Journal of Oceanography and Marine Science Vol. 3(2), pp. 19-31, February 2012
Available online at http://www.academicjournals.org/JOMS
DOI: 10.5897/JOMS11.020
ISSN 2141-2294 ©2012 Academic Journals

Full Length Research Paper

The impact of flow regime on the sedimentation pattern of Calabar River, South-East Nigeria

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Accepted 19 December, 2011

The sedimentation pattern of the lower reaches of Calabar River, on the south east coast of Nigeria was investigated with a view to evolving criteria for recognition of their ancient counterparts. Using grain size statistical parameters, the sediment-sediment relationships and flow structure of the river were examined from twenty-five georeferenced bottom samples. Results show that the tidal channel is uniformly impacted with eroded terrestrial sediments which have been delineated into A, B, and C distinct lateral facies. Facies A and B portrayed negatively skewed and near symmetric moderately sorted sands with a considerable upstream increase in kurtosis. But, Facie C depicted near symmetric, very leptokurtic well sorted sand, representing more of terrestrial-borne sediments inferring high rate of siltation/sediment accretion. Tidal flow measurements over-spring, mean and neap tidal cycles gave 0.59 m/s highest with maximum current velocity at neap tide flowing southerly. The mean near-bottom tidal velocity indicated a maximum of 0.40 m/s, predicting that bedforms such as ripples are likely to form based on empirical relationship between flow velocity and mean grain size distribution. The observed results are geared towards understanding the impact of flow regime on sediment mobility and the preservation potential of the environment.

Key words: Tidal channel, lateral facies, sediment accretion, tidal current velocities, Calabar River, Nigeria.

INTRODUCTION

Sedimentology is basically aimed at determining and defining the sedimentary materials, sedimentary processes and the products of sedimentation of a sedimentary deposit (Friedman and Sanders, 1978). Coastal fluvial environments constitute an important region with diverse and peculiar sedimentary characteristics. These environments are widespread today as they were in geologic times and may be tidal or non-tidal. Visher (1965) defined a tidal river as an upper estuary or a fluvial estuary characterized by freshwater but subject to daily tidal actions. In a geologic sense however, any fluvial system that is not directly linked to the ocean, but depicts daily tidal action can be considered as a tidal river. The aforementioned is exemplified by the lower reaches of Calabar River. The flow is bi-directional as in an estuary, which is in contrast to a typical fluvial environment. This is similar to reports from Prestrong (1965) who described a tidal river channel within San Francisco bay that showed tidal flow in two opposite directions daily with ebb-dominance. Consequently, sedimentary structures such as asymmetric ripples, channel scours and cross stratification are likely features in such rivers (Selly, 1988).

The grain size characteristics of sediment materials in a tidal river environment are dependent on flow structure, sediment source and distance of transport (Allen, 1965). Materials transported from fluvial portions of the Calabar River therefore dominate the tidal portions of the river. Despite the general view, ebb or flood flow dominance is also dependent on seasonal fluvial discharge, climate, and local energy conditions and to an extent, sea level changes (Yoshida, 2006). Chakrabarti (1971) reported from grain size analysis and flow structure of Riparian tidal river that in the dry season, the flood flow direction dominates, with the reverse being the case in wet season, where finer grained sediments with good sorting

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were transported downstream towards the estuary during ebb flow. Chakrabarti and Lowe (1981) also showed in a theoretical analysis that flow velocity and flow depth have a strong influence on the rate of deposition of sediments in a river. Sorting of the bed materials particularly appeared to exert a strong control on both grain size and deposition rate.

Accordingly, flow depth and flow velocity were discovered to be related to bedforms, especially small ripples in an experimental study using medium sand (Banks and Collinson, 1975). The details of sedimentary structures such as bed geometry, erosional surface, texture and lateral and vertical sedimentary structural sequences can be used to identify fluid motion and direction in a river channel, and also serve as an evidence for depositional environments (Allen, 1984; Boersma et al., 1981).

Study area

The study area (04°54'15"N, 08°16'08"E) (Figure 1), known as Calabar River, lies geographically between latitude 04°54'15"N and longitude 08°16'08"E; and latitude 04°56'40"N and longitude 08°18'14"E", located in Cross River system, South Eastern Nigeria. The Calabar River takes its rise from the Oban Hills in Akamkpa, Nigeria and flows southwards through the high rain forest of the south east coast of Nigeria before discharging into the Cross River Estuary at Calabar (Akpan, 2002). The river lies in the humid tropical rain forest belt. The zone is characterized by a long wet season between April and November, and a relatively short dry season from December to March. The coastal shoreline is characterized by thick vegetation, changing from freshwater to swamp ecology, to mangrove swamp towards the estuary. On the banks of the Calabar River, nipa palm (*Nypa fruticans*) of the family of *Arecaceae* dominates (Asuquo, 1999).

The geology of Cross River basin consists of crystalline basement complex, overlain by various sedimentary formations. The sediment texture ranged from silty-clay to sandy-clay with the abundance of silt/clay in the lower reaches (estuary) and sandy mud in the upper reaches predominating at regions < 2 m to the shoreline (Asuquo and Ewa-Oboho, 2006). The Calabar River, from its source cuts through black shales, siltstone, clayey and silt deposits, and also alluvial deposits before entering the Cross River at Alligator Island (Asuquo, 1999). The tidal Calabar River is generally devoid of strong ocean waves. However, it is influenced by wind induced waves from the south-west trade winds, and shockwaves produced by moving boats. The Calabar River has a semi-diurnal tidal range of 1.50 to 2.50 m (Asuquo and Tambe, 2010), and experiences both flood and ebb tidal stages, with the flood direction being northwards and southwards in the ebb direction. Activities such as fishing, lumbering, local and large scale agriculture, dredging, craftsmanship, and recreation are among the various occupations of the coastal dwellers around Calabar River.

MATERIALS AND METHODS

Five sets of bed samples were obtained from the river channel (about 6 km stretch) along georeferenced transect spaced at about 1.2 km apart from the river banks (Figure 2). Sediment samples were obtained using a Van veen grab sampler aboard a motor boat and stored in labeled bags. Samples were then oven dried at 75°C and sieved with Ro-tap sieve assemblage (25 mm to 20 µm) to obtain various sand sized fractions. Various size fractions were obtained from sieve analysis. Grain size statistical parameters were obtained using the formulation and verbal description of Folk and Ward (1957) represented as:

$$\text{Mean grain size, } (M_z) = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

$$\text{Sorting } (\sigma) = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

$$\text{Skewness, } (S_{KI}) = \frac{\phi 84 + \phi 16 - 2(\phi 50)}{2(\phi 84 - \phi 16)} + \frac{\phi 95 + \phi 5 - 2(\phi 50)}{2(\phi 95 - \phi 5)}$$

$$\text{Kurtosis, } (K_G) = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$$

Where Phi (ϕ) values represent cumulative percentiles.

River depth was also determined at strategic georeferenced locations using a depth sounder (Asuquo and Tambe, 2010). Flow direction and tidal flow velocity were determined using the Langragian method for neap, mean and spring tidal cycles (Asuquo, 1991). Possible bedform types were inferred from the stability diagram by Middleton and Southward (1978). This was achieved by relating tidal current velocity to mean grain size of sediments.

RESULTS

The particle size analyses of the river sediments are presented in Table 1. An analyses of the grain size statistical parameters and surface sediment distribution indicated that the mean grain size for the river channel sediments ranged between 0.85 to 3.48 ϕ, inferring increased deposition of terrestrial materials (Table 2a). Very fine grained sand dominates with patches of fine, medium and coarse sand close to the mouth with fine and medium sized particles further upstream. Sediments generally depict an upward fining pattern towards

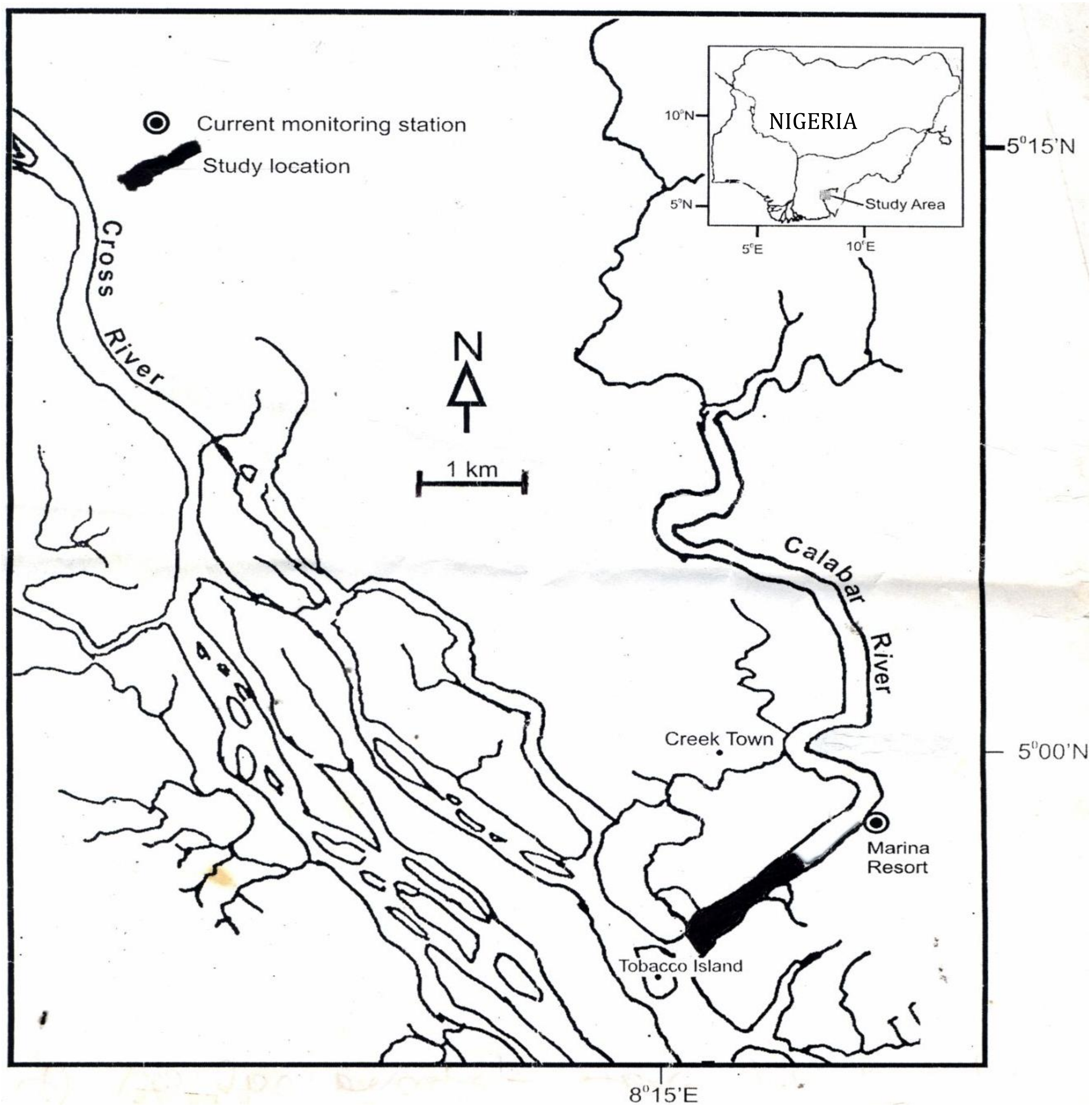

Figure 1. Map of the Cross River system showing Calabar River study location.

the banks from the mid-channel in the downstream direction, except for some portions with minor inclusions of coarse sands at the banks.

Sediments in the river varied from well sorted to poorly sorted sands within the range of 0.41 to 1.42 (Table 2a). The lower reaches of the river, towards the river mouth was generally moderately sorted. However, the upper portion of the studied area was dominated by moderately well sorted sediments. Sorting generally deteriorated away from the mid-channel, and improved downstream.

The river sediments were generally negatively skewed to positively skewed, ranging from -0.4 to 0.31 (Table 2a). Sediments were dominantly negatively skewed within the lower reaches of the river, close to the entrance. The upper portion of the river was dominated by near symmetric sediments. There was a significant decrease

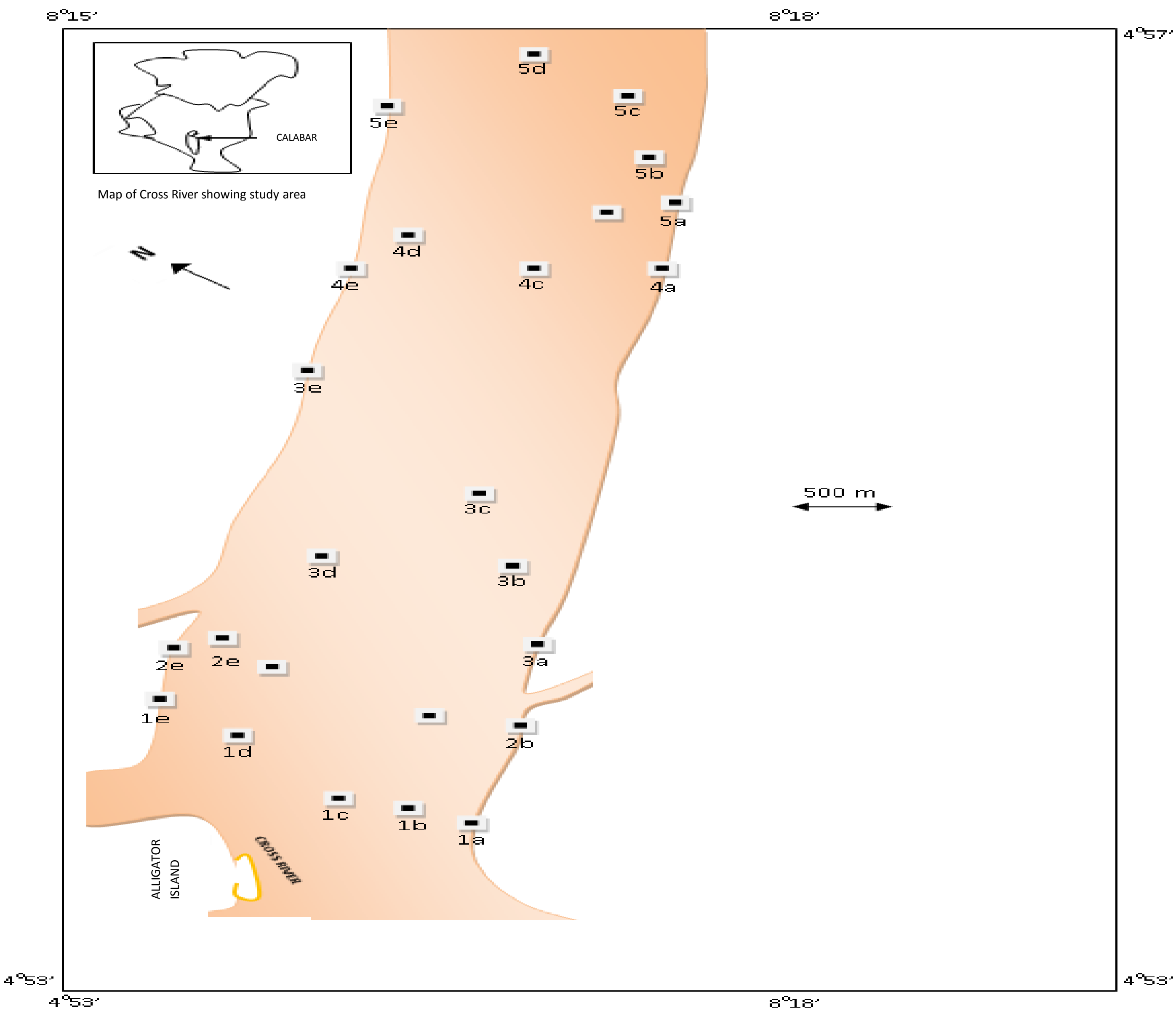

Figure 2. Sediment sampling stations at Calabar River, Nigeria.

in skewness from the east to the west bank, with an increasing trend upstream. Kurtosis within the studied area ranged from platykurtic to extremely leptokurtic (0.78 to 3.09) (Table 2b). Sediments were generally mesokurtic close to the mouth, and dominantly very leptokurtic further upstream. The middle portion of the river was dominated by leptokurtic sediments. The trend revealed a decrease in kurtosis from the east to the west bank. A bathymetric map was produced for the studied segment of the river. This revealed a depth range of about 7 to 11 m in the mid-channel, and about 2 m at the river banks (Figure 3). The mean monthly depth and tidal elevation is presented in Table 3. Study during neap, mean and spring tidal phases revealed maximum surface tidal current velocities of 0.59, 0.40, and 0.37 m/s respectively (Table 4 a, b, and c). Utilizing the stability diagram by Middleton and Southward (1978), (Figure 4) possible bedform types inferred for the studied area were small ripples in fine and medium sands at velocity of 0.40 m/s (maximum surface current velocity of approximately 0.59 m/s).

Three distinct facies delineated in the studied area, based on sorting, skewness and kurtosis were represented as Facies A, B, and C (Figure 5). Facie A, extending about 1.15 km and 11 m thick consists of mainly moderately sorted, near symmetric to dominantly negatively skewed, and mesokurtic sands. Facie B stretching 2.6 km from the distal end of Facie A, and 7 m

Table 1. Results on grain size analyses of Calabar River sediments (%).

Station No.			1					2				3				4				5			
			A	B	C	D	E	A	C	D	E	A	B	C	D	A	B	C	D	A	B	C	D
Weight retained (%)	Grain Size	-1	-	-	0.5	-	-	-	-	-	3.3	-	-	-	-	-	-	-	-	-	-	-	-
		0	-	-	3	-	-	-	-	-	14.7	-	-	-	-	-	-	-	-	-	-	-	1
		1	-	-	7	-	-	-	-	-	31.3	-	-	-	-	-	-	-	-	-	-	3	18.7
		2	-	14	54	16	-	-	9	6	42	-	-	-	6.7	30.7	4	4		34.7	8	68	68
		3	23	24	32	22	25	24	21	42	6	24	20	9.3	15.3	18	17	19	18	24.7	18	21	10.7
		4	57	50	3	44	52	60	54	45.3	2.7	57	53	80	66.3	34.7	67	66	62	23.3	62	7	1.3
		5	20	12	0.5	18	23	16	16	6.7	-	19	48	10.7	14.7	16.6	12	11	20	13.3	12	1	0.3
Cumulative weight (%)	Grain Size	-1	-	-	0.5	-	-	-	-	-	3.3	-	-	-	-	-	-	-	-	-	-	-	-
		0	-	-	3.5	-	-	-	-	-	18	-	-	-	-	-	-	-	-	-	-	-	1
		1	-	-	10.5	-	-	-	-	-	49.3	-	-	-	-	-	-	-	-	-	-	3	19.7
		2	-	14	64.5	16	-	-	9	6	91.3	-	-	-	6.7	30.7	4	4		34.7	8	71	88.7
		3	23	38	96.5	38	25	24	30	48	97.3	24	20	9.3	22	48.7	21	23	18	59.4	26	92	98.4
		4	80	88	99.5	82	77	84	80	93.3	100	81	52	89.3	88.3	83.4	88	89	80	86.7	88	99	99.7
		5	100	100	100	100	100	100	100	100	-	100	100	100	100	100	100	100	100	100	100	100	100

thick consists of moderately sorted, negatively skewed and near symmetric leptokurtic sands. Facie C extending about 2.4 km upstream of Facie B and 5 m thick consists mainly of moderately well sorted to moderately sorted sands, dominantly near symmetric with a leptokurtic to very leptokurtic distribution.

DISCUSSION

Results of the study showed well sorted finely grained sediment in the downstream direction, as well as towards the banks from the mid-channel (Figure 6a). The former conforms to the general rule that mean grain size would decrease in the direction of dominant flow (Shultz, 1941; Plumbey, 1948; Chakrabarti, 1971). Also, the deposition of fines towards the river mouth can be attributed to the effect of flow expansion, downstream at the wider (1.5 km) and deeper (11 m) river mouth. This is because of the dissipation of energy which causes the settling of fine sediments that were in suspension as energy reduces. The fining pattern of sediments towards the banks from the mid-channel is consistent with Semeniuk's (1981) observation, that continuous winnowing in a tidal channel gradually removes finer sediments from the channel and deposits them on the banks, leaving clearly washed coarse fragments within the channel. The slight improvement in the downstream direction indicates a downstream movement of sediments with accompanied accretion/siltation of the channel during ebb tide.

However, in the upstream portion of the studied area, a large patch of moderately sorted sands indicates a deposition of sediments by flood flow in the upstream direction (Figure 6b). These changes in sorting along the channel may be attributed to erosion and deposition caused by the bi- directional flow in the tidal river, which is evident from the flood-ebb time and velocity asymmetry which is almost symmetric in the study area. The observed patterns are consistent with the views of Chakrabarti (1971), and Krumbien and Sloss (1963) who suggested that in the direction of transport, sediments become better sorted. Also, the deterioration in sorting away from the mid-channels is an indication of winnowing of fines to the banks leaving better sorted and coarser sediments within the channel (Seminiuk, 1981; Buller and McManus, 1975; Gibbs, 1973). Skewness in the channel generally depicts a decreasing trend from near symmetric in the downstream direction, to negatively skewed further downstream (Figure 7a). This is consistent with the views of Selley (1988), who suggested

Table 2a. Summary statistics of grain size statistical parameters – mean grain size and sorting.

Transect no.	Sample station	Mean (Mz) (phi)		Sorting (σ)	
		Values	Interpretation	Values	Interpretation
1	A	3.45	Very fine sand	0.83	Moderately sorted
	B	3.22	Very fine sand	0.84	Moderately sorted
	C	1.71	Medium sand	0.71	Moderately sorted
	D	3.10	Very fine sand	1.04	Poorly sorted
	E	3.45	Very fine sand	0.73	Moderately sorted
2	A	3.40	Very fine sand	0.61	Moderately well sorted
	B	3.23	Very fine sand	0.79	Moderately sorted
	C	3.27	Very fine sand	0.82	Moderately sorted
	D	2.97	Fine sand	0.85	Moderately sorted
	E	0.85	Coarse sand	0.95	Moderately sorted
3	A	3.45	Very fine sand	0.74	Moderately sorted
	B	3.82	Very fine sand	0.82	Moderately sorted
	C	3.40	Very fine sand	0.41	Well sorted
	D	3.35	Very fine sand	0.73	Moderately sorted
4	A	2.67	Fine sand	1.42	Poorly sorted
	B	3.35	Very fine sand	0.63	Moderately well sorted
	C	3.30	Very fine sand	0.63	Moderately well sorted
	D	3.48	Very fine sand	0.59	Moderately well sorted
	E	2.53	Fine sand	1.32	Poorly sorted
5	A	3.23	Very fine sand	0.75	Moderately sorted
	C	2.60	Fine sand	0.45	Well sorted
	D	1.73	Medium sand	0.85	Moderately sorted

that finer sediments are weighted to the negative while coarser sediments tend to the positive considering the prevailing energy conditions and the homogeneity of the sediments. Therefore, the decrease in skewness towards the negative in the downstream direction, which corresponds with a downstream decrease in mean grain size of sediments in Calabar River, which is an indication of the dependence of skewness on mean grain size and the flow conditions typical of the studied area. Kurtosis generally decreased from very leptokurtic to mesokurtic downstream (Figure 7b). This can be related to sorting in conformity with the views of Phillip et al. (1968) and Folk and Ward (1957), who associated leptokurtic and very leptokurtic sediments to best sorting (Figures 6b and 7b).

Possible bedform types were inferred for Calabar River based on empirical relationship between mean grain size and mean flow velocity of Middleton and Southard (1978). At maximum near-bottom velocity of 0.42 m/s ripples are formed within very fine sand. The same applies for fine sand and medium sand. In Calabar River, the cross-stratified small ripples are oriented in the ebb-flow direction (downstream). This conforms to the views by Reineck and Singh (1980), who suggested that tidal channels are dominated by asymmetrical ripples with cross stratified internal structure. Chakabarti (1971) also reported a likely maximum sediment transport in the ebb-flow direction during wet season. This proposes a high preservation potential for small ripples as preserved bedforms in Calabar River for rock record reconstruction.

Conclusion

This preliminary report on the lithology of a segment of Calabar River revealed that the channel is characterized by coarse to very fine sand, well to poorly sorted, very negatively to very positively skewed, and platykurtic to extremely leptokurtic sediments. Three distinct facies (A, B and C) delineated based on the interpretation of grain size statistical parameters is highly relevant considering the magnitude and source of the sedimentary materials, which could be utilized as depositional indicators for developing conceptual models for the management of the channel and paleo-environmental reconstruction. The

Table 2b. Summary statistics of grain size statistical parameters – Skewness and kurtosis.

Transect no.	Sample station	Skewness (Ski)		Kurtosis (Kg)	
		Values	Interpretation	Values	Interpretation
1	A	-0.12	Near symmetric	1.36	Leptokurtic
	B	-0.05	Near symmetric	1.03	Mesokurtic
	C	-0.05	Near symmetric	1.01	Mesokurtic
	D	-0.61	Negatively skewed	1.02	Mesokurtic
	E	-0.03	Near symmetric	0.88	Platykurtic
2	A	0.19	Positively skewed	1.18	Leptokurtic
	B	-0.40	Very negatively skewed	1.43	Mesokurtic
	C	-0.21	Negatively skewed	1.31	Mesokurtic
	D	-0.38	Very negatively skewed	3.09	Extremely
	E	0.16	Positively skewed		Leptokurtic
3	A	-0.18	Negatively skewed	1.04	Mesokurtic
	B	-0.24	Negatively skewed	0.83	Platykurtic
	C	0.30	Positively Skewed	1.37	Leptokurtic
	D	0.11	Negatively Skewed	1.42	Leptokurtic
4	A	-0.33	Very negatively skewed	0.78	Platykurtic
	B	-0.13	Negatively skewed	1.51	Very Leptokurtic
	C	-0.03	Near symmetric	1.48	Leptokurtic
	D	0.31	Very positively skewed	1.07	Mesokurtic
	E	-0.06	Near symmetric	0.78	Platykurtic
5	A	-0.22	Near symmetric	1.58	Very Leptokurtic
	C	0.09	Near symmetric	1.73	Very Leptokurtic
	D	0.22	Positively skewed	1.84	Very Leptokurtic

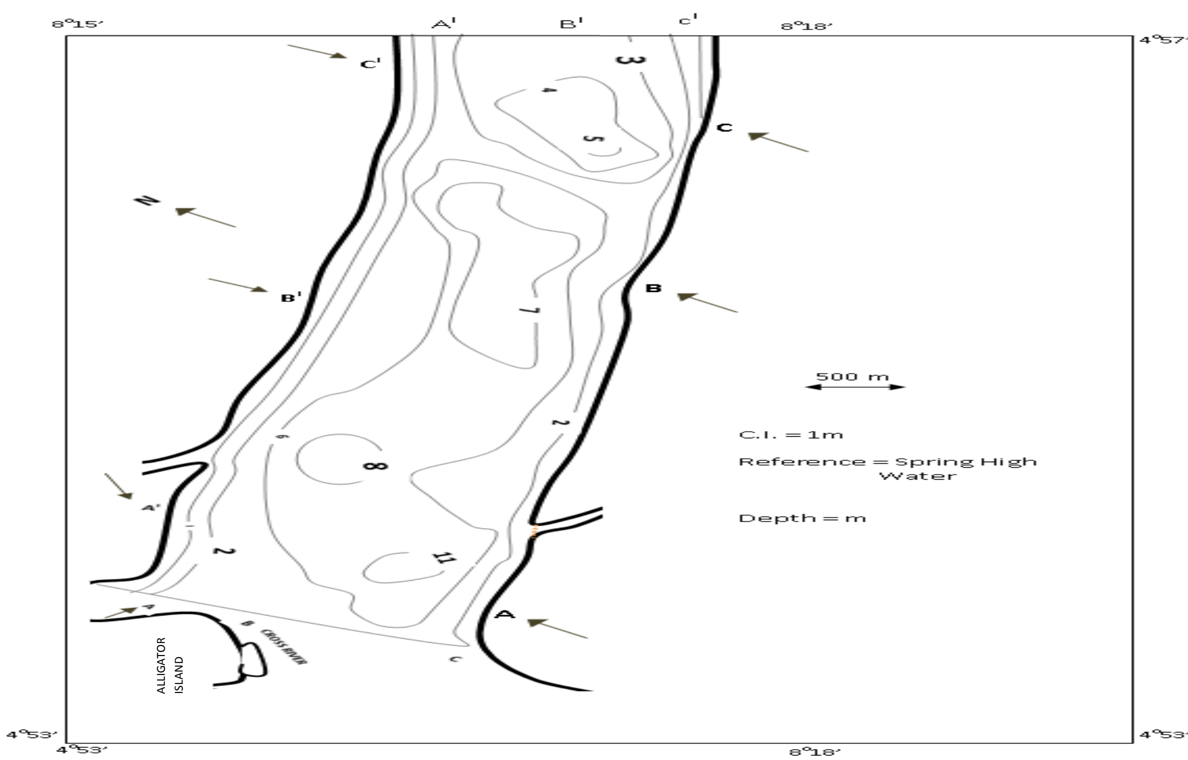

Figure 3. Contour profiles of the bathymetry of lower Calabar River, Nigeria.

Table 3. Values of mean monthly depth and tidal elevations at the sampling locations in Calabar River (April to September 2006).

Transect	Sample stations	Geographical coordinates		Mean monthly Depth (m)	Mean tidal elevation (m)
		Latitude	Longitude		
	A	4°54115''N	08°16'08E	4.25	1.35
	B	4°54^{1}17N	08°16'06E	4.35	1.37
1	C	4°54^{1}32N	08°16'59E	4.40	1.4
	D	4°54^{1}47N	08°16'52E	4.45	1.43
	E	4°54^{1}46N	08°16'38E	4.50	1.45
	A	4°54^{1}39N	08°16'28E	5.05	1.56
	B	4°54^{1}47N	08°16'11E	5.02	1.50
2	C	4°54^{1}54N	08°16'00E	5.00	1.50
	D	4°54^{1}58N	08°16'51E	4.55	1.47
	E	4°54^{1}00N	08°16'48E	4.52	1.45
	A	4°54^{1}52N	08°16'41E	5.13	1.55
	B	4°54^{1}03N	08°16'40E	5.15	1.55
3	C	4°54^{1}18N	08°16'39E	5.20	1.56
	D	4°54^{1}32N	08°16'37E	5.25	1.58
	E	4°54^{1}50N	08°16'41E	5.27	1.58
	A	4°54^{1}00N	08°16'37E	5.45	1.65
	B	4°54^{1}59N	08°16'25E	5.40	1.65
4	C	4°54^{1}58N	08°16'12E	3.35	1.63
	D	4°54^{1}59N	08°16'03E	5.33	1.63
	E	4°54^{1}02N	08°16'55E	5.30	1.60
	A	4°54^{1}12N	08°16'49E	5.47	1.68
	B	4°54^{1}22N	08°16'46E	5.53	1.70
5	C	4°54^{1}26N	08°16'41E	6.00	1.70
	D	4°54^{1}38N	08°16'04E	6.05	1.72
	E	4°54^{1}40N	08°16'14E	6.10	1.75

Table 4a. Data on surface current velocity – Neap tides (April –September 2006).

Time of day	Tidal phase	Range surface current velocity (m/s)	Mean surface current velocity (m/s)	Flow direction
Between 7.00 and 11.30 am	Flood	0.07 – 0.30	0.18(0.01)	North
Slack Tide at 11.45 am	Slack Tide	0.0	0.0	-
Between 12.15 and 18.45 pm	Ebb	0.11- 0.59	0.26(0.02)	South

Values in parentheses are the standard deviation values between 15 to 25 set of readings.

Table 4b. Data on surface current velocities – Mean tides (April to September, 2006).

Time of day	Tidal phase	Range surface current velocity (m/s)	Mean surface current velocity (m/s)	Flow direction
Between 7.00 and 10.00 am	Ebb	0.10 – 0.29	0.19 (0.12)	South
Slack Tide at 10.15 am	Slack tide	0.0	0.0	-
Between 10.30 and 14.15 pm	Flood	0.09 - 0.38	0.19 (0.11)	North
Slack Tide at 14.30 pm	Slack tide	0.0	0.0	-
Between 14.45 and 18.45 pm	Ebb	0.05 - 0.06	0.14 (0.03)	South

Values in parentheses are the standard deviation values between 15 to 25 set of readings.

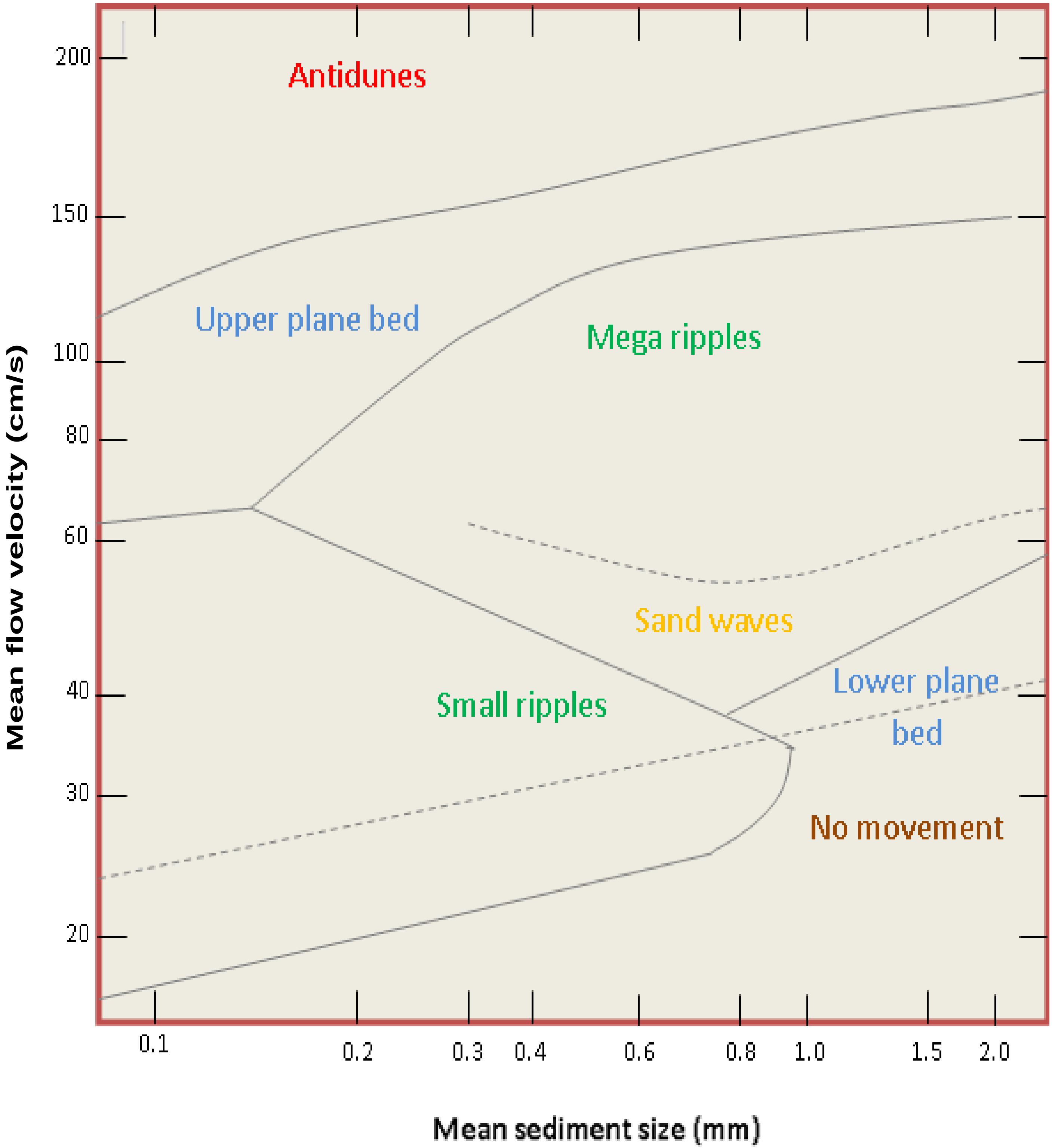

Figure 4. Mean grain size/ flow velocity diagram (Middleton and Southward, 1978).

enhanced mobilization of terrestrial-borne sediments by the inherent flow regime that resulted in frequent siltation of the channel suggest regular opening up /dredging of the navigational channel for accessibility by sea going

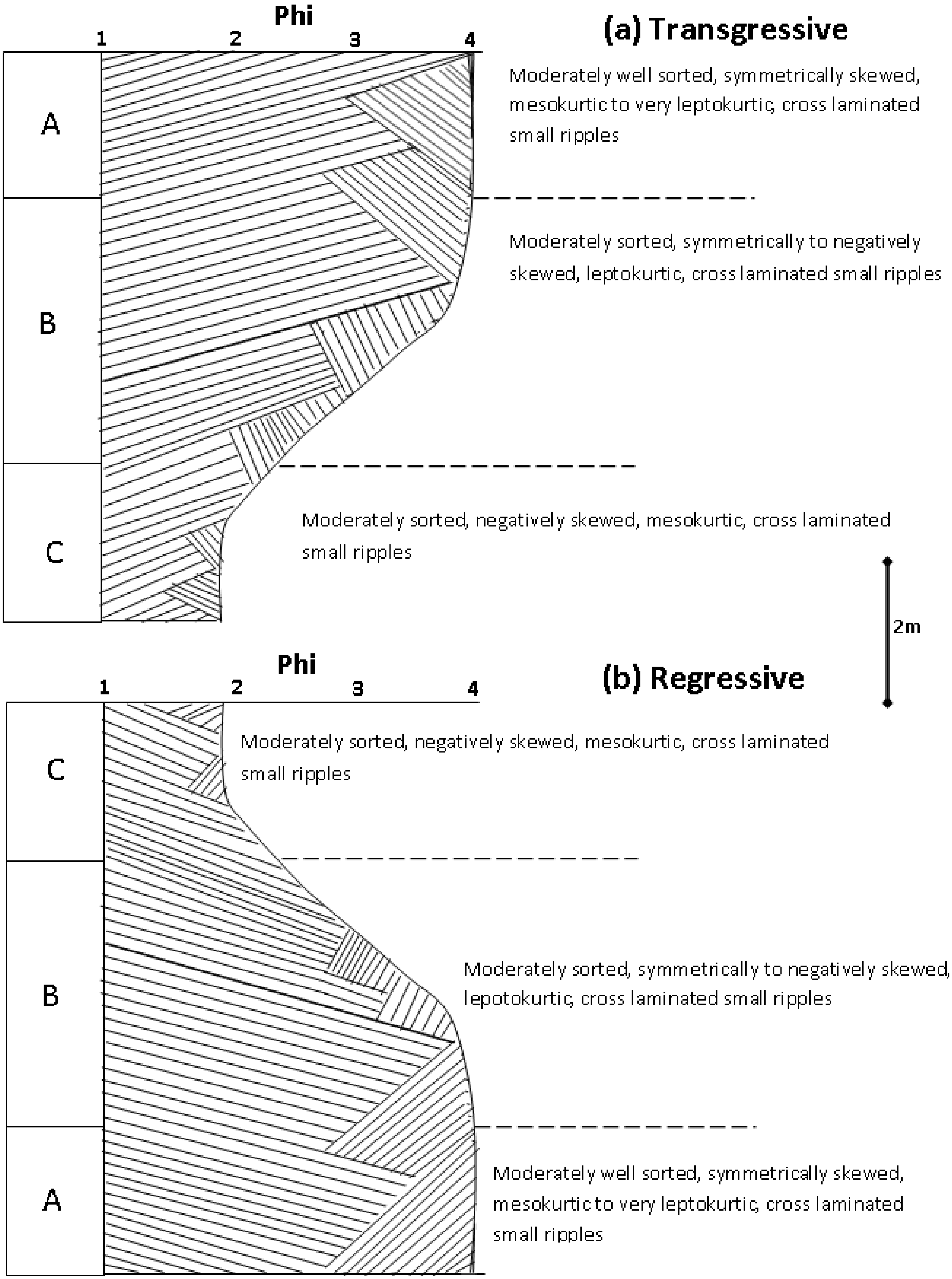

Figure 5. Typical stratigraghpic sequence models of Calabar Tidal River deposits; (a) Transgressive sequence, (b) regresive sequence.

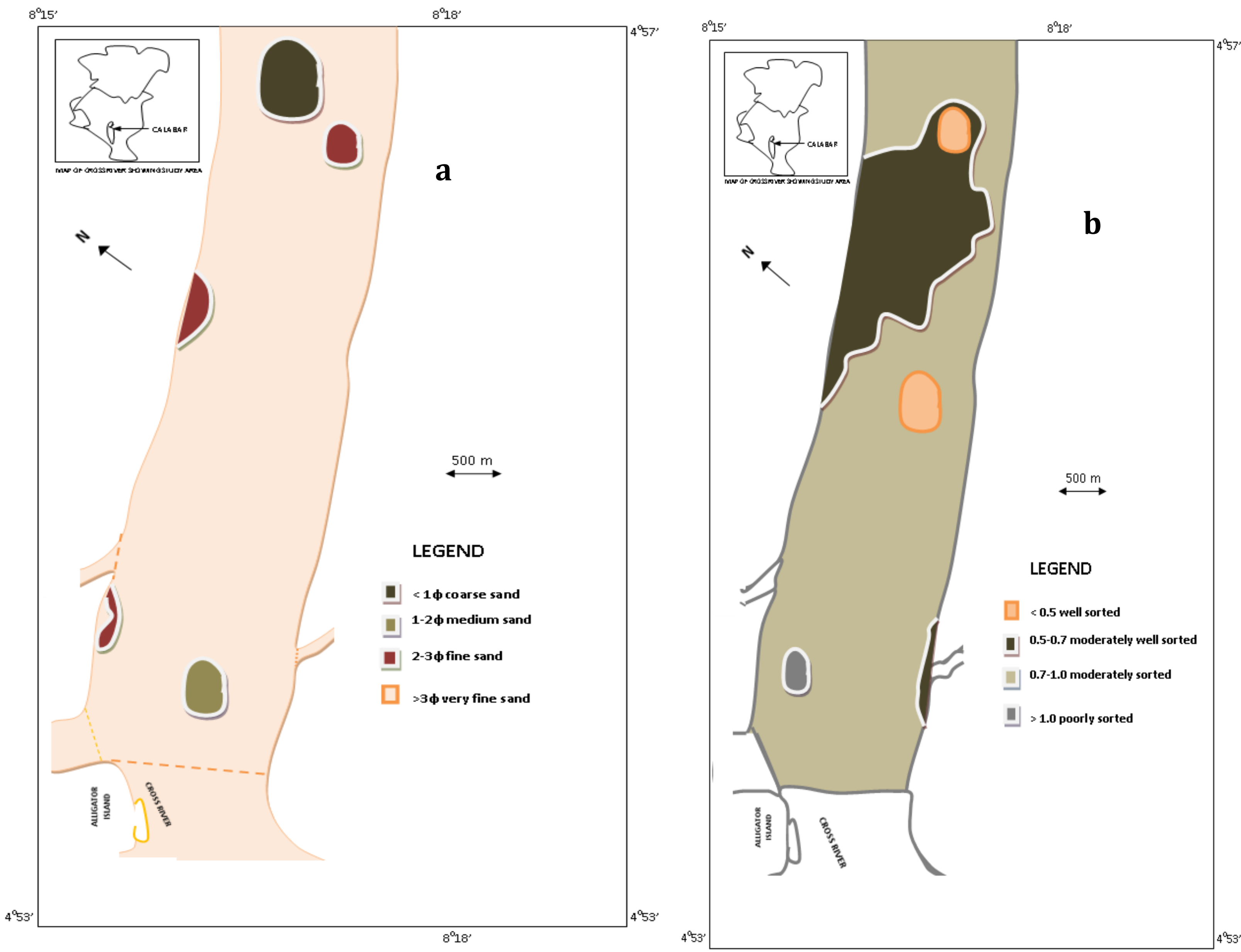

Figure 6. Surface Distribution of Upper Calabar River sediments; (a) Mean (b) Sorting.

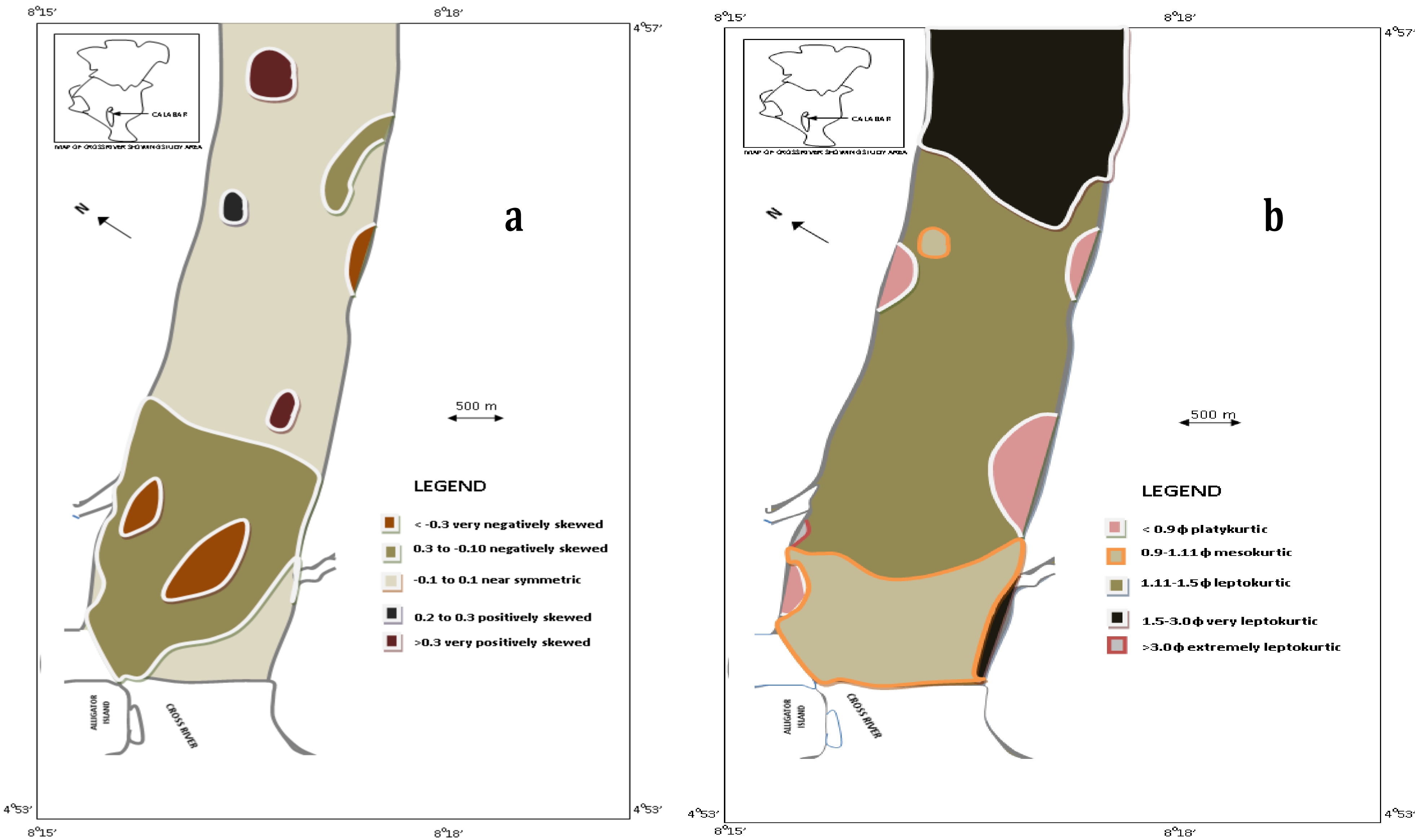

Figure 7. Surface distribution of skewness and kurtosis in lower Calabar River sediments.

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