Australian Journal of Basic and Applied Sciences, 4(12): 6623-6640, 2010
ISSN 1991-8178

Depositional Environments and Sequence Stratigraphic Interpretation of the Campano-Maastrichtian Nkporo Shale Group and Mamu Formation Exposures at Leru-Okigwe Axis, Anambra Basin, Southeastern Nigeria.

S.O. Onyekuru and C.J. Iwuagwu

Federal University of Technology, P.M.B. 1526, Owerri

Abstract: A total of six (6) lithofacies were distinguished from two (2) outcrop sections of Cretaceous succession of Nkporo and Mamu Formations exposed in a cascading topography on both sides of the Enugu-Port Harcourt expressway in Leru, Anambra Basin. The lithofacies include: Interstratified Calcareous Mudstone Shale Facies (A), Horizontal and Cross Stratified Sandstone Facies (B), Heterolithic Sandstone and Muddy Shale Facies (C), Heterolithic Shale and Siltstone Facies (D), Poorly Stratified Sandstone Facies (E) and Red Sandstone Facies (F). Interpretation of depositional environments using lithofacies stacking pattern, sedimentary structures and biostratigraphic analyses inferred an estuarine/lagoonal to tidal delta to shallow, open marine depositional model for the Nkporo Shale and an estuarine to tidal delta to shallow marine paleodepositional model for the Mamu Formation in the study area. Sequence stratigraphic interpretations established depositional patterns with one complete and one incomplete 3rd order sequences, comprising of Highstand Systems Tracts (HST) and Transgressive Systems Tracts (TST). The packages (Systems Tracts) formed distinct complexes consisting of a number of genetically linked retrogradational, progradational and aggradational deltaic systems. Major architectural facies elements in the packages include: shoreface deposits, channel fills, and prodelta shales in sediment starved areas. Two Type-1 Sequence Boundaries (SB), a condensed section and two chronostratigraphic significant surfaces (Maximum Flooding Surface; MFS) were delineated in the sections. The sequence boundary identified at the 68m level in Leru 1 is a textbook example of an onlap stratal termination pattern in outcrops. The surface provided the boundary between Nkporo Shale and Mamu Formation in the studied sections. Alternation of Highstand Systems Tracts and Transgressive Systems Tract sands and shales, in the studied sections provides a union of reservoir and seal rocks that are essential for hydrocarbon accumulation and stratigraphic trapping.

Key words: Lithofacies, reterogradation, Progradation, aggradation, Onlap, Sequence Stratigraphy, Chronostratigraphy, Depositional Systems

INTRODUCTION

The Leru Section is a Cretaceous succession and a composite outcrop of the Nkporo and Mamu Formations exposed in a cascading topography on both sides of the Enugu-Port Harcourt expressway where it breaches the Enugu escarpment at Leru in Abia State. The formations crop out at the foot of the cuesta: an assymetrical ridge, with its western end at the left bank of River Niger at Idah, where it stretches northeastwards and, very close to the River Benue, turns south past Enugu to just north near Arochukwu at the right bank of the Cross River (Fig.1).

The studied section starts at about km 68 on the Port Harcourt bound side of the Enugu-Port Harcourt expressway near Lekwesi Obiulo Gate and terminates at Leru/Isuochi road junction. The section is precisely described by Longitudes N5^{0}54^1 and N5^{0}55^1 and Latitudes and E07^{0}24^1 and E07^{0}25^1. The total logged section is about 80m, while the lateral spread of the outcrops is about 1km.

Several workers including Tattam (1944), Grove (1951), Simpson (1954), Reyment (1965), Murat (1972), have noted that the Nkporo Shale Group consists of dark grey, very fissile shales and mudstone with occasional thin sandy shale interbeds, fine grained sandstone and marl with coatings of sulphur and numerous white specks of *Bolivina explicate*. Other fossil assemblages include benthic forams such as *Buliminids*, *Bulimina fang*, *Bulimina prolix*, *Ammobaculites Sp* and *Gavelinela Sp*. Similarly, Tattam (1944), Simpson (1948, 1954), Reyment (1965), Murat (1972), Dessauggie (1974), described the Mamu Formation as the Lower Coal Measures,

Corresponding Author: S.O. Onyekuru, Federal University of Technology, P.m.b. 1526, Owerri
E-mail Onyekuru2001@yahoo.com

of Maastrichtian age. On surface sections, the Mamu Formation consists mainly of fine grained and well sorted sandstones, siltstones and shales. Cross stratification is very rare and carbonaceous material is present in varying amounts in the sandstones and occur either as streak on bedding planes or as irregular ramifications. Coal beds and carbonaceous shales are more concentrated in the lower sections of the formation and become rare towards the top, indicating progressive transition into a more open strand plain. The upper layer of the formation is barren while the deeper part is sparse in fauna consisting of ostracods and arenaceous foraminifera, mainly *Haplophragmoides*.

According to Nwajide and Reijers (1996), investigation of the Anambra Basin's fill in terms of sequence stratigraphic analysis has only recently started. They stressed that repeated allocyclic incursions of the sea into the Anambra Basin resulted in characteristic basin-wide genetic sequences, or parasequence sets. Only two allocyclic events, however, have so far been recognized in the Anambra Basin in contrast to the better studied Niger Delta with a more complete log record, where at least eleven events are reflected by a repetitive pattern of transgressive-regressive lithologies (Nwajide and Reijers, 1996).

In the light of the foregoing, therefore, sequence stratigraphic techniques were adopted in the interpretation of the Nkporo Shale Group and Mamu Formation exposures in Leru-Okigwe Axis, Anambra Basin, southeastern Nigeria. The study offers unifying concepts that provide the ability to predict the position of play elements, rock units continuity and extent and the recognition of constrained key surfaces for better mapping and correlation (Van Wagoner, *et al*., 1988).

Geological Setting:

Leru-Okigwe Axis lies in the Anambra Basin. The basin occupies the southernmost part of the Benue Trough which is one of the series of Cretaceous rift basins in central West Africa. The tectonic evolution of the Anambra Basin may be traced back to the late Jurrassic when convention currents in the asthenosphere caused the break-up of the Gondwana Supercontinent. The separation of the African and south American plates left the Benue Trough as an aulacogen, a failed arm of an RRR Triple Junction (Burke, 1972; Olade, 1975). The Benue Trough is itself a part of the very expansive west and central African rift system in which it opened as an extensive sinistral wrench complex (Emery *et al*., 1975; Whiteman, 1982; Genik, 1993). A reconstruction by Murat (1972) shows the southern part of the Benue Trough as longitudinally faulted, with its eastern half subsiding preferentially to become the Abakiliki depression. During the filling of the Abakiliki-Benue sector of the Benue Trough in the Albian-Santonian times, the proto-Anambra Basin was a platform that became only thinly sediment-draped (Nwajide and Reijers, 1997). Basin subsidence in the southern Benue Trough was spasmodic. It was at a high rate in pre Albian time, low in lower Cenomanian, and very high in Turonian; the latter was an important phase of platform subsidence (Ojoh, 1990). This is thought to be the actual time of initiation of the Anambra Basin; a process that gained momentum in the Coniacian and climaxed during the Santonian thermotectonic event (Nwajide, 2005).

Careful synthesis of the works of several authors (Murat, 1972; Nwachukwu, 1972; Weber and Doukoru, 1975; Benkhelil, 1982; Nwajide and Reijers, 1996; Mode and Onuoha, 2001; Obi, 2000) reveals that the Santonian movement or tectonic pulses (or compressional uplift) dating back to 84 Ma, was accompanied by widespread magmatism, folding and faulting that caused the Abakiliki area to become flexurally inverted to form the Abakiliki Anticlinorium. These forces displaced the depocentres to the west and southeastwards, forming the Anambra Basin and Afikpo syncline, respectively (Murat, 1972; Burke, 1972). Thereafter, the anticlinorium served as a sediment dispersal centre from which mineralogically mature detritus was shed into the Anambra Basin and Afikpo Syncline (Akaegbobi and Schmitt, 1998; Akaegbobi and Boboye, 1999). Other provenance areas for texturally mature sediments of the Anambra Basin include the crystalline Basement areas of the Oban Massif, southwestern Nigerian craton and Cameroon basement granites which had undergone prolonged chemical weathering (Hoque and Ezepue, 1977; Amajor, 1987; Nwajide and Reijers, 1996; Akaegbobi and Schmitt, 1998; Akaegbobi and Boboye, 1999).

Sediment deposition in the Anambra Basin started in the Campanian with a short marine transgression followed by a regression. The Nkporo Shale and its lateral equivalents, the Enugu Shale and Owelli Sandstone (Nkporo Group), constitute the basal beds of the Campanian period. The broad shallow sea gradually became shallower because of gradual subsidence, initiating regressive phase during the Maastrichtian that deposited deltaic foresets and flood plain sediments of the Mamu Formation (Lower Coal Measures). The Mamu Formation is overlain by the continental beds of Ajali Sandstone (False bedded Sandstone), followed by a return to partially paralic conditions and the deposition of the Nsukka Formation.

The stratigraphic sequence presented in table 1 and graphically illustrated in Fig. 2 represents the totality of the lithic fill of the study area and adjoining Tertiary Niger Delta.

Table 1: Stratigraphic Sequences in Anambra Basin (after , Nwajide, 2005)

Age	Basin	Stratigraphic Units						
Thanetian	Niger Delta	Imo Formation						
Danian								
Maastrichtian	Anambra Basin	Coal Measures	Nsukka Fm					
			Ajalli Fm					
			Mamu Fm					
Campanian		Nkporo Fm	Nkporo Shale	Enugu Fm	Owelli Ss	Afikpo Ss	Otobi Ss	Lafia Ss
Santonian	Southern Benue Trough	Awgu Fm						

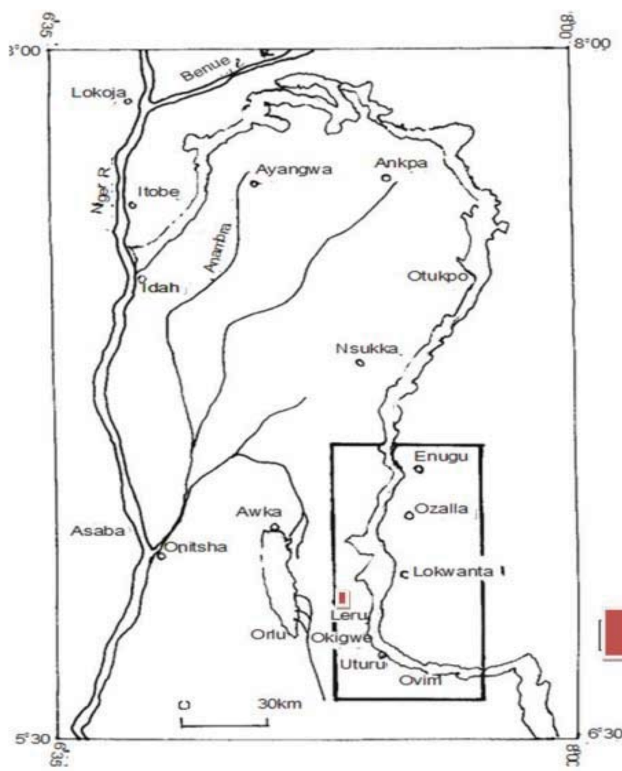

Fig. 1: Showing Study area and Cueseta Topography

Methods of Study:

Although sequence stratigraphy was originally designed for seismic sections, its principles can also be readily applied to outcrops, cores, and well logs (Van Wagoner *et al*, 1990).

The methodology for the application of sequence stratigraphic principles to outcrops in the study area followed the technique established by Van Wagoner *et al*., 1990 which is graphically presented in Fig. 3.

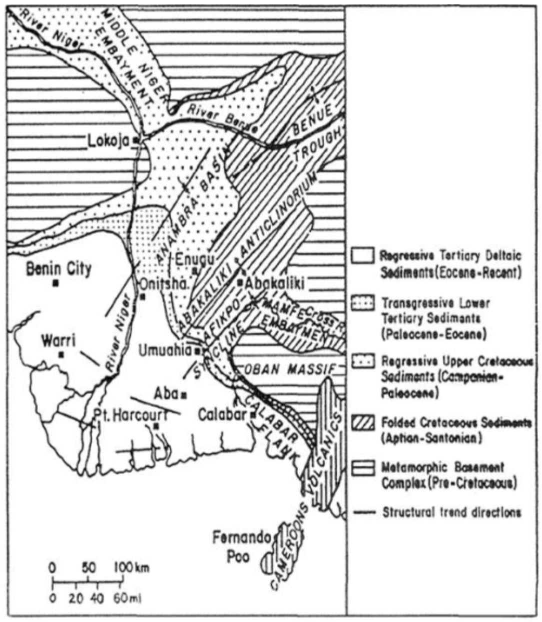

Fig. 2: Rrgional Stratigraphy of the Outcropping components of the Anambra Basin (modified from Hoque, 1977)

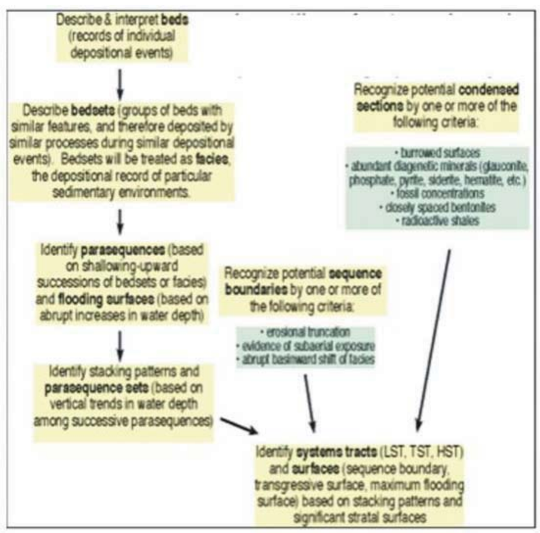

Fig. 3: An Outline of Outcrop-Based Sequence Stratigraphic Analysis (adapted from van Wagoner *et al.,* 1990)

RESULTS AND DISCUSSIONS

Lithostratigraphic Description of Leru I and II Sections:

The base of the Leru section was not precisely ascertained, but may be assumed to be marked by the occurrence of thin drapes of older formations and/or dolerite boulders seen around Lokpaukwu (near the study location). The lower part of the section is about 38m thick and consists of laminated, fossiliferous, pyritic, dark grey shales interbedded with thin beds of calcareous mudstones. The lowermost portion has profuse seepage of fluids suspected to be hydrocarbon (Fig. 4) following the course of Leru spring that emanated from the cuesta. The fossils identified in this lower section include bivalves and gastropod imprints and large assemblages of foraminifera and palynomorphs. Some of the identified forms also include: *Haplophragmoides sp, Ammobaculites sp, Ammotium nkalagum, Ammotium nwalium, Bolivina anambra, Bolivina sp, Bulimina kugleri, Ostracoda, Amenantherites sp, Andalusiella sp, Deflandrea, etc.*

Fig. 4: Seepage suspected to be Hydrocarbon in Leru I.

The middle portion of Leru I (Fig. 5), above the covered section is characterized by interbedded sandstones and shales. The lower section of this portion starts with a generally coarsening upward and thickening upward succession of sandstone beds, which are subsequently overlain by dark grey to black shale beds. The sandstones at the lower section of the middle portion are generally medium to coarse grained, and have occasional mud clasts. The sandstone beds are profusely burrowed with vertical and branching burrows belonging to the *Skolithos* and *Ophiomorpha* ichnogenera (Fig. 6). The characteristic sedimentary structures in the sandstone beds are planar and trough cross bedding, wave ripple lamination, and load (pillow) structures. Towards the top of the middle portion, a 0.7m thick medium grained cross bedded sandstone has a scoured erosive contact with a heterolithic shale-siltstone bed. The heterolith on the other hand is wave ripple bedded and capped by a ferruginized firm ground.

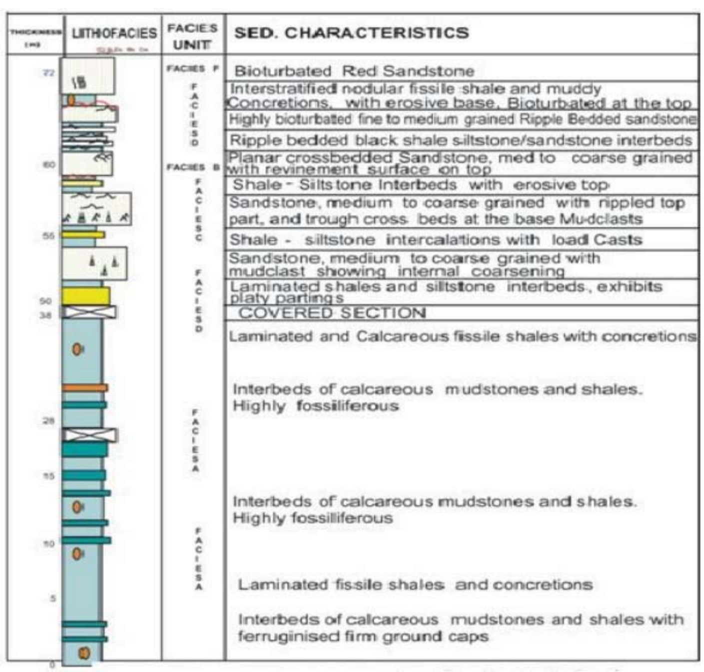

Fig. 5: litholog of Leru 1 along Enugu-PortHarcourt Road

The cross bedded sandstone beds are separated from the rest of the section by a rippled, 1m thick interbedding of black shale, siltstone and sandstone beds, overlain by another highly bioturbated fine to medium grained mega rippled sandstone bed (Fig. 7). The ripple bedded sandstone bed is quickly succeeded by interstratified bioturbated highly fissile shale and nodular mudstone bed. The nodular mudstone bed, made up of ironstone and calcareous concretions is overlain by a 1m-thick bioturbated red sandstone bed (Fig. 8) that caps the Leru I section and laterally extends towards Leru II where it becomes highly weathered. The bioturbated shale and nodular mudstone unit and the bioturbated red sandstone bed has a dip amount of 0^0 and overlies the $4\text{-}8^0$ dipping and truncated lower beds of Leru I (Fig. 9).

Towards the Leru/Isuochi Junction the older beds of the section except the bioturbated red sandstone units (of Leru 1), were abruptly truncated or tilted beneath an interstratified fissile shale-mudstone unit, which weathers to paper-like fragments (Fig. 10), and overlain by the bioturbated red sandstone bed, which is weathered at this section (and still profusely bioturbated). The red sandstone bed is subsequently overlain by a 5m thick horizontally bedded grey to dark grey, fissile mudstone-sand-shale heterolith, which becomes sandier up section, displaying a coarsening upward sequence as sand lenses in this portion become more frequent. The shales also weather to paper-like fragments. The topmost portion of this section consists of thick sequences of fine to medium grained sandstone beds. The lower sandstone unit is horizontally laminated with trace shales at the base (but the shales do not form distinct layers). The topmost sandstone units on the other hand, are lenticular and ripple laminated and arranged in stacks (bundles).

Fig. 6: Trace Fossil Assemblage in the Leru 1 Section

Fig. 7: Symmetric Mega Rippled Firm ground

Lithofacies Definitions and Descriptions:

A rock facies is a body of rock with specific characteristics. It may be a single bed, or a group of multiple beds. Ideally, it should be a distinctive rock that formed under certain conditions of sedimentation, reflecting a particular process, set of conditions or environments (Reading, 1978). De Raaf *et al*. (1965) distinguished facies by lithological, structural and organic aspects, detectable in the field. Facies may be defined on the basis of colour, bedding, composition, texture, fossils, sedimentary structures and geometry (Middleton, 1973; Selley, 1985). The facies so distinguished by such features would ultimately be given environmental interpretation. Facies may be subdivided into subfacies or grouped into facies associations. Facies grouped together into facies associations reflect groups of facies that are genetically related to one another, and which have some environmental significance (Collinson, 1963; Walker and Plint, 1992).

This concept of cyclic sedimentation or the idea that patterns of facies repeat throughout a succession, tends to emphasize similarities between sequences. The recognition of cycles formed the basis for the analysis of the two sections in Leru-Okigwe area.

After careful familiarization with exposures, the units were subdivided into six (6) lithofacies including Interstratified Calcareous Mudstone Shale Facies (A), Horizontal and Cross Stratified Sandstone Facies (B), Heterolithic Sandstone and Muddy Shale Facies (C), Heterolithic Shale and Siltstone Facies (D), Poorly Stratified Sandstone Facies (E) and the Calcareous Red Sandstone Facies (F). Informal designations (A, B, C, D, E, F) were given to the lithofacies for easy handling.

Fig. 8: Bioturbated Nodular Shale/Mudstone Bed, overlying Red Sandstone Bed.

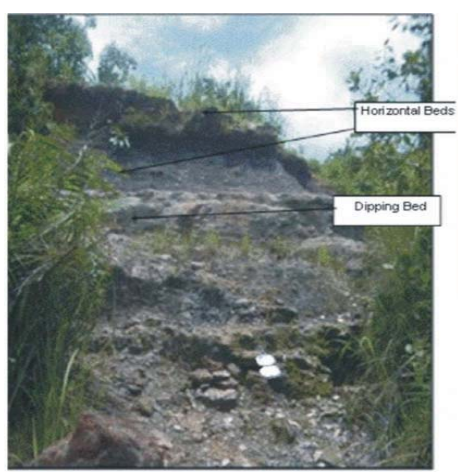

Fig. 9: Showing Horizontal Beds overlying Dipping Beds in the Leru Section

Interstratified Calcareous Mudstone and Shale Facies (A):

The Interstratified Calcareous Mudstone and Shale Facies forms units in the Leru I and II sections and are grey to dark grey, ferruginuous, subfissile to fissile and in places have interbedded thin calcareous mudstone beds and siltstone lenses. The shales are clayey in some places. These beds are laminated with mm-scale parallel lamination and lenticular in some sections; highly fossiliferous as evidenced by the presence of bivalves and large assemblage of palynomorphs like *Longapertites marginatus, Retidiporites magdalenensis, Cingulatisporites ornatus, Longapertites sp, Andalusiella sp, Senegalinium bicavactum, Ephedripites sp, Filtrotriletes nigerienis, Foveotriletes maganitae,* among others *(*Fig. 11). The mudstones are also light grey to dark grey, hard, massive and generally contain marine fossils. The centimeter - pyritic nodules, mostly elliptical in shape, occasionally occur sometimes as nodular beds/lenses or indiscriminately scattered nodules within the lamination/bedding planes. In some of the units, the nodules are calcareous.

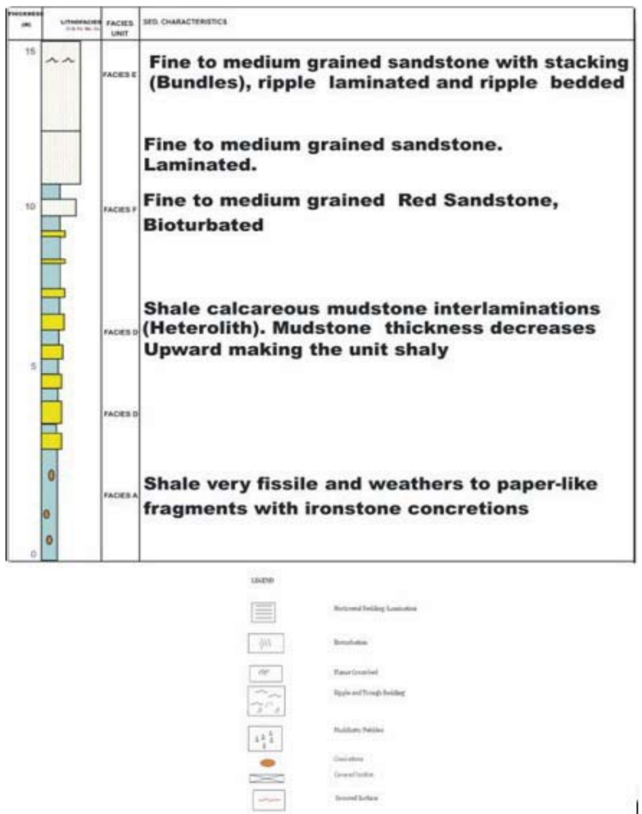

Fig. 10: litholog of Leru ll along Enugu-Port Harcourt Road

Horizontal and Cross Stratified Sandstone Facies (B):

This lithofacies in the sections of Nkporo Shale and Mamu Formation consists of medium to coarse and occasionally fine grained greyish white sandstones. The sandstones may be pebbly, poorly sorted and friable to weakly cemented. The poorly sorted grains are subangular to subrounded in shape. The facies assemblage generally displays a fining upward sequence. The main characteristic sedimentary structures are horizontal to planar/trough crossbeds with intervening mud drapes. The fossil assemblage of this facies includes *Skolithos* and *Ophiomopha* ichnogenera and some non-discrete horizontal burrows.

Heterolithic Muddy Shale and Sandstone Facies (C):

The lithology of Facies C exhibits sand-dominant interbeds of mudstones, shales and sandstones. The shales are dark grey with yellowish-brown mudstone concretions. The sandstones are mostly fine to medium grained, sometimes grading silt texture. They are horizontal to parallel laminated, trough cross-laminated and ripple laminated/bedded and heavily bioturbated. They are characterised by sharp bases which may or may not be loaded and are lenticular and tabular in form. In some cases especially in the thinner sand layers and interstratified muddy shale layers, the sharp bases are due to differences in grain sizes and colour; they rarely show incipient load casts, which are common on the thicker lenticular sand layers. Some of these thicker sandstones also show very shallow scouring. The facies shows a generally coarsening upward characteristic in the form of increase in the sand content and sand layer thickness upsection. This facies association is typical of Leru I section.

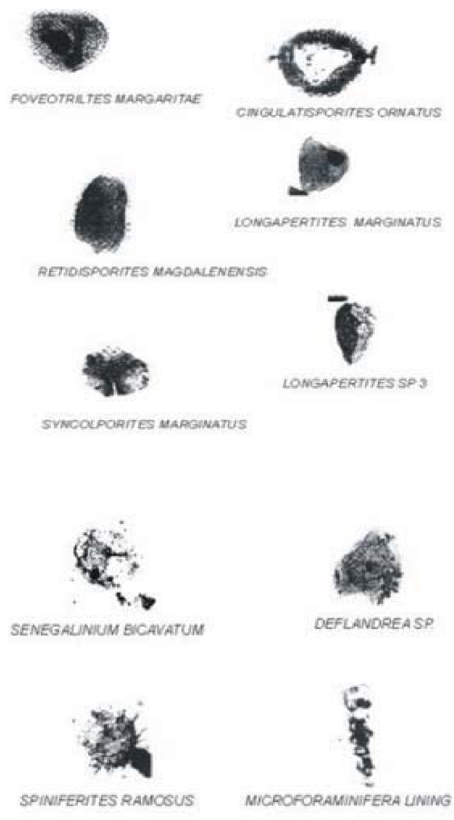

Fig. 11: Some Palynomorph Species in the Leru Section

Heterolithic Shale and Siltstone Facies (D):

Facies D is variously identified in the upper and lower sections of outcrops of Nkporo Shale and Mamu Formation in Leru I and II respectively. It comprises of a succession of siltstone-shale interbeds with sharp bases. They may be ripple or parallel laminated and bioturbated. Siltstone thicknesses and occurrence increase upwards in the sections. The shales are fissile and laminated with sharp bases and worm burrowed. Identifiable trace fossil assemblages are the horizontally to obliquely inclined burrows of *Thalassinoides paradoxicus* and a few benthic forms.

Poorly Stratified Sandstone Facies (E):

This facies comprises of fine–medium grained sandstones with scattered pebbles and admixtures of clay clasts, and characterized by poorly developed internal structures or faint indistinct stratifications. They sometimes exhibit stacking (bundles), and may be ripple laminated/bedded. The lithofacies occurs in the Leru II section.

Bioturbated Red Sandstone Facies (F):

The Bioturbated Red Sandstone Facies (F) were observed in the Leru I and II sections. They are fine to medium grained, clayey and ripple bedded in most places. They are highly bioturbated and were used as marker beds in sections where they crop out. They form onlap stratal termination pattern on scoured and/or erosional bases or top bedsets of the Nkporo Formation.

Facies and Facies Sequences: Depositional Environmental Interpretation:

The individual Facies Relationship Diagrams (FRD) of the two formations (Fig. 12) and the composite FRD of the Nkporo Formation (Fig. 13) show that the:

- Nkporo Formation is comprised of two distinct major facies assemblages represented by (a) A, D and F (b) B and C;
- Mamu Formation comprised of facies assemblages represented by A , D, B, F and E.

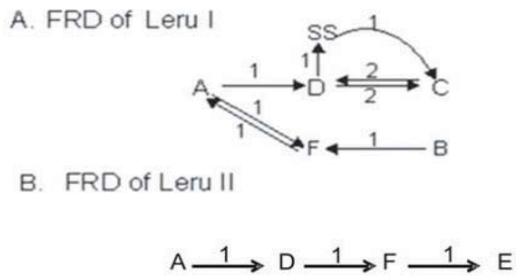

Fig. 12: FRD of Leru l and ll

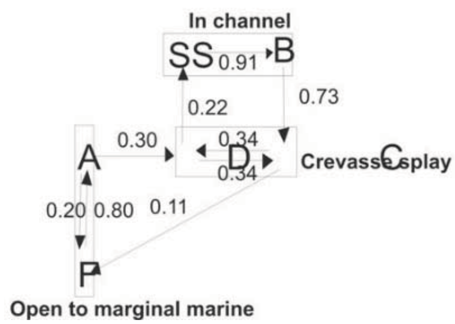

Fig. 13: Composite FRD of Nkporo Formation in the Study Area

Having defined the six lithofacies and established their preferred sequences with respect to their respective formations, the individual FRDs and composite FRD were interpreted based on their dominant physical (lithology, sedimentary structures and textural) and biological features and comparison with possible recent analogs. The resultant overall interpretations are compared with well documented facies models to buttress the inferred depositional interpretation. To avoid ambiguities, the depositional environmental and bathymertry range of Allen (1965, 1970; Fig. 14) was adopted.

Interpretation of Depositional Environments:

Facies A is interpreted as deposits in environments ranging from lagoonal to shallow, open marine shelf, in a transgressive marine setting (Visher, 1965, Nwajide and Reijers, 1996). The pyritic nodules, mostly elliptical in shape, occasionally occur sometimes as nodular beds/lenses or as sporadically scattered nodules within laminations/bedding planes. The presence of pyritic nodules, micritic and shelly limestone (calcareous) intercalations within the shale and mudstone lithofacies, support deposition in open marine settings (Nwajide, 2005). The preservation of primary lamination in the dark grey shales suggests absence of mud-eating benthos. Their formation in the Cretaceous is usually considered to have been related to warm climate and consequent stagnant oceans (Francis and Frakes, 1993). The low diversity and the dwarfed nature of forms suggest bottom anoxia for the dark grey shales. Such anoxia probably resulted from bottom water stagnation due to density stratification caused by high input of terrigenous organic matter and poor circulation (Petters and Ekweozor, 1982). Occasional climatic changes that formed chemical weathering and reduced clastic input, in conjunction with deepening, may have promoted the precipitation of microcrystalline calcite (micrite).

Planktonic and palynomorph assemblages recovered from Facies A comprised of foraminifera, ostracods, gastropods, among others, which indicate shelfal setting (Morkhoven, 1963; Heckel, 1972; Sliter, 1972).

The general absence of burrows in the sediments of this low energy shelf environment may also be attributed to hostile bottom conditions that precluded bottom organisms.

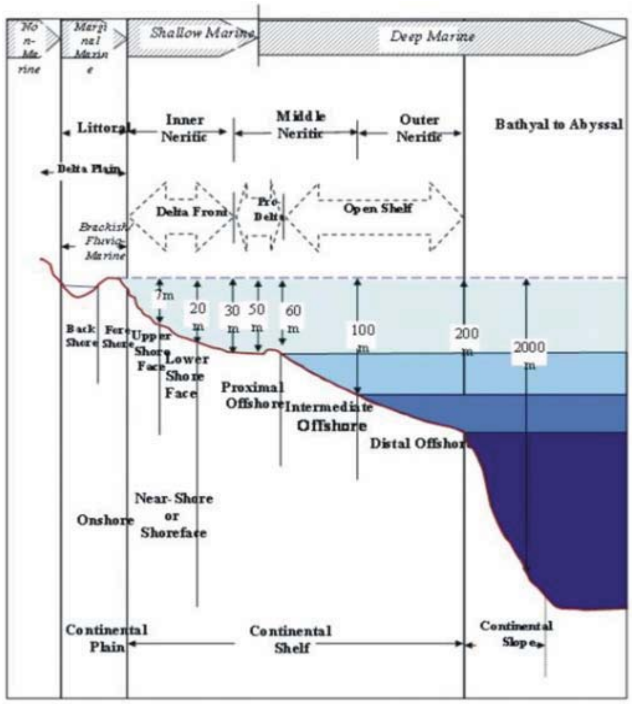

Fig. 14: Depositional Environments and Bathymetric Ranges (after, Alle, 1965; 1970)

The Heterolithic Sandstone and Muddy Shale Facies (C) overlying facies A in the studied sections is believed to be more continental than the underlying facies and hence interpreted as deposits of the lower delta front (distal bar) to nearshore environment with a considerable marine influence. The fluvial system flushes abundant clay to fine sand onto the delta front. These fine sediments in all probability are reworked by marine processes of moderate wave energy. The sedimentary structures (sharp base, horizontal lamination, minor trough cross-lamination and ripple cross-lamination, etc) and the textural variations within the sand layers (grading of some of the sands resulting in internal finning upward) indicate formation of the sandstones of this facies by single depositional episodes related to a waning current. Storm waves are thought to be responsible for the suspension, transportation and deposition of these sediments. That storm wave currents are capable of reworking fluvially flushed in clays and fine sands have been documented by Ager (1973), Goldring and Bridges (1973), Kumar and Sanders (1976). Other characteristics of facies C include overall coarsening upward sequences, with thicker sand units up section indicating a shallowing upward trend (progradational motif) in a marginal marine (Nearshore or Shoreface) environment.

The Shale and Siltstone Facies (D) in the sections, with little bioturbation and presence of shallow marine foraminiferal suites dominated by *Haplophragmoides* and *Ammobaculites* and abundant shallow marine palynormorphs is interpreted as prodelta or proximal offshore to shallow marine shelf deposits.

The Horizontal and Cross Stratified Sandstone Facies (B), Poorly Stratified Sandstone Facies (E), are interpreted as tidally influenced fluvial deposits in the estuarine to shelf environment.

The Horizontal and Cross Stratified Sandstone Facies (B) comprised of heterolithic sandstone and mudstone interbeds with minor interformational conglomerates that occasionally show finning and thinning upward packages and basal concave upward shapes. They are planar, trough cross bedded, sometimes, laminated and in general, poorly sorted sandstones. Additionally, abundant reactivation surfaces define foreset packages that are locally marked by mud drapes. The pebbles in Facies B are attributed to tidally-influenced fluvial channel. The presence of deposits with concave upward basal surfaces (scoured surface), though not exclusive to this facies, is suggective of flow confinement in channels. Where this feature was not observed, the finning/thinning upward facies successions are bounded by sharp, erosional basal surfaces, and attest to deposition during decreasing flow energy, as typical of channel fills. Facies B is therefore attributed to tidally-influenced fluvial channels formed in proximal estuarine areas, near the limits of the fluvial realm. It is believed that, weak tidal currents might reach these inner estuarine areas and rework sediments brought from the fluvial channel.

In consideration of the stratigraphic relationships, sedimentary structures, lithology, texture and micofauna, the Red Sandstone Facies (F) are interpreted as a barrier island (Shoreface to Beach) deposits, overlain and underlain by distal offshore mud and proximal offshore mud respectively. The Poorly Stratified Sandstone Facies (E) usually associated with Facies F is characterized by poorly developed internal structures or faint indistinct stratifications. They are interpreted as distributary channels/fluvial point bars.

Sequence Stratigraphic Intrepretations of Outcrop Sections

Leru Composite Sections I and II: Nkporo and Mamu Formations (Sequences I & II):

Sequence stratigraphic interpretation of outcrop-based data in the study area, is based on vertical relationship of lithofacies, macrofossil, palynological and foraminiferal assemblages, sequence stratigraphic model (Fig. 15) adapted from Van Wagoner *et al*., 1988, and existing stratigraphic framework of late Cretaceous to Tertiary sediments in southeastern Nigeria already established by Petters (1983), Nwajide and Reijers (1996), Doust and Omatsola (1990), Reijers *et al.* (1997), Obi (2000), Oboh-Ikuenobe *et al.* (2005). Each of the studied formations was analyzed in terms of main systems tracts, Sequence Boundaries (SB), Transgressive Surface of Erosion (TSE) and Maximum Flooding Surfaces (MFS).

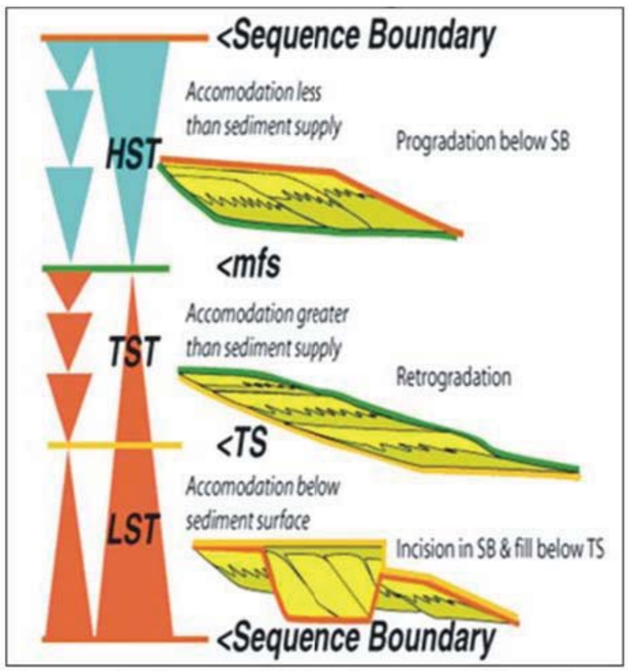

Fig. 15: Sequence Stratigraphic Model for the Interpretation of Systems Tracts and Accompanying Key Stratigraphic Surfaces (after, Van Wagoner *et al.,* 1988)

Sequence I:

Dolerites and/or thin drapes of older sediments that may underlie the Nkporo Shales in the Leru I section mark an angular unconformity, which had been recognized as a Sequence Boundary (SB) by Nwajide and Reijers (1996). Directly overlying the SB is Facies A, which displays a retrogradational stacking pattern, interpreted as deposits ranging from lagoonal to shallow, open marine shelf parasequence. This parasequence is a Transgressive Systems Tract (TST), inferred due to identified parasequence trend (Fig. 16) and presence of abundant marine to shallow marine fossils, like bivalve and gastropod imprints, large assemblages of foraminifera and palynomorphs, like *Haplophragmoides sp, Ammobaculites sp, Ammotium nkalagum, Ammotium nwalium, Bolivina anambra, Bolivina sp, Bulimina kugleri, Ostracoda, Amenantherites sp, Andalusiella sp,* *Deflandrea, etc.* This systems tract is enveloped by a Marine Flooding Surface (MFS) inferred at the 38m level that marks a turnaround from retrogradational to progradational parasequence stacking.

The Maximum Flooding Surface (MFS) separates the underlying Transgressive Systems Tract (TST) from the overlying Highstand Systems Tract (HST) of Facies C and D that comprise of Heterolithic Sandstone and Muddy Shale Facies and Heterolithic Shale and Siltstone Facies, respectively. These facies reflect aggradational to progradational stacking patterns, displaying almost equal thicknesses of shales/mudstones, sandstones and siltstone interlayering. The trend indicates parasequence association in a marginal marine environment.

Another Sequence Boundary (SB) is observed at about the 68m level of Leru I section after the Highstand Systems Tract (HST). The surface represents a clear-cut sharp discontinuity marked by differential erosion, bioturbations, direct evidence of subaerial exposure (hard ground), and an abrupt basinward shift of facies from proximal offshore settings to shoreface parasequences indicating minimum base level fall and increased sediment supply.

The surface additionally demonstrates an onlap stratal termination pattern in the Leru I section (Fig. 9). Onlap is formed above a sequence boundary, when horizontal strata (Dip amount =0º) overlie dipping strata (Van Wagoner *et al*., 1988; Fig. 17). This pattern was established between the overlying Red Sandstone (Facies F)/Nodular Shales (of Facies D) and the underlying fine to medium grained Ripple Bedded Sandstone (also of Facies D; Fig. 16). The onlap pattern is expressed as the dipping fine to medium grained Ripple Bedded Sandstone Facies/underlying Heterolith Facies with dip amounts ranging between 4 and 8^0 becomes truncated beneath the Red Sandstone Facies and the Nodular Shale Facies with a dip amount of approximately 0^0. These characteristics satisfy the conditions for the establishment of a Type 1 Sequence Boundary (SB) at that level, which marks the end of Sequence 1.

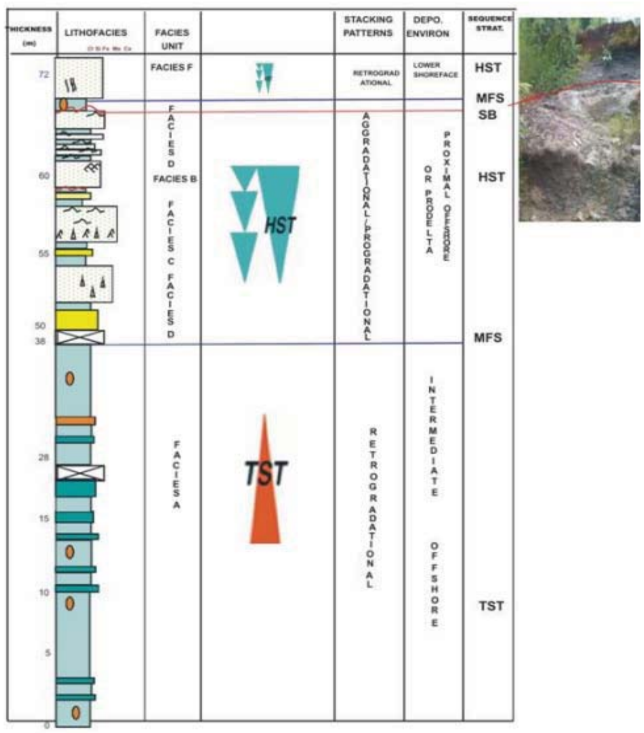

Fig. 16: Sequence Stratigraphic Interpretationsaf Leru 1 Section

Sequence ii:

Prodelta Nodular Shales of Facies (D) that subsequently overlies the SB at the Leru I section marks a return to retrogradational parasequences and an increase in water depth/sediment starvation. The parasequence reflects a Transgressive Systems Tract (TST), which also marks the beginning of another sequence in the Leru I section. The Lowstand Systems Tract, overlying the SB may have been removed by erosion or is positioned downdip of the basin. A Transgressive Surface of Erosion (TSE) is inferred to coincide with the Sequence Boundary (SB) at the 68m level (Fig. 16).

Presence of unusual burrowed surfaces by substrate-controlled ichnofossil suites e.g. *Glossifungites* ichnofacies associations of the *skolithos*, *ophiomorpha*, and *rhizocorallium ichnogenera* (Fig. 8) and abundant diagenetic materials (pyritic nodules and concretions) within the upper sections of the Nodular Shales of Facies (D) after the TSE/SB confers the upper sections of Facies A potential condensed section as established by Pemberton *et al*., 1992. Another Maximum Flooding Surface (MFS) is inferred at the end of the maximum deepening, enveloping the condensed section. The Bioturbated Red Sandstone Facies (F), directly overlying the MFS represents deposits of the early stage of decrease in accommodation after maximum deepening and flooding, which marks the on set of aggradational to progradationa parasequences of the Highstand Systems Tract (HST). The trend represents beach environment on a sandy, wave- or fluvially-dominated shoreline parasequence package.

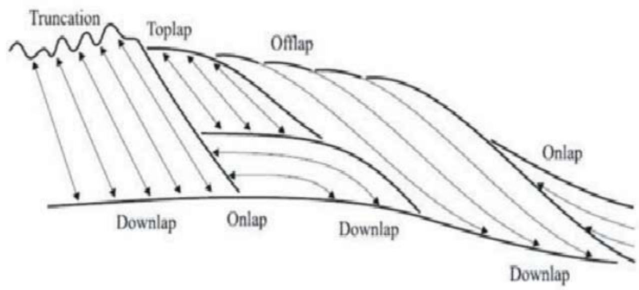

Fig. 17: Stratal Terminations Patterns (modified after, Van Wagoner *et al.,* 1988)

In the Leru II section, the Transgressive Systems Tract (TST) of the prodelta parasequence (Interstratified Calcareous Mudstone Shale Facies A) becomes interbedded with mudstones to present a retrogradational stacking pattern of open marine setting. The sequence is enveloped by the Maximum Flooding Surface (MFS) observed in Leru I section and now inferred at about the 9m interval in Leru II (Fig. 18). The Red Sandstone Facies (Facies F) inferred as deposit of beach on a sandy, wave- or fluvially-dominated shoreline parasequence, identified in the Leru I section now overlies Facies A in the Leru II section.

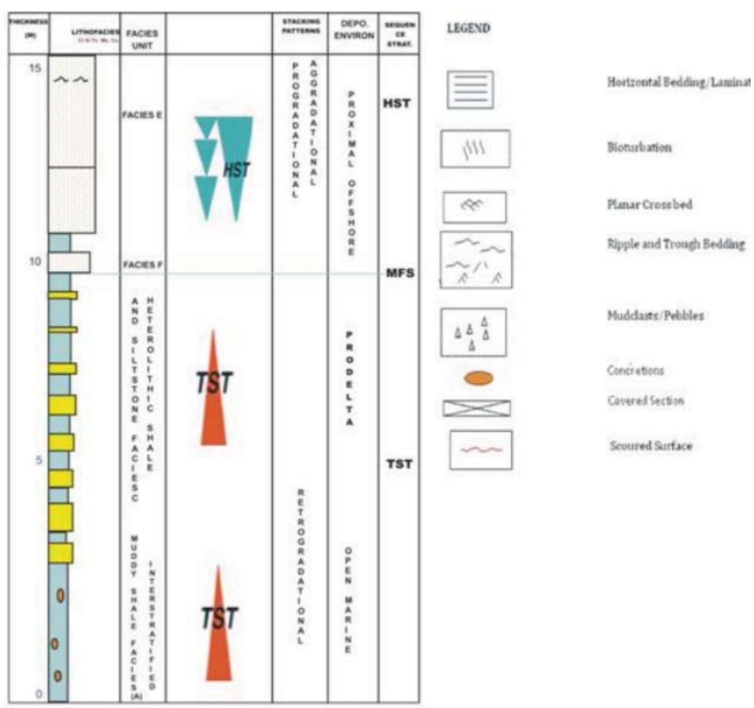

Fig. 18: Sequence Stratigraphic Interpretationsaf Leru ll Section

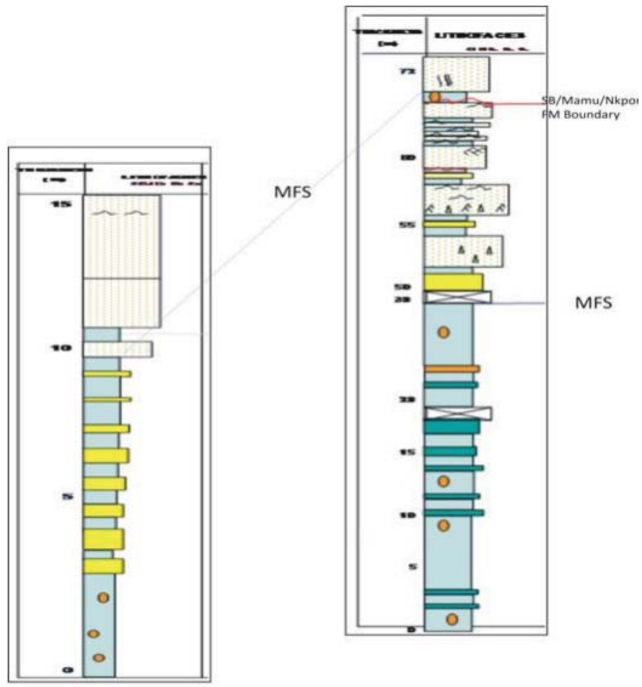

Fig. 19: Correlation of Leru l and ll Sections using (MFS)

Facies F is subsequently overlain by a the Poorly Stratified Facies (E) of very fissile mudstone-sand-shale heterolith, which becomes sandier up section displaying a coarsening upwards sequence as the sand lenses become more frequent. This progradational parasequence is interpreted as a Highstand Systems Tract (HST).

Discussions

Sequence Stratigraphy and Petroleum Potential of the Study Area:

A preliminary model is proposed, which relates the depositional sequences, accompanying systems tracts and identified boundaries to potential generation and accumulation of hydrocarbon in the study area.

The model presents only middle to outer shelfal patterns where rates of subsidence, sediment supply and sea level changes are favourable. Both transgressive and regressive sediment packages were preserved. Sand-rich sediments deposited during initial transgressions, were inferred from facies packages, stacking patterns, minimal and very low abundance of microfossils in outcrop sections. Microfossil assemblage in the sediment packages also indicated paleobathymetric minima. Sediments of the Transgressive Systems Tract (TST) that terminate at Maximum Flooding Surfaces were identified by upward increasing microfossil abundance and diversity and reterogradational stacking patterns that suggest upward increase in clay-shale contents.

On the shelf, relatively regular changes in facies assemblages, forming heteroliths of sand-shale packages with maximum shale content at the Maximum Flooding Surfaces (MFS) to minima at the next overlying sand package, are interpreted as representing the fore stepping, aggrading/prograding beds of the Highstand Systems Tracts.

The determination of types of systems tracts and identification of systems tracts associated with hydrocarbon reservoirs, seals and source rocks are predicted by sequence stratigraphy. The morphology and importance of reservoirs and seals vary greatly between systems tracts. The development of excellent reservoir sands and seals arise from shales of the upper Transgressive Systems Tract (TST) enveloping sands on the outer shelf characterized by the Highstand Systems Tract (HST). The alternation of Highstand Systems Tracts and Transgressive Systems Tract sands and shales respectively provides a union of reservoir and seal rocks that are essential for hydrocarbon accumulation and stratigraphic trapping.

Sequence Stratigraphy and Mapping in the Anambra Basin:

Sedimentary sequences of the proximal slope and basin floor complex tend to be dominated by the

Lowstand Systems Tracts (LST; Vail, 1987). The Lowstand Systems Tract (LST) was not observed in the outcrop sections studied. It is important to stress, however, that not all of the constrained surfaces or systems tracts may be present within any given sequence in an outcrop or well log. The absence of one or more surfaces or systems tracts may provide important clues to the relative position of the outcrop/well within the basin. For example, Lowstand Systems Tracts (LST) are commonly absent in updip areas where the transgressive Surface (TS) and Sequence Boundary (SB) are merged as one surface as is the case in the studied sections. In such areas, significant portions of the Lowstand and Highstand Systems Tract (HST) may have been eroded away and the SB is marked by the beginning of retrogradational stacking. In downdip areas, the Transgressive Systems Tract (TST) and Highstand Systems Tracts (HST) may be thin and relatively mud-rich, whereas the Lowstand Systems Tract (LST) may be characterized by an abrupt appearance of thick sandy facies. Many more variations are possible and many basins are characterized by a typical pattern of sequence architecture.

It is in the light of the forgoing that the studied Leru sections are considered to be positioned in the updip areas (i.e. fringe) of the Anambra Basin. This assertion is validated by the proximity of older and tectonically deformed Benue Trough Sediments near the Leru section.

Correlation of Leru I and II sections (Fig. 19) using the identified constrained surface has aided the delimitation of the probable contact between the Nkporo Formation and Mamu Formation in the studied sections. This boundary can conveniently be placed at the 68m level, where the onlap stratal pattern and the Sequence Boundary (SB) were established.

Some other contacts can also be established using sequence stratigraphic techniques. This will assist in the elimination of confusions between formation boundaries in the Anambra Basin thus helping to remap the Anambra Basin Fills.

Summary and Conclusion:

The study examined paleodepositional environments and sequence stratigraphic interpretation of Campano-Maastrichtian sediments in the Leru-Okigwe axis, Anambra Basin, southeastern Nigeria, in order to provide a framework for facies analysis, delineation of constrained surfaces and system tracts (depositional systems) thus providing a high degree of facies predictability for better mapping and improved analysis of play elements (source, reservoir, seal and traps) in the study area.

A total of six (6) lithofacies were distinguished from the two (2) outcrop sections studied. These include: Interstratified Calcareous Mudstone Shale Facies (A), Horizontal and Cross Stratified Sandstone Facies (B), Heterolithic Sandstone and Muddy Shale Facies (C), Heterolithic Shale and Siltstone Facies (D), Poorly Stratified Sandstone Facies (E) and Calcareous Red Sandstone Facies (F)

Interpretation of the paleodepositional environments for the different depositional units in the study area was achieved by integration of results of lithofacies analysis, sedimentary structures interpretation and biostratigraphic analyses. Based on these analyses an estuarine/lagoonal to tidal delta to shallow, open marine depositional model was proposed for the Nkporo Shale in the study area; an estuarine tidal delta to shallow marine paleodepositional environmental model was proposed for the Mamu Formation, which also has been described as a regressive offlap sequence of sandstone, siltstone, mudstone, shales, and sandy shales with interbedded coal seams.

Sequence stratigraphic interpretation based on vertical facies relationships, biostratigraphic analysis in the study area and on existing stratigraphic framework of the late Cretaceous to Tertiary successions in southeastern Nigeria established middle to outer shelfal depositional patterns with Sequence Boundaries, Transgressive Surface of Erosion (TSE) and Maximum Flooding Surfaces enclosing Highstand and Trangressive Systems Tracts. The packages (Systems Tracts) formed distinct complexes consisting of a number of genetically linked retrogradational, progradational and aggradational deltaic systems. Major architectural facies elements of the delta systems in the packages include: shoreface deposits, channel fills, and prodelta shales in sediment starved areas. One complete and one incomplete 3rd order sequences were identified in the late Cretaceous sediments in Leru I and II. Two Type-1 Sequence Boundaries (SB), one Transgressive Surface of Erosion and two chronostratigraphic significant surfaces (Maximum Flooding Surface, MFS) were delineated in the outcrop sections. The sequence boundary identified at the 68m level is a textbook example of an onlap stratal termination pattern in outcrops. The surface was used to mark the boundary between the Nkporo Shale and the Mamu Formation.

The determination of types of systems tracts associated with hydrocarbon reservoirs, seals and source rocks are predicted by sequence stratigraphy. The morphology and importance of reservoirs and seals vary greatly between systems tracts. The development of excellent reservoir sands and seals arise from shales of the upper Transgressive Systems Tract enveloping sands on the outer shelf characterized by the Highstand Systems Tract.

The alternation of Highstand Systems Tracts and Transgressive Systems Tract sands and shales respectively provides a union of reservoir and seal rocks that are essential for hydrocarbon accumulation and stratigraphic trapping. This union has been identified in the study area and will help to improve the hydrocarbon prospectivity of the Leru-Okigwe axis in the Anambra Basin

REFERENCES

Ager, D.V., 1973. The Nature of the Stratigraphical Record. Macmillian, London, pp: 114.

Akaegbobi, I.M. and M. Schmitt, 1998. Organic Facies, Hydrocarbon Source Potential and Reconstruction of the Depositional Paleoenvironment of the Campano–Maastrichtian Nkporo Shale in the Cretaceous Anambra Basin

Akaegbobi, I.M. and A.O. Boboye, 1999. Textural, Structural Features and Microfossil Assemblage Relationship as a delineating criteria for the stratigraphic Boundary between Mamu Formation and Nkporo Shale within the Anambra Basin, Nigeria. *NAPE Bulletin,* 14(2): 193-207.

Allen, J.R.L., 1965. Late Quarternary Niger Delta and adjacent areas-Sedimentary Environments and Lithofacies. *American Association of Petroleum Geologists Bulletin,* .49: 547-600.

Allen, J.R.L., 1970. Studies in Fluvial Sedimentation: A comparison of Finning-Upward Cyclotherms, with special reference to coarse-member Composition and Interpretation. *Jour. of Sedimentary Petrology*, 40: 298-323.

Amajor, L.C., 1987. Paleocurrent, Petrography and Provenance Analysis of the Ajali Sandstone (Upper Cretaceous). Southeastern Benue Trough, Nigeria. Sed. Geology, 54: 47-60.

Amajor, L.C., 1991. Sedimentary Facies Analysis of the Ajali Sandstones (Upper Cretaceous), Southern Benue Trough. *Nig. Jour. Min. Geol*. 21(1&2.): 171-176.

Benkhelil, J., 1982. Benue Trough and Benue Chain. *Geol. Mag*., 119: 155-168.

Burke, K., 1972. Longshore Drift, Submarine Canyons and Submarine Fans in the Development of Niger Delta: *American Assoc. Petrol. Geologists*, 56: 1975-1983.

Collinson, J.D., 1963. The Sedimentology of the Grindslow Shales and the Kinderscout Grit: A Deltaic Complex in the Namurian of Northern England. *J. Sed. Pet.,* 39: 194-221.

Dessauvagie, T.F.J., 1974. A geological map of Nigeria scale 1: 1,000,000. Nig. Min, Geol and Metallurgical Society 1.

De Raaf, J.F.M., H.G. Reading and R.G. Walker, 1965. Cyclic Sedimentation in the lower Westphalian of north Devon. *Sedimentology*, 4:. 21-74.

Doust, H. and E. Omatsola, 1990. Niger Delta. *In*: Edwards, J.D., Santogrossi, P.A. (Eds.), Divergent/Passive Margin Basins. *American Association of Petroleum Geologists Memoir*, 48: 201-238.

Emery, K., O.E. Uchupi, J. Philips, C. Brown and J. Masle, 1975. Continental Margin off West Africa, Angola to Sierra Leone, *AAPG Bull.,* 59: 2209-2265.

Francis, J.E. and L.A. Frakes, 1993. Createaceous Climates. *In* Wright, V.P., (ED.). *Sedimentology review*, 1: 17-30.

Genik, G.J., 1993. Petroleum Geology of Cretaceous–Tertiary Basins in Niger, Chad and Central African Republic. *AAPG Bull*., 77: 1405-1434.

Goldring, R and P. Bridges, 1973. Sublittoral Sheet Sandstones. *Jour. Sed. Pet*., 43: 736-747.

Grove, A.T., 1951. Land use and soil conservation. Bull Geol. surv. Nigeria, 21: 54p. Hailwood, E.A. 1989; Magnetostratigraphy: Geol. Soc. Special Report 19, Blackwell Scientific pub., Oxford, pp: 84.

Heckel, P.H., 1972. Recognition of Ancient Shallow Marine environment. In Recognition of Ancient Sedimentary Environments. SEPM, Spec. Published., 16: 226-286.

Hoque, M. and M.C. Ezepue, 1977. Petrology and Paleography of the Ajali Sandstone Journal. Sed Petrology; 46: 579-594.

Hoque, M., C.S. Nwajide, 1985. Tectono-sedimentological evolution of an elongate intracratonic basin (aulacogen): The case of the Benue Trough of Nigeria. *Journal of Mining and* Geology, 21: 19-26.

Kumar, N. and J.E. Sanders, 1976. Characteristics of Shoreface Storm Deposits: Modern Ancient examples. *J. Sedim. Petrl.* 46: 145-165.

Middleton, G.V., 1973. Johanne's Walther's Law of the Correlation of Facies. *Geol. Soc. Amer. Bull.,* 84: 979-988.

Mode, A.V. and K.M. Onuoha, 2001. Organic Matter Evaluation of the Nkporo Shale, Anambra Basin, from Wireline logs. *Global J. App. Sci*., 7: 103-109.

Morkhoven Van. F.P.C.M., 1963. Post-Palaeozoic Ostracoda: their Morphology, Taxonomy and economic use. *Elsevier Publ. Co*. New York. pp: 476.

Murat, R.C., 1972. Stratigraphy and Paleogeography of the Cretaceous and Lower Tertiary in Southern Nigeria. In Dessauvagie, T.T.J., and white man, A.J. (Eds), African Geology, University of Ibadan Press, Nigeria, pp: 251-266.

Nwachukwu, S.O., 1972. The Tectonic Evolution of the southern portion of the Benue Trough, Nigeria: Geology Magazine, 109: 411-419.

Nwajide, C.S. 2005. Anambra Basin of Nigeria: Synoptic Basin Analysis as a Basis for Evaluatin its Hydrocarbon Prospectivity, *In* Okogbue, C.O., (Ed.), Hydrocarbon Potentials of the Anambra Basin. *PTDF Chair,* pp: 2-46.

Nwajide, C.S. and T.J.A. Reijers, 1996. Sequence Architecture in Outcrops. Examples from the Anambra Basin, Nigeria. NAPE Bull., 11(01): 23-32.

Nwajide, C.S. and T.J.A. Reijers, 1997. Sequence Architecture of the Campanian Nkporo and the Eocene Nanka Formations of the Anambra Basin, Nigeria. NAPE Bull., 12(01): 75-87.

Obi, G.C., 2000. Depositional Model for the Campanian-Maastrichtian Anambra Basin, southern Nigeria. Unpublished Ph.D. Thesis, University of Nigeria, Nsukka, pp: 291.

Oboh-Ikuenobe, F.E., O. Yepes, O.D Leg, 1997. Palynofacies analysis of sediments from the Coˆte d~Ivoire-Ghana transform margin: preliminary correlation with some regional events in the Equatorial Atlantic. Palaeogeography, Palaeoclimatology, Palaeoecology, 129: 291-314.

Oboh-Ikuenobe, F.E., G.C. Obi and C.A. Jaramillo, 2005. Lithofacies, Palynofacies and Sequence Stratigraphy of Paleogene Strata in southeastern Nigeria; Journal of African Sciences, 38: 99-108.

Ojoh, K.A., 1990. Cretaceous Geodynamic Evolution of the southern part of the Benue Trough (Nigeria) in the equatorial Domain of the south Atlantic Stratigraphy Basin Analysis and Paleogeography. *Bull. Centres Rech. Explor-Prod, Elf-Aquaintine,* 14: 419-442.

Olade, M.A., 1975. Evolution of the Nigerian Benue Trough (Aulocogen): A Tectonic Model. *Geol*. *Mag*., 12: 575-583.

Pemberton, S.G., J.A. MacEachern, R.W. Frey, 1992. Trace fossil facies models: environmental and allostratigraphic significance. In: Walker, R.G., James, N.P. (Eds.), Facies Models: Response to Sea Level Change. Geological Association of Canada, pp: 47-72.

Petters, S.W. and J.J. Edet, 1996, Shallow shelf and anoxic facies in the Late Campanian – Early Maastrichtian of S. E. Nigeria: Geologie de I'Afrique et de I'Atlantque Sud Actes Colloques Angers 1994, pp: 219-233.

Petters, S.W., 1983. Gulf of Guinea planktonic foraminiferal biochronology and geological history of the South Atlantic. Journal of Foraminiferal Research, 13: 32-59.

Petters, S.W. and C.M. Ekweozor, 1982. Petroleum Geology of the Benue Trough and southeastern Chad Basin, Nigeria. AAPG Bull., 66: 1141-1149.

Reading, H.G., 1978, Sedimentary Environments and Facies: New York, Elsevier Press, pp: 557.

Reijers, T.J.A., S.W. Petters, C.S. Nwajide, 1997. The Niger Delta Basin. *In*: Selley, R.C. (Ed.), African Basins. Elsevier, Amsterdam, pp: 151-172.

Reyment, R.A., 1965. Aspects of the Geology of Nigeria. Ibadan University Press., pp: 145.

Selley, R.C., 1985. Ancient Sedimentary Enironments. Chapman and Hall, London, pp: 317.

Sliter, W.V., 1972. Cretaceous Foraminiferas-Depth Habits and their Origin. *Nature*, 239: 514-515.

Tattam, E.M., 1944. A Review of Nigerian Stratigraphy. Geol. Sur. of Nigeria., pp: 27-47.

Vail, P.R., 1987. Seismic Stratigraphy interpretation procedure, *in*. A. W. Belly (ed.), Atlas of Seismic Stratigraphy, v 1. AAPG Studies in Geology, 27: 1-10

Van Wagoner, J.C., H.W. Posamentier, R.M. Mitchum, P.R. Vail, J.F. Sarg, T.S. Loutit, and J. Hardenbol., 1988. An overview of Sequence Stratigraphy and key definitions, in C. W. Wilgus *et al*., (Eds.), Sea level changes: an integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication, 42: 39-45.

Visher, G.S., 1965. Grain size distribution and depositional processes. Journal Sed. Petrol., 39: 1074-1106.

Walker, R.G. and A.G. Plint, 1992. Wave- and storm-dominated shallow marine systems. In: Walker, R.G., James, N.P. (Eds.), Facies Models: Response to Sea Level Change. Geological Association of Canada, pp: 219-238.

Weber, K.J. and E. Dakoru, 1975. Petroleum geology of the Niger Delta. 9th Petroleum Congress. Tokyo., 2: 209-221.

Whiteman, A.J., 1982. Nigeria. Its Petroleum Geology, Resources and Potentil. Graham and Trotman, London, 39p Wright, J. B., 1968, South Atlantic continental drift and the Benue Trough: *Tectonophysics*, 6: 301-310.