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THE SEDIMENTARY ENVIRONMENTS OF TROPICAL AFRICAN ESTUARIES: FREETOWN PENINSULA, SIERRA LEONE

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SUMMARY

Four main environments are described from tropical estuaries of the Freetown Peninsula, Sierra Leone: A) sand bars, B) channels, C) intertidal flats and D) mangrove swamps. The sand bars are predominantly well-sorted medium sands, with dunes as the main bed form. The channel sediments vary in grain size and bed form up the estuaries, but generally contain lag deposits (mostly of shell debris and laterite pebbles) coarser than the adjacent intertidal sediments. The intertidal flats are mostly muddy sands, commonly with scour pits and current lineation. The sedimentary structures are obliterated by infaunal bivalves and burrowing crustaceans. The mangroves, developed peripherally around the estuaries, are important in trapping and binding the finer grades of sediment.

Sierra Leone has an extreme two-season climate, considerably affecting the estuarine sediments. During the dry season, a period of accretion, much sediment (mainly bed load) is taken into the estuaries from offshore. Crustaceans and bivalves increase in numbers and occupy a larger area of the intertidal flats. During the wet season, mud and plant debris are brought down by the rivers and some bed load is moved down or out of the estuaries.

With rising sea level, the estuarine deposits are prograding landward, over fluviatile sediments and soils (laterite in this case), producing a coarsening upward sequence from rootlet beds through bioturbated muddy sands to well-sorted cross-bedded medium sands.

INTRODUCTION

Estuaries are an important feature of West African coastal sedimentation. Along the Sierra Leone coast, where detailed studies have been carried out, estuaries vary from drowned river valleys a few hundred metres long to large complex estuaries and swamps, with numerous distributary channels covering many hundreds of square km. Two easily accesible estuaries (Aberdeen Creek and Black Johnson) on the Freetown Peninsula coast (fig. 1) have been examined in detail, involving several hundred grain size analyses, trenching, observations of bed forms (both exposed and subaqueous) and hydrographic surveys (salinity, pH and current velocities).

This paper describes the sedimentary environments which can be distinguished in the estuaries from a study of the sediment, bedforms, fauna, flora and hydrography. Previous work on estuarine and tidal flat sediments has been concentrated in temperate regions, particularly along the North Sea coast with studies by Häntzschel (1938, 1939), van Straaten (1950, 1954 and others), Reineck (1958, 1963 and others), Evans (1965) and others. Little attention has been paid to tropical estuarine environments, particularly those with two distinct climatic seasons, the work of Day (1951) and coworkers in South Africa being an exception.

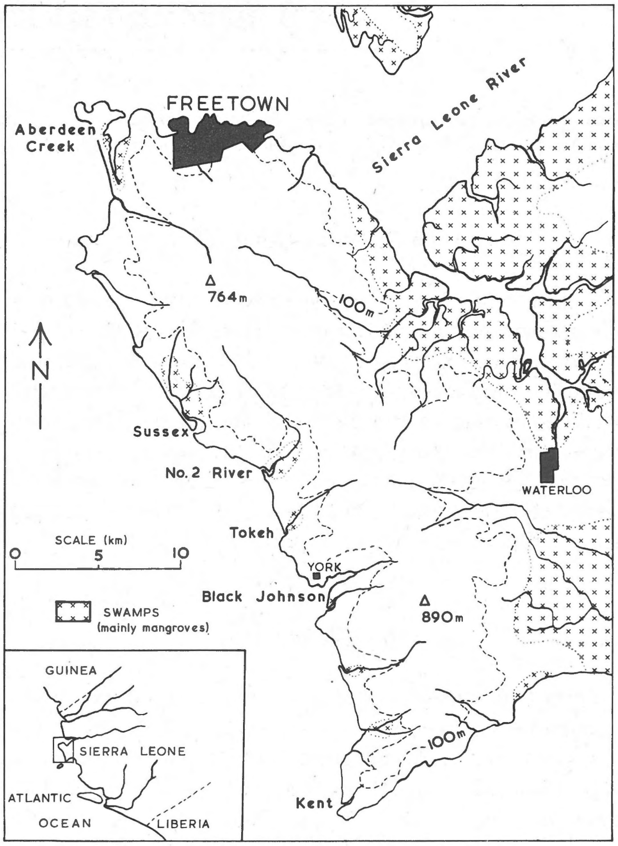

Fig. 1
Location map of the Freetown Peninsula, Sierra Leone.

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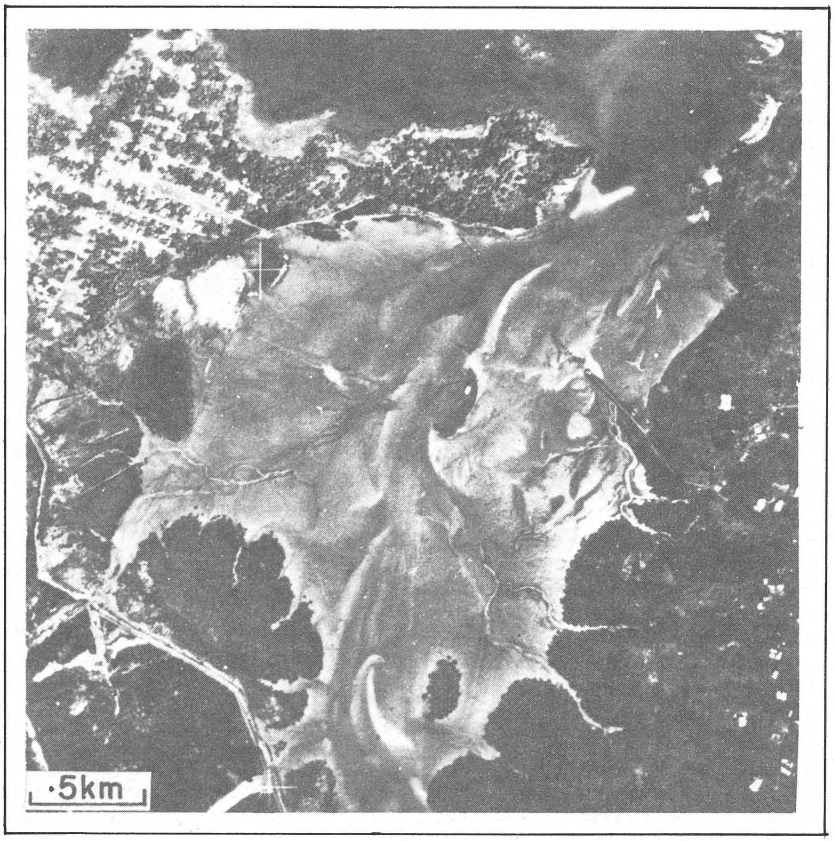

Fig. 2
Aerial photograph of Aberdeen Creek, Freetown, Sierra Leone, Sandbars are mostly developed adjacent to the main channel. Note vast area of intertidal flats (chiefly muddy sands) with meandering drainage channels.

BACKGROUND GEOLOGY

Immediately adjacent to the Freetown coast, a range of hills (composed of Pre-Cambrian layered gabbro and anorthosite) rises to nearly 900 m. The Freetown Layered Gabbroic Complex is surrounded by Tertiary and Quaternary paralic sediments of the Bullom Series. Along the western side of the Freetown Peninsula a coastal plain (sloping from 200 to 15 m O.D. and generally less than 5 km wide) is formed of severely lateritized beach and estuarine sediments of the Bullom Series resting on gabbro (Gregory, 1962).

CLIMATE

Sierra Leone has a two season climate, with a wet season generally lasting from June till September and the dry season from December to March. The mean maximum temperatures range from 25°C in August to 29°C in March and the minimum varies from 21°C in August to 22°C in April (Clarke, 1969). The humidity is generally over 80 per cent. The rainfall averages around 310 cm a year, but of this, 280 cm falls between June and September. Winds blow mostly from the west during the dry season, and from the southwest during the wet season, bringing the monsoonal-type rains.

THE ESTUARIES

The Freetown Peninsula coast consists of long sandy beaches separated by rocky headlands and drowned river valleys (the estuaries) (figs. 2 and 3). The estuaries vary in size from a few hundred metres to several km in length, and from less than 50 m to 2 km in width Sandspits at the mouths of the estuaries deflect and partly block the rivers. Indeed, during the dry season, persistent wave action and low or negligible river discharge, may result in the estuaries being entirely cut off from the sea by the sandspits (producing blind estuaries, Day, 1951). Soon after the onset of the wet season, the spits are broken down by the increased river discharges.

Elsewhere along the Sierra Leone coast, beach ridges (Worrall, 1969), tidal flats, wide estuaries and vast areas of mangrove swamp with meandering channels are developed. Prevailing southwesterly winds lead to long shore drift in a

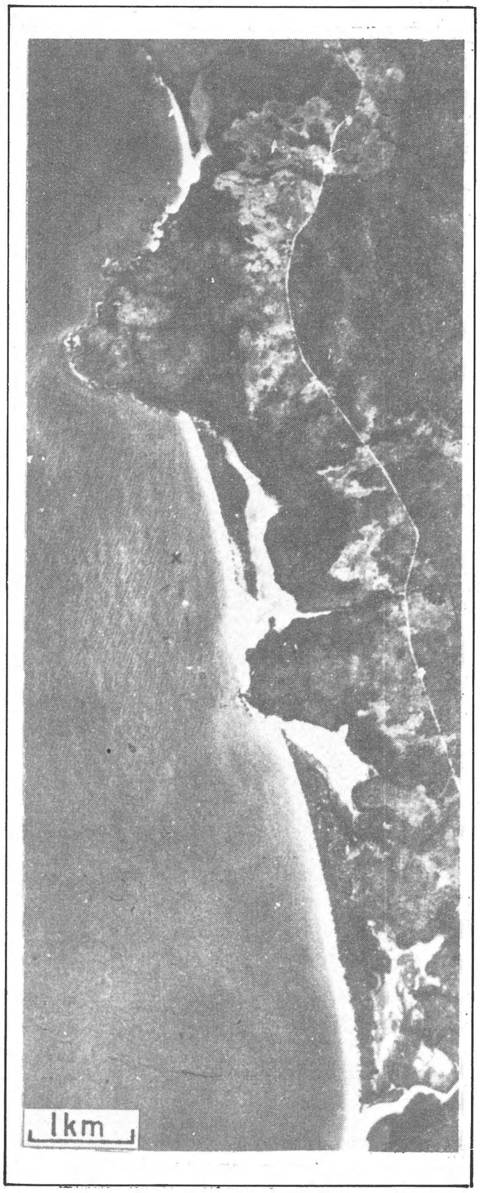

Fig. 3
Aerial photograph of coast south of York Freetown Peninsula. Black Johnson estuary is the most northern (at top). Headlands are of layered troctolite and gabbro.

northerly direction along this part of the West African coast. However, along the Freetown Peninsula coast, river mouth deflection by sandspits has been in both a northwest and southeast direction. This is probably the result of secondary circulations caused by the Banana Islands (off the southwestern point of the Peninsula) which deflect sand brought along the coast from the southeast, offshore into the region of St. Ann's Shoals.

The semidiurnal tide along the Freetown coast has a range of 3.0 m at spring tides and 1.2 m at neap tides. The Guinea Current, slow moving warm water above the thermocline, flows from the northwest as part of the main Atlantic circulation system (Longhurst, 1962).

Salinity values vary in the estuaries from 11.5 ‰ to 38 ‰. Low salinities are characteristic of the wet season, and fresh water dilution has been recorded up to 40 km off the Sierra Leone coast (Watts, 1958). During the dry season, normal marine water (35 ‰) penetrates up the estuaries, but hypersalinities are only developed in small pools on the intertidal mudflats where water temperatures may reach 40°C. pH values of the estuarine water vary from 8.2 for fully marine, to 6 to 6.5 for freshwater at the heads of the estuaries.

Salinity and pH values of intertidal sediment pore waters generally reflect those of the overlying estuarine water at high tide, except in the areas of mangroves and muds where decomposing organic matter reduces the pH to 5.5-6.

ESTUARINE DEPOSITIONAL PROCESSES

Within estuarine environments, the current regime (tidal and river currents) is the main factor governing sediment transportation and deposition (Postma, 1967). This is in contrast to tidal flats where wave action is considered more important. In the tropical estuaries of Sierra Leone, it is chiefly the tidal currents – with velocities generally between 15 and 50 cm/sec at mid-flood tide – which control the sediment distribution and movement. Other factors affecting the sediments are a) salt-wedges, b) wind-generated waves, c) low-tide drainage in semipermanent channels, d) river flow and e) atmospheric precipitation (rain).

The gradual movement of a salt-water wedge up an estuary leads to the onshore movement of bed load (Meade, 1969); this is probably taking place in the large Sierra Leone River estuary immediately to the north of the Freetown Peninsula (Longhurst, 1958). Wave action is only important around the mouths of the estuaries and results in the formation of sandspits and minor beaches. Within the estuaries, bed forms may be smoothed and rounded by wind-wave action at low stages. Drainage channels, which are pathways for sediment movement, appear on the intertidal flats during the later stages of ebb-current run-off. This open channel flow occurs in semipermanent channels on muddy sand flats and in the troughs of progressively emergent dunes on sand bars (as described by de Vries, Klein, 1970, from the Bay of Fundy). The effect of river flow is important during the wet season and enhances the ebb currents. Much suspended matter (silt, laterite and organic material) is brought down from the hinterland at this time of the year. Rain, which can be torrential and/or persistent has a considerable effect on estuarine sedimentation during the wet season. Much terrestrial material (mostly laterite and plant debris) is washed onto the intertidal flats to be transported by river and tidal currents and some is incorporated in the estuarine sediments. Small precipitation run-off channels are formed on the intertidal flats during heavy storms and bed forms are commonly obliterated.

SEDIMENTARY ENVIRONMENTS

The Freetown Peninsula estuaries can be subdivided into four main environments, differing in sediment grain size characteristics, bed forms, fauna, flora and location. These are a) sand bars, b) channels, c) intertidal flats and d) mangrove swamps. Within the intertidal flats, three sub-environments can be recognised, the *Uca* fine sands, muddy sands and mudflats. Each environment will be described separately. Their distribution within the estuaries of Aberdeen Creek (fig. 2) and Black Johnson (fig. 3) is shown in figs. 4 and 5. Grain size analyses of sediments from these two estuaries are shown in figs. 6A and 6B.

SAND BARS

The sand bars are generally elongate with the flow direction and occur predominantly in the lower reaches of the estuaries. The sand bodies occur as subtidal or intertidal sand bars within the main channel, intertidal point bars attached to the inner bends of channel meanders or as isolated bars within the intertidal flat areas (mostly muddy sand).

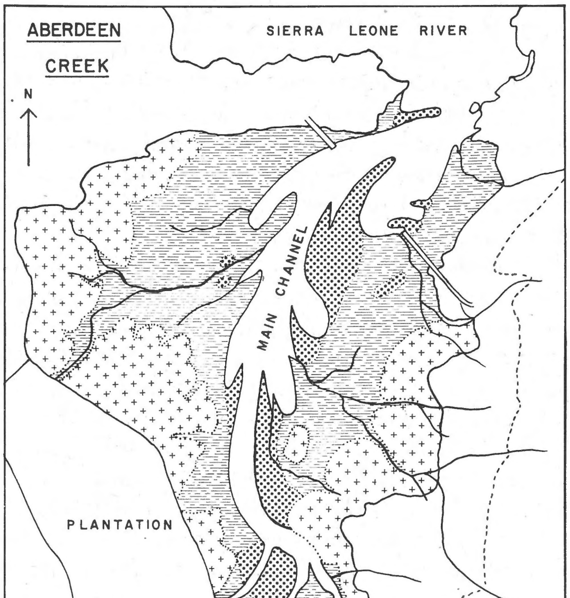

Fig. 4
Map showing the distribution of the three main estuarine environments in Aberdeen Creek.

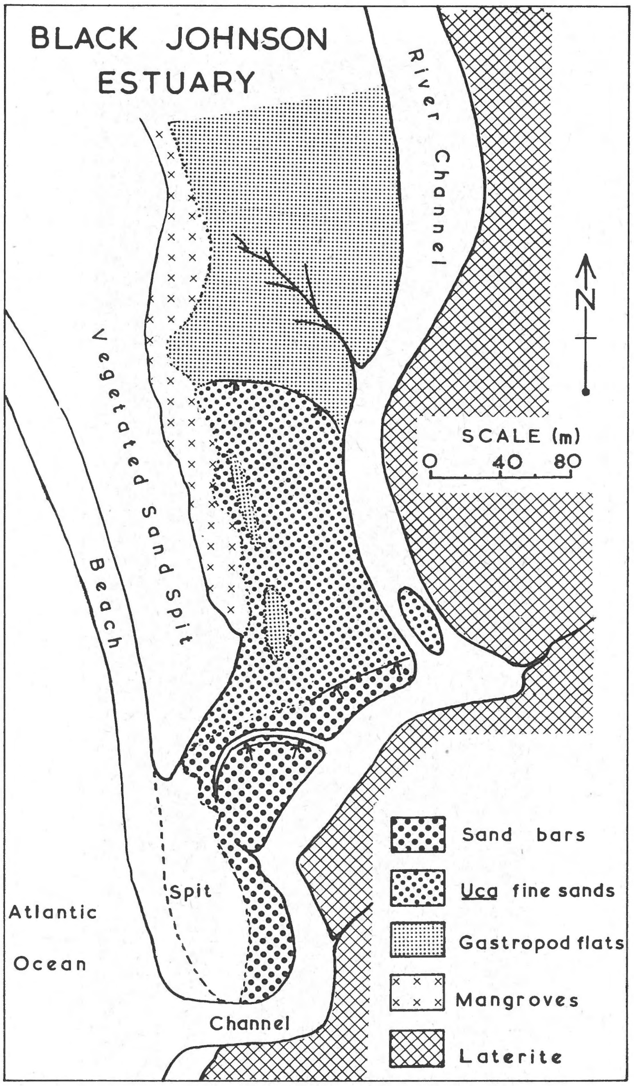

Fig. 5
Distribution of the sedimentary environments in Black Johnson estuary. The gastropod flats (muddy sands) extend 500 m further up the estuary than shown on the map. The position of prominent slip faces of sand waves is shown by arrows.

Intertidal sand bars are developed in the higher energy zones, particularly near the mouths, of many estuaries (and tidal flats) and have been described by van Straaten (1954), Reineck (1963), de Vries Klein (1963, 1970), Land and Hoyt (1966), Kulm and Byrne (1967) and others.

The sediment of the sand bars is invariably medium sand (1.0 to 1.5 ϕ) although in some estuaries (e.g. Aberdeen Creek) coarse sands may predominate locally. Generally the sediment is well to moderately well sorted ($\sigma\,\phi = 0.4$ to 0.6, sorting index of Folk and Ward, 1957). The sediment consists chiefly of well-rounded quartz sand, although in the coarser fractions highly polished laterite clasts are common. The quartz grains (commonly with inclusions of rutile) are of two types: clean grains and grains coated with iron hydroxide. The brownish coating, imparting an overall yellow colour to the sand, is considered to form through subaerial processes (lateritization) and is typical of many present-day continental shelves covered in relict sands (Swift et al, 1971; Judd et al, 1970).

Bed forms are well developed on the sand bars and vary up the estuaries, reflecting changes in the power of the tidal currents. Dunes are the characteristic bed form and generally have a chord (terminology of Allen, 1968) of 1.0 to 3.0 m and a height of 20 to 30 cm, with internal cross-bedding of 20 to 30°. The dunes are mostly sinusoidal and catenary in plan, less commonly linguoid. lunate, or straight-crested.

The orientations of the dune structures on the intertidal sand bars vary with the seasons. During the wet season, the greater river discharge enhances the ebb tidal currents, and generally all dunes (and superimposed ripples) are directed downstream. However, during the dry season, when river discharge is minimal, the dune orientations change up the estuaries. In the lower parts of the estuaries dunes on emergent sand bars have an ebb (downstream) orientation, but in the upper reaches the dunes are invariably flood orientated and have superimposed ebb-formed structures (rarely even flood-formed ripples are superimposed on flood dunes). In the central parts of the estuaries, dunes may be rounded symmetrical forms, but are commonly ebb oriented with internal flood-formed cross-bedding and reactivation surfaces (de Vries Klein, 1970). The sequence of bed forms, as seen during the dry season, indicates a progressive decrease up the estuaries in the ability of the ebb currents to form dunes, and change the bed roughness developed during the flood stage.

Prominent slip faces, giving rise to a low-angle cross-bedding (10 to 20°) may divide the sand bars into several sand waves (chord 10 to 20 m). These slip faces also occur along the borders of the sand bar areas where the latter are prograding over muddy sands or *Uca* fine sands, of the intertidal flats. During the dry season, the bar slip faces are mostly directed upstream, through the dominance of flood tidal currents over those of the ebb. However, during the wet season, the slip faces are directed downstream and may be the fore sets of small deltaic structures with horizontal top sets and current lineation.

Late-stage run-off commonly leads to the development of superimposed ripples on the dune crests and ripplefans (Allen, 1968) in the troughs. In areas of higher stream power the stoss sides are plane surfaces with current lineation.

Some parts of the sand bars do not have dune structures but are covered by linguoid ripples with a chord of 10 to 20 cm, span of 8 to 15 cm, and height of 2 to 4 cm. Sinusoidal and less commonly transverse ripples also occur. Other parts of the sand bars are smooth surfaces (underlain by even lamination) with current lineation.

The periodic bed load movement in a sand bar environment inhibits colonisation by surface and burrowing organisms (Day, 1951). Infaunal bivalves are absent and polychaetes (especially *Diopatra*) which build sand tubes are only locally present. Burrows of *Callianassa balsii*, with walls composed of pellets of muddy sand, occur rarely in the lower intertidal part of some bars.

Pits and trenches cut in the sand bar sediments reveal structures produced by the bed forms described above (cross-bedding, cross-lamination and even lamination) but rarely any bioturbation.

CHANNEL SEDIMENTS

Sediments in the estuarine channels are generally coarser than those of the adjoining intertidal area. In lower reaches of the estuaries, lag disposits may reach pebble grade and consist of locally-derived laterite clasts. Shell debris is concentrated in the channel sediment, and includes pelecypods and gastropods washed in from offshore. Dunes and plane beds are commonly developed in channels where the sediment is medium sand. Only in smaller estuaries are standing waves and antidunes formed. The orientation of bed forms reverses with the tide except during the dry season when flood dunes may still be present during falling water in higher parts of the estuaries. There is a gradual decrease in sediment grain size up the channels, concomitant with the decrease in strength of the tidal currents, so that in the higher parts muddy sand is prevalent and flat surfaces and small-scale ripples of low stream power are developed.

Channel migration produces coarse beds, below the intertidal flats, rich in shell debris and pebbles (channel lag deposits) passing up into low-angle cross-bedded sand and silt formed by deposition on the migrating channel bank (the lateral sedimentation of van Straaten, 1954 and Reineck, 1967).

Within the channel sediments, bivalves, crustaceans and polychaetes are only present in the finer-grained areas in the upper parts of the estuaries. Sediment-ingesting fish are common and contribute in a small way to sediment mixing. They produce cylindrical faecal pellets (up to 5 mm in length and 2 mm in diameter), which on exposure consolidate and are then capable of being transported. Greenish-blue sponges (*Adocia* sp.) and brown algae may develop in quieter, but fully marine, parts upon muddy sand at certain times of the year. Oysters (*Ostrea tulipa*) colonise bed rock adjacent to the channel.

In many respects the channel sediments resemble fluviatile channel deposits (Allen, 1965) but could be distinguished on faunal considerations, a bimodal current system, and overall context.

INTERTIDAL FLATS

The intertidal flats are areally the most important environ-

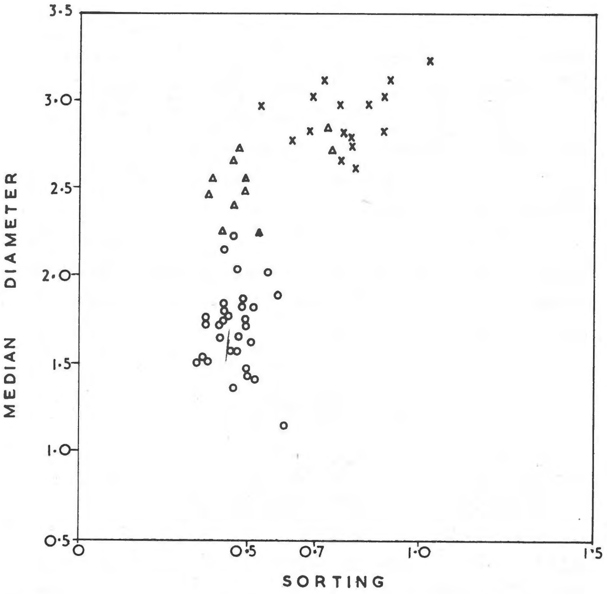

Fig. 6
A. Plot of median diameter (in phi) against sorting index ($\sigma\phi$) for sediment samples from Black Johnson estuary. Circles indicate samples from sand bars, triangles those from *Uca* fine sands and the crosses those from muddy sand intertidal flats. There is a decrease in grain size and degree of sorting up the estuary.

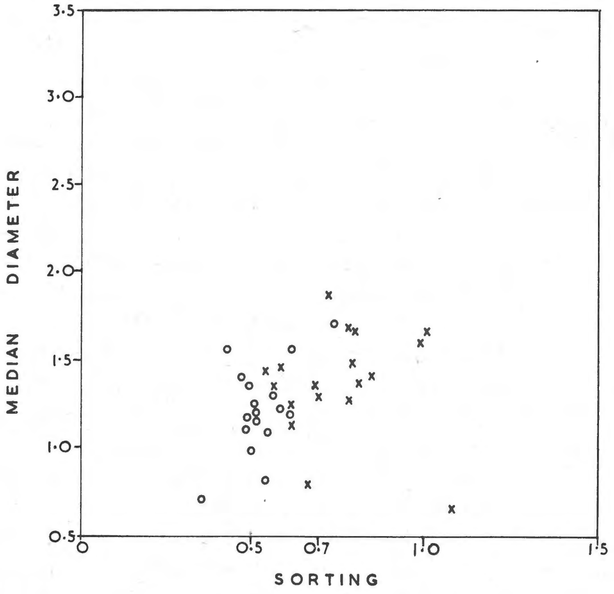

Fig. 6
B. Plot of median diameter (in phi) against sorting index ($\sigma\phi$) for sediment samples from Aberdeen Creek. Circles represent samples from sand bars, crosses are samples from muddy sands of the intertidal flats.

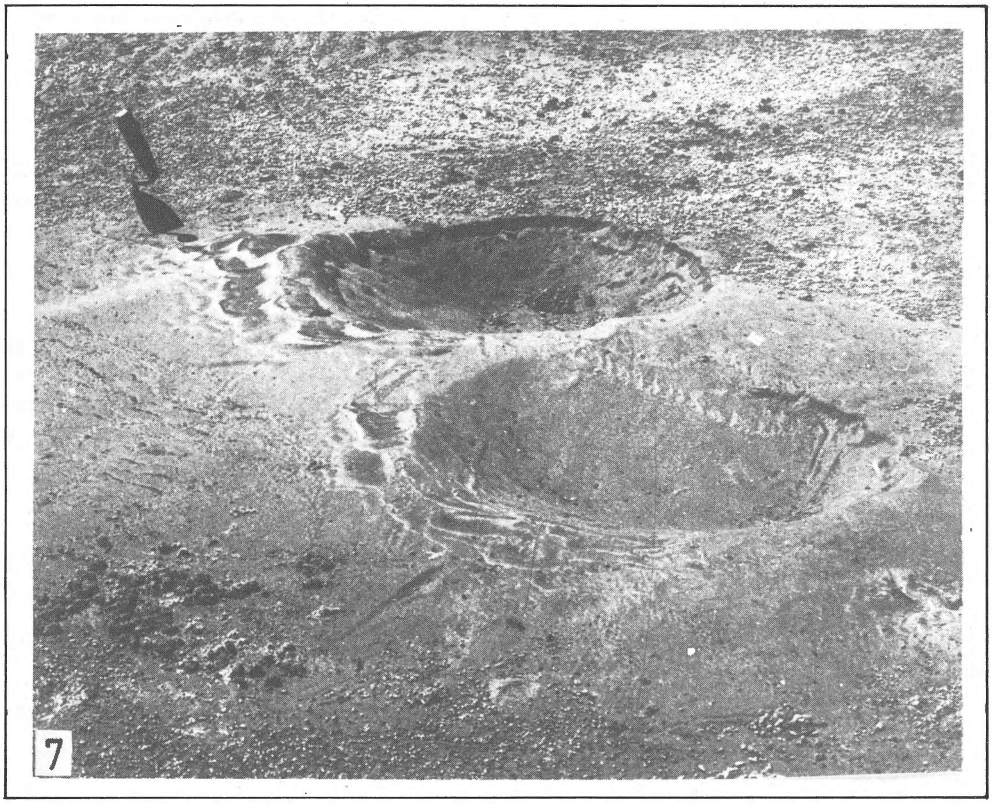

Fig. 7
Two well-developed scours in *Uca* fine sands, formed by ebb currents flowing right to left. Note sand build-up with ripples on downstream side of scour. Black Johnson, towards the end of the wet season. Trowel is 25 cm long.

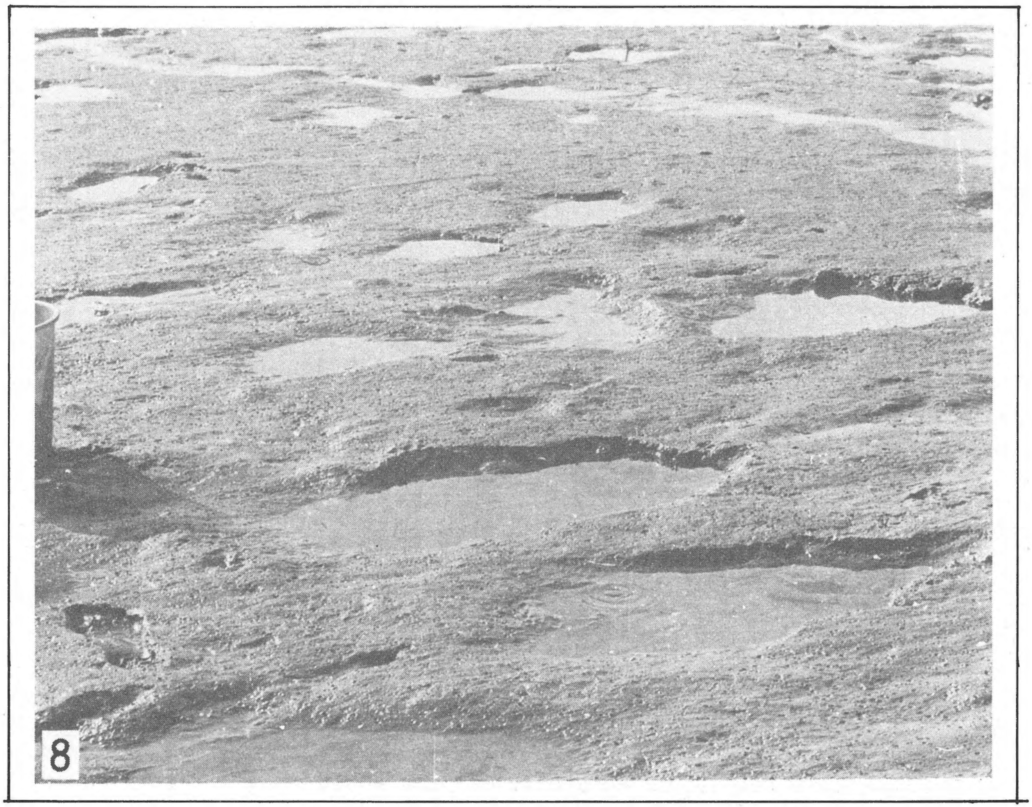

Fig. 8
Pools of standing water on muddy sand flats formed by ebb-tidal scour. Aberdeen Creek, towards the end of the wet season. Bucket is 30 cm high.

ment of the estuaries and have a median grain size varying from clay to medium sand (fig. 6). Bed forms and faunas vary with grain size and situation within the estuary relative to the main channel. Three subenvironments can be recognised, muddy sands, *Uca* fine sands and mud flats.

Muddy sands

Muddy sand, occupying the greatest area of the intertidal flats, is a moderately to poorly sorted, positive skewed sediment, with up to 10% shell debris (mostly pelecypod).

Characteristic of areas of muddy and fine sand are scour pits (figs. 7 and 8). These are generally oval depressions up to 15 cm deep and from a few cm to 1 m in length. Scours on the muddy sand flats are mostly filled with standing water (fig. 8). Those formed close to the main channel are asymmetrical with the upcurrent side (where erosion takes place) steeper than the downstream side, where deposition commonly occurs forming a sediment mound. Linguoid ripples may be superimposed upon the latter (fig. 7). The scours are produced in a similar way to flutes (Allen, 1969) by erosion through separated flow around an inhomogeneity on the sediment surface. The inhomogeneity is commonly a crustacean burrow, a sandy worm-tube or a pelecypod shell (fig. 9). The scours are most commonly formed by ebb tidal currents, but in some cases, those produces by flood tidal currents are still preserved after emergence. Scour pits are active bed forms which migrate upcurrent and leave behind up-current directed low angle ($< 10^\circ$) cross lamination, upon an erosion surface.

Semipermanent dendritic and meandering channels drain the muddy sand flats and their migration leads to the concentration of shell debris, upon erosion surfaces (lateral sedimentation). Apart from the scour structures, few bed forms are developed upon the flats. Straight-crested asymmetrical ripples (chord 8 to 12 cm, height 1 to 3 cm) and plane surfaces with current lineation may be developed on the muddy sands adjacent to the main channel.

The muddy sands are considerably affected by organisms living upon and within the sediment. Four species of infaunal bivalves are important: *Arca senilis, Tagelus angulatus, Iphigenia laevigata* and *Tellina nymphalis.* Of these, *Tagelus, Tellina* and *Iphigenia* burrow to a depth of 20 to 40 cm and their siphons produce a characteristic stellate feeding pattern on the sediment surface. These bivalves live within the reduction zone of the sediment and commonly their shells are without a periostracum through the acid pore water. *Acra senilis,* a suspension feeder, has a thick, heavy shell, up to

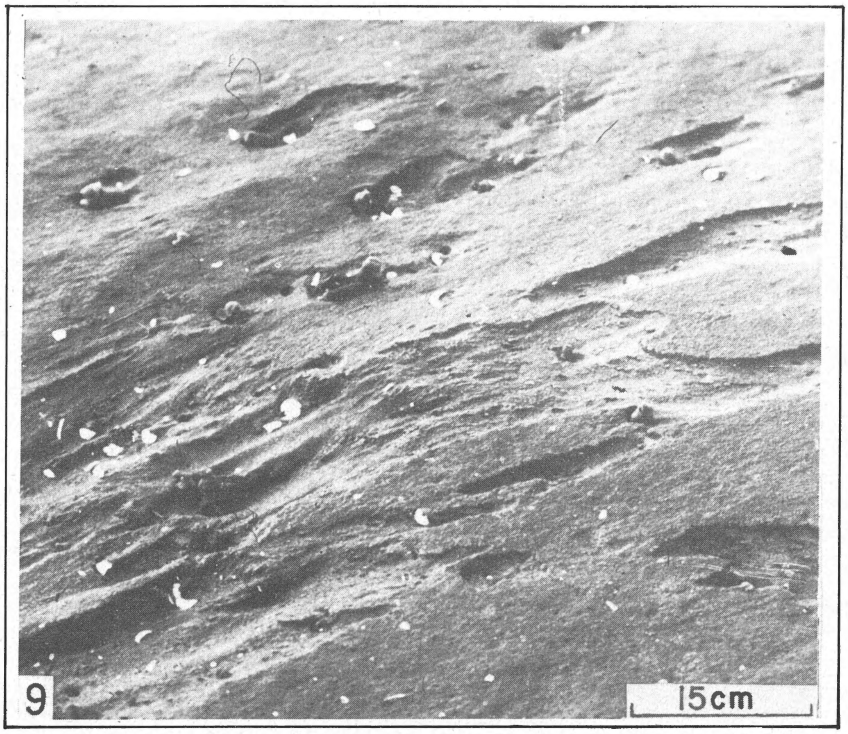

Fig. 9
Incipient scour marks developing around worm tubes and shell debris in muddy sand. Aberdeen Creek.

10 cm in diameter, and lives just below the sediment surface. These infaunal bivalves may be present in numbers up to 20 per m^2.

Polychaetes (e.g. *Glycera* and *Aglaophamus*) and thin red nemertine worms are common in the muddy sands. Burrowing crustaceans contribute to the sediment reworking, occurring particularly in the drier parts of the flats. Genera present include *Upogebia, Callianassa, Squilla* and *Alphus.* On the surface of the muddy sand flats, two species of turritellid gastropod (*Tympanotomas fuscata* and *Pachymelania fusca*) are locally present in great profusion. *P. fusca* lives within the top cm of the sediment and there may be as many as 50 individuals per 100 gm of sediment. The shells of *T. fuscatus,* are commonly inhabited by the hermit crab *Clibinarius africana* and *C. cooki.* The gastropods (filter feeders) cover the sediment surface in numerous trails (fig. 10).

During the dry season, algal mats dominated by the blue-green alga *Lyngbya confervoides* grow in pools and channels on muddy sand flats. These mats are important in binding and inhibiting erosion of the sediment (a process fully described by Neumann et al, 1970 from the Bahamas). The algae commonly grow upon sediment ridges (several cm high), which are transverse to the current direction and built up by the binding action of the algae and the erosion between the ridges. Associated with the algae are numerous micro-organisms such as nematodes, coccoid algae, diatoms (particularly *Amphora, Navicula* and *Nitzschia*), foraminifera and peridinians.

When an estuary is cut off from the sea towards the end of the dry season, a gelatinous algal mat commonly develops over the sediment surface in many parts of the estuary. Genera common in this mat are *Microcoleus plastus, Spirulina subsulpha* and *Arthrospira* sp. Bed forms in such an estuary are gradually rounded and flattened by wind-wave action.

Plant debris is an important constituent of the muddy sands. Finely disseminated organic matter, seeds, pollen etc., may constitute 20% by volume of the sediment, and larger plant fragments abound within the sediment and on the sediment surface, particularly during, and for a time after the wet season.

Sections cut in the sediment of the muddy sand flats may show little primary structure. The sediments are commonly mottled and some sediment filled burrows are locally discernible. Open burrow structures (of bivalves or crustaceans) are commonly lined by a thin oxygenated zone of reddishbrown sediment. Flaser bedding and lenticular bedding (Häntzschel, 1936; Reineck, 1967; Reineck and Wunderlich, 1968) may occur in sections cut close to channels where ripples develop in fine sand and are partly buried by slack-water mud deposition.

Uca fine sands

Fine sands within the estuaries are generally inhabited by the burrowing fiddler crab *Uca tangeri*. This subenvironment

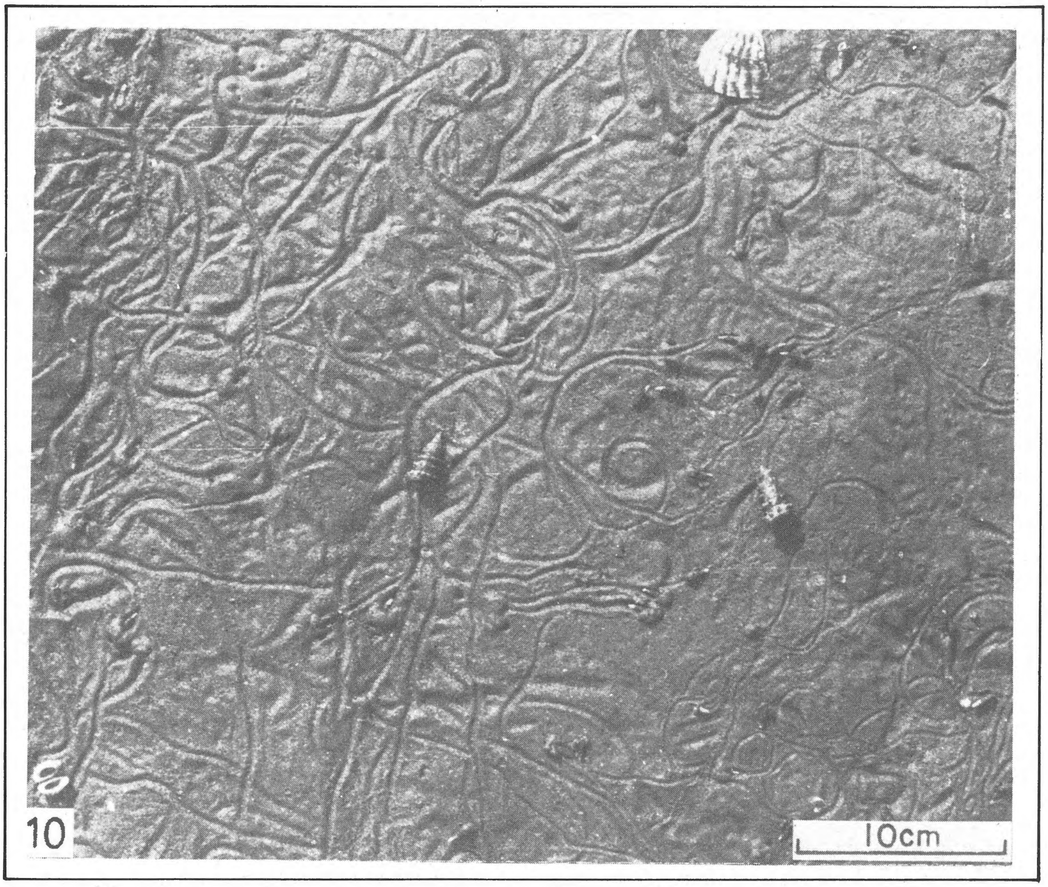

Fig. 10
Surface of intertidal flats covered in trails of turritellid gastropods. Black Johnson.

occurs within the higher intertidal area where the water table is 10 to 40 cm below the sediment surface at low tide. In small estuaries such as Black Johnson (fig. 5), the crabs occupy the sediment higher up the estuaries than the sand bar environment, with muddy sands, densely populated by gastropods, beyond. In larger estuaries, such as Aberdeen Creek (fig. 2), the fine sands with *Uca* occur along the sides of the estuaries in the lower reaches and as small emergent bars in the upper parts. The equivalent sediment in a temperate environment is habited by the crustacean *Corophium* (Buller and McManus, 1972).

The sediment (median grain size 2.5 ϕ) is generally greyish-yellow or brown, with a sorting index ($\sigma\,\phi$) of 0.5 (fig. 6). Shell material is insignificant, normally constituting less than 2%.

The crabs, which may attain a density of 25 per m^2, are important in obliterating the depositional structure of the sediment. Feeding pellets (1 to 4 mm in diameter) are produced by scraping and ingesting the surface sediment (fig. 11). Larger pellets (up to 1.5 cm) are produced by their burrowing activity. The burrows penetrate down to 40 cm, are curved and rarely branch. The activity of *Uca* has been described in detail by Braithwaite and Talbot (1972) from studies in the Seychelles.

Areas of fine sand are generally flat and covered by small straight crested and sinusoidal (less commonly linguoid) current ripples (chord 10 to 20 cm, height 1 to 3 cm) which may be rounded by wave action. Oscillation ripples and scour pits also occur. In areas close to the main channel are plane surfaces with current lineation.

Pits cut into the *Uca* fine sands show little structure. Cross lamination and even lamination are present where crab activity has been minimal. The intense bioturbation by the fiddler crabs has removed much of the structure and the sediment is commonly mottled.

Apart from *Uca,* other burrowing crabs present are *Sesarma* and *Sarmatium.* Polychaetes are not abundant.

Mud Flats

Muds are of restricted occurrence in the Freetown Peninsula estuaries and only accumulate in quiet upper reaches, where current strengths are always low. The mud, a dark grey or black colour, is mostly composed of about 50% quartz silt

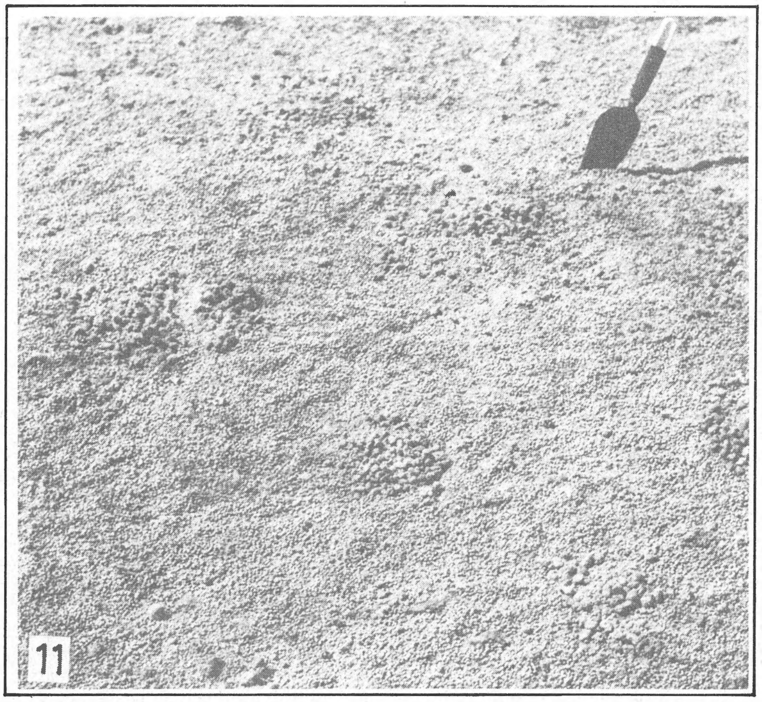

Fig. 11
Surface of fine sands covered in feeding pellets and burrow pellets of the fiddler crab *Uca*. Black Johnson.

and 50% clay (chiefly kaolinite, determined by X-Ray diffraction, and fine laterite). Few bivalves inhabit the mud which is cohesive and sapropelic.

The paucity of infaunal organisms in this type of mud is probably related to the lack of oxygen. Thin red polychaete worms (eg. *Glycera*) are common, however, and some burrowing crustaceans (notably the rundskipper (*Periophtalamus*) and crabs (eg. *Upogebia*) are present. The surface of the mud is commonly covered by numerous gastropods (*Pachymelania*). The mud has little structure, save from the effects of the infaunal organisms.

Mud assumes a greater importance in creeks and backwaters of the larger estuaries along the Sierra Leone coast (such as the Sierra Leone and Scarcies rivers). The intertidal mud shows the same features, however, of a dominance of surface organisms over infaunal ones and little sedimentary structure.

MANGROVE SWAMPS

Mangroves in the Sierra Leone estuaries grow in the upper intertidal and low supratidal environments. The species *Rhizophora mangle* and *R. harrisonii* are the main components of the mangrove flora with *Avicennia nitida* and *Laguncularia racemosa* locally dominant on higher ground (Gledhill, 1963). The sediments of the mangrove areas are generally black or dark grey, muddy silts and sandy muds, which contain much organic matter, mostly fine rootlets and thicker roots of *Rhizophora.* The mangroves trap and bind sediment (as described by Scoffin (1970) from the Bahamas) building up an elevated area which is commonly delineated by a bank, up to 30 cm above the intertidal flats.

The mangrove plants themselves are colonised by oysters (*Ostrea tulipa*) small gastropods (*Littorina angulifera*) and barnacles (*Chthamalus*). Burrowing crustaceans abound between the mangroves, particularly *Periophthalmus,* and large crabs.

The sediment of the mangrove swamps is generally mottled and churned, through the high density of roots and the burrowing activity of the crustaceans.

SEDIMENT PROVENANCE

Three sources are generally considered for the provenance of estuarine sediments (Guilcher, 1967): offshore (marine), inland, (fluviatile) and bank erosion. In some estuaries, it has been demonstrated that sediment is derived from all three sources (e.g. Kulm and Byrne, 1967), and this is also the case in the Sierra Leone estuaries. Most of the quartz sand is derived from offshore, as is shown by the absence of quartz in the country rock and the iron oxide coatings on the grains which is typical for modern continental shelf sediments (Swift et al, 1971). These sands were brought down to the shelf at a time of low sea-level stand and are now being brought back onshore to fill the estuaries by tidal currents and saline bottom currents. The continental shelf off Sierra

TABLE 1
A comparison of Sierra Leone estuaries in the wet and dry seasons.

WET SEASON	DRY SEASON
1. Estuaries: open	may be cut off from sea (blind).
2. Wave action: may be intense during storms.	persistent, leading to spit development.
3. Tidal currents: ebb currents dominate	flood currents dominate.
4. River discharge: high	low or negligible.
5. Direct climatic effects: intense precipitation leading to channel formation, bed form obliteration and rain pitting.	evaporation leading to local development of hypersalinities and mudcracks.
6. Salt water: driven out of estuary	greater penetration of salt water up estuary.
7. Sand bars: main bed form is ebb-formed dunes	main bed form is flood-formed dunes.
8. Scour pits: common	rare.
9. Flora: much plant material brought down by rivers	development of algal mats on intertidal flats and in blind estuaries.
10. Fauna: decrease in number of crabs and bivalves	increase in number of crabs at beginning of dry season and subsequent migrations to occupy larger areas of intertidal sediment.
11. Sediment: much suspended load carried downstream.	much bed load brought in from off-shore and moved upstream by flood tidal currents.

Leone is covered by relict sands and silts (McMaster et al, 1971) and the former courses of rivers and deltas which existed on the shelf before the Flandrian transgression can still be discerned from Admiralty hydrographic charts. Laterite in the sediments is derived from erosion of outcrops along the banks of the estuaries, and also along the coast, from where it is brought into the estuaries by long shore drift and tidal action. Clay in the estuarine sediments is derived mainly from inland and is brought down to the coast (where it flocculates in the estuaries) chiefly during the wet season.

DISCUSSION AND COMPARISON

Wet season versus dry season processes. There is a marked contrast between wet and dry season processes. The wet season is a period of high river discharge, when much sediment, mostly in suspension, and plant debris is carried out of the estuaries. Nearly all bed forms have an offshore orientation (formed by offshore directed currents) and scour pits are common on the intertidal flats. The dry season on the other hand is a period of deposition in the estuaries, of sediment mostly derived from offshore by tidal currents. Bed forms mostly have an onshore orientation and sand bars migrate upstream. The dry season is also a time of greater organic activity; for example sediment-binding algal mats develop on the intertidal flats and over the subaqueous sediment-surface in blind estuaries, and the activity of burrowing crabs and bivalves increases as new populations develop. The main differences within estuaries during the wet and dry seasons are given in table 1.

Comparisons with temperate estuarine sediments. – Sediments and bed forms within temperate and tropical estuaries show many similarities, allowing for differences of provenance. However, scour pits, a conspicuous feature of the tropical intertidal flats described in this paper (figs. 7, 8 and 9), do not appear to be so common in equivalent temperate environments. The influence of climate on the estuarine sediments is greater in the tropics (see above and table 1) than in temperate areas. For example, bed forms are commonly destroyed by tropical rain storms and precipitation run-off channels develop on the intertidal flats. Precipitation is rarely so intense in temperate environments as to produce features other than rain spots. Plant debris, mostly derived from the surrounding mangrove swamps and brought into the estuaries during the wet season, is a more important sediment component of tropical than temperate estuaries. The mangroves of the tropics are replaced in temperate estuaries by salt-marsh grasses (especially *Obione* and *Puccinellia*) which have a similar binding effect on the sediments.

ESTUARINE SEDIMENTARY SUCCESSIONS

The coast of West Africa, as many world coastlines, has been subjected to a rising sea-level over the past 20,000 years as a result of the melting of the Pleistocene ice sheets. Drowned river valleys (estuaries) produced by the transgression are the depositional sites of sediment both brought down the rivers and transported shoreward from the continental shelves. The latter appear to be the most important sources of bed load and the former of suspension load (Mead, 1968; Howard et al, 1971). Within an estuary, there is generally a net build-up of sediment, produced by flood tide deposition prevailing over ebb tide erosion, resulting from the effects of settling lag and scour lag (van Straaten and Kuenen, 1958; Postma, 1967). With a continuing rise in sea-level, the estuarine sediments prograde landward and are in turn overlain by marine deposits of the transgressing sea. A cessation of the transgression, or a high fluviatile sediment influx, would result in seaward progradation and the generation of a deltaic system.

The areal distribution of sedimentary environments in the

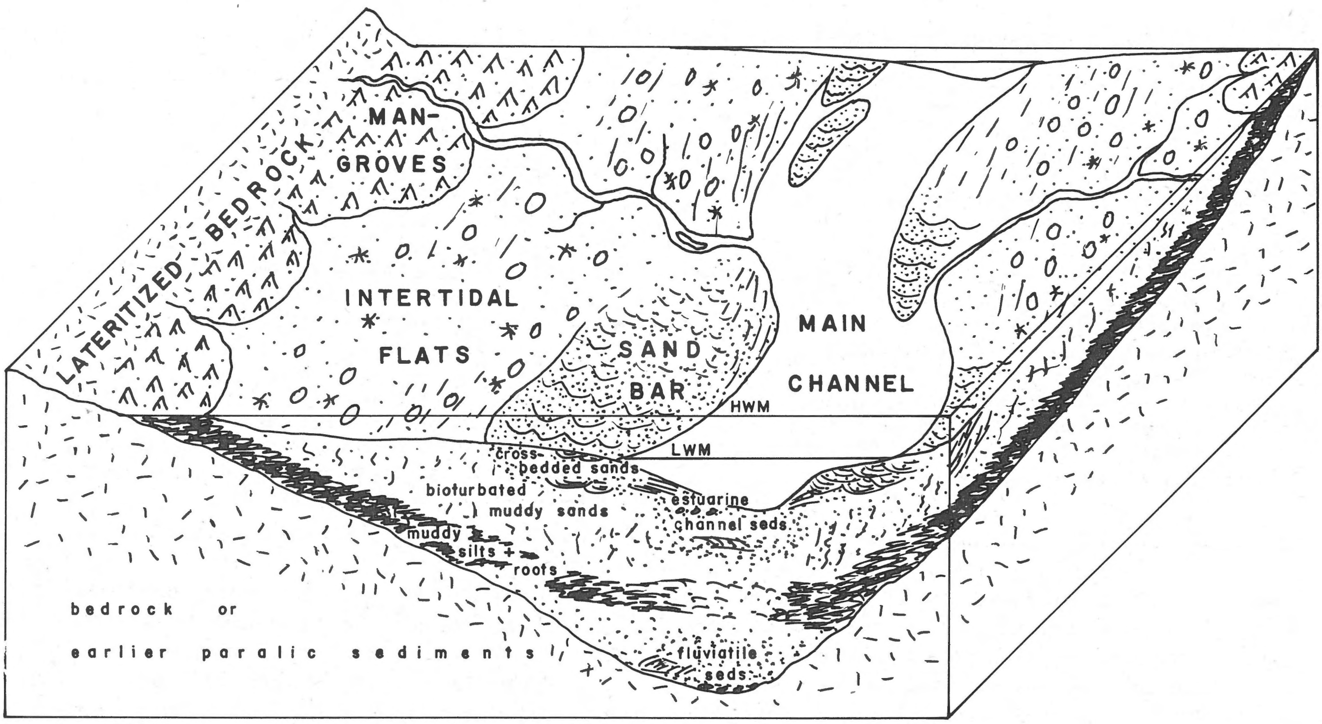

Fig. 12
Block diagram to show the spatial arrangement of the estuarine sedimentary environments of the Freetown Peninsula estuaries.

Sierra Leone estuaries (and most others) is basically one where the grain size decreases upstream from the mouth, and also away from the main channel, with the mangroves growing peripherally. Pits dug to a depth of a metre of more in the estuaries commonly show sediments coarsening upwards, and below the muddy sand of the intertidal flats mangrove roots are frequently encountered. This indicates a general progradation up the estuary of the coarser deposits from the lower reaches over the finer deposits of the intertidal flats, which in turn prograde over mangroves, fluviatile sediments and soils. Cores taken from Aberdeen Creek (Gledhill, 1963) show the estuarine sediments (up to 4.5 m thick) to be lying on a laterite gravel (? representing fluviatile lag deposits) which rests on lateritized bed rock.

A consideration of the overall sediment distribution pattern within the estuaries indicates that a coarsening upward sequence will be produced during a marine transgression, with a basal root bed (representing the mangrove swamp environment), passing up into bioturbated muddy sands (intertidal flats), and overlain by cross-bedded medium sands (sand bars)(fig. 12). Such a sequence will probably rest upon fluviatile sediments, deposited in the region at the time of lower sea-level stand. The estuarine sediments will in turn be overlain by a fining-upward sequence of normal marine sediments, if the rise in sealevel continues. However, it is probable that during the marine transgression some of the estuarine sediments will be removed by erosion at the base of the surf zone as it moves landward (Swift, 1968). Minor regressive phases or uplift of the coastal area during the transgressive period, may lead to the development of fining upward cycles (formed by the seaward progradation of intertidal muddy sands over the sand bars) within the general coarsening upwards sequence of the estuarine sediments. Estuarine sediments with both coarsening and fining upward sequences have been described from the Dutch coast (Terwindt, 1971).

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