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Sedimentary Processes and Depositional Environments of Part of the Benin Formation in the Calabar Flank, Southeastern Nigeria

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Authors' contributions

This research work was carried out in collaboration between both authors. Author NUE designed the study and wrote the protocol while author EEO performed the statistical analysis and wrote the first draft of the manuscript. Both authors managed the analyses of the study, read and approved the final manuscript.

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ABSTRACT

This research work involves the study of the sedimentological processes and depositional environment from two major exposed sections of the Benin Formation in the vicinity of the southern fringes of the Calabar Flank. Stratigraphic logs were produced; 20 samples collected from the sandstone intervals and subjected to sieve analysis. Within the mudstone interval, lenticular beds and skolithos traces were observed. Other sedimentary structures (cross beds, ripple marks) were measured and analysed for paleocurrent patterns. The results from the textural analyses of the sandstones show that the sediments were predominantly medium to coarse grain (ϕ -0.13 – 1.63), moderately to poorly sorted (ϕ 1.02 – 2.03). Skewness and kurtosis values range from strongly coarse - coarse skewed (ϕ -0.66 – 0.13) and leptokurtic to platykurtic (ϕ 0.72 – 2.00) respectively. Bivariate analysis reveal that 100% of the sandstone samples are fluvial in origin with predominant deposition within rolling and saltation sub-population of the C-M plot. The points were restricted to the P-Q section of the C-M plot signifying high energy deposition. Lenticular beds characterized

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tidal influence in the thick mudflat deposit. Break in sedimentation was identified by the presence of a paleosol and the unimodal and unidirectional pattern of the paleocurrent markers suggest fluvial setting.

Keywords: Sedimentological processes; paleocurrent; bivariate analysis; depositional environment.

1. INTRODUCTION

The Benin Formation is the youngest lithostratigraphic unit of the tripartite subdivision of the Niger Delta. The Niger Delta is essentially a Paleogene-Recent basin which began progradation during late Eocene times. The clastic fills of the Niger Delta and other coastal sedimentary basins in Nigeria developed as a result of alternations between transgressive and regressive phases. Contributions to the understanding of the Niger Delta stratigraphic record is largely linked to the fact that it is the focus of hydrocarbon exploration in Nigeria. Nigeria, amongst most countries of the world have received attention in this regard since the late 1930's which led to detailed exploration for hydrocarbon in the Niger Delta targeting mostly onshore regions, and have since shifted to the offshore parts of the Niger Delta. The map (Fig. 1) of the northern part of Calabar Metropolis shows where the road cuts selected for this study is located. Textural characteristics and sedimentary structures have presented indispensable tools for interpretation of the mechanisms of sediment transport, sedimentary processes and depositional environment of the Benin Formation, herein lies the focus of the paper.

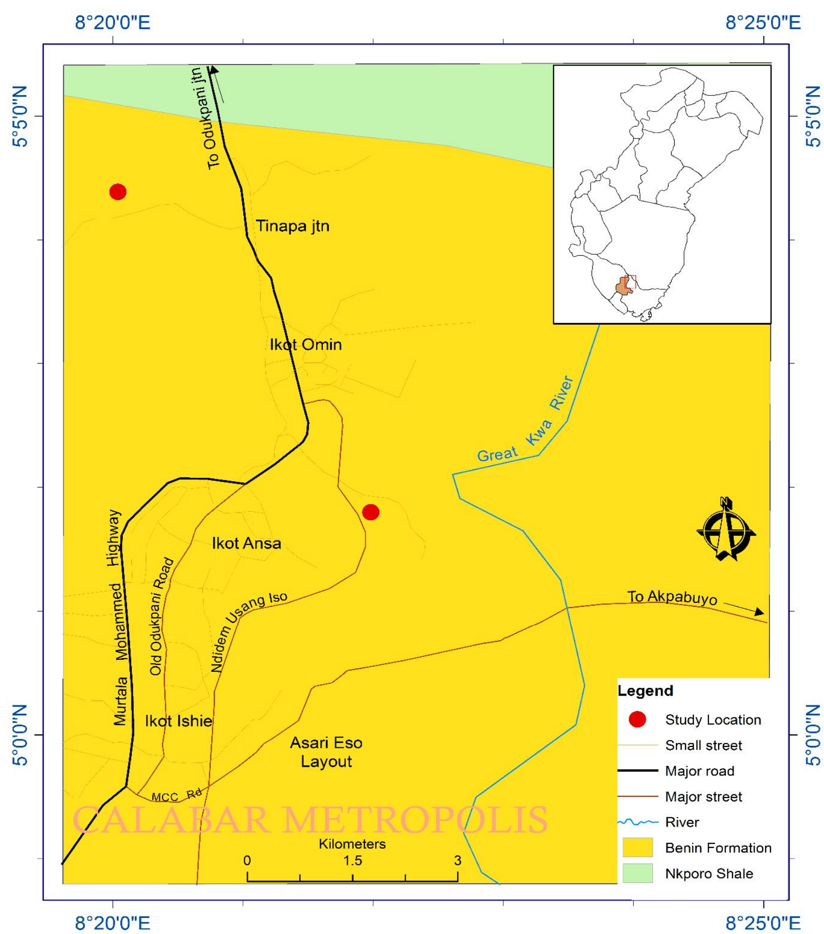

Fig. 1. Map of the northern Calabar municipality showing the study locations

2. GEOLOGICAL SETTING

The Niger Delta is located southwards of the Benue trough at the interception beneath the zone of a triple junction developed during the separation of Africa and South America [1]. It began development down-dip of the Anambra basin in southern Nigeria during latest Eocene [2]. The aerial extent of the Niger delta is about 140,000km^2 with sediment thickness in the range of about 12km ([3], [4], [5]). The Niger Delta originated during the third phase of Murat's [2] megatectonic framework that led to the development of southern Nigerian sedimentary basins.

The stratigraphy of the Niger Delta though broadly subdivided into three main lithostratigraphic units viz: The Akata Formation, Agbada Formation and Benin Formation, is complicated by syndepositional collapse of the clastic wedge as the shaly Akata Formation is progressively mobilized under excessive loading of the prograding parallic Agbada and fluvial Benin Formation deposits.

The sedimentary evolution of the Niger Delta has been examined using the conceptual 'Escalator Regression' model of Knox and Omatsola [6]. The model explained the responses of over-pressured marine shales to gravity loading of deltaic sediments. This according to their model results in a step-wise outbuilding of the delta and creation of new accommodation space for incoming sediments accumulation by submergence and then deposition of blankets of fluvial sands [6]. These seeming complexities in sedimentation styles prompted [7] to propose the elevation of the three lithologic units of the Niger delta to Group status. Structurally the Niger delta is characterized by growth faults and roll over anticlines, shale ridges and diapirs, toe thrusts and well as deep cut and fill channel sequences which originates in response to sea level changes [6].

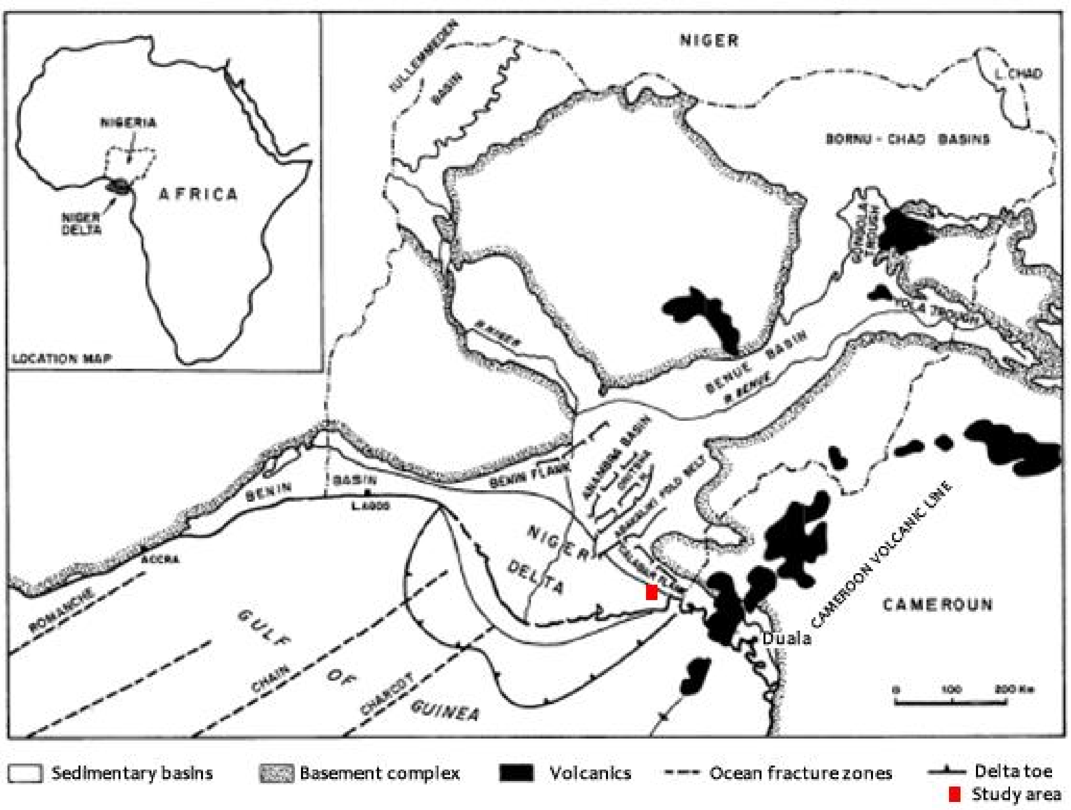

Fig. 2. Regional setting of the Paleogene – Recent Niger Delta (Modified after Knox and Omatsola [6])

3. METHODOLOGY

Field studies involving sedimentological and stratigraphic description of two exposed north of Calabar Metropolis was carried out. During the field studies, sedimentary structures were observed and described including ripple marks, cross stratifications, sediment grading patterns (Fig. 6a - d) and trace fossils (Fig. 6e); measurements were taken where appropriate. Twenty unconsolidated sediment samples within the sandstone units were collected and subjected to laboratory analysis (conventional sieve analysis using 1ϕ interval within the sand size category). Graphical computations according to [8] was used for calculating the grain size statistical parameters. These include Inclusive graphic mean (Mz), Graphic standard deviation (δ_I), Inclusive graphic skewness (SK_I) and Graphic Kurtosis (K_G).

For further characterization of the depositional processes, the CM pattern of [9] was used. Environment of deposition and paleocurrent patterns were diagnosed using bivariate analyses and sedimentary structures respectively.

4. RESULTS AND DISCUSSION

The studied deposits of the Benin Formation occur along road-cuts north of Calabar Metropolis (Figs. 3 and 4). Sedimentological parameters such as lithology, bedding, types, trace fossils were noted in areas of clear exposures. Textural characteristics of the sandstone units was investigated and characterized using statistical approach.

4.1 Univariate and Bivariate Analyses

The result of grain size statistical parameters computed are presented in Table 1. Most of these parameters have been used as close indicators of depositional processes and environments. When one parameter is used for characterizing the depositional process, such analysis is referred to as univariate analysis.

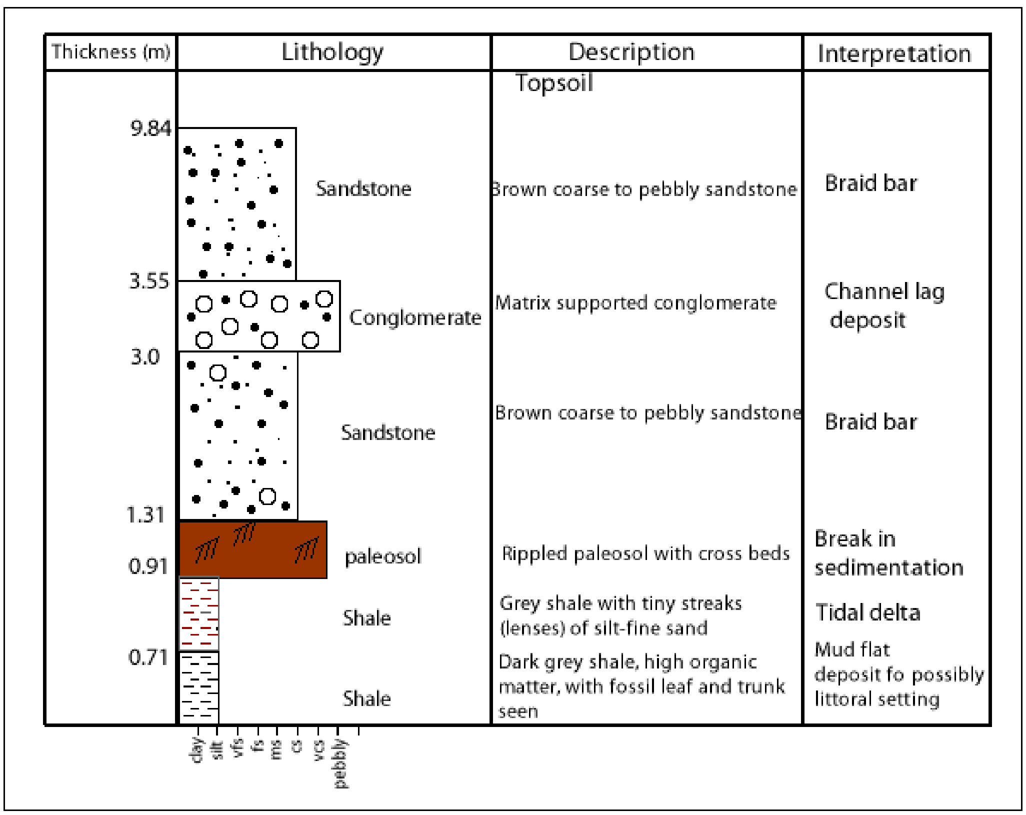

Fig. 3. Lithologic section for the road-cut of part of the Benin Formation by Parliamentary extension

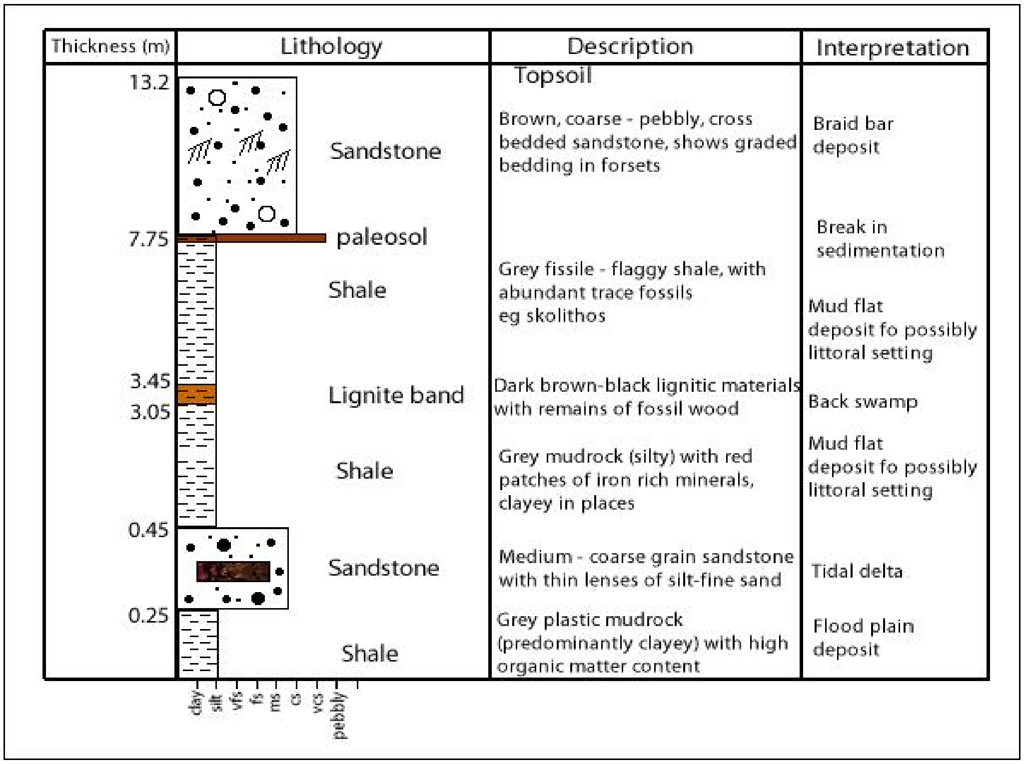

Fig. 4. Lithologic section for the road-cut of part of the Benin Formation exposed near Tinapa, Calabar

In this study the mean size was used to approximate of the energy regime operational during sedimentation. The mean size range from ϕ -0.13 – ϕ 1.63 suggesting high energy during deposition. Such high energy is common to sands deposited within most coastal (barrier-bar, beaches) and fluvial (braided streams during torrential floods) settings. Here lies the ambiguity in the use of one parameter. The graphic sorting for the sediments range from ϕ 1.02 – ϕ 2.03 signifying moderately sorted to poorly sorted. This range does not imply very long distance of transportation. Such sorting can be exhibited by many river sands, some continental shelf sands below wave base and glacio-fluvial sands [10]. The effectiveness of the transporting medium may not have been large enough to properly sort the sediments during its transportation.

Skewness and kurtosis values range from (-0.66 – 0.13) and (0.72 – 2.00) respectively. These directly imply that the sediments were dominantly coarse skewed and straddle between being mesokurtic and leptokurtic sands. Because of the overlaps in depositional environment characteristics, bivariate analysis became necessary to further characterize the sediments and known discrimination diagrams were employed to discriminate between environments. Based on the scholarly works of [11,12,13,14], river sands can be distinguished from beach and dune sands by the nature of their sorting and respective skewness. The characteristics of the sediments in this study (coarse skewness, moderately to poorly sorted sands) fall within the characteristics of river sands (Fig. 5a and 5b). According to [13], most beach sands (95%) are negatively (coarse) skewed and moderately to well sorted; while dune and river sands are predominantly positively (fine) skewed, river sands are moderate - poorly sorted and dune sands moderate – well sorted sands. This necessitated the plots of skewness against sorting and sorting against mean size. The demarcation of the fields is based on earlier work by [13] who carried out studies on known environments spanning dune, beach and river environments. From the plots, 100% of the sediment fall within the river sands field, which means that fluvial processes were dominant during deposition. Characterizing the sediment based on their first percentile against the average grain size [15] further facilitates the distinction between inland dunes and river sands

(Fig. 5c). This further attest to the continental (fluvial) origin for the deposit. The C-M plot of [16] was used to characterize the transport mechanism (mode of transportation) of the sediments and it indicated that the sediments were deposited predominantly by saltation and rolling (P-Q region of the plot) typically characterized by high energy regime during deposition (Fig. 5d).

4.2 Sedimentary Structures and Paleocurrent Analysis

The sedimentary structures observed in the study area include lenticular bedding pattern, skolithos traces and paleosols upon which asymmetrical ripple marks and planar cross beds were observed, these were analysed and used for interpretation of paleocurrent. Routine paleocurrent analysis deals with the relationship between these directional properties recorded on the sediments and the processes that deposited them. The presence of lenticular bedding (Fig. 6a and 6b) is an indication tidal influence. It is characterized by thick mudstone and thin sand lenses. The skolithos traces (Fig. 6e) are essentially dwelling traces that accommodates suspension feeding worm-like animals. Their presence indicates littoral settings where sedimentation rates are relatively high and particulate food materials are kept in suspension by active currents [17].

Table 1. Result showing the statistical parameters computed for the sediments and their interpretation

S/No	Sample No	Median (M)	Mean (Mz)	Sorting (σ)	Skewness (Sk)	Kurtosis (KG)	Interpretation
1	S01	0.80	0.53	1.68	-0.15	0.87	Coarse grain, poorly sorted, coarse skewed, mesokurtic sands
2	S02	0.80	0.37	2.03	-0.21	1.10	Coarse grain, poorly sorted, coarse skewed, leptokurtic sands
3	S03	1.40	1.46	1.53	0.06	0.92	Medium grain, poorly sorted, near symmetrical, mesokurtic sands
4	S04	1.50	1.47	1.69	-0.13	1.26	Medium grain, poorly sorted, coarse skewed, leptokurtic sands
5	S05	1.20	0.73	2.18	-0.28	0.93	Medium grain, very poorly sorted, coarse skewed, mesokurtic sands
6	S06	1.60	1.63	1.46	0.13	0.97	Medium grain, poorly sorted, fine skewed, mesokurtic sands
7	S07	1.40	1.50	1.25	0.12	1.20	Medium grain, poorly sorted, fine skewed, leptokurtic sands
8	S08	1.50	1.37	1.57	-0.03	1.29	Medium grain, poorly sorted, near symmetrical, leptokurtic sands
9	S09	1.50	1.53	1.51	0.03	0.80	Medium grain, poorly sorted, near symmetrical, mesokurtic sands
10	S10	1.70	1.57	1.54	-0.13	0.93	Medium grain, poorly sorted, coarse skewed, mesokurtic sands
11	S11	1.50	1.50	1.80	-0.05	0.96	Medium grain, poorly sorted, near symmetrical, mesokurtic sands
12	S12	1.40	1.06	1.59	-0.22	0.91	Medium grain, poorly sorted, coarse skewed, mesokurtic sands
13	S13	1.10	0.63	1.81	-0.15	0.90	Coarse grain, poorly sorted, coarse skewed, mesokurtic sands
14	S14	-0.20	-0.13	1.93	-0.66	0.72	Coarse grain, poorly sorted, strongly coarse skewed, platykurtic sands
15	S15	1.60	1.50	1.02	-0.13	2.00	Medium grain, poorly sorted, coarse skewed, leptokurtic sands
16	S16	1.40	1.40	1.29	0.02	1.15	Medium grain, poorly sorted, near symmetrical, leptokurtic sands
17	S17	1.30	1.03	1.16	-0.24	1.00	Medium grain, poorly sorted, coarse skewed, leptokurtic sands
18	S18	1.60	1.33	1.27	-0.24	1.20	Medium grain, poorly sorted, coarse skewed, leptokurtic sands
19	S19	1.40	1.30	1.18	-0.07	1.17	Medium grain, poorly sorted, near symmetrical, leptokurtic sands
20	S20	1.20	0.93	1.24	-0.24	1.32	Coarse grain, poorly sorted, coarse skewed, leptokurtic sands

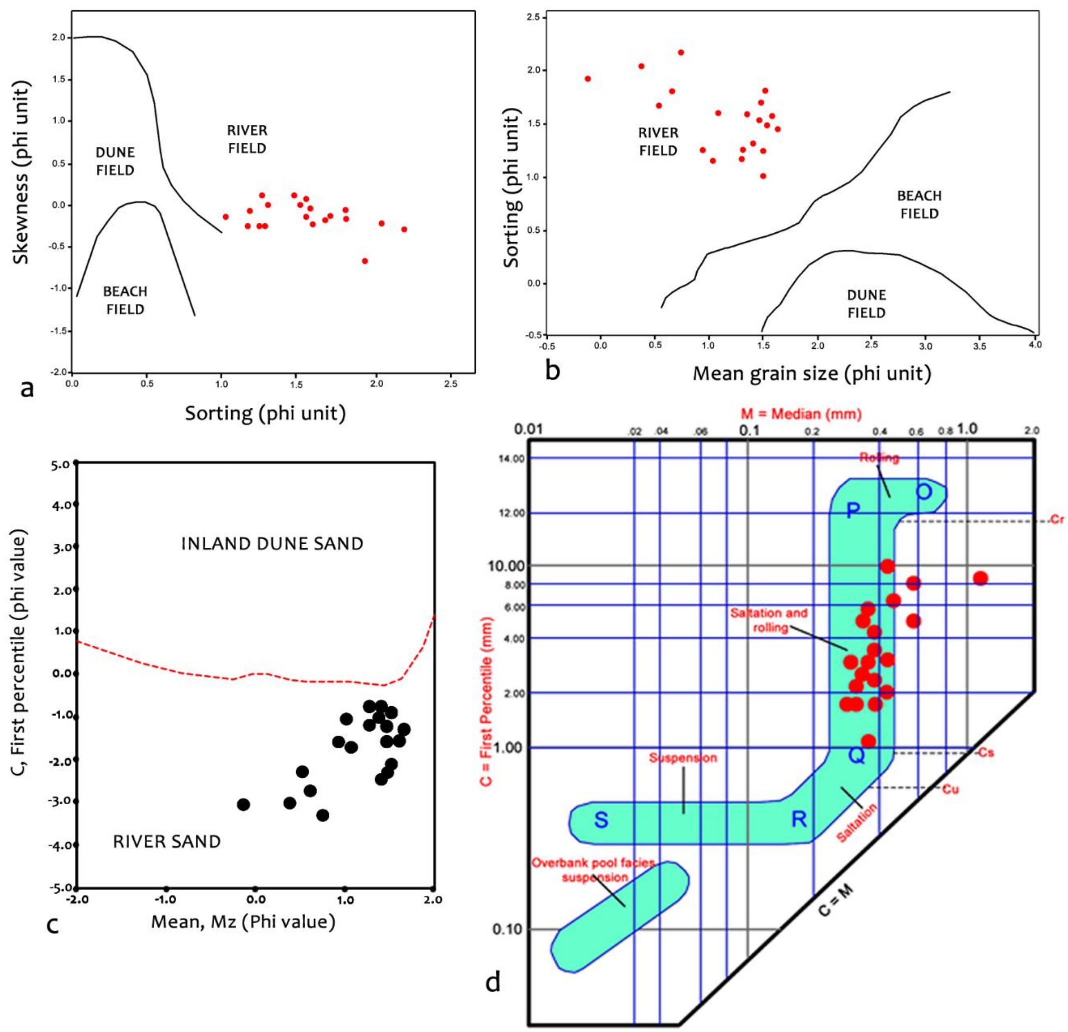

Fig. 5. (a) Bivariate plot of skewness against sorting (Martins [13]), (b) Bivariate plot of sorting against mean grain size (Martins, [13]), (c) Bivariate plot of the first percentile against mean grain size [15] and (d) C-M diagram for characterization of the mode of transportation (Modified from Passega, [16])

This unit is directly overlain by a paleosol unit having a sharp contact and characterized by ripple marks (6c and 6d) and planar cross bed. The paleosol is an indication of a cessation in deposition which resumed with the deposition of conglomeratic sandstones. Ripple marks refer to the rhythmic undulations usually less than 1m long in occurrence and are preserved on sedimentary surfaces ([18] and [19]). They form in granular materials at the sedimentary interface in response to a moving fluid, either air or water [20]. The typical ripple marks observed in this study are asymmetrical ripples, with straight crest, parallel and transverse to current direction and this point to unidirectional flow. They are well exposed along the Parliamentary extension road-cut section and are oriented in the WSW direction and are likely to have been formed in a fluvial setting, not too far away from the shore. Ripple marks are important sedimentary structures that give clear indication of specific depositional process and environment. Their significance in facies analysis facilitates the determination of paleoslope, however due to the variability in water depth responsible for the creation of ripple marks [21], elucidation of water depth using ripple marks may not exactly be accurate/reliable due to compaction and over burden pressure effects. This is because, compaction as well as decrease in ripple height (due to compaction) is capable of increasing the ripple index for the sediment. Such paleoenvironmental deduction should be carried out with high amount of caution and integrated with other parameters. The azimuths of planar cross beds were used to determine the dominant paleoflow direction (Fig. 7) for the sediments.

The current rose gives an indication of the paleocurrent direction while the vector mean and magnitude present some degree of certainty in the overall paleocurrent direction. This was found to be 167° towards the SSE and its unidirectional pattern further suggests fluvial setting for the sandstones. The vector magnitude is quite low (2) implying that there is little variation in the degree of dispersion of the data set.

Fig. 6. Sedimentary structures observed within the study area. (a) Lenticular bedding with lenses of fine sand within the plastic shales unit, (b) Rippled paleosol exhibiting sharp contact with lenticular bedded mudstone (c) Plan view of the asymmetrical ripple marks, (d) asymmetrical ripple marks (ball pen on the crest-to-crest) with planar cross bedding, and (e) Skolithos observed within the shales

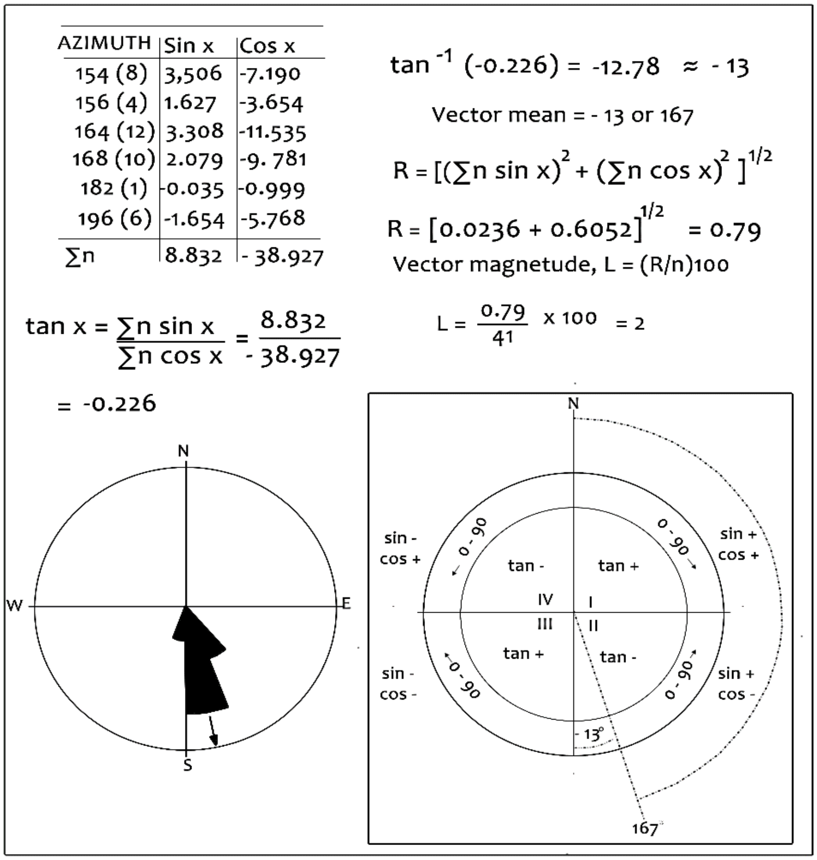

Fig. 7. Vector mean and magnitude for the planar cross beds of Benin formation

5. CONCLUSION

In summary, the result of this study has strongly revealed the significance of textural parameters in discriminating between depositional environments and the inherent strength in integrating sedimentary structures to such interpretations. The study reveals that the sediments were deposited in a mixed environmental setting. The near shore (tidally influenced) mudflat setting, characterized by skolithos ichnofossils and followed by a break in sedimentation (characterized by the presence of the paleosol) and then sedimentation resumed with the accumulation of thick ridges of conglomerates and pebbly sandstones. These sandstones depict deposition under high energy environment and persistent fluvial influence typified by unidirectional flow pattern. The paleocurrent pattern for the sandstones of the Benin Formation exposed north of Calabar Metropolis depict unimodal and unidirectional pattern in the SSE direction indicating fluvial setting for the deposit.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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