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VORTEX WAVE RIPPLES FROM AFIKPO SANDSTONE, AFIKPO SUB- BASIN, SOUTHEASTERN NIGERIA: SIGNATURE TO PALEOWAVE HISTORY AND ANCIENT SEA CONDITION

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Abstract

Vortex wave ripples from the clayey, fine grained, laminated sandstone lithofacies of Afikpo Sandstone have been studied for the purpose of reconstruction of the paleowave characteristics and ancient sea condition. The methodology adopted include: field measurements and calculations of parameters using analytical formulae. Result show that the average wavelength, height and orbital diameter of the wave ripples are 16.50 cm, 2.48 cm and 24.42 cm respectively. The ripples began to form on the sand of median grain size of 0.014 cm in diameter at a threshold orbital velocity of 14.75 cm/s and reached its maximum at bottom orbital velocity of 51.31 cm/s. The Campanian- Maastrichtian Afikpo Sea was characterized by a wave period of 1.47 – 5.25s suggesting low to moderate wave conditions. Deep water wavelength on the average varied from 3.42 to 45.51 m and height from 0.49 to 6.50 m. Average bathymetric estimate for the ancient sea is 22.76 m. This is suggestive of shallow water depth for the epeiric sea. The average wave energy and power in deep water range from 0.37 to 61.95kJ and 0.40 to 297.40 kW respectively. The low wind speed of 4.19m/s with duration of 8.85hrs and a fetch of 51.81 km are also characteristics of the epiericsea.

Keywords: *Vortex wave ripples, Paleowave history, Ancient sea, Sandstone, Period, Velocity*

Introduction

Symmetrical wave ripples are small bedform which are essentially straight- crested and partly bifurcated with length varying from 0.9 to 200 cm, and height from 0.3 to 23 cm. It has a ripple index which varies from 4 to 13 (Reineck and Singh, 1980). Wave ripples form on sandy bottom when the velocity of wave propagation exceeds about 9 cm/s and disappears when the velocity exceeds about 90 cm/s (Inman, 1957).

Wave ripple marks have proven to be a very useful tool in the reconstruction of paleodepth, paleowave climate and ancient sea conditions (e.g Harm, 1969; Tanner, 1971; Komar, 1974; Allen, 1979, 1980, 1982; Allen, 1981a &b,1984; Miller and Komar, 1980a; Clifton and Dingler, 1984; Diems, 1985; Okoro and Arua, 1990; Mode and Samaila, 1993; Okoro et al., 2011).

Allen (1981a) employed wave generated sedimentary structures in the nearshore lacustrine sediments in the estimation of ancient wave conditions and interpreted water depths, formative wave periods as well as length and width of the lake. Allen (1984) also reconstructed wave conditions as well as width of depositional environment from wave ripple marks. Clifton and Dingler (1984) summarized the published research on wave- formed structures and outlined the procedure in using them in the interpretation of ancient depositional environments. Diems (1985) evaluated paleodepth and paleowave conditions from wave ripple marks. He noted the significance of paleodepth and paleowave climate estimation in the reconstruction of vertical movements related to basin subsidence, local and regional ancient climate trend and the basin shape.

Okoro et al. (2011) made use of the analytical methods of Komar and Miller (1973), Komar (1974), Miller and Komar (1980a &b), Allen (1981b) and Diems (1985) in the evaluation of ancient wave climate and epierogeny using oscillatory wave ripples from the Anambra Basin and Afikpo Sub- Basin.

In this paper, more recent analytical equations of Sorensen (2006), Coastal Engineering Manual (2008) as well as Reeve et al. (2012) will be employed in the estimation and interpretation of deep water wave characteristics and the condition of the Campanian- Maastrichtian Afikpo Sea.

The analytical equations are clearly stated in the methodolology. The result that will be obtained using these expressions will be compared with that of Okoro et al. (2011). Wind speed and duration, momentum flux and energy density will also be calculated in this work.

Regional Tectonics and Stratigraphic Setting

The evolution of the Afikpo Syncline and the Anambra Basin are linked to the development of a Benue Trough which was installed as a failed arm of trilete rift (aulocogen). The development of the Benue Trough occurred during the breakup of the Gondwana supercontinent and the opening of the southern Atlantic and Indian Oceans in the Jurassic (Burke et al., 1972; Benkelil. 1982, 1989; Hoque and Nwajide, 1984; Fairhead, 1988). Two cycles of marine transgressions and regressions from the middle Albian to the Coniacian filled the trough with mudrock, sandstones and limestones with an estimated thickness of 3,500 m (Murat, 1972; Hoque, 1977). These sediments constitute the Asu River Group and the Mfamosing Limestone (Albian- Cenomanian), the Eze- Aku Group (Turonian) and the Awgu Shale (Coniacian). The sediments were folded and uplifted during the Santonian epeirogenic tectonics (Murat, 1972) into the Abakaliki- Benue Anticlinorium with a simultaneous subsidence of the Anambra Basin and the Afikpo Syncline to the northwest and southeast of the folded belt respectively (Murat, 1972; Burke, 1972; Mode and Onuoha, 2001).

Nwajide (2013) considered the Afikpo Syncline as part of Anambra Basin on the basis that both are product of the same Santonian thermotectonic event in the southern Nigeria. Also, that there is no physical barrier or separation between the two areas and no tectonic definition of the Afikpo area into a depression separate from the area to the northwest. He noted the sediment packages for the two areas to be common and stratigraphically continuous southeastwards across to Afikpo area and Calabar Flank.

The Campanian- Maastrichtian Nkporo Group constitutes the basal lithostratigraphic unit in both the Anambra and the Afikpo Sub- Basin (or Syncline) and overlies an angular unconformity. The Afikpo Sandstone, a formation of Nkporo Group (Table 1) constitutes the basal component of the Sub- basin in the re- entrant between the Oban Massif and the Abakaliki anticlinorium (Nwajide, 2013). The formation in its type area south of Afikpo town lithologically consists of sandstones and shales (Akaa, 1995).

Methodology

The length and height of 15 symmetrical wave ripples recorded on clayey, fine grained, laminated sandstone lithofacies of Afikpo Sandstone were measured (Fig. 2) and their corresponding ripple indices calculated. Two samples of the laminated fine grained sandstone lithofacies were collected for sieve analysis and the photograph of the wave ripple marks was taken (Fig. 3).

The sandstone samples collected were carefully disaggregated and sieved using a Ro- Tap sieve set. The median grain (ϕ_{50}) was estimated from the cumulative curves of the samples based on Folk and Ward (1957). Average median grain size value was taken.

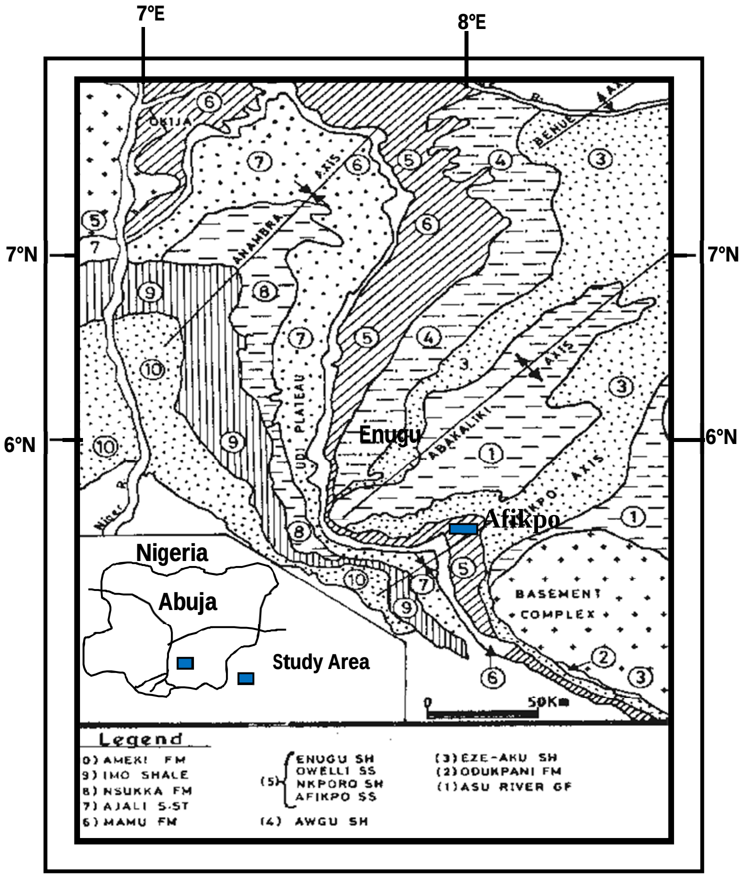


Fig. 1: Geologic map of southeastern Nigeria showing the study area (modified from Hoque, 1977)

Table 1: Lithostratigraphic units of the Anambra Basin (after Nwajide, 2013)

Age	Basin	Stratigraphic unit						
Thanetian	Niger Delta	Imo Formation						
Danian								
Maastrichtian	Anambra Basin	Coal Measures	Nsukka Fm.					
			Ajali Fm.					
			Mamu Fm.					
Campanian		Nkporo Gp	Nkporo Fm.	Enugu Fm.	Owelli Sst.	Afikpo Sst.	Otobi Sst.	Lafia Sst.
Santonian	Southern Benue Trough	Awgu Fm						

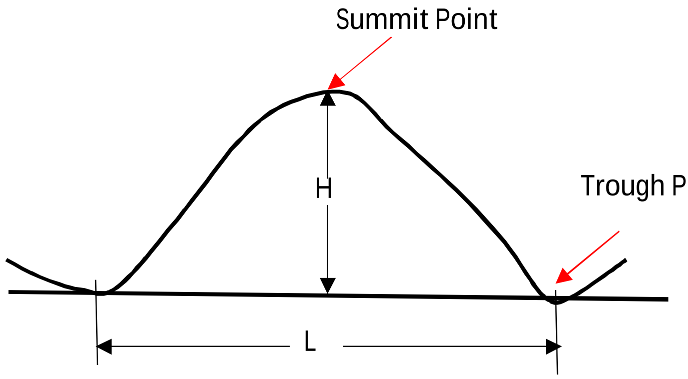


Fig. 2: Symmetrical wave ripple length and height measurement in the field

Fig. 3: Symmetrical wave ripples from the Afikpo Sandstone exposed at Ebonyi Hotel, Afikpo.

Wave ripple parameters employed in paleowave climate estimation include the ripple spacing (wavelength), the ripple height and the median grain diameter of the rippled sandstone. The ripple index (vertical form index) and orbital diameter were calculated using the ripple spacing and ripple heights while the median diameter was deduced from sieve analysis. The analytical equations used in the work is shown in Tables 2a and b.

Table 2a: Analytical methods employed in the calculation of wave parameters

S/N	Wave parameter	Method
1.	Orbital diameter (d_o) in cm	$d_o = \lambda/0.65$ (Miller and Komar, 1980; Allen, 1984) ------------- 1
2.	Vertical form index (VFI)	L/H --- 2 Where L = ripple length and H= ripple height
3.	Threshold orbital velocity (U_{min}) in cm/s	U_{min} for $D_m < 0.5$ mm $= [0.21 (d_o/ D_m)^{1/2} * (\rho_{s-} \rho)g\, D_m/\rho]^{1/2}$ ----------- 3 Where D_m = median grain size, ρ_s = density of quarz sand given as 2.65g/cm^3, ρ = density of water given as 1.00g/cm^3, acceleration due to gravity (g) = 980 cm/S^2 (Komar and Miller, 1973).
4.	Maximum bottom orbital velocity (U_{max}) in cm/s	$U_{max} \leq \sqrt{0.112 g d_o}$ ----------------------------- 4 Diems (1985)
5.	Wave period (T) in sec.	$T = \pi d_o/U_{max}$ ---------------------------------- 5 Le Mehauté et al. (1969)

Table 2b: Analytical methods for estimation of wave characteristics in deep water (after Sorensen, 2006; Coastal Engineering Manual, 2008; Reeve et al., 2012)

S/N	**Parameter**	**Method**
1.	Relative depth (d/L) in m	$d/L > 1/2$, $kd > \pi/2$ for deep water --------- 6
2.	Deep water wave celerity in m/s	$C_o = L_o/T = gT/2\pi$ ----------------------------- 7
3.	Deep water wavelength in m	$Lo = gT^2/2\pi = C_oT$ ---------------------------- 8
4.	Deep water group velocity in m/s	$Cg_o = ½\ C_o = gT/4\pi$ ---------------------------- 9
5.	Deep water energy density (E)	$E_o = \rho g H_o^2/8$ ------------------------------------10
6.	Deep water wave power (P)	$P_o = E_o\, Cg_o = ½\ E_o\, C_o$ ------------------------ 11
7.	Radiation stress for deep water	$Sxx_o = ½\ E$, $Syy_o = 0$ ------------------------ 12
8.	Wave steepness for deep water	H_o/L_o --- 13
9.	Breaker line	$h_b = 1.28\ H_b$ ------------------------------------ 14
10.	Breaking index (Υ)	$\Upsilon = H/h = 0.78$ ------------------------ 15
11.	Wind speed (U_w) in m/s	$U_w = (H_f g/ \lambda_5)^{1/2}$ -------------------------- 16 Where U_w= wind speed, H_f = wave height, g = acceleration due to gravity and λ_5 = dimensionless constant = 0.27 (Coastal Engineering Manual, 2008)
12.	Wind Duration (t)	$T = 77.23X^{0.67}/U^{0.34}g^{0.33}$ -------------- 17 (Coastal Engineering Manual, 2008)
13.	Fetch	From $H = 0.0016g^{-1/2}UX^{1/2}$ (Smith, 1991) -- 18 $X = H^2g/(0.0016U)^2$ ------------ 19 Where X = fetch, H = wave height and U = wind speed

Result

The vortex wave ripples occur on the clayey, fine grained, laminated sandstone which was underlain by very coarse to pebbly clayey sandstone lithofacies. It occurs as a straight- crested ripple with minor bifurcations. The troughs are commonly rounded while the crests are sharp (Fig. 3). The wavelength (L) ranges from 10 to 29 cm, whereas the height or amplitude (H) varied between 1.2 and 3.5 cm (Table 3).

Table 3: Wave ripple data from the Afikpo Sandstone

S/N	Length (cm)	Height (cm)	VFI (L/H)	Orbital diameter (d_o)	Ripple Type
1	22.00	3.00	7.33	33.84	Vortex
2	29.00	3.00	9.67	44.61	Post- vortex
3	22.00	1.70	12.94	33.84	Post- vortex
4	19.00	3.50	5.43	29.23	Vortex
5	11.00	2.00	5.50	16.92	Vortex
6	14.00	1.70	8.24	21.54	Post- vortex
7	12.00	1.20	10.00	18.46	Post- vortex
8	19.00	2.80	6.79	29.23	Vortex
9	20.00	2.50	8.00	30.77	Post- vortex
10	19.00	2.70	7.04	29.23	Vortex
11	14.00	2.00	7.00	21.54	Vortex
12	13.00	2.30	5.65	20.00	Vortex
13	18.00	2.30	7.83	27.69	Post- vortex
14	12.00	1.50	8.00	18.46	Post- vortex
15	10.00	1.50	6.67	15.38	Vortex

The average median grain size calculated from the sieve analysis of the sandstone samples is 0.014 cm. This falls within the range of fine sand.

According to Reineck and Singh (1980), symmetrical wave ripples have wavelength (L) of between 0.9 and 200 cm, heights (H) that ranges from 0.3 to 23 cm and VFI (L/H) which varies from 4 to 13. The L, H and VFI of the fifteen wave ripple data gathered in this study fall within these specified ranges and thus are symmetrical wave ripples. The symmetrical wave ripples were distinguished into two types namely; the vortex and post- vortex wave ripples (Table 3) using the criteria that vortex wave ripples have VFI of less than 7.5 whereas the VFI of the post vortex ones exceed 7.5 (Sleath, 1975, 1976; Allen, 1981, 1984). Vortex ripples have been described as steep trochoidal ripple marks with VFI of less than 7.5 formed under ocean waves (Miller and Komar, 1980) whereas post- vortex ripples are flatter- topped ripple marks with VFI greater than 7.5 formed at high oscillatory shear stresses (Allen, 1984). This shows that the symmetrical wave ripple marks have wide range of ripple steepness. Based on Allen (1981), the use of ripple mark data with wide range of ripple steepness in the reconstruction of ancient wave conditions is hazardous and unacceptable because it gives a wide range of estimated orbital diameters and thus do not supply reasonable estimates of wave conditions. Therefore, vortex ripple marks are preferred for such reconstruction because they are better indicators than the post- vortex ripple marks.

Out of the fifteen (15) symmetrical wave ripple data gathered from the field, eight (8) meet the criteria for vortex ripples (Table 3). Analysis of data also show that the orbital diameter of near-bottom- beds generally increased with increasing ripple wave lengths (L) measured in the field (Table 3).

The values of the wave parameters calculated from the vortex wave ripples are shown in Table 4.

Table 4: Wave parameters calculated from the vortex wave ripples of Afikpo Sandstone

S/N	Ripple length (L in cm)	Ripple height (H in cm)	Orbital diameter (d_o)	U_{min} (cm/s)	Umax (cm/s)	Period (T in s)
1.	22.00	3.00	33.84	15.28	60.94	1.75- 6.96
2.	19.00	3.50	29.23	14.73	56.64	1.62- 6.24
3.	11.00	2.00	16.92	18.97	43.09	1.23- 2.80
4.	19.00	2.80	29.23	14.73	56.64	1.62- 6.24
5.	19.00	2.70	29.23	14.73	56.64	1.62- 6.24
6.	19.00	2.00	21.54	13.64	48.62	1.39- 4.96
7.	13.00	2.30	20.00	13.39	46.85	1.34- 4.69
8.	10.00	1.50	15.38	12.54	41.09	1.18- 3.85
AVE	**16.50**	**2.48**	**24.42**	**14.75**	**51.31**	**1.47- 5.25**

Wave period (T): This is the time interval between the passage of two successive wave crests or troughs at a given point (U.S. Army Corps of Engineer, 2002). Wave period is measured in second. The linear wave theory (Le Méhauté et al., 1969) employed in the calculation of T gave an average values of between 1.47 and 5.25s (Table 4). According to Ippen (1966), as wave propagates from deep water into the shore, the wave period remains constant because the number of waves passing sequential points in a given interval of time must be constant.

Paleowave Climate and Ancient Sea Condition

Water waves are mechanical waves that propagate along the water surface and with the restoring force provided by gravity (Mei, 1989; Lamb, 1995). The ancient deep water wave characteristics and paleo sea condition estimated is shown in Table 5.

Wavelength, wave height, wave celerity and water depth

The wavelength is the horizontal distance between identical points on two successive wave crests or two successive wave troughs (U.S. Army Corps of Engineers, 2002). Result shows that the average deep water wavelength varied from 3.42- 45.51m, wave height from 0.49- 6.50m, wave celerity from 2.29- 8.18m/s and group velocity from 0.99- 4.09m/s. The average bathymetric estimate for the ancient Afikpo Sea is about 22.76 m deep (Table 5a).

Energy density, wave power and momentum flux (radiation stress)

Energy density or specific energy is the total average wave energy per unit surface area. The average estimated value for the energy density vary from 0.37- 61.95kJ

Wave power or wave energy flux is the rate at which energy is transmitted in the direction of wave propagation across a vertical plane perpendicular to the direction of wave advance and extending down the entire depth. The estimated average for wave power vary from 0.40- 297.40kW (Table 5a).

Momentum flux or radiation stress is defined as force per unit area which arises because of excess momentum flux due to the presence of waves. This results from orbital motion of individual water particles in the wave and in which the particle motions produce a net force in the direction of propagation (S_{xx}) and a net force at right angles to the direction of propagation (S_{yy}). More momentum flux are recorded in the direction of wave advance because velocity (U) is in the direction of wave propagation under the wave crest when the instantaneous water surface is high (wave crest) and in the opposite direction when the water surface is low (wave trough). Also the pressure stress acting under the wave crest is greater than the pressure stress under the trough. This leads to a net stress over a period. Radiation stresses are as a result of the finite amplitude (height) of waves (Coastal Engineering Manual, 2008). The momentum flux of the ancient Afikpo Sea wave in the direction of propagation (S_{xx}) gave an average of between 0.17- 30.98kJ (Table 5a)

The breaker line was estimation from the expression; $h_b = 1.28H_b$ stated as equation 14. The average breaker line for the wave in this study is at 0.63m depth. Two criteria were employed in order to determine the breaking index. These include limit to wave steepness whereby the height of deep water wave is limited to $H/L < 1/7$ and ratio of height to depth (H_o/h_o). The breaking index (Υ) = H/h is stated as equation 15. The calculated breaking index averaged 0.78 (Table 5a). Reeve et al. (2012) noted that in practice Υ can vary from about 0.4 to 1.2 depending on beach slope and breaker type.

Wind Speed, Wind Duration and Fetch

Wind that blows along the shoreline – longshore winds affect waves. The height of waves are affected by wind speed, wind duration (i.e how long the wind blows), and fetch. If wind speed is slow, only small waves result, regardless of wind duration and fetch. Even if the wind speed is great and the duration short with unlimited fetch, or strong and blew for a long time but over a short fetch, no large waves will form. Large waves occur only when the three factors combine (Duxbury et al., 2002).

The wind speed and duration for the Afikpo Sea estimated from equations averaged 4.19- 14.89m/s and 8.85hrs respectively (Table 5b)

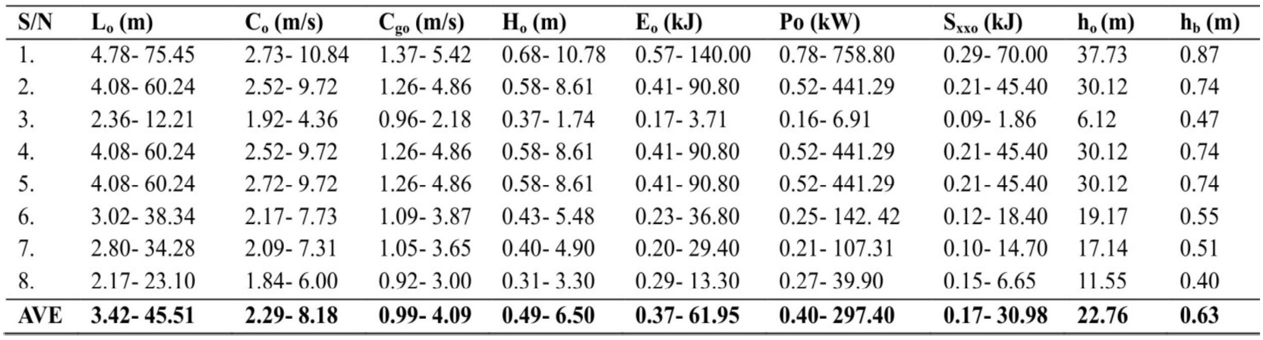
Fetch is the horizontal distance over water that wave generating wind blows in a single direction. Fetch length, along with the wind speed (wind strength), determines the size (sea state) of waves produced. The direction of wind is considered constant. The longer the fetch and the faster the wind speed, the more wind energy is imparted to the water surface and the larger the resulting sea state will be. The estimated fetch for the Afikpo Sea averaged 51.81km (Table 5b).

Discussion

The estimated value ranges of 47.75- 51.42cm/s for bottom orbital diameter, 1.36- 4.35s for wave period, 1.46- 1.70 m and 26.05- 29.44 m for minimum and maximum wavelengths respectively, 0.41- 0.47m for wave height and 0.66- 0.78kW for wave power as well as the bathymetric and fetch estimates of between 14.82- 16.62m and 40- 50km respectively have been assigned to the ancient Afikpo Sea (Okoro et al., 2011).

The values of the deep water wave length, height, wave period, wave power, water depth and fetch gotten from this work are comparable to that estimated by Okoro et al. (2011) for the ancient Sea. The estimated wave period of 1.47- 5.25s for the Afikpo Sea suggests low to moderate wave conditions (Diems, 1985) and can been attributed to shallow (inner shelf) sedimentation, possibly in the tidal flat to shoreface regime (Okoro et al., 2011). This interpretation is in agreement with the synthetic section of the Afikpo Sandstone in its type area by Okoro (2009) and Nwajide (2013). On the other hand, Nkporo Shale which is referred to as the stratigraphic equivalent of the formation has been assigned to restricted and shallow marine depositional environment (Nwajide, 2013). This was on the basis of the recovered foraminiferal assemblages consisting of abundant benthic forms together with general absence of planktic forms and the presence of the ammonites *Libycoceras afikpoensis* and *Innoceramus* sp. as well as fish teeth, echinoids, bryozoans and crabs. Such foraminiferal assemblages include *Bolivina explicita, Bulimina fang, Ammobaculites* sp. among others.

Table 5a: Estimated wave parameters for the ancient Afikpo Sea



S/N	L_o (m)	C_o (m/s)	C_{go} (m/s)	H_o (m)	E_o (kJ)	Po (kW)	S_{xxo} (kJ)	h_o (m)	h_b (m)
1.	4.78- 75.45	2.73- 10.84	1.37- 5.42	0.68- 10.78	0.57- 140.00	0.78- 758.80	0.29- 70.00	37.73	0.87
2.	4.08- 60.24	2.52- 9.72	1.26- 4.86	0.58- 8.61	0.41- 90.80	0.52- 441.29	0.21- 45.40	30.12	0.74
3.	2.36- 12.21	1.92- 4.36	0.96- 2.18	0.37- 1.74	0.17- 3.71	0.16- 6.91	0.09- 1.86	6.12	0.47
4.	4.08- 60.24	2.52- 9.72	1.26- 4.86	0.58- 8.61	0.41- 90.80	0.52- 441.29	0.21- 45.40	30.12	0.74
5.	4.08- 60.24	2.72- 9.72	1.26- 4.86	0.58- 8.61	0.41- 90.80	0.52- 441.29	0.21- 45.40	30.12	0.74
6.	3.02- 38.34	2.17- 7.73	1.09- 3.87	0.43- 5.48	0.23- 36.80	0.25- 142. 42	0.12- 18.40	19.17	0.55
7.	2.80- 34.28	2.09- 7.31	1.05- 3.65	0.40- 4.90	0.20- 29.40	0.21- 107.31	0.10- 14.70	17.14	0.51
8.	2.17- 23.10	1.84- 6.00	0.92- 3.00	0.31- 3.30	0.29- 13.30	0.27- 39.90	0.15- 6.65	11.55	0.40
AVE	**3.42- 45.51**	**2.29- 8.18**	**0.99- 4.09**	**0.49- 6.50**	**0.37- 61.95**	**0.40- 297.40**	**0.17- 30.98**	**22.76**	**0.63**

Table 5b: Estimated parameters for the ancient Afikpo Sea condition

S/N	U_w (m/s)	t_w (hrs)	X (km)
1.	4.97- 19.78	10.47	71.66
2.	4.59- 17.68	9.68	61.12
3.	3.66- 7.95	7.76	39.12
4.	4.59- 17.68	9.68	61.12
5.	4.59- 17.68	9.68	61.12
6.	3.95- 14.10	8.35	45.37
7.	3.81- 13.34	8.05	42.19
8.	3.35- 10.94	7.10	32.78
AVE	**4.19- 14.89**	**8.85**	**51.81**

The estimated wave power, wind speed and fetch show that the Campanian- Maastritchtian Afikpo Sea is relatively large.

Conclusion

Vortex wave ripples on the clayey fine sandstone of Afikpo Sandstone has been used to reconstruct the paleowave history and condition of the ancient Afikpo Sea. The sea was shallow with wave period of 1.47- 5.25s and low to moderate hydrodynamic energy. Calculations show that ancient wind with the speed of 4.19m/s and duration of 8.85hrs blew over a fetch of 51.81km. The ancient sea is relatively large.

References

Akaa, O.O., 1995. Petrology and depositional environment of the upper Cretaceous sedimentary sequence in the Afikpo area of southeastern Nigeria. Unpubl. B.Sc Project, Dept. Geol. Univ. Nig. Nsukka

Allen, J.R.L., 1979. A model for the interpretation of wave ripple marks using their wave length, textural composition and shape. Journ. Geol. Oc. Lond., 136: 673- 682

Allen, J.R.L., 1980. Sand waves; a model of origin and internal structures. Sediment. Geol., 26: 281- 328

Allen, J.R.L., 1982. Sedimentary structures- Their character and physical basis, 1 (Development in Sedimentology, 30A). Elsevier, Amsterdam, 593pp.

Allen, P.A., 1981a. Wave generated structures in the Devonian Lacustrine sediment of S.E Shetland and ancient conditions. Sedimentology, 28: 369- 379

Allen, P.A., 1981b. Some guidelines in reconstructing ancient sea conditions from wave ripple marks. Mar. Geol., 43: M59- M67

Allen, P.A., 1984. Reconstruction of ancient sea conditions with an example from the Swiss Molasse. Marine Geology, 60: 455- 473

Benkhelil, J., 1982. Benue Trough and Benue Chain, Geology magazine, 119:155- 168.

Benkhelil, J., 1989. The origin and evolution of the Cretaceous Benue Trough (Nigeria). Journal of African Earth Sciences, 8: 251- 282.

Burke, K.C.B., 1972. Longshore drift, sub- marine canyon and submarine fans in the development of Niger Delta, American Association of Petroleum Geologist Bulletin, 56: 1975- 1983.

Burke, K.C., Dessauvagie, T.F.J., and Whiteman, A.J., 1972. Geological history of the Valley and its adjacent areas" (Eds, Dessauvagie, T.F.J. and Whiteman, A.J.,), African Geology. University of Ibadan Press, pp. 187- 205.

Clifton, H.E., and Dingler, J.R., 1984. Wave- formed structures and paleoenvironmental reconstruction. Marine Geology, 60(1-4): 165- 198

Coastal Engineering Manual 2008. Water wave mechanics. U.S. Army Corps of Engineers Engineering Manual EM 1110- 2- 1100 Chapter I Part II

Diems, B., 1985. Analytical method for estimating paleowave climate and water depth from wave ripple marks. Sedimentology, 32: 705- 720

Duxbury, A., Duxbury, A.C., and ASvrd, K., 2002. Fundamentals of oceanography, 4th ed., New York, 344p

Fairhead, J.D., 1988. Mesozoic plate tectonic reconstruction of the central South Atlantic Ocean: the role of the West and Central African Rift Systems, Tectonophysics, 155: 181- 191.

Folk, R.L., and Ward, W.C., 1957. Brazos River bar, a study in significance of grain size parameters. J. Sed. Petrol., 27: 3- 26

Harm, J.C., 1969. Hydraulic significance of some ripples. Geol. Soc. Am. Bull., 80: 363- 396

Hoque, M., 1977. Petrographic differentiation of tectonically controlled Cretaceous sedimentary cycles, southeastern Nigeria. Sedimentary Geology, 17: 235- 245.

Hoque, M. and Nwajide, C.S., 1984. 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.

Inman, D.L., 1957. Wave generated ripples in nearshore sands. U.S. Technol. Memo. Beach Erosion Board, 100, 42pp

Ippen, A.T., 1966. Estuary and Coastline Hydrodynamics, Mc Graw- Hill, New York

Komer, P.D., 1974. Oscillatory ripple marks and the evaluation of ancient wave conditions and environments. Journal of Sedimentary Petrology, 44(1): 169- 180

Komar, P.D., and Miller, M.C., 1973. The threshold of sediment movement under oscillatory water waves. J. Sed. Petrol., 43: 1101- 1110

Lamb, H., 1995. Hydrodynamics. Cambridge University Press, Cambridge

Le- Méhauté, B., Divoky, D., and Lin, A., 1969. Shallow water waves: a comparison of theories and experiments. Am. Soc. Civ. Eng. Proc. 11th Conf. Coastal Engineering. 86- 96

Mei, C.C., 1989. The Applied Dynamics of ocean surface waves. World Scientific, Singapore.

Miller, M.C., and Komar, P.D., 1980. Oscillatory and sand ripples generated by laboratory apparatus. Journal of Sed. Petrol., 50(1): 173- 182

Mode, A.W., and Samaila, N.K., 1993. Reconstruction of ancient sea conditions using wave formed ripple marks: an example from the Cenomanian Yolde Formation, Northeastern Nigeria. J. Min. Geol., 29(2): 119- 124

Mode, A.W. and Onuoha, K.M., 2001. Organic matter Evaluation of the Nkporo Shale, Anambra Basin, from wireline logs. Global Journal of Applied Science 7: 103- 107.

Murat, R.C., 1972. Stratigraphy and paleogeography of the Cretaceous and Lower Tertiary in southern Nigeria. In: A.J. Whiteman (ed.), African Geology, University of Ibadan press, Nigeria, 251- 266.

Nwajide, C.S., 2013. Geology of Nigeria’s Sedimentary Basins. CSS Press, Lagos, Nigeria. 548p

Okoro, A.U., 2009. The sedimentological and stratigraphic analysis of the Campanian-Maastrichtian sediment fills of the Afikpo Sub- Basin, S.E. Nigeria. Unpubl. Ph.D Thesis Univ. of Nig. Nsukka, 389p

Okoro, A.U. and Arua, I.A., 1990. Reconstruction of paleowave and paleodepth regimes of the Nkporo Sea (Campanian- Maastrichtian) using wave- formed ripple marks. Nigerian Journal of Mining and Geology 26: 291- 295

Okoro, A.U., Onuoha, K.M., and Okogbue, C.O., 2011. Oscillatory ripple, evaluation of ancient wave climates and epierogeny in the Anambra Basin and Afikpo Sub- Basin, southeastern Nigeria. Global Journal of Geological Science 9(1): 11- 17

Reeve, D., Chadwick, A., and Fleming, C., 2012. Coastal Engineering, processes, theory and design practice, 2nd ed. Spon Press, London and New York, 552p

Reineck, H.E. and Singh, I.B., 1980. Depositional Sedimentary Environments. Springer- Verlag, Berlin Heidelberg, New York, 549p

Sleath, J.F.A., 1975. A contribution to the study of vortex ripples. J. Hydraul. Res., 13: 315- 328

Sleath, J.F.A., 1976. On rolling grain ripples. J. Hydraul. Res., 14: 69- 80

Smith, J.M., 1991. Wind- wave generation on restricted fetches. Coastal Engineering Research Center, U.S. Army Corps of Engineers. Washington, DC, 20314- 1000

Sorensen, R.M., 2006. Basic Coastal EngineeringXIII. Springer, 324p

Tanner, W.F., 1971. Numerical estimation of ancient waves, water depths and fetch. Sedimentology, 16:71- 88

U.S. Army Corps of Engineers, 2002. Coastal Engineering Manual: Washington DC, US Army Corps of Engineers, Engineer Manual 1110- 2- 1100, 6001