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OSCILLATORY RIPPLES, EVALUATION OF ANCIENT WAVE CLIMATES AND EPIEROGENY IN THE ANAMBRA BASIN AND THE AFIKPO SUB-BASIN, SOUTHEASTERN NIGERIA

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ABSTRACT

The analyses of geometrical properties of wave ripple marks from the Campanian – Early Maastrichtian sandstone units of the Nkporo and Enugu Formations in the Afikpo Sub-basin and the Anambra Basin respectively, have permitted a reconstruction of the ancient oceanographic conditions, epierogenic patterns and paleogeographic history of the basins. The Nkporo Sea in the Afikpo Sub-basin was characterized by low bottom water orbital velocity (47.75 cm/s - 51.42 cm/s) and low wave periods (1.36 – 4.35 s). The minimum and maximum estimated wavelengths vary from 1.46m -1.70m, and 26.05m - 29.44m respectively. The wave heights range from 0.41m – 0.47m while the wave power is from 0.66 kw/m – 0.78 kw/m. The bathymetric estimates for the rippled deposits range from 14.82 – 16.62 m, suggesting shallow water depths for the units. The Campanian Sea of the Anambra Basin had low bottom water orbital velocity waves (57.17 – 58.41 cm/s) and low to moderate wave periods (1.63 – 5.90 s). Minimum and maximum wavelengths of 2.10 - 2.19 m wavelengths of 50.74 – 54.23 m were estimated for the ancient sea respectively. The wave heights varied from 0.61 – 0.64 m while the wave power varied from 2.04 – 2.32kw/m. The paleowater depth varied from 31.35m – 33.65m. These estimated wave climates and water depths indicated that the Campanian – Early Maastrichtian Seas were shallow and marked by low to moderate hydrodynamic energy conditions. The short to intermediate wave periods indicates a 40 – 50 km fetch while the relatively higher wave power in the ancient Anambra Sea indicates a larger and wider basin than the ancient Afikpo Sub-Basin Sea. The epierogenic behavior interpreted from the maximum paleowater depths and shoreface stratigraphic thicknesses confirm dominance of the ancient Anambra Sea by retrogradational base level dynamics while the ancient Afikpo Sea, with an initial prograding shoreline, later became retrogradational.

INTRODUCTION

Vortex-type oscillatory ripples are common in shallow marine to considerable water depths on the continental shelves of all the oceans of the world (Miller and Komar, 1980b). The geometry and morphology of the ripples have provided useful data in the evaluation of local paleowave climates and trends in ancient wave dominated environments as well as in the prediction of epierogenic movement related to basin subsidence (Harms, 1969; Diem, 1985). Evans (1941) on the basis of studies on wave–induced oscillatory ripples, provided insight into the inter–relationships between oscillation ripple geometrical properties, namely ripple spacing, bifurcation, steepness, height, symmetry/asymmetry and wave conditions such as velocity, period, height, among others and bathymetry. Recently, Harms (1969), Tanner (1971), Komer and Miller (1973) Komar (1974), Clifton (1976), Allen J.R.L (1979), Miller and Komar (1980a and b), Allen, P.A (1984, 1981a and b) and Diem (1985) have independently established theoretical models and empirical relationships between oscillatory flow conditions and the resulting ripple geometries. These have been used to estimate ancient wave climates and paleobathymetry in oceanic and lacustrine regimes.

In this study, the guidelines, analytical equations and models which guarantee narrow paleowave climate ranges have been used to evaluate data from oscillatory ripple marks (Komar and Miller, 1973; Komar, 1974; Miller and Komar, 1980a; Allen, P.A, 1981b and Diem, 1985). The objectives are to interprete the local paleowave climates and trends as well as to infer from them, the relative rates of vertical epierogenic movements in relation to the Campano-Maastrichtian basin subsidence, shoreline movements and relative sizes of the ancient ocean basins. Data from oscillatory ripple marks were collected from the rippled sandstone units of the Nkporo and the Enugu Formations (Campanian – Maastrichtian) exposed at Afikpo, Etiti Edda, Leru and Ikem (Fig. 1)

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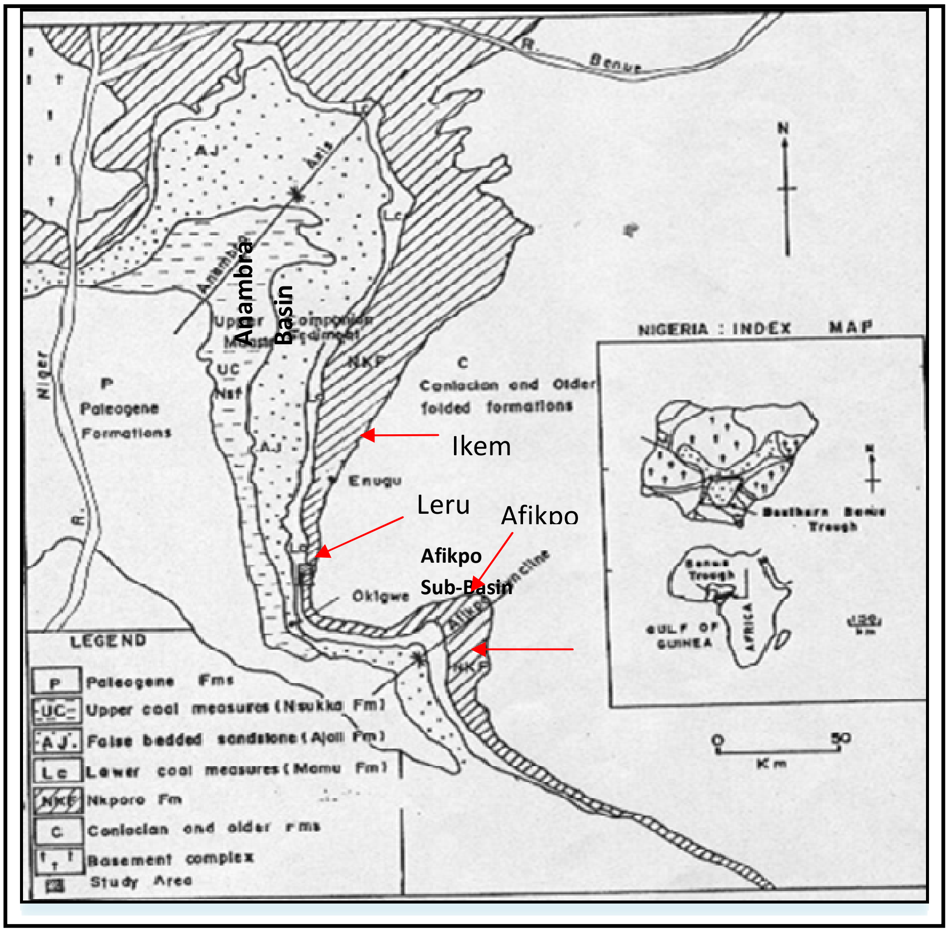


Fig. 1: Geological Map of Anambra Basin and the Afikpo Sub-basin showing the Campanian – Maastrichtian sedimentary Package and Location of study area.

Geologic Setting

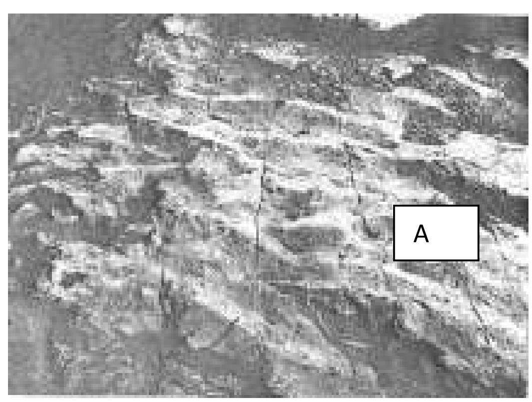
The Nkporo and the Enugu Formations dated Campano-Maastrichtian (Simpson, 1954; Reyment, 1965; Zarborski, 1983), are the basal lithostratigraphic units outcropping in the Afikpo Sub-basin and the Anambra Basin, respectively.

The Nkporo Formation is composed dominantly of dark grey to black shale and thin fossiliferous limestone interbedded with the Afikpo Sandstone (Simpson, 1954). The Enugu Formation also contains the Owelli Sandstone in the south and the Otobi Sandstone in the north (Simpson, 1954).

Reijers *et al.* (1995) has interpreted the sediments of the Nkporo Formation as deposits of shallow marine shelf setting, which graded upwards into channelized low energy marshes. Analyses of the upward-coarsening (UC) and upward-fining (UF) motifs of the Afikpo Sandstone have shown that they comprise of estuarine fluvial/tidal channel and shoreface deposits in a fluvio-deltaic setting (Okoro, 2009).

Oscillatory ripple morphology

Morphologically, oscillation ripples are symmetrical or near symmetrical, straight and continuous crested ripples that show frequent bifurcations (Collinson and Thompson, 1982; Reineck and Singh, 1973). Fig.2a and b shows wave-formed ripple marks exposed in the Leru and Etiti Edda outcrop sections respectively in the study area. The critical parameters that control oscillation ripple characteristics include sediment calibre (grain size and grain density), near- bed orbital diameter and near-bed orbital velocity of water particles. These determine the ripple mark symmetry/asymmetry, ripple size (spacing or wavelength), ripple height (amplitude), steepness and degree of bifurcation in natural environments.



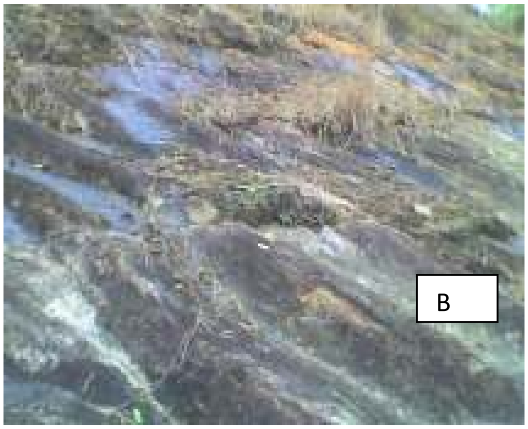


Fig.2A: Wave ripple marks on the sandstone outcrop in Leru. B: Megaripple marks in Afikpo Sandstone voutcrop besibe the Amoba Primary School, Etiti Edda.

METHODOLOGY

A minimum of twenty rippled bed geometries were measured from each of the four (4) outcrop localities in order to select equilibrium-type ripple marks for hydrodynamic analysis. Grain size distribution of the rippled sediments was obtained by sieving and applying the inclusive graphic method of Folk and Ward (1957) to obtain the median grain size of the sediments. The wave ripple parameters used in this study are illustrated on Fig 3.

The mean ripple spacing (λ), mean ripple height (H), and median grain size (D_m),

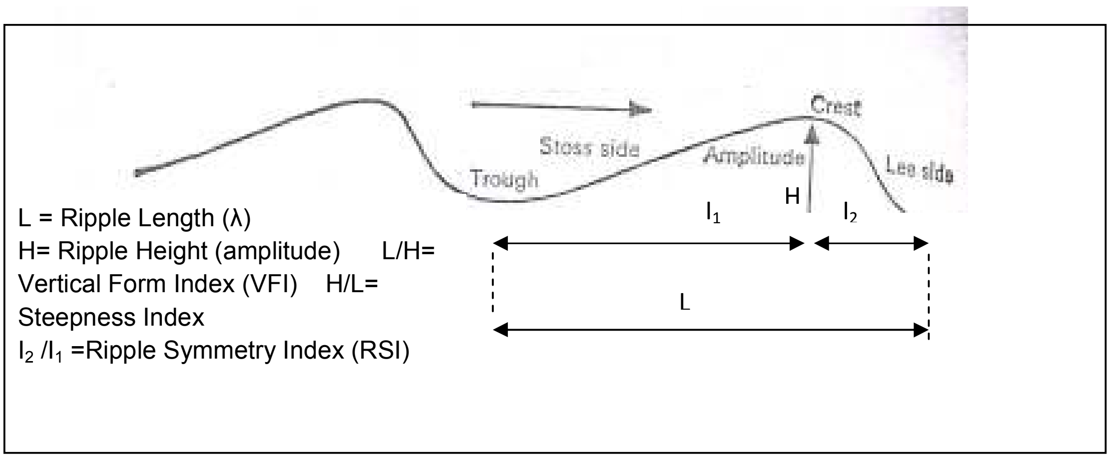


Fig.3: Sketch diagram showing ripple parameters measured in the field.

were obtained by averaging several measurements from the selected equilibrium-type vortex ripples with appropriate ripple symmetry index (RSI) of 1.4 or less, vertical form index (VFI) of 9.0 or less and steepness index (H/λ) of 0.15. The fluid density (ρ_w) for non-turbid water was taken as 1.00 gm/cm^3; the grain density (ρ_g) for clean quartz sand as 2.65 gm/cm^3 and the acceleration due to gravity (*g*) as 980 cm/sec^2 (Diem, 1985). Table 1 shows the mean ripple mark data collected from the four localities of this study.

Table1: Field data collected from rippled surfaces at the four locations

Location	**Afikpo**	**Etiti Edda**	**Leru**	**Ikem**
Av. Ripple spacing, L (in cm)	13.80	15.66	20.20	19.35
Av. Ripple Height, H (in cm)	2.25	2.39	3.00	2.04
Av. Steepness index, H/L	0.17	0.15	0.15	0.16
Av. Vertical from index L/H	6.00	6.55	6.73	6.60
Av. Ripple symmetry index RSI	1.25	1.04	1.10	1.07
Av. d_o/D_m	786	730	1480	1418
Av. Median Grain size, D_m of Rippled sediment. (cm)	0.027	0.033	0.021	0.021
Sediment Grain density, P_g (clean quartz sand)	2.65gm/cm^3	2.68 gm/cm^3	2.65gm/cm^3	2.65 gm/cm^3
Fluid density, (ρ_w)	1.00gm/cm^3	1.00gm/cm^3	1.00gm/cm^3	1.00gm/cm^3

The analytical methods of Miller and Komar (1980a and b), Komar and Miller (1973), Allen, P. A. (1981b), Diem (1985), Komar (1974) and Le Mehaute (1976) were applied in estimating the paleowave climates (Table 2).

The equations employed depended on how accurately they would conceptualize natural paleowave conditions and environments. The equations must be able to define the narrowest paleowave and paleodepth ranges possible. The basic equation for near-bed bottom orbital diameter, $d_o = \lambda/0.65$ of Miller and Komar (1980b) was used in this study, provided that the ripple spacing (λ cm) and the grain size (D_m μ) satisfy the relationship $\lambda < 0.0028D_m^{1.68}$. The threshold velocity to initiate grain movement (U_t) was estimated with the equation of Komar and Miller (1973) while the maximum bottom orbital velocity (U_m) was calculated using the equation of Diem (1985) (Table 2). The minimum and maximum wavelengths (L_{min} & L_{max}) wave height (H_w), wave power (P) and paleowater depth (h), were also estimated with the analytical equations of Diem (op. cit) (Table 2). The maximum possible deep water wave length (L_o) was estimated with the equation of Allen, P. A. (1981b) (see also Table 2).

RESULTS

The results of these analyses are given in Table 3.

Bottom orbital diameter (d_o):

This was estimated using the relationship $d_o = \lambda/0.65$ (Miller and Komar, 1980b). The bottom orbital diameter is the maximum length of the oscillatory orbit of the near-bottom water particles (Clifton, 1976). It is dependent on the wave period, T; wave height, H_w; and water depth, h and basis for determining other paleowave parameters. The estimated orbital diameters that generated the ripples in the ancient Campanian Sea of the Afikpo Sub-basin were 20.77cm and 24.09 cm as calculated from the Afikpo and Etiti Edda outcrops respectively. Estimates for the ancient Anambra Basin Sea were 31.10 cm and 29.78 cm as determined at Leru and Ikem respectively. (Table 3).

Bottom orbital velocities (U_t and U_m): These represent both the threshold velocities required to initiate sediment movement and that at which rippled beds

Table 2: Analytical equations for paleowave climate and paleodepth estimations for four locations in the Afikpo Sub-basin and the Anambra Basin

Paleowave parameter	Symbol	Equation	Source
1. Bottom orbital diameter	d_o	$d_o = \lambda / 0.65$. provided $\lambda < 0.0028\ D^{1.68}$	Miller & Komar (1980a & b)
2. Threshold velocity	U_t	$U_t = [0.21(d_o/D_m)^{1/2}(P_s - P_w)\ gD_m/P_w]^{1/2}$. Provided D_m <0.50mm.	Komar & Miller (1973)
3. Maximum bottom orbital velocity	U_m	$U_t < U_m \leq \sqrt{0.112gd_o}$	Diem (1985)
4. Wave period	T	$\pi \sqrt{8.9d_0/g} \leq T < \pi\ d_o/U_t$	Diem (1985) Komar (1974)
5. Maximum possible deepwater wave length	L_{too}	$L_{too} = (ngd_o)^2\ (2U_t^2)$	Allen, P. A. (1981b)
6. Maximum and minimum water wavelength	L_{max} and L_{min}	$L_{max} = L_{too}/\sqrt{2} * \sqrt{1+\sqrt{\frac{1-80.4U_t^4}{(g^2do^2)}}}$ $L_{min} = L_{too}/\sqrt{2} * \sqrt{1-\sqrt{\frac{1-80.4U_t^4}{(g^2do^2)}}}$	Diem (1985)
7. Water depth	h	$h < (L_{max}/2\pi)\ \text{arcosh}\ (0.142L_{max}/d_o)$	Diem (1985)
8. Water depth range at L_{max}	h_R	$(L_{max}/2\pi)\ \arctan\ (L_{max}/L_{min}) < h \leq (L_{max}/2\pi)\ \text{arcosh}\ (L_{max}\ 0.142/d_o)$	Diem (1985)
9. Wave height	H_w	$H_w < d_o \sinh(2\pi h / L_{max})$	Diem (1985)
10. Wave power	P	$P = \{P_w\ gH_w^2/16\} * (1+4\pi h)/L_{max} \sinh(4\pi h / L_{max}) * \sqrt{(gL_{max}/2\pi)} \tanh(2\pi h/L_{max})$	Diem (1985).

Table 3: Paleowave climate, paleodepth and wave energy estimates for four locations in Afikpo Sub-basin and Anambra Basin

Paleowave Parameters	McGregor Hill section (Afikpo Sub-basin)	Etiti Edda section (Afikpo Sub-basin)	Leru section (Anambra Basin)	Ikem section (Anambra Basin)
1. Bottom orbital diameter (d_o)	21.23 cm	24.09 cm	31.10 cm	29.78 cm
2. Threshold velocity (U_t)	15.95 cm/s	17.40 cm/s	16.56 cm/s	16.39 cm/s
3. Maximum bottom orbital velocity (U_m)	≤ 47.75 cm/s	≤ 51.42 cm/s	≤ 58.41 cm/s	≤ 57.17 cm/s
4. Wave period (T)	1.37s ≤ T < 4.10s	1.47s ≤ T < 4.35s	1.67s ≤ T < 5.90s	1.63s ≤ T < 5.71s
5. Maximum deepwater wave length (L_{too})	26.09 m	29.49 m	54.23 m	50.82 m
6. Maximum deepwater wave length (L_{man})	26.05 m	29.44 m	54.19 m	50.78 m
7. Minimum deepwater wave length (L_{min})	1.46 m	1.70 m	2.19 m	2.10 m
8. Paleowater depth (h)	< 14.82 m	< 16.62 m	< 33.65 m	< 31.35 m
9. Paleowater depth range h_R	3.15 – 14.82 m	3.56 - 16.62 m	7.09 - 33.65 m	5.78 - 31.35 m
10. Wave height, H_w	0.41m	0.47 m	0.64 m	0.61 m
11. Wave power	0.66 kw/m	0.78 kw/m	2.32 kw/m	2.04 kw/m

converts to flat beds respectively, (Komar and Miller, 1973; Clifton, 1976 and Allen, J. R. L., 1979). The threshold velocity, $U_{t,}$ has been estimated with the equation of Komar and Miller (1973). The U_t for the ancient Campanian Sea of the Afikpo Sub-basin was 15.95cm/sec. and 17.40 cm/sec. at Afikpo and Etiti Edda, respectively. The maximum orbital velocities ($U_{m)}$ are determined with the equation of Diem (1985) as ≤ 47.75 cm/sec. and ≤ 51.42 cm/sec. for both localities, respectively (Table 3). The U_t has been indicated at 15.94 cm/sec and 15.31 cm/sec., while the U_m are estimated at ≤ 58.43 cm/sec and ≤ 57.17 cm/sec for the ancient Anambra Basin Sea (Table 3). The U_m values obtained in this study are well within the orbital velocities in the ripple existence field (Diem, 1985).

Wave period (T): The wave period (T), is the time interval required for the periodic wave motion to complete a cycle and begin to repeat itself. It has been estimated using the equation of Komar (1974) and Diem (1985) for the upper and lower bounds, respectively. The result shows that the minimum wave periods for the Afikpo Sub-basin Sea vary from 1.36 sec to 1.47 sec while the maximum vary from 4.09 to 4.35 sec. The minimum wave periods for the Anambra Basin Sea vary from 1.63 sec to 1.67 sec while the maximum varies from 5.71 sec to 5.90 sec.

Water wavelengths (L_∞, L_{max}, L_{min}): The wavelength of surface water is the distance between successive wave crests in the direction parallel to wave propagation. The maximum possible deep water wavelength L_∞, has been estimated in this study using the equation of Allen, P. A. (1981b). The L_{oo} for the Afikpo Sub-basin Sea ranged from 26.05 to 29.49 m. That for the Anambra Basin Sea ranges from 50.82 - 54.23 m. The minimum and maximum wavelengths, L_{min} and L_{max} respectively in the ripple-existence field are estimated using the equation of Diem (1985). The results show that the $L_{min\ for}$ the Afikpo Sub-basin Sea varies from 1.46 to 1.70 m, while the L_{max} varies from 26.05 to 29.44 m. The L_{min} for the Anambra Basin Sea varies from 2.10 to 2.19 m while the L_{max} varies from 50.78 to 54.19 m.

Wave height (H_w): The wave height is the oscillatory amplitudes of the waves as they move. It has been estimated by applying the analytical equations of Diem (1985) (Table 2). The estimated wave height (H_w) at Afikpo and Etiti Edda in the Afikpo Sub-basin Sea were 0.41 m and 0.47 m respectively while the wave heights estimated from the outcrops at Leru and Ikem in the Anambra Basin Sea were 0.64m and 0.61m respectively (Table 3). Wave height (H_w) is directly controlled by maximum wavelength (L_{max}) and water depth (h) (Clifton, 1976) which impose a constraint on natural limits of wave height. For stable waves, $H_w/L_{max} \leq 0.142$ and $Hw/h < 0.78$, otherwise the wave will be unstable and will tend to break (Collins, 1976). The estimated wave heights, H_w, for all the four localities fall within the above limits.

Water depth (h): The maximum ancient water depths were estimated using the analytical equation of Diem (1985). The paleowater depths from the Afikpo and Etiti Edda outcrop sections in the Afikpo Sub-basin were estimated at ≤ 14.82 m and ≤ 16.62 m respectively. The paleowater depths reached a maximum of 33.65 m and 31.35 m for Leru and Ikem rippled sections in the Anambra Basin Sea, respectively.

Wave power (P): Wave power or energy flux per unit wave length (P), has been estimated using the analytical equation of Le Mehaute (1976) (Table 2). The wave power for the lower stratigraphic surface mapped from the Afikpo Sandstone has been estimated at 0.66 Kw/m. Wave power was estimated at 0.78 Kw/m for the upper stratigraphic surface mapped at Etiti Edda beside the Amoba Primary School,

The wave power in the Anambra Basin Sea was estimated at 2.32 Kw/m and 2.04 Kw/m from the Leru and Ikem outcrops, respectively (Table 3).

DISCUSSION

The Late Campanian – Early Maastrichtian Sea has been estimated to be relatively shallow based on estimated bottom orbital diameters and water depth of 14.82 m - 33.65 m using oscillatory ripple events from the Afikpo Sandstone of the Nkporo Formation and the Owelli and Otobi Sandstones of the Enugu Formation. Relatively low wave periods ranging from 1.36 – 4.35 s in the Afikpo Sub-basin Sea and 1.63 – 5.90 s in the Anambra Basin Sea are also indicative of shallow water environments of deposition. Wave periods of 2 s – 4 s (short period waves) are more prevalent in lakes, enclosed bays, estuaries and shallow shelves and can ripple sediments up to a depth of 25 m (Clifton, 1976). Intermediate period waves of 5 s – 8 s are common along margins of enclosed or semi-enclosed seas and open ocean coasts and have been found to ripple sediments up to 100 m water depth (Clifton, 1976; Diem, 1985).

The estimated wave periods of 1.36 s – 4.35 s in the Afikpo Sub-basin Sea and 1.63 – 5.90 s in the Anambra Basin Sea suggest shallow (inner shelf) sedimentation, possibly in the tidal flat to shoreface regimes. This corroborates interpretations based on ammonite and microfossil evidences for these formations (Reyment, 1965; Zarboski, 1983; Petters and Edet, 1996; Gebhardt, 1998).

Wave periods have been shown to be related to fetch (Collins, 1976). Fetch is the distance away into the sea/ocean where a wave is generated. It is a reflection of the size of the sea or basin (Allen, P. A., 1981a; Clifton, 1976). Diem (1985) and Allen, P. A (1981a) described wave periods of less than 10 s as indicative of fetch between 40 – 50 km. The 1.36 – 5.90 s (short to intermediate) wave periods estimated from the ripple marks suggest limited fetch of less than 40 km. The Anambra Basin Sea with a higher wave period is interpreted to have a deeper offshore fetch than the Afikpo Sub-basin Sea, and therefore bigger (deeper and wider) than the later. This is corroborated by the higher wave powers of 2.32 - 2.04 Kw/m estimated for the Anambra Basin Sea. It is also indicative of a deeper and wider depositional basin than the Afikpo Sub-basin Sea with lower wave powers between 0.66 – 0.78 Kw/m. The Afikpo Sub-basin Sea characterized by smaller water wave lengths is also interpreted to be a smaller basin with smaller volume of water mass than the Anambra Basin Sea with higher water wave lengths. Paleogeographically, the Campanian – Early Maastrichtian Sea of the Anambra Basin was larger, wider and more voluminous than the Afikpo Sub-basin Sea.

Diem (1985) used water depth estimated from wave-formed ripple marks and stratigraphic thickness to evaluate epierogenic character and to predict the relative movements of the shoreline (retrogradation and progradation). Diem (1985) used the relationship between the maximum water depth (h) and the stratigraphic thickness (x) of shoreface beds between the rippled surface and the overlying marine beds to predict relative rates of basin subsidence in the Lower marine molasses deposits of Switszerland. Accordingly, if the ratio of the stratigraphic thickness of shoreface deposits above the rippled surface (x) to the estimated water depth (h) is less than 1, then the rate of space creation or subsidence exceeded the rate of sediment supply. The result is relative base level rise and shoreline retrogradation (or transgression). When $x/h>1$, then subsidence rate lags behind rate of sediment supply resulting in shoreline progradation (or regression). The lithologic profiles of the rippled sections evaluated in the Afikpo Sub-basin showed that the thickness of the upward- coarsening (UC) shoreface sands (x), above the rippled surfaces were logged at 20.80 m (Ebonyi Hotel section) and 10.40 m (Amoba Primary School section) (Okoro, 2009). In the Leru section, the marine black shale occurs 11.50 m above the rippled beds while at the stream channel section at Ikem, the ammonite bearing shales occur 20.72 m above the rippled beds. The maximum water depths (h), estimated for these sections are 14.82 m, 16.62 m, 33.65 m and 31.35 m for the Afikpo, Etiti Edda, Leru and Ikem sections, respectively (Table 3). The x/h ratio for the lower stratigraphic section at the Mcgregor Hill section is 1.4. This suggests an initial period of progradation where the rate of sediment supply exceeded the rate of creation of accommodation space in the basin. At the upper stratigraphic level (Amaoba Primary School Section), the x/h ratio dropped to 0.62 suggesting subsidence rate greater than rate of sediment supply and a retrogrational (transgressive) shoreline movement. In the Leru and Ikem areas, $x/h < 1$, suggesting that the rate of subsidence was higher than the rate of creation of accommodation space, favoring shoreline retrogradation. The progradational situation noted in the lower stratigraphic interval in the Afikpo Sub-basin is consistent with depositional geometries during early base level rises in estuarine depositional settings (Catuneanu, 2007). From this analysis, the base level dynamics appears to favour a dominant retrogradational shoreline behavior during the Late Campanian – Early Maastrichtian when the Nkporo Formation of the Afikpo Sub-basin and its lateral equivalent, the Enugu Formation in the Anambra Basin were deposited.

CONCLUSIONS

The results of this study have shown that the Campanian – Maastrichtian Seas of the Afikpo Sub-basin and the Anambra Basin were relatively shallow. The estimated threshold orbital velocities and wave powers indicate a low to moderate hydrodynamic energy regime for the ancient Seas. The wave periods indicate estuarine to shallow marine environments, limited fetch of less than 40 km and a relatively narrower and less voluminous Afikpo Sub-basin than the Anambra Basin. Epierogenic character indicates that subsidence rates and creation of accommodation space outpaced the rate of sediment supply and ensured transgressive (or retrogradational) shoreline movements for most part of the Late Campanian – Early Maastrichtian period.

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