphaeridium* sp., *Impletosphaeridium* sp. and *Spiniferites ramosus.*

6.4 Age of the Mamu Formation

Early to Mid Maastrichtian age is proposed for the Mamu Formation based on the following stratigraphically important palynomorphs (Figures 8 and 9); *Spinizonocolpites baculatus, Spinizonocolpites echinatus, Spinizonocolpites kotchiensis, Monocolpites marginatus, Proteacidites dehaani, Proteacidites sigalli, Retitrilete* sp., *Tricomonosulcites* sp., *Psilastephanocolporites* sp., *Proxapertites marginatus, Scabratisporites simpliformis, Ariadnaesporites spinosa* and *Ariadnaesporites nigeriensis, Laevigatosporites* sp. and *Tubistephanocolpites cylindricus.*

6.5 Campano- Maastrichtian Boundary

The Late Campanian boundary was marked using the index palynomorphs *Syncolporites sphaeroidites* (Late Campanian) of Adebayo and Ojo, (2004). Many marine dinoflagellates such as *Senegalinium bicavatum, Homotryblium tenuispinosum, Impletosphaeridium* sp., *Phanthanoperidinium* sp., *Polysphaeridium* sp., *Phelodinium* sp. and sporomorphs like *Syncolporites usame* and *Syncolporites sphaeroidites* disappeared at this boundary. However, the dinoflagellates '*Spiniferites ramosus'* and sporomorphs such as *Psilastephanocolpites* sp., *Spinizonocolpites kotchiensis* and *Psilatricolporites* sp. made their first appearance in the study area.

6.6 The Maastrichtian Stage

The Early/ Mid Maastrichtian boundary was marked using the index palynomorphs '*Monoporites marginatus'* (Early Maastrichtian) of Edet and Nyong (2003). Maastrichtian period was a time of flourishing, evolution and disappearance of many terrestrial sporomorphs (Figure 8).

7. Discussion and Conclusion

The paleo-depositional changes observed throughout the successions of the Enugu and the Mamu Formations are as a result of base level changes in a relatively shallowing sea. Late Campanian was marked by marine transgression during which the fossiliferous grey to dark shale facies that constitute the basal part of the Enugu Formation were deposited. Seaward advancement of the shoreline however, began in the Early Maastrichtian in the Enugu Formation and continued into Mid Maastrichtian in the Mamu Formation. This is evidenced by the few to lack of marine indicator dinoflagellates, coupled with the total dominance of terrestrial sporomorphs, especially towards the Mamu Formation. The heterolithic facies that consists of alternations of thin units of fine sandstone and shale that grades upwards into sandy shale and shaly sandstone and the wave ripple laminated sandstones (i.e coarsening upwards of succession) of shallow marine to coastal swamp also suggest the shallowing of the sea.

Transgressions and regressions were responsible for the deposition of the Enugu and the Mamu Formations respectively. The lower part of the Enugu Formation was deposited during the Late Campanian by a marine transgression while the upper part marks the commencement of the regressive phase in the basin and thus is characterized by both shallow marine and coastal swamp facies association. The Mamu Formation is a product of deposition under regressive setting.

Campano- Maastrichtian and Maastrichtian ages have been proposed for the Enugu Formation and the Mamu Formation respectively. This is based on index palynomorphs recovered from the outcrops.

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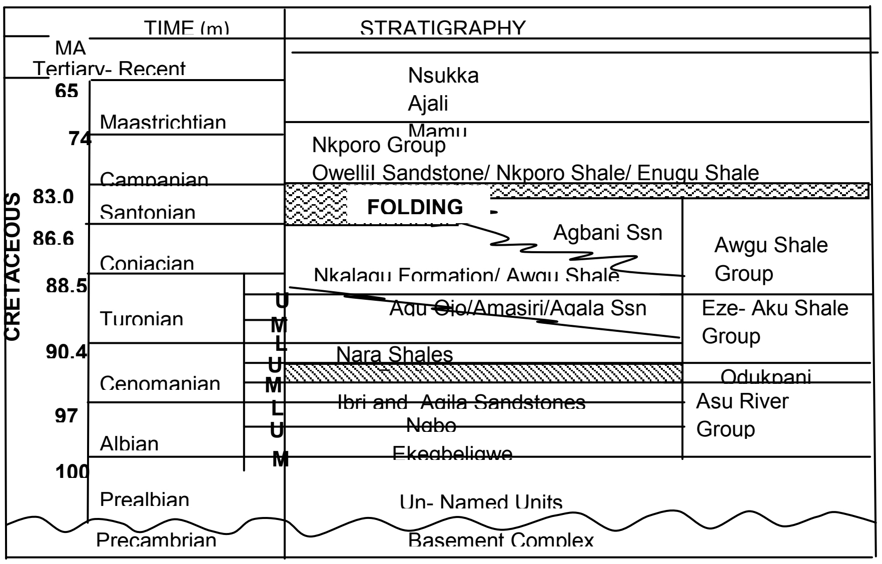
Table 1: Summarized stratigraphy of the Benue Trough and Anambra Basin (after Reyment, 1965 and Ojo, 1992).



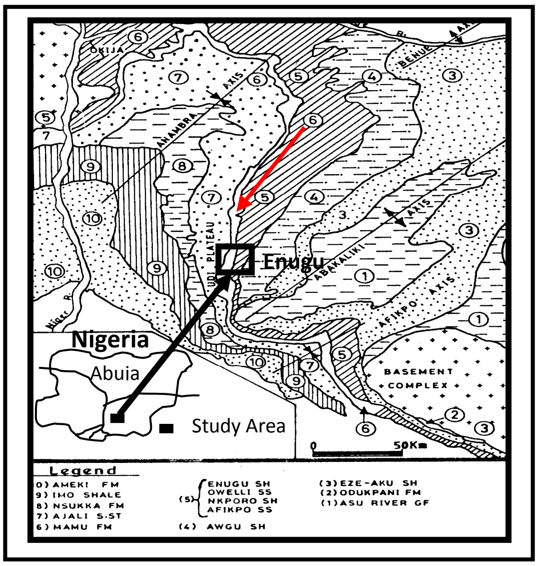


Figure 1: Geologic map of southeastern Nigeria showing the study area (Modified from Hoque, 1977)

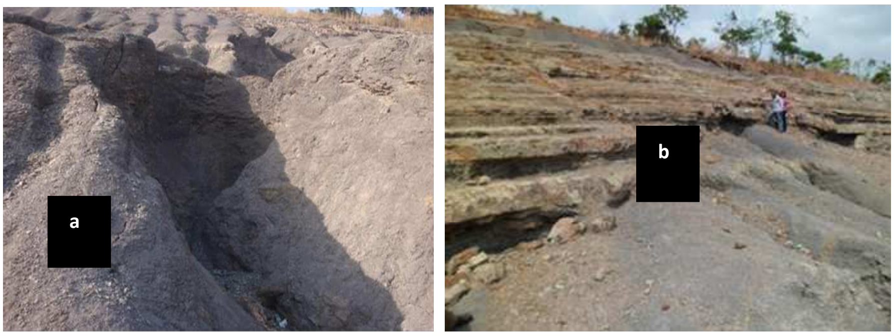


Figure 2: Outcrop section of the Enugu Formation exposed near flyover, Enugu- PH expressway, Enugu. (a) The Lithofacies A (b) The sand-dominant heterolithics (lithofacies B) at the middle part of the Formation

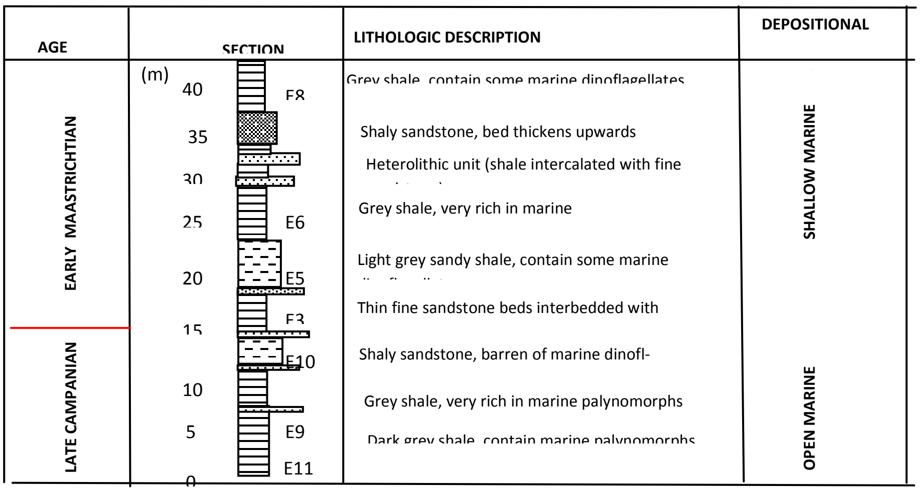


Figure 3: Stratigraphic section of the Enugu Formation exposed near flyover, about 200 m away from the NNPC Filling Station, Enugu.

Figure 4: Outcrop section of the Mamu Formation exposed opposite Onyeama Coal Mine along the Enugu- Onitsha Express way (b) Outcrop section of the Mamu Formation exposed under the bridge, near Proda, and the Onyeama Coal Mine.

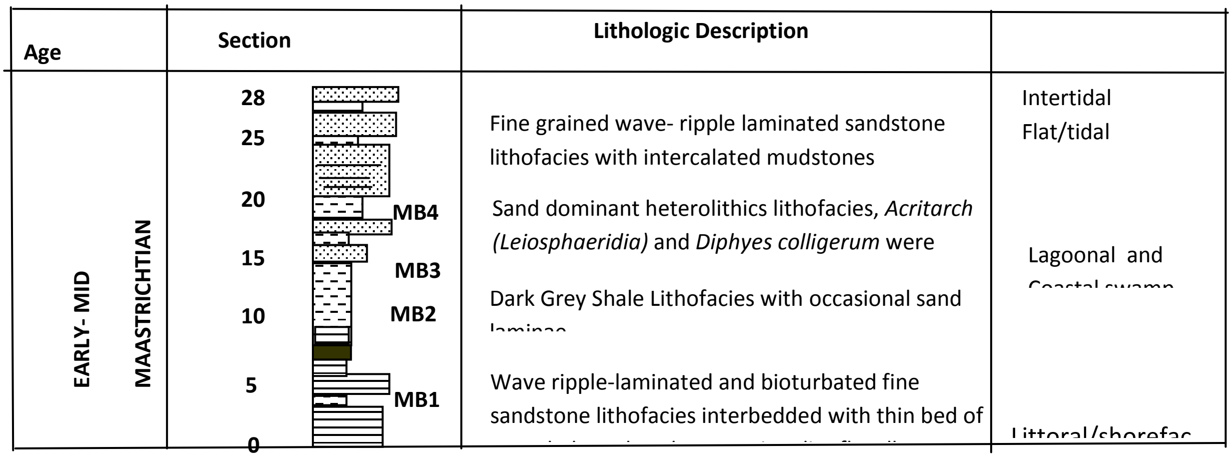


Figure 5 Stratigraphic section of the Mamu Formation exposed opposite Onyeama Mine, along Enugu-Onitsha Expressway, Enugu.

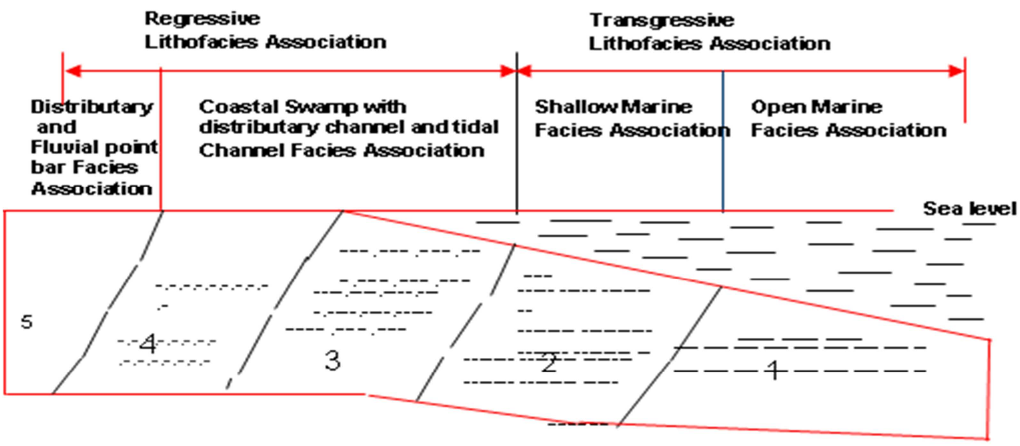


Figure 6: Paleogeographic Model for Late Campanian- Mid Maastrichtian in the Anambra Basin.

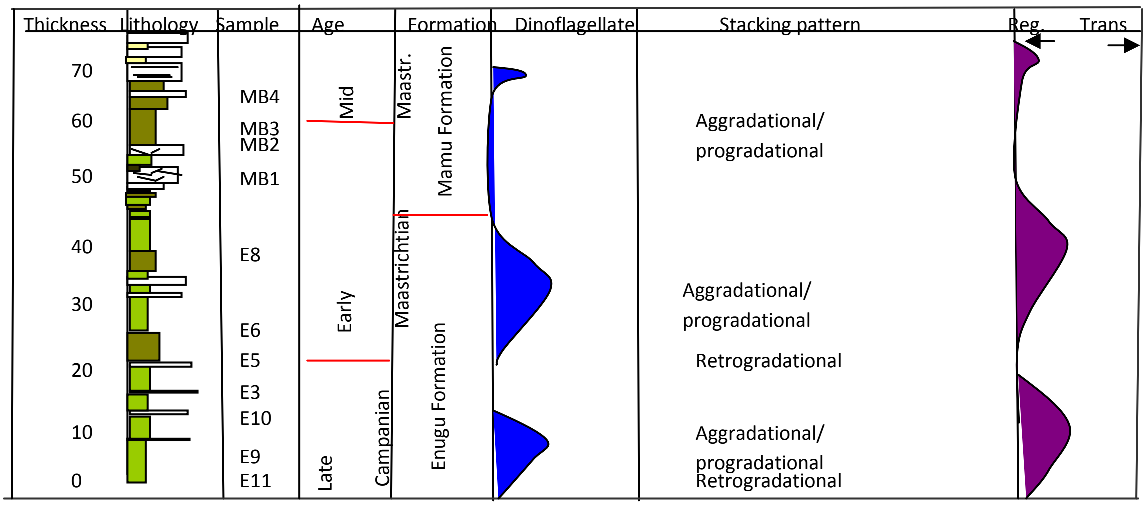


Figure 7: The sequence stratigraphic model for the Campanian- Maastrichtian in the Anambra Basin showing the phases of marine transgression and regression

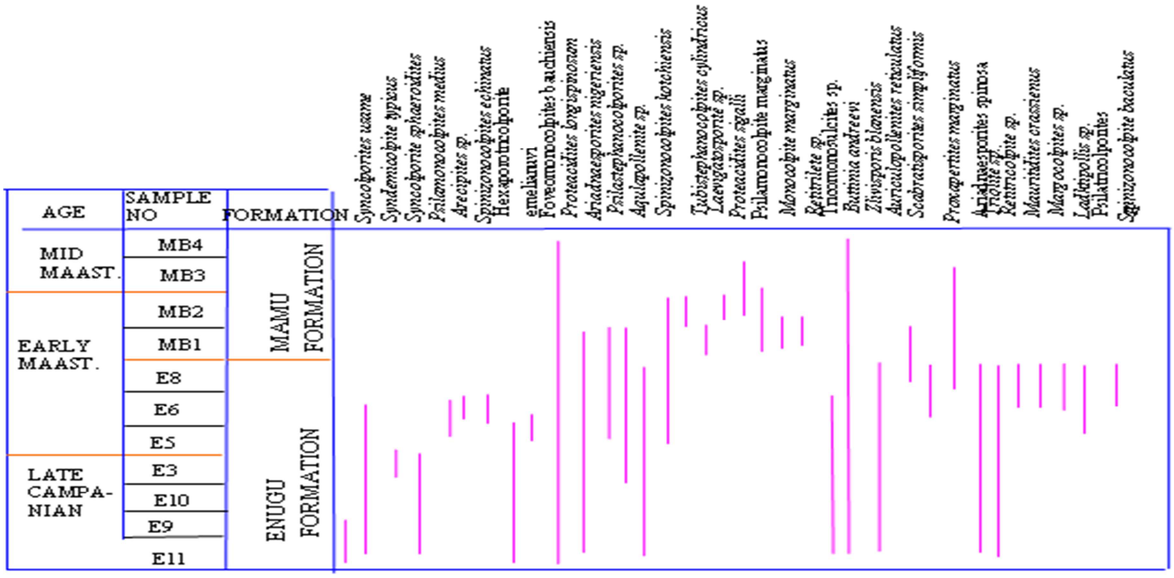


Figure 8: Stratigraphically important sporomorphs from the Enugu and Mamu Formations

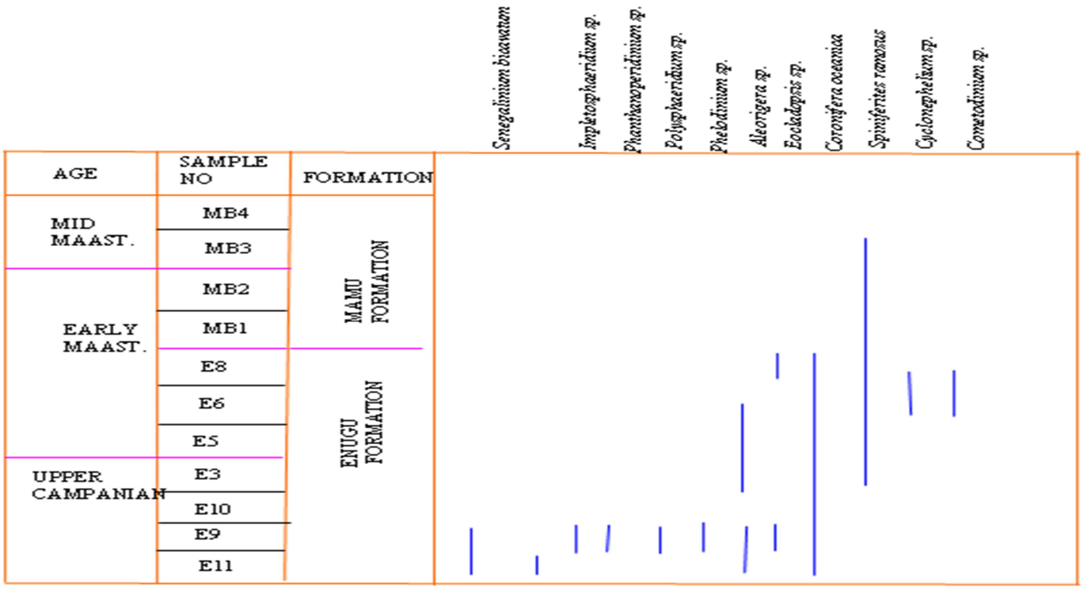


Figure 9: Stratigraphically important dinoflagellates from the Enugu and the Mamu Formations.

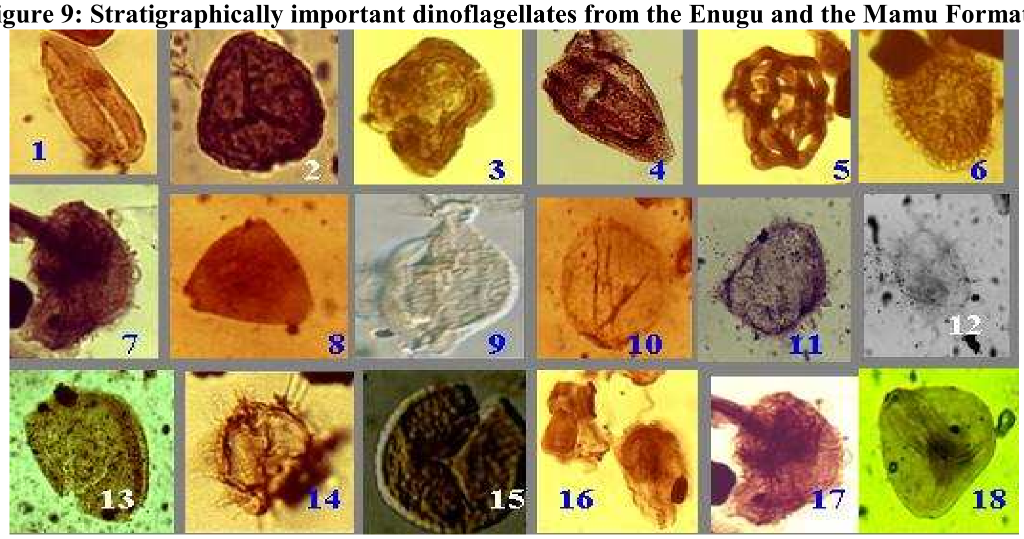


Figure 10: Palynomorph assemblage from the study area
Selected palynomorphs recovered from the studied outcrops

1. *Monocolpite marginatus* Van der Hammen, 1954 ×400
2. *Distaverrusporite simplex* Muller, 1968 ×400
3. *Cingulatisporites ornatus* Van Hoeken- Klinkenberg, 1964 ×400
4. *Longapertites vandeenburgi* Germeraad *et al*., 1968 ×400
5. *Buttinia andreevi* Boltenhagen, 1967 ×400
6. *Constructipollenite ineffectus* Van Hoeken- Klinkenberg, 1964 ×400
7. *Ariadnaesporites* Protonie, 1956 ×400
8. *Monocolpopollenites sphaeroidites* ×400
9. *Auriculopollenites reticulates* ×400
10. *Senegalinium* Jain and Millipied, 1975 ×400
11. *Areoligera* sp. ×400
12. *Spiniferites* Loeblich and Loeblich, 1966 ×400
13. *Longapertites marginatus* Van Hoeken- Klinkenberg, 1964 ×400
14. *Cleistosphaeridium* sp. Davey *et al*., 1966 ×400
15. *Proteacidites dehaani* Germeraad *et al*., 1968 ×800
16. & 17 *Ariadnaesporites* sp. ×400
18. *Cyathidites minor* ×400