TECHNICAL REPORT WC/96/42
Overseas Geology Series

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EXECUTIVE SUMMARY

In 1995 a coastal zone pollution monitoring programme for developing countries, the Land-Ocean Contamination Study (LOCS) was initiated by the British Geological Survey under funding from the UK Overseas Development Administration (ODA) Natural Resources Division. The central objectives of LOCS are (i) the provision of data regarding the sources, transport pathways and fates of contaminant metals and selected organic compounds along urbanised coastal margins, and (ii) promotion of the use of such data in integrated coastal zone management (CZM).

A systematic geochemical and hydrochemical survey of the estuarine creek systems of Mombasa, Kenya was carried out under the LOCS programme in liaison with the Kenya Marine and Fisheries Research Institute between September 1995 and February 1996. The main objective of this was to assess the concentration of heavy metals, alkanes, polycyclic aromatic hydrocarbons and organochlorines in water, suspended particulate matter and sediment at forty eight localities within the creek systems and nearby reef-fronted waters. The survey also focused on the storage and transport of these contaminants within the waters and sediments of the creek systems. Such physical aspects of the creek settings are addressed by this report, which complements that of Williams et al. (1996[a]) on the geochemical and hydrochemical settings.

The estuarine creek systems consist of inland lagoons connected to the ocean by laterally-confined channels. One-dimensional (segmented) box modelling shows that the average residence time of contaminated water within the lagoons is likely to be less than a week, and less than two days in the confined-channels. Contaminants are likely to reside longer during neap tides and in the wet season, although they will be most widely dispersed during spring tides and in the dry season.

The distribution of sediments reflects the ebb dominance of the creek systems as fluvially derived sediments are generally transported seawards and open marine sediments only occur towards the seaward end of the confined-channels. The periodicity of the, extremely sporadic, major bedload transport events is unknown. Although those parts of the lagoons that are removed from channels are likely to have the highest sedimentation rates, all parts of the systems may be regarded as potential contaminated sediment sinks because of the degree of active bioturbation in all inter- and sub-tidal environments.

The results of the survey illustrate the importance of understanding the hydrodynamic and sedimentological setting of estuarine environments in order to understand the storage and flux of contaminants within them. Although this survey adopted those techniques that are most appropriate for analysis of the environments and available datasets of Mombasa, the approach used will be equally applicable to similar settings.

The geochemical, hydrodynamic and sedimentological data collated during the LOCS survey provide a valuable baseline against which to evaluate the effects of future urban and industrial development at Mombasa. In an attempt to maximise the utility of the survey outputs in practical CZM and planning, a GIS has been developed (Williams et al. 1996[b]) allowing interrogation of pollution data in conjunction with pre-existing information concerning land- and marine-resource use.

1: INTRODUCTION

1.1: Background:

In February 1995, the British Geological Survey (BGS) initiated a coastal-zone pollution monitoring programme for developing countries, the Land-Ocean Contamination Study (LOCS), under funding from the UK Overseas Development Administration, Natural Resources Division. The central objective of LOCS is the provision of contaminant monitoring, impact amelioration and integrated coastal-zone management techniques to meet the specific social, technical and economic requirements of the targeted study regions.

This report outlines the methodology, preliminary results and implications of research into the transport and storage of contaminants in the waters around Mombasa Island, Kenya, executed in September 1995 in conjunction with the Kenya Marine and Fisheries Research Institute (KMFRI) as a component of the East African Phase of the LOCS project. It focuses on the physical setting of the district, and the identification of probable transport pathways, storage areas and dispersal mechanisms of industrial contaminants, rather than sewage (see Norconsult 1975), within the inshore waters. A complementary report (Williams et al. 1996^{a}) outlines the distribution and concentration of metals and organic contaminants in water, suspended particulate matter (SPM) and sediment within the same study area. A further report (Williams et al. 1996^{b}) describes a Geographic Information System, relating to LOCS data, that may be used in environmental management of the Mombasa area.

1.2: Focus of Report

The distribution, transport, and deposition of dissolved and particulate contaminants in estuarine and marine systems is predominantly controlled by hydrodynamic (currents and tidal flushing mechanisms) and sedimentological factors (sediment type and bed morphology). A full understanding of the interaction of such variables is a vital precursor to accurate prediction or modelling of contaminant residence-times and dispersal paths at any location and, with respect to Mombasa, forms the principal focus of this report.

Following this introduction (1) the report is broken down into discrete sections describing: the regional setting (2), the hydrodynamics of Mombasa's estuarine creek systems and the fate of water-borne contaminants (3), the sedimentary dynamics of the creek systems and the fate of sediment-hosted contaminants (4) and conclusions and recommendations for future environmental control (5).

1.3: Notes and abbreviations.

All grid references, enclosed in [ ] brackets, relate to the Kenyan grid and when quoted should be preceded by the 100 000m square identifier letters EF.

Some common abbreviations are used throughout the report:

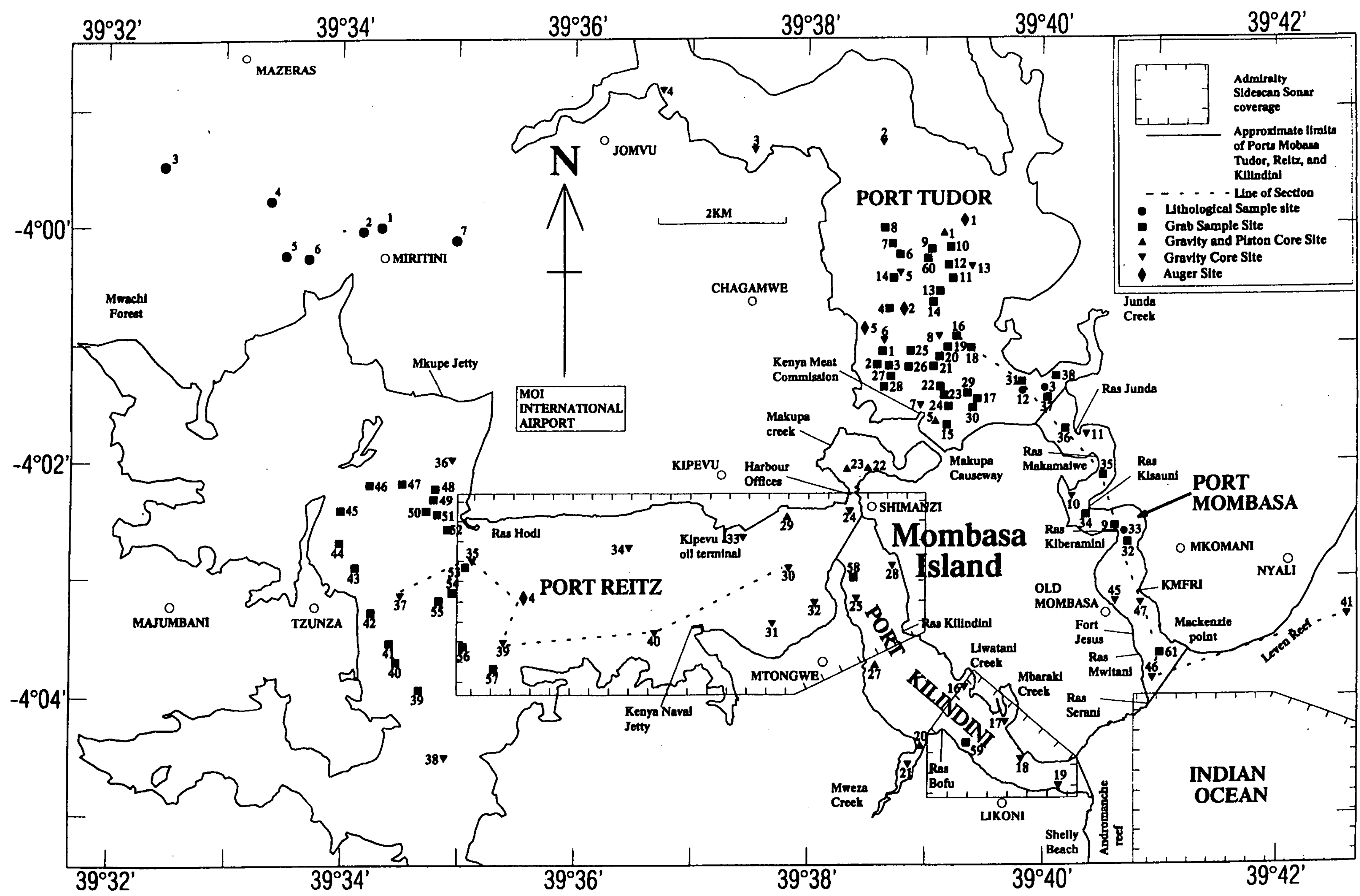
LAT	Lowest Astronomical Tide
LWS	Low Water Spring Tide
MSL	Mean Sea Level Tide
HWN	High Water Neap Tide
HWS	High Water Spring Tide

2: REGIONAL SETTING

2.1: Geographic setting

Mombasa, Kenya's second largest city, is sited on an island overlooking the equatorial Indian Ocean at about latitude 04° 05' S and longitude 39° 65' E. The island, which was joined to the mainland by the Makupa causeway earlier this century, separates two major inland lagoons. That to the north is known as Port Tudor and is joined to the ocean by a laterally-confined, steep-sided channel, Port Mombasa, to the east of the island. The large inland lagoon west of Mombasa, Port Reitz, is similarly joined to the ocean to the south of the island by a laterally-confined channel, Port Kilindini (Figure 1).

Figure 1 **(Overleaf). Setting of the creek systems, showing the limits of ports Mombasa, Tudor, Reitz and Kilindini, areas of side-scan coverage, sample sites and lines of section illustrated in Figures 13 and 14 (Port Tudor- Port Mombasa) and Figure 15 (Port Reitz).**


39°32'
39°34'
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39°38'
39°40'
39°42'
-4°00'
-4°02'
-4°04'
Admiralty Sidescan Sonar coverage
Approximate limits of Ports Mombasa Tudor, Reitz, and Kilindini
Line of Section
Lithological Sample site
Grab Sample Site
Gravity and Piston Core Site
Gravity Core Site
Auger Site
N
2KM
MAZERAS
MIRITINI
Mwachi Forest
Mkupe Jetty
MOI INTERNATIONAL AIRPORT
JOMVU
CHAGAMWE
PORT TUDOR
Junda Creek
Ras Junda
Kenya Meat Commission
Makupa creek
Makupa Causeway
KIPEVU
Harbour Offices
SHIMANZI
Ras Makamaiwe
Ras Kisauni
PORT MOMBASA
Ras Kiberamini
MKOMANI
NYALI
KMFRI
Mombasa Island
OLD MOMBASA
Fort Jesus
Ras Mwitani
Mackenzie point
Leven Reef
Ras Serani
Ras Kilindini
Liwatani Creek
Mbaraki Creek
PORT KILINDINI
Ras Bofu
LIKONI
Mweza Creek
Shelly Beach
Andromanche reef
INDIAN OCEAN
MTONGWE
Kenya Naval Jetty
Kipevu oil terminal
Ras Hodi
PORT REITZ
MAJUMBANI
TZUNZA

These inland lagoons and associated channels form creek systems that provide natural harbours, and have been exploited by shipping for many centuries. The importance of Mombasa as a port caused the growth of several industrialised settlements on the mainland, particularly after the construction of Makupa causeway and Nyali bridge over Port Mombasa, near Ras Kisauni (Figure 1). Mombasa is now the largest port in East Africa and the population of its administrative district exceeds half a million people. It has a wide spectrum of associated industries, including oil refining, manufacturing and warehousing, which today is largely centred on Port Kilindini and Port Reitz.

2.2: Physiographic and geological setting

The creek systems of Mombasa occupy a dissected coastal plain, less than 4.5km wide and up to 200m high. The plain is separated from the highlands of the Nyika, that are over 500m high, by the Foot Plateau (Okemwa et al. 1994). Although the creek systems of Mombasa occur within the coastal plain, most of the catchments of the rivers that discharge into them lie in the Foot Plateau and Nyika, that are underlain by an outcrop of the Karoo system. The constituent Taru, Maji ya Chumvi, Mariakani and Mazeras Formations of the system are of Upper Carboniferous to ?Lower Jurassic age (Rais-Assa 1988) and unconformably overlie Archean basement. They consist mainly of sandstones, sandy shales and conglomerates.

Of the overlying Jurassic rocks, that dip towards the coast (Figure 2), the most westerly, the Middle to Upper Jurassic marine shales, sandstones, limestones and conglomerates of the Kambe Formation (Rais-Assa 1988), are resistant to incision and form a broad ridge to the northwest of the coastal lagoons. Almost the entire lagoonal area occurs within the outcrop of Upper Jurassic marine shales, sandstones and limestones of the Mtomkuu Formation (Rais-Assa 1988) (Figure 2). Shales of this formation are extensively exposed around the edges of the lagoons and, where broken-up underwater, form shale-gravels.

Locally the Jurassic rocks are unconformably overlain by the Magarini Sands of Pliocene age. Outcrops of these friable orange-brown sands cap hills of Jurassic rocks both north of Port Reitz in the vicinity of Moi International Airport, and between the River Majera and the Pleistocene rocks to the south of Port Reitz.

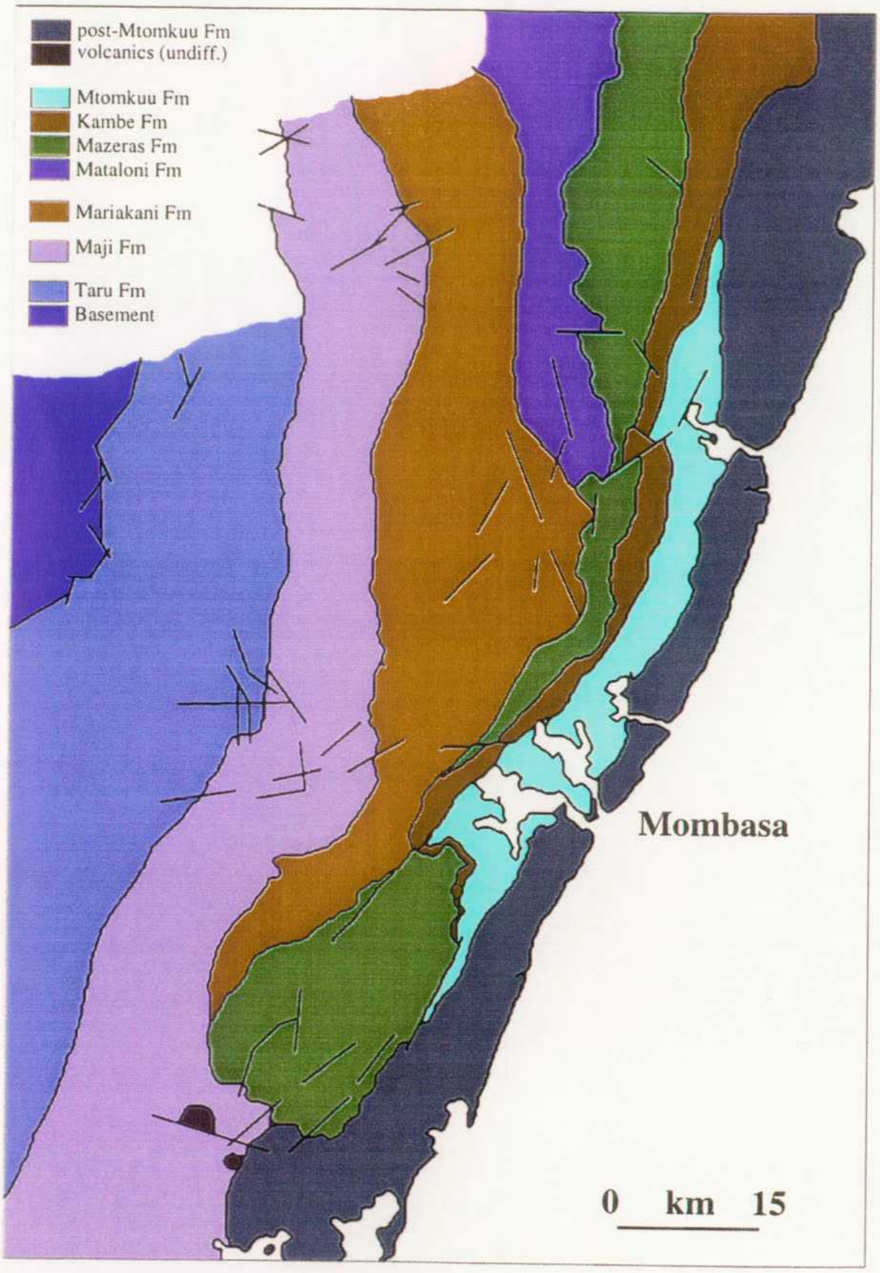


Figure 2 Simplified geological map of the Mombasa district

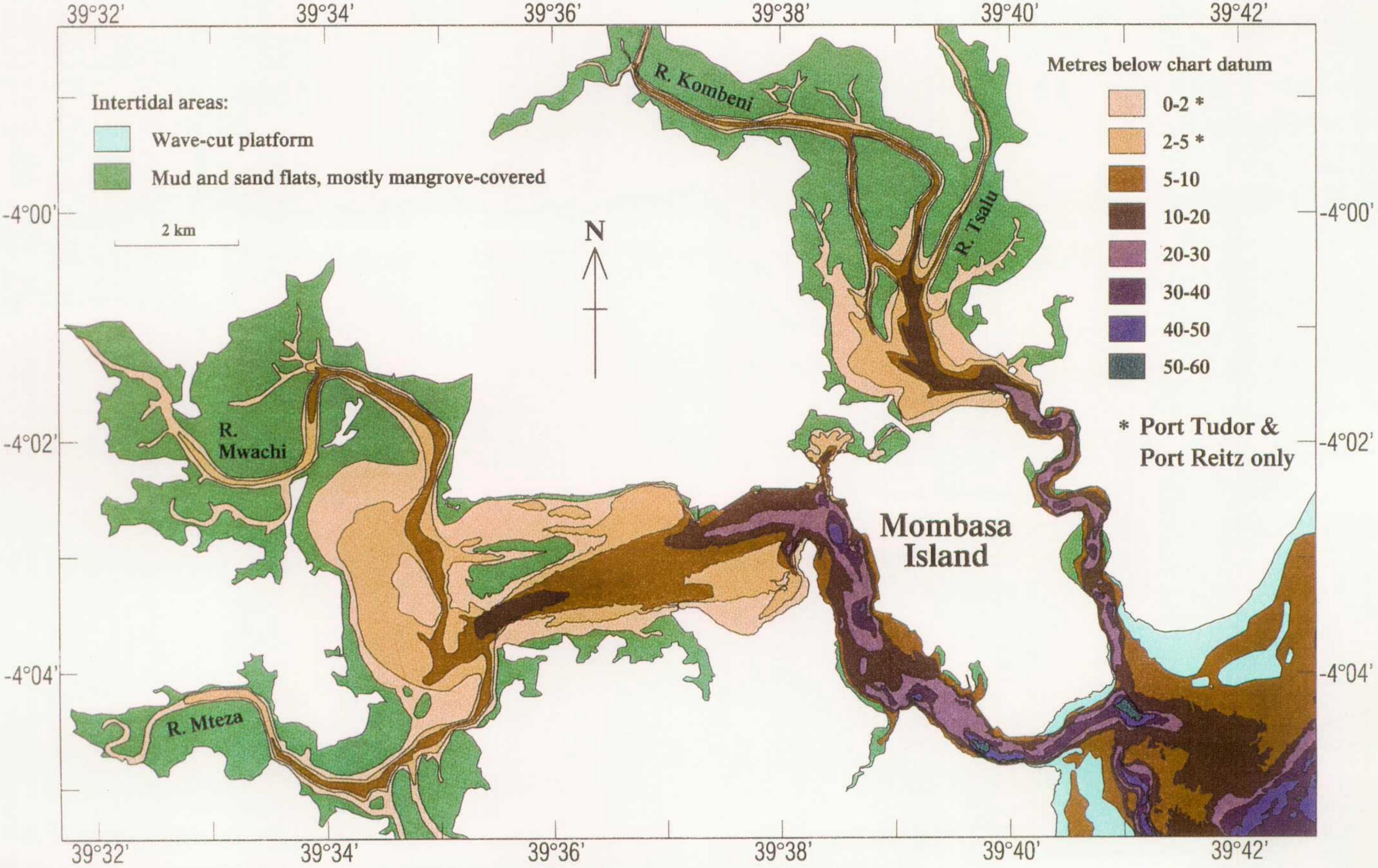
The inland lagoons are separated from the coast by Pleistocene coral reef limestones and back-reef deposits (Caswell, 1953; 1956; Carruthers 1985) (Figure 2) that commonly form a topographically proud coastal barrier system. The Pleistocene rocks are traversed by the steep-sided channels of Port Mombasa and Port Kilindini. The rocks also form steep-sided or cliffed terrains along parts of the coast to the north and south of Mombasa, described by Abuodha et al. (1994). On the seaward side of cliffed coasts, the Pleistocene limestones form wave-cut platforms (Figure 3). These are separated from the present reefs by shallow back-reef lagoons.

2.3: Climatic setting

The Kenya coast has two monsoons, separated by transitional periods. The monsoons have a great influence on the oceanography of the region, both in the open ocean and creek systems. They influence the transport of water-borne contaminants as river discharge (controlled by the rainy seasons at the beginning of the monsoons), as well as wind direction.

The northeasterly monsoon extends between November and March, when the warmest temperatures occur, reaching 28°C- 29°C in February and March. During this period wind speeds average 8.5 m/s and blow offshore. The winds are strong through the afternoon and evening, though at night the wind is light and variable. The winds blow to the east for about half the time and to the south or southwest for the rest of the period. The peak rain season occurs between November and December and accounts for approximately 30% of annual rainfall.

Figure 3 **(Overleaf). Bathymetry of the creek systems**


39°32'
39°34'
39°36'
39°38'
39°40'
39°42'
-4°00'
-4°02'
-4°04'
Intertidal areas:
Wave-cut platform
Mud and sand flats, mostly mangrove-covered
2 km
N
Metres below chart datum
0-2 *
2-5 *
5-10
10-20
20-30
30-40
40-50
50-60
* Port Tudor & Port Reitz only
R. Kombeni
R. Tsalu
R. Mwachi
R. Mteza
Mombasa Island

The southeasterly monsoon lasts from mid-April to early October when the coolest temperatures occur, with mean temperatures as low as 24°C in July. The winds during this monsoon average about 6.5 m/s and are relatively constant, except for early in the morning. They blow to the north for about 75% of the time, and to the northeast for about 25%. Daily maxima are about 9.5 m/s (Norconsult 1975). The peak long rain season lasts between April and June and accounts for about 40% of annual precipitation.

Annually rainfall averages between 760 and 1270 mm, the minimum being in the main dry season of January and February. The relative humidity is high throughout the year, but varies on a daily basis. The highest humidities, between 92-94%, occur at night and fall in the day, reaching a low of 60-70% in the afternoon. The potential evaporation rate (from pan measurements) ranges from 2200 to 2400 mm per year (Griffiths 1972). The climatic setting and selected records for Mombasa were presented by Norconsult (1975).

2.4: Oceanographic setting

The tides in the Mombasa area are semi-diurnal (with a form number of 0.18) and astronomical tides account for over 80% of water level variations (Odido 1994). Water levels vary sinusoidally with two unequal peaks daily. Mean spring ranges of 3.15 m and mean neap ranges of 1.14 m have been measured at Kipevu [c.707 534] in Port Kilindini (Pugh 1979) and equate well with measurements made in Port Tudor (3.12 m, 0.91 m) and Port Mombasa (2.76 m, 0.86 m) by Odido (1994). The variation in tidal range between Port Kilindini, Port Reitz (Miritini (Mkupe) Jetty [642 549] Figure 1), Port Mombasa (Kidomoni (Marina) club [c.755 520]) and Port Tudor (Kenya Meat Commission [721 549] Figure 1) measured over the 8th-10th September 1974 was less than 0.15m. These levels are elevated in relation to water levels outside the creek systems. The mean phase difference between high water times at Port Mombasa entrance and Kenya Meat Commission in Port Tudor is 9.6 minutes at high water, and 1.1 minutes at low water.

The marine setting outside the creek systems has been reviewed by Norconsult (1975). Circulation in the eastern Indian Ocean during the northeasterly monsoon (November to March) is characterised by two west-trending currents (focused on 2-8°N and 10-20°S), separated by the easterly flowing Equatorial Counter-Current. In the vicinity of Mombasa, water flowing towards the Counter-Current runs northwards along the coast during this period, although southward flows prevail along the coast north of Malindi (about 100 km north of Mombasa). With the onset of the southeasterly monsoon (May to September) the Equatorial Counter-Current disappears and all surface currents parallel to the Kenya coast flow northwards.

Nearshore, the ocean currents are modified by local reef configurations, bed mophologies, winds and tides. Predominantly northerly nearshore currents with velocities of 0.3-0.5 m/s prevail throughout most of the northeasterly monsoon, although a southerly current develops during a 2-3 week period prior to the monsoon interchange in February or March. The northerly currents continue to prevail during the southeasterly monsoon, with velocities generally accelerated by southeasterly winds. Persistent modifications of this northerly nearshore current trend have, however, been recorded at the entrances to Port Mombasa and Port Kilindini due to the influence of tidal currents of 0.25-0.5 m/s running parallel to the open coastline.

Tidal movements in the shallow lagoonal systems developed behind the modern reefs constitute the principal determinant of current directions and velocities within them. High velocity currents are generated in the vicinity of channels connecting these during the initial stages of the flood tide (producing onshore currents) and the latter stages of the ebb tide (creating offshore currents). Longshore currents produced by wave action in the these lagoons may attain velocities of 0.5 m/s.

Waves in the eastern Indian Ocean are highest during the monsoons, particularly in July and August during the southeasterly monsoon, when they have a maximum height of about 3 m with a period of about 10-15 seconds.

Beyond the limits of the modern reefs the waters of the Indian Ocean deepen abruptly to the southwest down the continental slope; within 7 km of the tip of Mombasa Island water depths exceed 200m.The creek systems are connected to the edge of the continental shelf by steep-sided submarine channels

3: HYDRODYNAMICS OF THE CREEK SYSTEMS

The need for high-quality hydrodynamic data is essential in understanding contaminant residence and transport in estuarine settings. Consequently, in order to gain a better understanding of these features in the Mombasa creek systems an initial hydrodynamic study was undertaken by Norconsult (1975) to investigate sewage dispersal from Port Mombasa and Port Kilindini. Later, Nguli (1994) and Odido (1994), concentrating mainly on tidal currents, studied the hydrodynamic setting of Port Mombasa and Port Tudor. The data from these studies have been augmented by the modelling undertaken within the LOCS project, described below.

3.1: Morphology of the creek systems

Both the creek system comprising Port Tudor and Port Mombasa, hereafter referred to as the Tudor-Mombasa system, and the creek system comprising Port Reitz and Port Kilindini, hereafter referred to as the Reitz-Kilindini system, share many features that allow their geometries to be readily compared. They both have broad inland lagoonal areas, which only locally exceed 10m in depth, that are connected to the Indian Ocean by somewhat sinuous, laterally-confined channels with deeper, though very variable, bathymetries. The lagoons and channels were cut during a sea-level low stand. The channels are laterally-confined relative to the lagoons because the Pleistocene limestones they straddle are much harder than the Jurassic shales that underlie the lagoons (Figure 2).

The Tudor-Mombasa system consists of a lagoon, Port Tudor, which is connected to the ocean by a laterally-confined channel, Port Mombasa. The latter is here defined as extending to a line between Ras Serani [756 504] and McKenzie point [761 512] at its seaward end, and a line between Ras Saadi [739 548] to the southern shore of Junda Creek [743 553] where it joins Port Tudor, a distance of about 5 km (Figure 1). It has a markedly sinuous form which precludes access to large shipping and the modern development of Port Tudor. Consequently it tends to be used mainly for mooring and repair work on small ocean-going vessels. The waters of Port Tudor extend 12.5km inland from Port Mombasa. The end nearest the entrance forms an open lagoon which in places is over 4km across at HWS, and at LAT is still up to 2km wide. The surface area of Port Tudor and its associated distributary channels at LAT is 9.0 km^2 and at HWS is 24.9 km^2. The limited depth of Port Tudor, and its restricted accessibility via Port Mombasa has limited its industrial development. Consequently it is used almost exclusively for recreational activities or small-scale fishing. The mangrove stands act as nurseries for many varieties of marine fish.

The Reitz-Kilindini system consists of a lagoon, Port Reitz, connected to the sea by the confined-channel of Port Kilindini. The channel is defined here as extending between a line joining Ras Mwa Kisingo [748 489] and Ras Mzimle [745 494] at its seaward end and a line joining the tip of Ras Kikaangoni [709 525] and Kipevu Jetty [711 533] where it meets Port Reitz. It is approximately 5.5 km in length, though compared with Port Mombasa, Port Kilindini has a considerably less-tortuous morphology, with no major salients along its length. Because of this it has been accessible to large ocean-going ships, and numerous berths and shipyards have developed on its northeastern shore. The waters of Port Reitz form a wide inland lagoon; the main body of open water measures over 5km in length by 2km in width, and is connected to a network of creeks that extend over 15km from the entrance to Port Kilindini. Much of the margin of the lagoon is fringed by stands of mangrove vegetation (Figure 4), which form extensive swamps over large parts of the inland intertidal area.

Figure 4 **(Overleaf). Intertidal settings around the lagoons. a) Mangrove swamp inundated at high water, Port Tudor. b) Mangrove swamp at low water showing the nature of the sediment surface, Port Tudor. c) Outcrop of barnacle-encrusted, and mangrove- vegetated, Jurassic shale on the margin of a distribuary channel mouth bar, Port Tudor.**

a

b

c

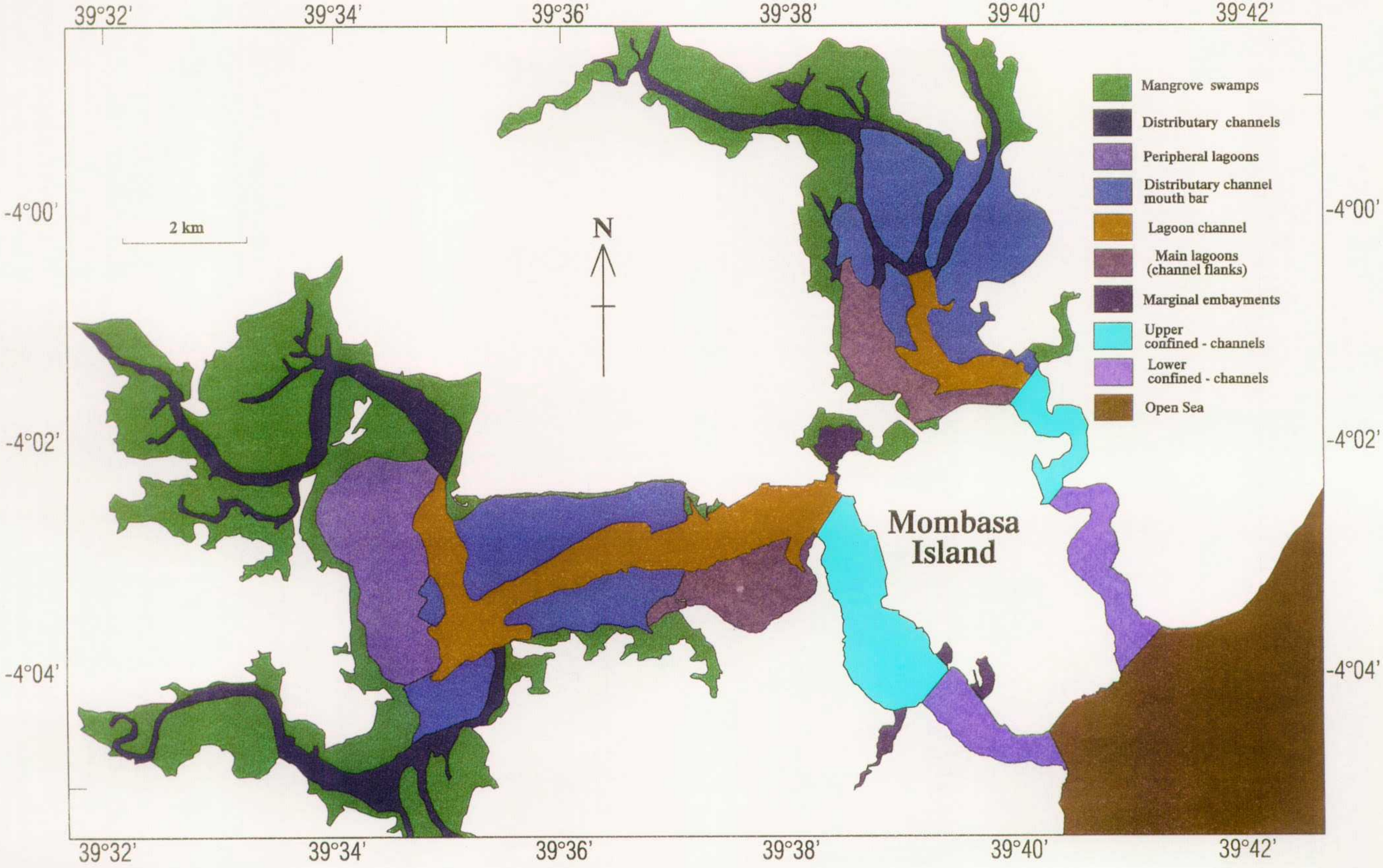
3.2: Intra-creek environmental zonation

Each of the creek systems may be subdivided into several zones. The bathymetric and vegetational patterns of these are outlined here, from the least marine-influenced parts of the system, to the most. Figure 5 illustrates the distribution of the zones discussed.

The **mangrove swamps** are thickly vegetated intertidal areas that are inundated fully by marine waters only during extreme HWS tides. They are laterally extensive especially in the northern part of Port Tudor, and the western end of Port Reitz, covering over a third of the entire area of the each of the creek systems. Elsewhere narrow swamps fringe the edges of the lagoons and to a lesser extent, the confined-channels. The swamps generally have a subdued gross morphology, dissected by dense channel systems which drain into the distributary channels. They are mostly covered by a small number of mangrove species (Figure 4a). The swamp surface, consists of very soft sandy muds, with an irregular topography (Figure 4b) caused by burrowing crustaceans, mangrove pneumatophores, and rotting vegetation. The surfaces grade into those of the distributary channels; no cliffs, suggestive of erosion, were noted during the recent survey. At their landward edges the mangrove shelve abruptly onto Jurassic shales. Locally the mangroves swamps are being worked for timber, though at present such activities are limited in extent.

The **distributary channels** dissect the mangrove swamps and, in Port Tudor, where no peripheral lagoon has been recognised, also the sand banks of the distributary channel mouth bars. The distributary channels are only more than 10m deep where they pass into the lagoon channel in Port Tudor. The distributary channels in the latter have an average width of about 100m, but those of the rivers Mwachi and Mteza are up to 600m wide, and are over 100m wide within 2km of their non-tidal reaches.

Figure 5 **(Overleaf). Intra-creek environmental zones**


39°32'
39°34'
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39°38'
39°40'
39°42'
-4°00'
-4°02'
-4°04'
2 km
N
Mangrove swamps
Distributary channels
Peripheral lagoons
Distributary channel mouth bar
Lagoon channel
Main lagoons (channel flanks)
Marginal embayments
Upper confined - channels
Lower confined - channels
Open Sea
Mombasa Island

The **peripheral lagoon** occurs in Port Reitz, where the main body of mostly open water is divisible into three zones on bathymetric grounds: the main lagoon body, separated from a smaller and shallower body, the peripheral lagoon, by distributary channel mouth bars. The origin of these zones is discussed in Section 4.3. The peripheral lagoon covers an area of about 7 km^2, though is less than 5 m deep. It occurs on the margin of the deeper lagoon channel and is fringed on its western side by mangrove stands. Because of its shallow nature many fish-traps have been constructed within the lagoon.

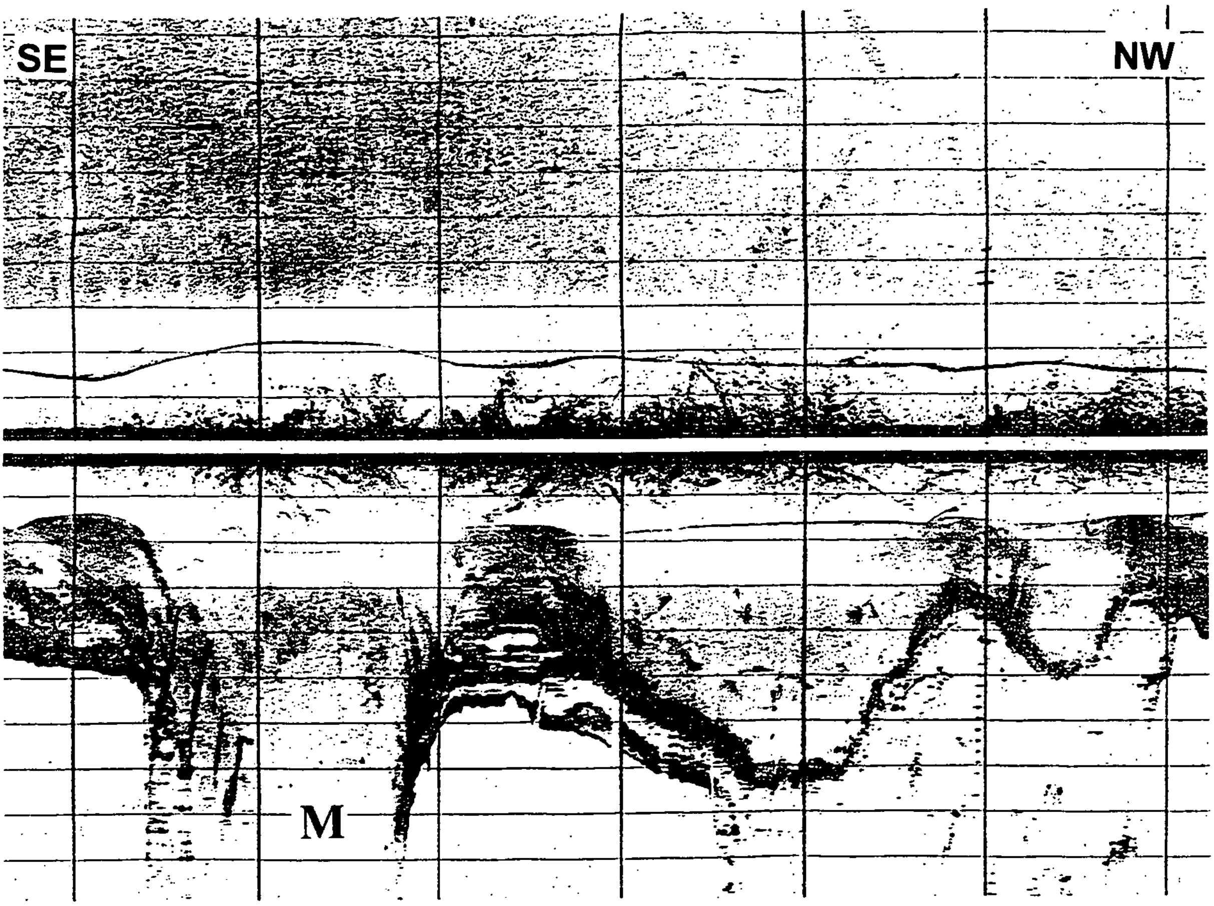
The **distributary channel mouth bars** are totally submerged during HWS tides but locally form islands at low water. They cover an area of approximately 8 km^2 in both Port Tudor and Port Reitz. Most are less than 2 m deep at low water, though locally bars, or accumulations of sand derived from them, extend into waters over 5 m deep. Individual bars are separated by lagoon channels or distributary channels. Parts of the mouth bars that are intertidal are densely vegetated by mangroves. The surface characteristics of the mouth bar are the same as those of the mangrove swamps (see above). Locally the mouth bars lap onto barnacle-encrusted Jurassic rocks (Figure 4c); narrow sandy beaches are common in such situations.

The **main lagoon** (channel flank) in both systems is mostly less than 5 m deep, though deepens to about 10 m near the lagoon channel. The lagoons are characterised by a subdued bathymetry, and in both Port Tudor and Port Reitz are flanked by the lagoon channel to the north and narrow stands of mangroves to the south.

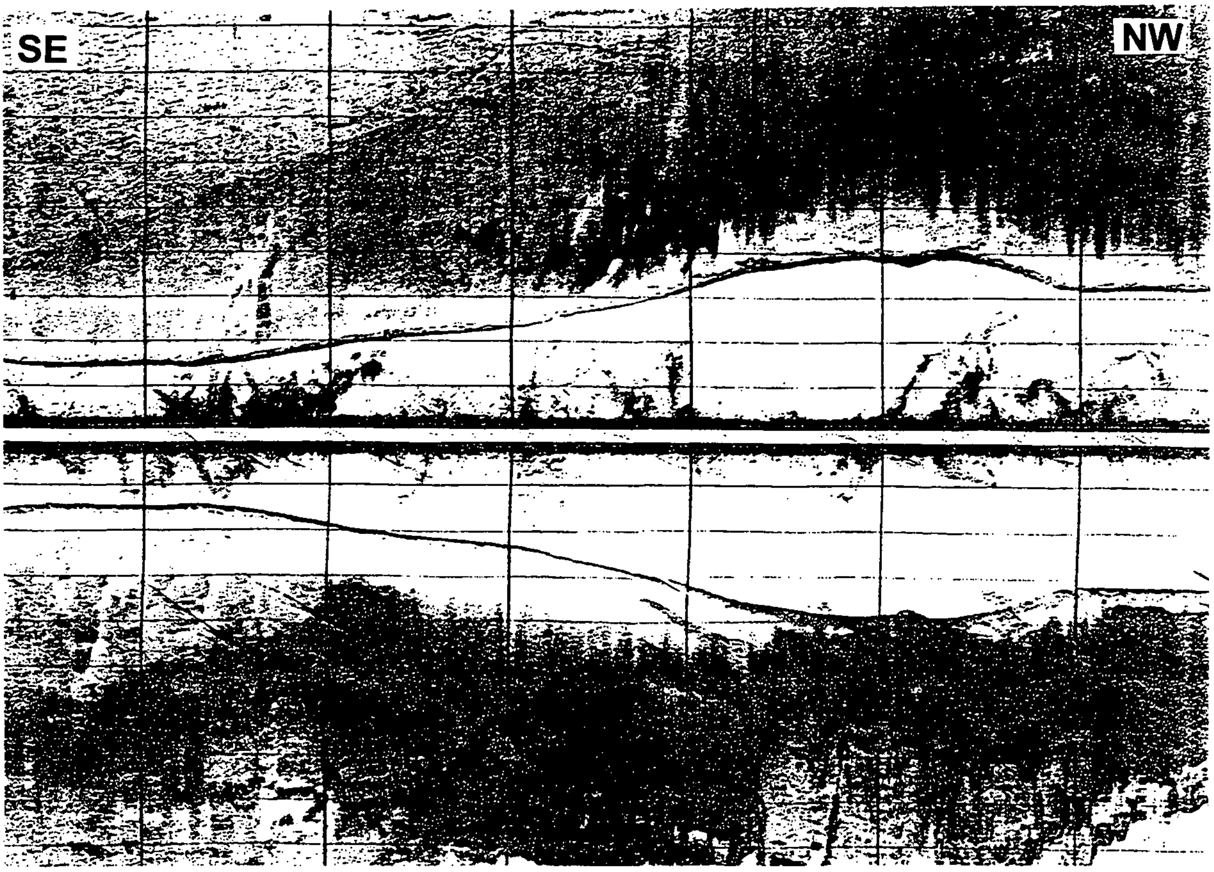
The **marginal embayments** are recognised only in the vicinity of the confined-channel of Port Kilindini, and comprise Makupa Creek to the northwest of Mombasa Island, Liwatoni and Mbaraki creeks to the southwest of Mombasa Island and Mweza Creek on the southwestern side of Port Kilindini (Figure 1). They are characterised by high depth: area ratios (all are at least 5m deep, and Makupa Creek locally exceeds 20m depth), and have notably steep sided entrances, fringed by Pleistocene limestones (Figure 6a).

Figure 6 **(Overleaf). Side-scan sonar data, Port Kilindini a) shows the submarine cliffs of Pleistocene limestone on the flanks of the confined channel; M is the entrance to Mbaraki Creek. b) shows a tidal scour cauldron. Horizontal lines at 15 m intervals (water depth), vertical lines at 150 m spacing.**

a



b



All the marginal emabyments are flanked by mangrove stands, often behind narrow beaches. However, all except those of Mweza Creek (Figure 7a) are impoverished because of pollution or ship-berthing.

A **lagoon channel** forms the axis of both Port Tudor and Port Reitz. The channels are over 5m deep and link the distributary channels at the landward end of the lagoons to the confined-channels of Port Mombasa and Port Kilindini. In Port Tudor the channel generally deepens seawards, reaching over 20m depth at its southeastern end. In Port Reitz it extends west-southwestwards from its entrance to the north of Dongo Kindu [660 510]. It is over 10m deep at its western end, shallows to less than 6.5m in the central area of Port Reitz, and deepens again to over 30m where it enters Port Kilindini.

The **upper confined-channels** are defined as the landward parts of the channels linking Port Tudor and Port Reitz to the sea. That of Port Mombasa ranges between 290m and 390m in width and averages about 14m in depth, though in places it is over 35m deep. The deepest parts on either side of the salient features of the channel, probably are tidal scour-cauldrons (see Section 4.5). Mangroves are mostly confined to narrow fringes along the edge of the channel, though form larger stands where tributaries discharge into the channel. Where the sides of the channels are not precipitous, steep, narrow beaches occur. The upper confined-channel of Port Kilindini is broad, extending between 600 and 1400m in width and generally deeper than Port Mombasa, reaching 50m depth locally. It is lined on its eastern side by berths, slipways, and industrial facilities.

The **lower confined-channels** are flanked for parts of their lengths by wave cut platorms, some of which have been covered by intertidal muds and silts, especially in Port Mombasa near the old town (Figure 3). The sides of the platforms, and submarine Pleistocene limestone bluffs illustrated in Figure 6a, are very steep, between 600 and 420m wide.

Figure 7 **(Overleaf). Intertidal settings around the confined-channels. a) View from Port Kilindini looking into Mweza creek. Note the steep, narrow beach, backed by Pleistocene limestone cliff. b) View looking seawards in Port Tudor, showing ship repair in intertidal areas and Pleistocene limestone cliffs on margins of the confined-channel. c) View from Mackenzie Point looking landwards into Port Tudor across the Pleistocene limestone wave-cut platform. Note the notched Pleistocene limestone cliff.**

a

b

c

The lower confined-channel of Port Mombasa is slightly wider than its upper part (ranging between 320m and 520m in width) and has some muddy sand flats (locally used for ship-repair- Figure 7b) and narrow sandy beaches. The lower-confined channel of Port Kilindini is between 600 and 420m wide and locally (in a probable tidal scour cauldron- Figure 6b) is over 60m deep. The wave-cut platforms widen considerably on the seaward side of the confined-channel entrances (Figure 7c).

3.3: Volumetric modelling of the creek systems

The bathymetry of the creek systems has been taken mainly from published charts (Admiralty 1985, 1990). Where pre-existing data were sparse, particularly in Port Tudor, and the western end of Port Reitz, the bathymetry was determined from soundings undertaken during the course of the LOCS survey in September 1995. The tidal limits have been taken from Kenya Survey 1:50 000 scale Y731 series sheets 201/1 Mombasa, edition 5-SK (1973) and 198/3 Mazeras, edition 5-JICA (1991).

Detailed modelling of the volumetrics of the creek systems has been prevented by conflicting data presented on the Kenya Survey sheets which show several internal discrepancies, mainly between flooding areas (taken to represent the state of the creek systems at HWS), and the 0 m contour, representing MSL. Also many data conflict with those depicted on the Admiralty charts, possibly because the data were collected from aerial photography, and ground surveys of different vintages. The lowest tidal limits shown on the Kenya Survey sheets are taken to represent water levels at LAT. There appears to be little difference between these lines and those of chart datum (LAT) on the Admiralty charts. Without a full scale topographical survey of the estuarine creek systems to enable detailed volumetric modelling, such as has been undertaken in other estuaries (e.g. Woodroffe 1985), the calculation of flooding areas, and volumes, as described below, is tentative. Nevertheless, the limited differences in tidal range (less than 0.15m) between different parts of the creek systems of Mombasa at any tidal state (Norconsult 1975) suggests that volumetric modelling may give a crude approximation of the tidal prism present in either system at any time within the spring-neap cycle.

The volumetrics of the creek systems have been calculated by 3-D modelling of bathymetry using Intergraph Terrain Modeller (Newsham and Rees, 1996). This was achieved by digitising and triangulating the bathymetric data, forming grids upon the triangulations (using a bicubic spline interpolation and inferred breaklines at the base of channels) and then triangulating these grids to form a Digital-Terrain Model (DTM). These models were intersected by horizontal planes at different heights above that datum, representing different states of the tide. The area of the plane, and the volume between it and the DTM, within the estuary was readily calculated. The flooding areas and volumes of water contained in Port Tudor, Port Mombasa, Port Reitz and Port Kilindini at different tidal states are shown in Tables 1 and 2.

TIDAL STATE	LWS + x (m)^a	Area (km^2) Tudor	Volume (km^3) Tudor	LWS +x (m)^b	Area (km^2) Mombasa	Volume (km^3) Mombasa	Area (km^2) TOTAL	Volume (km^3) TOTAL
HWS	3.46	24.930	0.092	3.06	2.886	0.043	27.816	0.135
HWN	2.18	18.109	0.055	1.96	2.571	0.039	20.680	0.094
MSL	1.73	16.100	0.047	1.53	2.486	0.038	18.586	0.085
LWN	1.27	13.021	0.038	1.10	2.391	0.036	15.412	0.074
LWS	0.34	11.160	0.034	0.30	2.350	0.035	13.510	0.069
LAT	0.00	9.021	0.030	0.00	2.305	0.034	11.326	0.064

Table 1 **Area and volume of water in Port Tudor and Port Mombasa at different tidal states ^{a} Tidal gauge Port Tudor ^{b} Tidal gauge Port Mombasa.**

TIDAL STATE	LAT + x (m)	Area (km^2) Reitz	Volume (km^3) Reitz	Area (km^2) Kilindini	Volume (km^3) Kilindini	LAT +x (m)	Area (km^2) TOTAL	Volume (km^3) TOTAL
HWS	3.50	49.785	0.227	5.033	0.103	3.50	54.818	0.330
HWN	2.40	38.527	0.152	4.692	0.095	2.40	43.219	0.245
MSL	1.85	35.806	0.133	4.618	0.093	1.85	40.424	0.206
LWN	1.30	30.213	0.113	4.529	0.090	1.30	34.704	0.203
LWS	0.30	27.584	0.105	4.491	0.088	0.30	32.075	0.193
LAT	0.00	23.851	0.095	4.444	0.087	0.00	28.295	0.182

Table 2 **Area and volume of water in Port Reitz and Port Kilindini at different tidal states. For key to abbreviations, see Table 1.**

3.4: Freshwater discharge

Variations in freshwater discharge in the creek systems are strongly influenced by rainfall patterns. Discharge is thus very seasonal, being highest at the beginning of the monsoons. The discharge from the catchments of the main rivers entering the creek systems has been estimated by Norconsult (1975) using data from the 3MH-10 recording station on the Pemba river. Estimated discharge into the Tudor-Mombasa system is shown in Table 3, and that into the Reitz-Kilindini system in Table 4. Several smaller rivers discharge only in the rainy seasons.

The estimated freshwater flow into Port Tudor averages about 0.8m^3/s, with the Kombeni accounting for 0.6 m^3/s and the Tsalu 0.2 m^3/s. The average monthly discharge reaches a maximum in April during the northeasterly monsoon and a minimum in February before the onset of the southeasterly monsoon.

River	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tsalu	57	29	73	443	392	229	46	49	171	163	365	182
Kombeni	190	97	243	1481	1312	766	213	162	572	540	1221	608
TOTAL	247	126	316	1924	1704	995	277	211	743	703	1586	790

Table 3. **Predicted flow in litres/second of main rivers entering Port Tudor (after Norconsult 1975)**

The estimated freshwater flow into the Reitz-Kilindini system is considerably greater than that of the Tudor-Mombasa system, averaging about 4.4 m^3/s, with the Mwachi accounting for 3.0m^3/s, and the Mteza 1.4 m^3/s. The average monthly discharge reaches a maximum in April during the northeasterly monsoon and a minimum in February before the onset of the southeasterly monsoon.

River	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mwachi	892	456	1144	6962	6167	3602	1000	764	2691	2540	6497	2859
Mambome	106	53	133	809	717	419	116	89	313	295	667	332
Pemba	354	181	454	2764	2448	1430	397	303	1068	1008	2279	1135
TOTAL	1352	690	1731	10353	9332	5451	1513	1156	4072	3843	9443	4346

Table 4. **Predicted flow in litres/second of the main rivers entering Port Reitz (after Norconsult 1975). The Mambome and Pemba combine to form Mteza creek.**

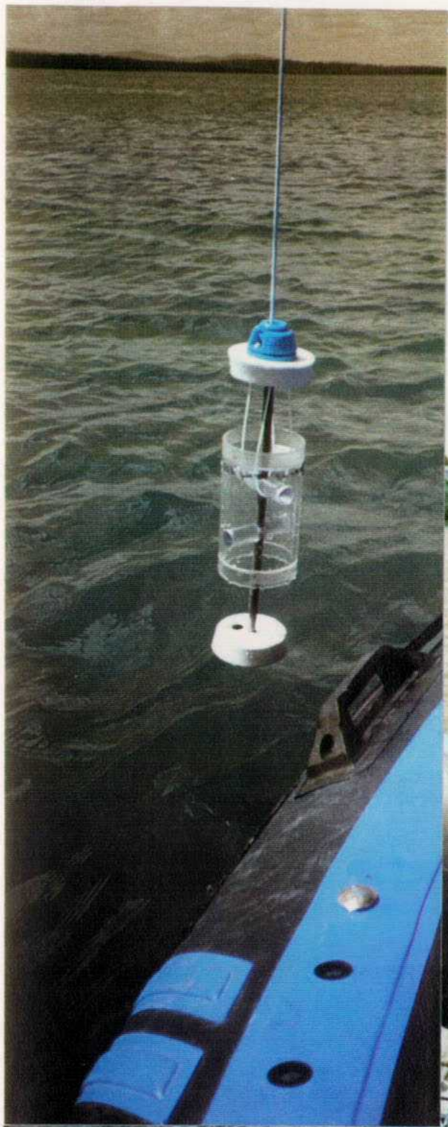
3.5: Physical and chemical properties of the creek waters

Limited measurements of water chemistry and quality were made by Norconsult (1975), Nguli (1994) and Odido (1994). More comprehensive measurements were made during the September 1995 LOCS survey when dissolved oxygen, oxygen saturation, pH, Eh, turbidity, conductivity and salinity were routinely measured at all coring sites using a pHOX^{TM} model 902 sonde. Suspended particulate matter (SPM) was routinely sampled at mid-water depth using a 2.5 l acrylic Kemmerer sampler (Figure 8a) and analysed. A detailed account of the chemistry of waters and sediments in the creek systems is presented by Williams et al. (1996^{a}).

The turbidity of waters was consistently low during the recent surveys and very low values (<50 turbidity units- FTU) were measured even at the landward end of the systems. Elevated turbidities (>80FTU) were measured at the confluence of the Tsalu and Kombeni in Port Tudor, where bottom sediments are entrained, and near a sewage discharge outlet. Filtered SPM was mostly brown, rather than green, in colour suggesting that it is largely inorganic; the chemistry of muds below mangrove stands is very similar to the SPM in the distributary channels (Williams et al. 1996^{a}), suggesting that the SPM is mostly derived from the mangrove swamps. It is likely that turbidities during the wet season, particularly during high discharge events, are much higher than those measured during the dry season.

Figure 8 **(Overleaf). Sampling equipment. a) 2.5 l acrylic Kemmerer water sampler with top and base open, ready to sample. b) Sediment sampling using the 20 kg Wildco^{TM} gravity corer. c) The Wildco^{TM} gravity corer and sample core. These sit on the surface of the Pleistocene limestone wave-cut platform.**

a



b

c

The salinity patterns of the creek systems change with the seasons. During the wet season the waters become more saline towards the ocean, though markedly lower salinities commonly only occur towards the inland extremities of the creek system. Stratification events, where the surface waters in inland waters are largely brackish probably are rare, and coincide with periods of peak river discharge. In the dry seasons salinities in the lagoons may exceed those of the open sea because of evaporation; during these periods the lagoons are inverse estuaries, or hypersaline lagoons (Dyer, 1979). It is unlikely that stratification as a result of hypersalinity (c.f. Meshal 1984) occurs, as the waters appear to be well mixed. Despite this, the horizontal density gradient may still force a transient salt wedge at neap tides, as has been recorded in other inverse estuaries (De Silva Samarasinghe and Lennon 1987). Measurements made in the dry season by Nguli (1994) and by Williams et al. (1996 [a]) showed a seaward increase in salinity, though salinities at the seaward end of the confined channels were only marginally greater than in the landward reaches of the lagoons. This is illustrated by measurements of 33g/l taken in Port Tudor, that were only slightly less than those at the entrance to Port Mombasa, which averaged about 35g/l. The lower salinities measured towards the landward end of the systems were coupled with lower values of dissolved oxygen and pH compared with open marine waters (Williams et al. 1996 [a]).

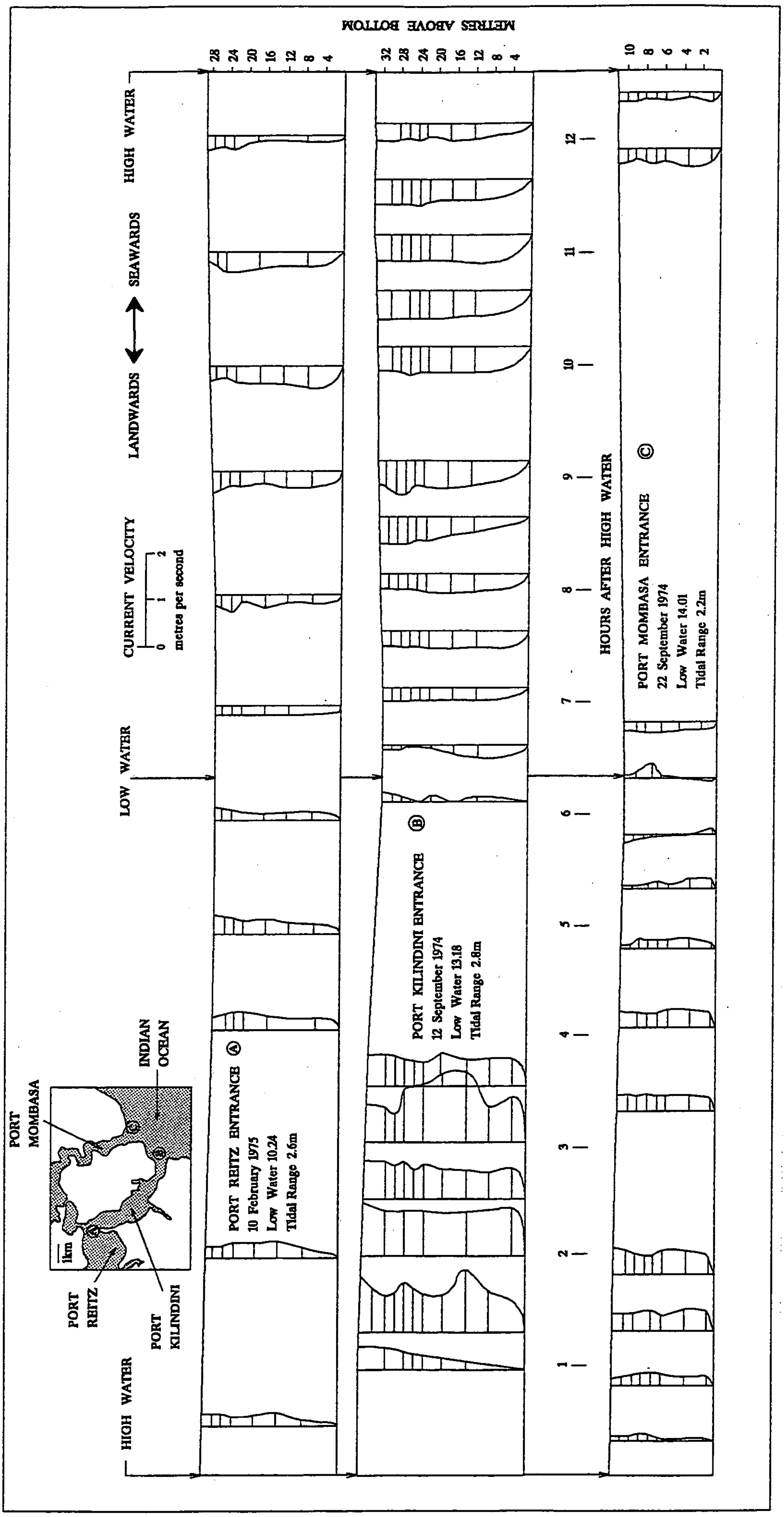
3.6: Currents

Direct current velocity measurements have been made in both creek systems by Norconsult (1975) and KMFRI using pendulum current meters. Current velocities measured strongly reflect the tidal range as well as the period of the flood and ebb tides. The mean flood tide lasts for 6.5 hours and the mean ebb tide for 6.3 hours. The shorter ebb tide accounts for higher current velocities measured, relative to those of the flood tide. Current patterns in the Reitz-Kilindini system have been investigated by Norconsult (1975), and in the Tudor-Mombasa system by KMFRI. An indirect assessment of the current patterns away from sites of direct measurement may be gained from mapping of the mobile sediments (see Section 4).

In the Tudor-Mombasa system maximum current strengths of about 1 m/s were recorded during spring tides, and 0.6 m/s for a tidal range of 2.2 m. Currents were found to be close to uniform with depth, as may be seen in Figure 9. The variation in current velocity associated with the tidal asymmetry was demonstrated at selected tidal stations within the Tudor-Mombasa system by Nguli (1994) and Odido (1994). Current patterns in Port Mombasa were recorded by current drogues released at 4 m water depth at Spring tide by Norconsult (1975).

Current velocities in the Reitz-Kilindini system were obtained by Norconsult (1975) at the seaward entrance to Port Kilindini [c.743 492] and off Ras Kikaangoni [709 528] using a series of 10 current meters which recorded the velocity and direction in intervals of 1-2 hours. The vertical profiles are shown in Figure 9 and indicate that the tidal currents normally range between 0.3 m/s and 0.6 m/s, except for a period of about an hour at low and high water. However, the maximum ebb and flood velocities during spring tides may locally exceed 1.0 m/s. Current patterns in Port Kilindini were measured by Norconsult (1975) tracing drogues at 4 m water depth. Just after high water and just before low water the currents along the central part of Port Reitz are directed along the creek bend, and sweep out along the berths on the east side of the harbour between Ras Kilindini and Shimanzi (Figure 1). During flood tides, the fastest currents in Port Kilindini tend to occur mainly along the berths between Ras Mkadini and Makupa Creek. This path is also indicated by the local absence of argillaceous sediments (by winnowing) in these areas. The lack of fine-grained sediment, including sand in places, indicates that the greatest current velocities in Port Reitz probably occur along this path, which passes into the lagoonal channel of Port Reitz and of distributary channels carrying river waters into the system (see Section 4.3).

Figure 9 **(Overleaf). Vertical current profiles from Port Kilindini and Port Mombasa (after Norconsult 1975).**


HIGH WATER
LANDWARDS ↔ SEAWARDS
CURRENT VELOCITY
0 1 2
metres per second
LOW WATER
HIGH WATER
METRES ABOVE BOTTOM
28 24 20 16 12 8 4
32 28 24 20 16 12 8 4
10 8 6 4 2
HOURS AFTER HIGH WATER
1 2 3 4 5 6 7 8 9 10 11 12
PORT MOMBASA
INDIAN OCEAN
PORT REITZ
PORT KILINDINI
1km
A
B
C
PORT REITZ ENTRANCE Ⓐ
10 February 1975
Low Water 10.24
Tidal Range 2.6m
PORT KILINDINI ENTRANCE Ⓑ
12 September 1974
Low Water 13.18
Tidal Range 2.8m
PORT MOMBASA ENTRANCE Ⓒ
22 September 1974
Low Water 14.01
Tidal Range 2.2m

3.7: Residence of water-borne contaminants

Contaminant residence time may be defined as the duration over which a water-borne pollutant remains within any given water body before leaving the system. In the case of the Mombasa creek systems the residence time, before pollutants reach the open ocean, can be calculated either by assessing the tidal volume flux (taking into consideration the mixing of waters within the estuary), or by calculating the salinity gradient between different parts of the estuary and the open ocean (taking into consideration evaporation, evapo-transpiration and freshwater supply).

The second approach has been attempted for the Mombasa-Tudor system in the principal dry season by Nguli (1994), using salinity data collected at various times during 1992 and 1993, in conjunction with the data already presented for evaporation and freshwater input, given in Section 3.4. On the basis of these data, he estimated that the residence time of water in the Tudor-Mombasa system was in the order of two weeks. However, he qualified this conclusion by pointing out that the method and conclusion may be subject to error because of uncertainties about the effects of evapo-transpiration, as opposed to evaporation, the collection of salinity data only from surficial waters, the limited number of sampling stations utilised in the estimate, and the effect of the changing tidal prism through tidal cycles. Taking these uncertainties into consideration we decided to investigate the first approach, the calculation of residence time using the tidal volume flux.

A simple 1-D box model (segmented model) is used to determine the residence time of contaminated water which is perfectly distributed throughout the lagoon (either Port Tudor, or Port Reitz) at the start of the model through successive tidal cycles within the lagoon and confined-channel (Port Mombasa or Port Kilindini).

The volumes in the calculations are derived from the volumetric modelling of the creek systems (see Section 3.3) and are presented in Table 5.

Port	Spring neap cycle stage	High water vol. km^3	Low water vol. km^3	Tidal prism vol. km^3	Water Exchange %
Tudor	Spring tides	0.920 (V^L)	0.034 (V^l)	0.058	63.04
Tudor	Neap tides	0.055 (V^L)	0.038 (V^l)	0.017	30.90
Reitz	Spring tides	0.227 (V^L)	0.105 (V^l)	0.122	53.74
Reitz	Neap tides	0.152 (V^L)	0.133 (V^l)	0.019	12.50
Mombasa	Spring tides	0.043 (V^C)	0.035 (V^c)	0.008	18.60
Mombasa	Neap tides	0.039 (V^C)	0.036 (V^c)	0.003	7.69
Kilindini	Spring tides	0.103 (V^C)	0.088 (V^c)	0.015	14.56
Kilindini	Neap tides	0.095 (V^C)	0.090 (V^c)	0.005	5.26

Table 5 **Volumes of water in Ports Tudor, Reitz, Mombasa and Kilindini at different tidal states and the tidal prisms and percentage water exchange during these tidal states**

The volume of contaminant-bearing water in the lagoon at the start of the model is equivalent to the capacity of the lagoon at high water; therefore: $C^L=V^L$, where C^L is the volume of contaminated water in the lagoon at high water in any cycle and V^L is the volume of water in the lagoon at high water. The ratio of $C^L:V^L$ decreases over successive tidal cycles.

The volume of contaminated moving from the lagoon into the confined-channel on the falling tide is: C^L-V^1, where V^1 is the volume of water in the lagoon at low water. The same volume of water as that carrying the contaminant from the lagoon to the channel will be also be displaced from the confined-channel into the sea during the same falling tide. However, the volume of original contaminated water entering the sea on any falling tide is determined by: C^c/V^c, where C^c is the volume of contaminant which entered the confined-channel from the lagoon during the last tidal cycle as well as the volume of contaminant residing in the confined-channel from preceding tidal cycles and V^c is the volume of the confined channel at low water. During spring tides, however, the volume of water entering the confined-channel from the lagoon exceeds the volume of water in the confined-channel at low water, so the volume of originally contaminated water entering the sea is: $(V^L-V^1)-V^c$.

Upon the rising tide water enters the confined-channel from the sea and water in the confined-channel enters the lagoon. Following this, the volume of contaminant in the lagoon at High water during spring tides, where $V^c<V^{L-}V^l$, will be: C^l+C^c. However, during neap tides, where $V^c>V^{L-}V^l$, the same figure is calculated using: $(C^c/V^c)+C^l$, again, where C^c represents contaminant residing in the channel from the last and previous tidal cycles.

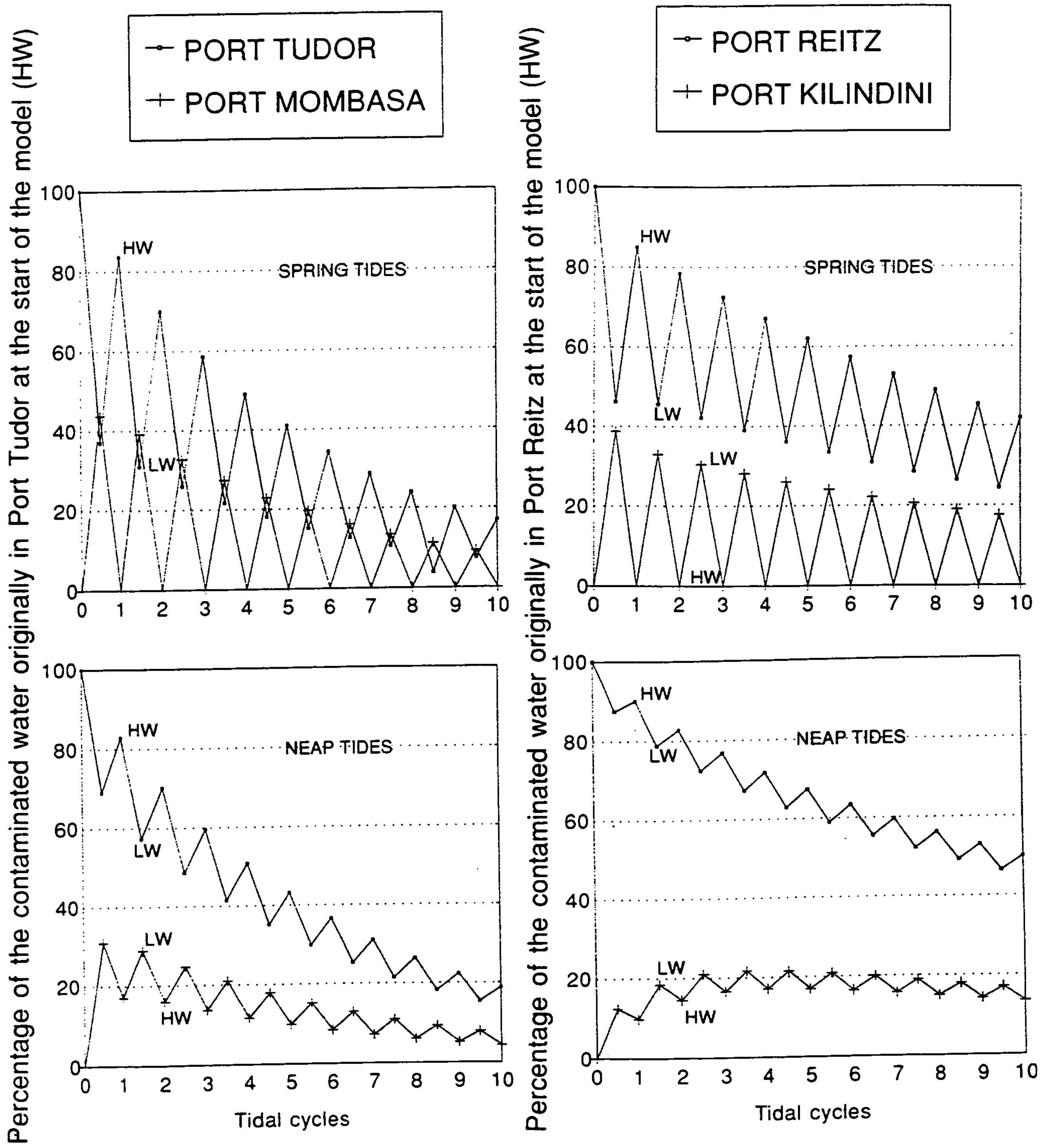
Application of a sine curve to the spring and neap tidal volumes, allows calculation of the volume of contaminated water present within the confined-channel and lagoon at any one time to be made. For purposes of illustration, Figure 10 simply shows ten spring and 10 neap tidal cycles.

The model incorporates some basic assumptions.

Firstly it is assumed that contaminated water leaving the seaward entrance of the confined-channel (Port Mombasa or Port Kilindini) during the falling tide is dispersed, and that none re-enters the confined-channel during the rising tide. Whilst, in reality this is strictly not the case, oceanic currents predominate over tidal currents, and effectively disperse any contaminants by the time creek waters reach the seaward limit of the modern reef (Norconsult 1975) .

Secondly the model assumes perfect mixing of waters within the confined-channels and lagoons. Whilst this is unrealistic, use of a 1-D model instead of a 2-D model (cf. Pritchard 1969), is justified as the mixing of waters within the confined-channels and lagoons is probably efficient within the creek systems. The form of the confined-channels encourages thorough mixing and circulation of waters passing through them. Both Port Mombasa and Port Kilindini have great variation in depth along the confined-channel thalweg, most pronounced in the former, encouraging vertical mixing. The confined-channels also have tortuous planforms, again, particularly in the case of Port Mombasa, causing horizontal mixing. In Port Kilindini, although the principal salient features within the confined-channel sides are the points of Ras Kikaangoni and Ras Mzimba at either end of the channel, man-made constrictions and

Figure 10 Percentage of contaminated water resident in Ports Tudor, Reitz, Mombasa and Kilindini after successive tidal cycles, calculated using a 1-D box (segmented) model (see Section 3.7 for details).



several indentures occur in the channel flanks, which are important in longitudinal dispersion (Pritchard 1969), and increase mixing, as does horizontal circulation and switching of tidal patterns with the changing tide. Mixing of waters in the lagoons is enhanced by the extent of mangrove vegetation within the intertidal areas; waters which inundate these areas are well mixed by the roots of the mangroves. In the dry season, the effective value of the longitudinal diffusivity of waters in mangrove-fringed tidal rivers is increased by typically two orders of magnitude from its value in the absence of mangrove swamps (Wolanski and Ridd, 1986).

Thirdly, the model takes no account of river discharge, evaporation or evapo-transpiration. However, as the tidal volume flux vastly exceeds the volume of both river discharge and water loss through evaporation/ evapo-transpiration the latter factors have little influence on currents within the creeks. Furthermore, during the dry season the effects of the limited discharge of rivers into the lagoons fails even to compensate for the increased evaporation or evapo-transpiration. During such periods the creeks are better considered as inverse estuaries, or mesotidal creeks, which have little freshwater influence, rather than true estuaries. Despite this, the influences of discharge, evaporation and evapo-transpiration *could* have a significant effect on the volume of water in the creek systems exchanged in a tidal cycle, but only in the case of meteorological extremes. Although the average peak river discharge in April (based on the figures presented in Section 3.4) amounts to less than 3% of the water exchanged in the lagoons in a tidal cycle, freak discharge events may cause much larger volumes of fresh water to enter the lagoons and flush contaminants through the systems more rapidly. Likewise in the dry season, during an extended period of low rainfall and cloud cover the amount of water loss in the lagoon through evaporation and evapo-transpiration may be much greater than has been measured or inferred to date. Such an event would substantially extend the residence times of contaminants within the lagoon and confined-channel systems.

The model shows that during Spring tides the amount of contaminated water originally residing in the lagoon is reduced by half within 4 tidal cycles (approximately two days) in the case of Port Tudor and within 8 tidal cycles (approximately four days) in the case of Port Reitz. The greater rate of exchange in the case of Port Tudor is caused by its shallow hypsometry (the distribution of basin surface area with height; Boon and Byrne 1981), and higher ratio of intertidal area to open lagoon. The amount of contaminant in the confined-channel of Port Mombasa also decreases more quickly than that in the confined-channel of Port Kilindini. However, the percentage of contaminated water at low water during spring tides in either channel never exceeds 50%, and is less than 25% within 9 tidal cycles (about four and a half days), even after taking the diminution of tides over this period into consideration. At high water the confined-channels are filled totally from their seaward ends. Because the tidal prisms of the lagoons exceed the volume of the confined-channels at low water any contaminant entering either of the confined-channels at high water is likely to be flushed out to sea upon the falling tide.

During neap tides the amount of contaminated water remaining in the lagoons (Port Tudor and Port Reitz) is only marginally more than during the Spring tides over the same number of tidal cycles. However, considerably more contaminated water resides in the lagoon during low water than during corresponding spring tides. The amount of contaminated water stored during high water in the confined-channels of Port Mombasa and Port Kilindini is considerably more than during Spring tides, and contaminated water occurs within the confined-channels during all phases of the tidal cycle. The smaller tidal prism of Port Tudor in relation to the volume of Port Mombasa, to that of Port Reitz in relation to Port Kilindini, causes the contaminant residence peak to occur in Port Mombasa within one tidal cycle of the start of the model, but to take 3.5 tidal cycles in Port Kilindini. Despite the slower decrease in the volume of contaminants resident within the lagoons during neap tides, Figure 10 clearly shows that the average residence time of contaminants within Port Tudor is 8 tidal cycles (about four days) and within Port Reitz is 10 tidal cycles (about five days).

These estimations of water-borne contaminant residence times, derived from determining tidal volume flux, contrast somewhat with those based on salinity gradients for the same areas by Nguli (1994). However, the differences may only reflect the difference between average residence times for contaminated water in Port Tudor, and residence times near the periphery of the lagoon (which are likely to be considerably longer). The disparity serves mainly to illustrate the very crude nature of the data available for modelling and the models themselves, and demonstrates that there is a basic requirement for accurate measurements of salinity and basin hypsometry to be made in the creek systems so that more accurate water exchange and contaminant residence models may be readily applied. With accurate long time-series tidal, discharge, salinity, evaporation and evapo-transpiration and temperature data, numerical 2-D or 3-D time-dependant models may be utilised. These would not only look at average residence times of contaminants within the lagoons and confined-channels, but allow local residence times and transport paths of contaminants within them to be effectively tested and calibrated. Such models would incorporate the dynamics of plumes of pollutants, their horizontal and vertical dispersion, and their dilution and changing density, relative to creek waters with time, and take full account of physical and density mixing (cf. Officer and Lynch 1981) within the creeks. The existence of such models, based on accurate data, would have many benefits to planning authorities at Mombasa, particularly in determining the probable transport and fate of any contaminant released from a point source within the creek systems. These detailed models would demonstrate the susceptibility of parts of the creek systems to extended residence periods of contaminants, and the likely nature of water exchange during any phase of the spring-neap cycle or during specific climatic conditions. In the absence of such models it is possible to give only a qualitative assessment of patterns of water exchange, and therefore of the susceptibility to contamination, by water-borne pollutants, of the intra-creek environmental zones outlined in Section 3.2.

During spring tides in the wet season it is likely that freshwater will be trapped within the **mangrove swamps** for long periods following the passage of short-lived floods, (cf. Wolanski and Ridd 1986). During HWS the presence of this water may inhibit extensive inundation of the swamps by any contaminated saline waters. In the dry season evaporation and evapo-transpiration during HWS tides may draw saline waters further into the swamps. Clearly during such periods there is a danger that water-borne contaminants will effectively be transported and dispersed towards the peripheries of the swamps. During neap tides, incursions of contaminated waters are likely to affect the margins of the swamps only.

The **distributary channels** in the wet season will carry a high volume of fresh water, derived from the catchments of the rivers Mteza, Mwachi, Kombeni and Tsalu. Thus it is unlikely that saline (lagoonal) waters will extend below their lower reaches, particularly during neap tides. In the dry season the waters in the distributary channels will be largely brackish, with highest salinities during spring cycles and lowest during neap tides. During HWS tides the channels may effectively carry contaminants present in the saline waters into the mangrove swamps. Most of the waters that have not moved from the distributary channels into the swamps by high water will re-enter the peripheral lagoon or main lagoon on the falling tide.

Because the **peripheral lagoon** is bounded on its seaward edge by the distributary channel mouth bars, during the wet season the waters of the rivers Mteza and Mwachi cause the waters in the lagoon to become notably brackish in character (Norconsult 1975). This is likely to be most notable during neap tidal cycles, when the volume of the tidal prism is smallest and it is possible that stratification may occur, as during spring cycles the greater volumes of water exchanged during each tide are likely to prevent such stratification. The residence time of contaminants in saline lagoonal waters is likely to be reduced in such circumstances. In the dry season, although it may be expected that evaporation will cause lagoon waters to be drawn in, this is likely to be subdued by the continuing, but limited, discharge of the rivers Mteza and Mwachi.

The small area, and shallow depth of the peripheral lagoon will cause the currents to be tidally driven; the strength of wind-generated currents will be negligible. The residence period of any contaminant within the lagoon is likely to be influenced by its proximity to the lagoon channel.

Rather like the mangrove swamps, the **distributary channel mouth bars** are likely to be completely inundated by saline waters, and any water-borne contaminants, during Spring tides. Likewise, they are likely to be flushed by fresh water during the wet season (apart from those in Port Reitz, which are not flanked my mangrove swamps or distributary channels). All the mouth bars appear to be drained preferentially by channels flowing parallel to the rectilinear tidal flows of the lagoon channel.

The residence time of contaminants within the **main lagoon** (channel flanks) is likely to be influenced by their proximity to the lagoon channel. Rates of transport will be highest near the channel, and during spring tides. Tidal currents will control the transport of most contaminants, though the transport and distribution of floating hydrocarbons may be greatly influenced by wind patterns, which in turn, are largely controlled by the monsoons. Any floating contaminants will move at considerably less than 2-3% of wind speed, because of the limited fetch of water in the lagoons.

The **marginal embayments** are likely to have a rapid exchange of water, particularly during spring tidal cycles, because they have large tidal prisms in relation to their relatively small areas, and because they occur in the vicinity of the confined-channels. Their water exchange times are thus likely to be measurable in terms of a few days. During heavy rains in the wet season ephemeral drainage systems may feed the embayments, allowing brackish water to accumulate within them.

Waters in the **lagoon channels** are likely to have short residence times, akin to those of the confined-channels which they join. The tidal current patterns, as shown by drogue studies (Norconsult 1975) and the Admiralty (1990), are rectilinear and are likely to be strongest during Spring tides, and during the rainy season (when river discharge is greatest). The exchange of water between the lagoon channel and the confined-channel is likely to be rapid at all states of the spring-neap cycle.

Waters in the **Upper and lower confined-channels** have short residence times, as already outlined. They will be greatest in the Upper channels, particularly in the wider parts of Port Kilindini. Regular tidal flushing will maintain levels of pollution, and salinities, at about those of the open sea.

4: SEDIMENTARY DYNAMICS OF THE CREEK SYSTEM

As heavy metals are readily adsorbed onto clay minerals from the water column (cf. Vasconcelos et al. 1995, Badarudeen et al. 1996, Williams et al. 1996 [a], and references therein) the longer-term residence history of contaminants (beyond that of tidal or seasonal cycles) is influenced largely by the transport and depositional patterns of the sediments within an estuary. As a consequence, one of the main objectives of the study was to analyse the distribution of sediments within the creek systems and so gain an understanding of their dynamics and contaminant storage patterns.

The sediment distributions were mapped by sea-bed sampling, interpretation of side-scan sonar records, and interpretation of Admiralty sample data. Sediments were recovered by augering, gravity coring, grab sampling and by piston coring by BGS. The distribution of sample sites and side-scan coverage is shown in Figure 1.

4.1: Sediment sampling and analysis

The gravity cores (maximum length c.0.5m) were taken during the 1995 survey using a 20kg Wildco^{TM} gravity corer (Figures 8b-c), and a 1.1m pneumatic piston corer was used to get longer cores (up to 80cm) in 1996 (see Williams et al. 1996 [a] for details).

These cores were collected by boat, but longer cores (maximum length 5.60m) were taken of the sediments underlying the mangrove canopy using an Eigelkamp piston auger, comprising of a tube containing a piston that may be retracted (by rope) during withdrawal from the auger hole. The resulting cores were c.30mm in diameter, in contrast to the 50mm diameter gravity and piston cores. Five holes were augered in all, four in Port Tudor, and one in Port Reitz.

The grab samples, taken using a stainless steel Van-Veen grab (operated using an aircraft cable) which recovers approximately 0.01m^3 of sediment, were mostly taken to extend the sediment map in areas not covered by side-scan sonar.

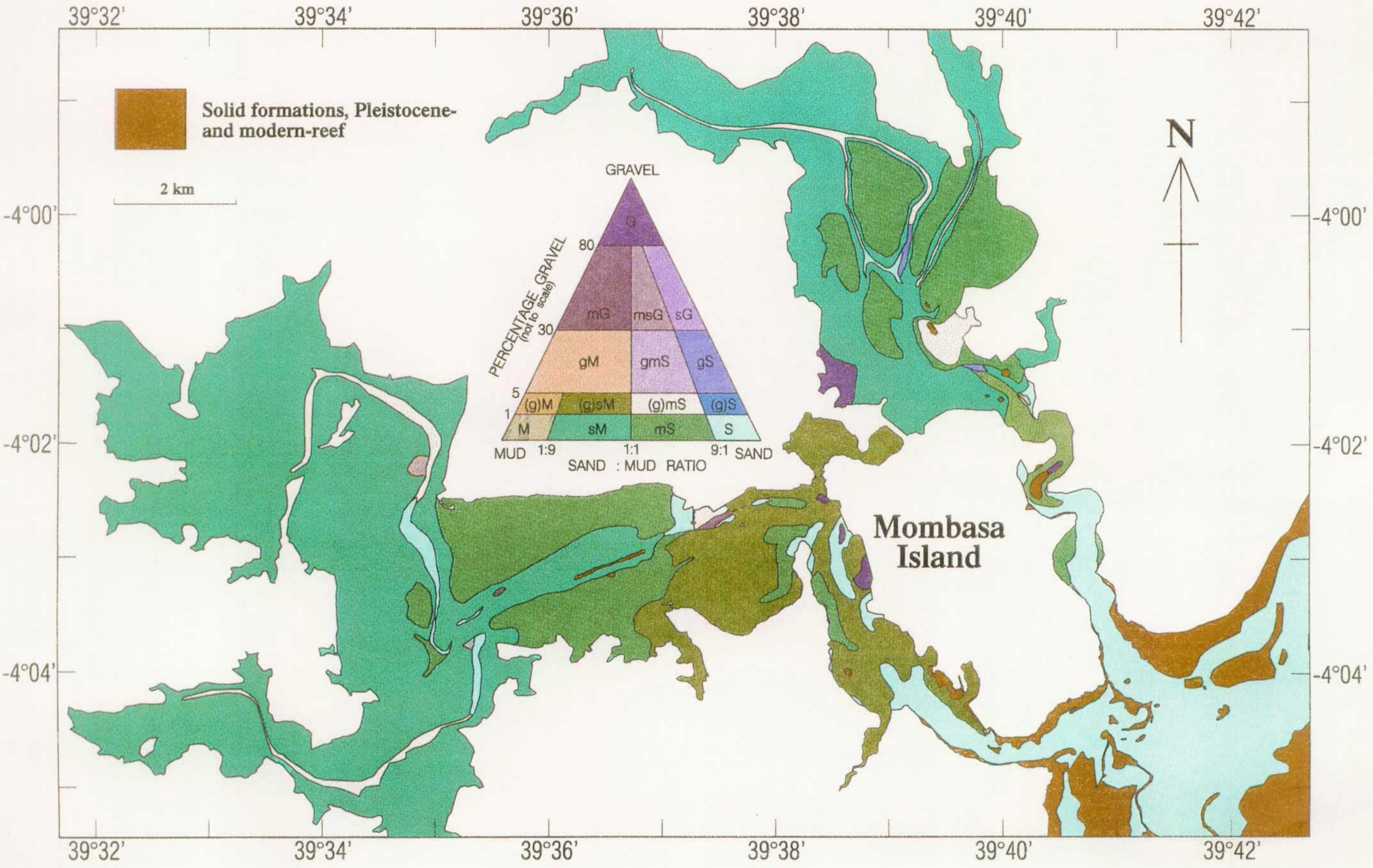
All cores were logged on-site or at the KMFRI laboratories. All sediments in core and grab samples were classified prior to sub-sampling for geochemical analysis. Selected core and grab samples were transported to BGS for particle size analysis.

Particle size analysis was performed by wet-sieving samples to separate the <63 µm and >63 µm fractions. The >63 µm fraction was dried before being dry sieved and weighed at 0.5 ϕ intervals. The <63 µm fraction was dried, weighed, and, after dispersal in a solution of sodium hexametaphosphate, the proportions of silts and clays falling into different 0.5 ϕ intervals were calculated using the Micrometrics Sedigraph 5100 ™ particle size analysis system. The particle size distributions were plotted as histograms, the sediment types classified according to Folk (1954), and mapped out (Figure 11). The boundaries between the sediment types, in areas not covered by side-scan sonar, were interpreted using bathymetric and other data.

4.2: Side-scan sonar

The Admiralty surveyed large areas of Port Kilindini and Port Reitz between 1984 and 1986 using side-scan sonar (Figure 1). Records of these surveys were made available to BGS and sediment distributions mapped on the basis of reflectance and sediment

Figure 11 **(Overleaf). Sediment distributions within the creek systems.**


39°32'
39°34'
39°36'
39°38'
39°40'
39°42'
-4°00'
-4°02'
-4°04'
Solid formations, Pleistocene- and modern-reef
2 km
N
GRAVEL
G
80
mG
msG
sG
PERCENTAGE GRAVEL
(not to scale)
30
gM
gmS
gS
5
(g)M
(g)sM
(g)mS
(g)S
1
M
sM
mS
S
MUD
1:9
1:1
9:1
SAND
SAND : MUD RATIO
Mombasa Island

textures observed in the records, in conjunction with data based on sampling using a wax charged lead line (Admiralty 1990). Sediment distributions in parts of Admiralty sheet 666 not covered by side-scan sonar were interpreted on the basis of samples collected during former Admiralty surveys.

4.3: Sediment distribution

Each of the intra-creek environmental zones (outlined in Section 3.2) have characteristic facies associations; these are defined below.

The **mangrove swamps** are underlain by a distinctive suite of remarkably homogeneous and sandy muds which have a notable pale grey (N4) hue. The muds show little or no textural variation within a few metres of the sediment surface. Most shelly grains comprise crustacean fragments. Mangrove roots extend as a matted fabric throughout the sediments, though decrease in density with depth. The predominance of clay minerals in the mangrove muds is illustrated by the proportion of Al_2O_3 (up to 15%) and K_2O (up to 2.5%) within them (Williams et al. 1996[a]).

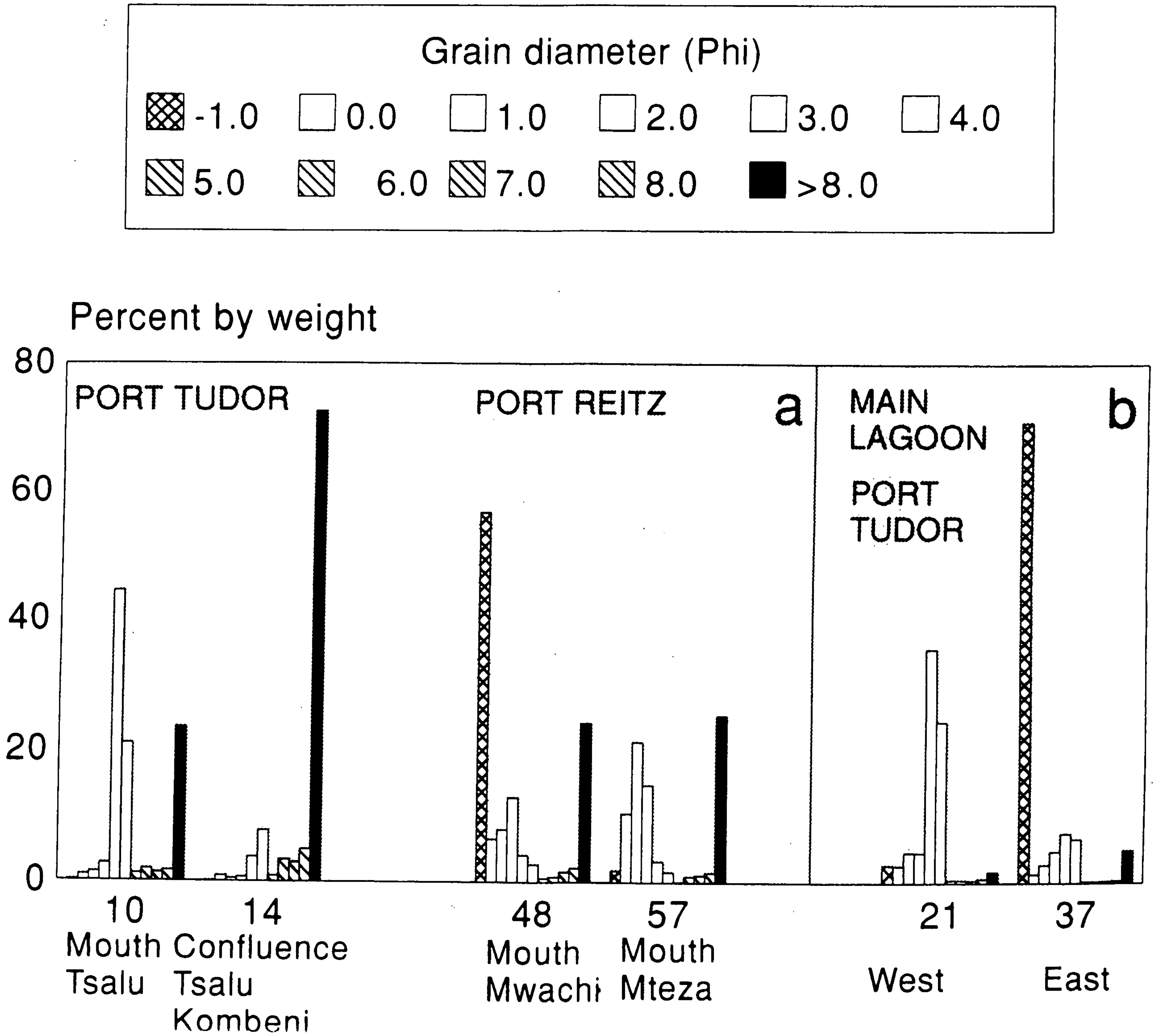
The limited resources of the recent surveys prevented detailed examination of the extensive mangrove swamps at the western and northern ends of the creek systems so little is known of the sediment textural variations within these areas. Although the mapped sediments (Figure 11) are shown as sandy mud, it is probable that they pass into muddy sands, laterally, on the margins of channels, and with depth, into moribund mouth bars (see below) that have been carpeted by finer-grained sediments as the depositional system prograded towards the main lagoon (Section 4.5).

The **distributary channels** are floored mostly by sands or gravels consisting of resistates (quartz, feldspar) and lithic grains or aggregates that appear to originate from the catchments of the main rivers flowing into the creek systems (see below). The high proportion of resistates in the channels (relative to the adjacent mangrove swamps) is indicated by an enhanced SiO_2 content (>60%), detailed by Williams et al. (1996[a]). Limited sampling suggests that the grade of sand entering Port Reitz and Port

Tudor (Figure 12) may differ; the sands from the floors of the Mwachi and Mteza being coarser than those of the Tsalu and Kombeni. The proportion of lithic grains in the coarser component in all the mouths of the channels (the Mwachi and Mteza where they discharge into the peripheral lagoon at the western end of Port Reitz and the Tsalu and Kombeni where they flow into the main lagoon of Port Tudor) is substantial (e.g. Grab sample 10, Figures 1 and 13; for grain size, also see Figure 14). These grains consist mainly of sandstone fragments, largely of litharenite, but also comprise silty shale. A significant part of some samples of distributary channel sand consists of plant debris; such sands from the mouth of the Tsalu and Kombeni (Grab sample 14, Figure 1) lost 5.16 weight percent upon ignition. The gravel component of the tidal reaches of both distributary channel systems consists largely of bored and abraded shelly detritus. Although most of this is modern, and probably derived from fauna living in the adjacent mangrove swamps, a small fraction of it appears to have been derived from the Pleistocene limestones.

The siliciclastic grains in the distributary channels appear to be characteristic of those of the creek systems as a whole (see below). We wanted to confirm that all the grain types (identified in a limited study by binocular microscope) recorded in the distributary channels have equivalents in the formations of the watersheds draining into the creek systems (establishing that they are the likely sources of sand and gravels in the distributary channels, and elsewhere in the creek systems). Consequently a traverse was undertaken across the supra-Karoo Series formations between the Miritini and Mazeras areas to the north of Port Reitz and west of Port Tudor (Figure 1). The aim of this survey was to observe the range of lithologies present in the parts of the drainage systems nearest to the coastal lagoons, and characterise the sandstones at seven key localities. The nature of the sandstones at each of these is outlined in Table 6.

Figure 12 -- **(Overleaf). Particle size distributions a) of sediments in the channels entering Port Tudor and Port Reitz, and b) of sediments on the flanks of the lagoon channel in Port Tudor. Phi classes and equivalent grain types are: -1, Granules; 0, Very coarse sand; 1, Coarse sand; 2, Medium sand; 3, Fine sand; 4, Very fine sand; 5-8, Silt; >8, Clay (after Wentworth (1922).**


Grain diameter (Phi)
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
>8.0
Percent by weight
80
60
40
20
0
PORT TUDOR
PORT REITZ
a
MAIN LAGOON
PORT TUDOR
b
10
Mouth Tsalu
14
Confluence Tsalu Kombeni
48
Mouth Mwachi
57
Mouth Mteza
21
West
37
East

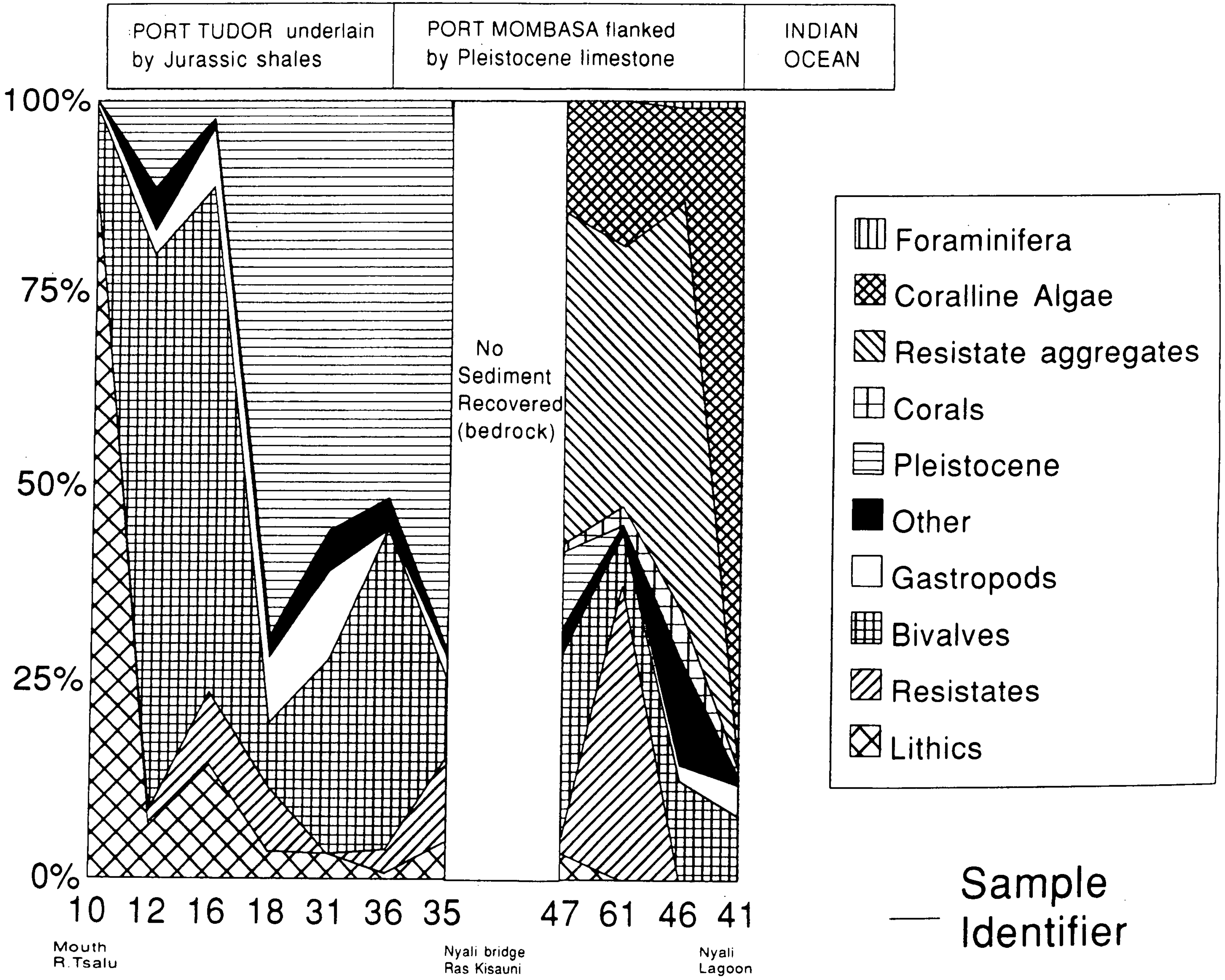
Rock sample	Grid Reference	Formation (Rais-Assa 1988)	Description
1	634 579	Mtokmkuu Formation	Very fine-grained sandstone, yellowish grey (5Y7-2) weathering greyish orange (10YR7-4). Poorly sorted, silty and micaceous litharenite.
2	632 578	Mtokmkuu Formation	Very fine-grained sandstone, light olive grey (5Y5-2) weathering moderate yellowish brown (10YR5-4). Poorly sorted, silty and micaceous litharenite.
3	601 579	Kambe Formation	Medium-grained sandstone, yellowish grey (5Y7-2). Well sorted arkosic arenite, grains angular to sub-angular.
4	618 583	Mtokmkuu Formation	Very fine-grained sandstone, light olive grey (5Y5-2). Moderately well sorted litharenite.
5	619 575	Mtokmkuu Formation	Fine-grained sandstone, light olive grey (5Y5-2) weathering moderate yellowish brown (10YR5-4). Poorly sorted arkosic sublitharenite.
6	623 575	Mtokmkuu Formation	Gravelly very coarse-grained sand, yellowish grey (5Y7-2). Moderately well sorted subarkose, grains angular.
7	641 576	Magarini Sands	Fine grained sands (friable and poorly-cemented) light brown (5YR5-6). Well sorted arenite, grains sub-angular.

Table 6 **Lithological samples of supra-Karoo System formations taken from an inland traverse between and Mazeras and Miritini areas to the northwest of Mombasa. Colours are from the Munsell Colour Chart.**

The traverse established that there is substantial lithological variation in the Supra-Karoo Series rocks, but that all of the common lithic, aggregate and mineral grains identified in the sediments of the distributary channels in this limited study may have been derived from these rocks.

Muds on the margins of the mangrove swamps most commonly grade laterally into sands of the distributary channels, but locally also extend across most of the width of the channel, restricting the sands to the channel axis. Near the (unsampled) tidal limits of the channels it is possible that the entire channel width may consist of muds. Such muds are likely to have been deposited in the turbidity maximum which would be

Figure 13 **(Overleaf). Grain type analysis performed on medium, coarse and very coarse sand and granules from samples taken on the transect from the mouth of the River Tsalu through Port Mombasa to the sea at Nyali (see Figures 1 and 14). Counts based on miniumum of 100 grains.**

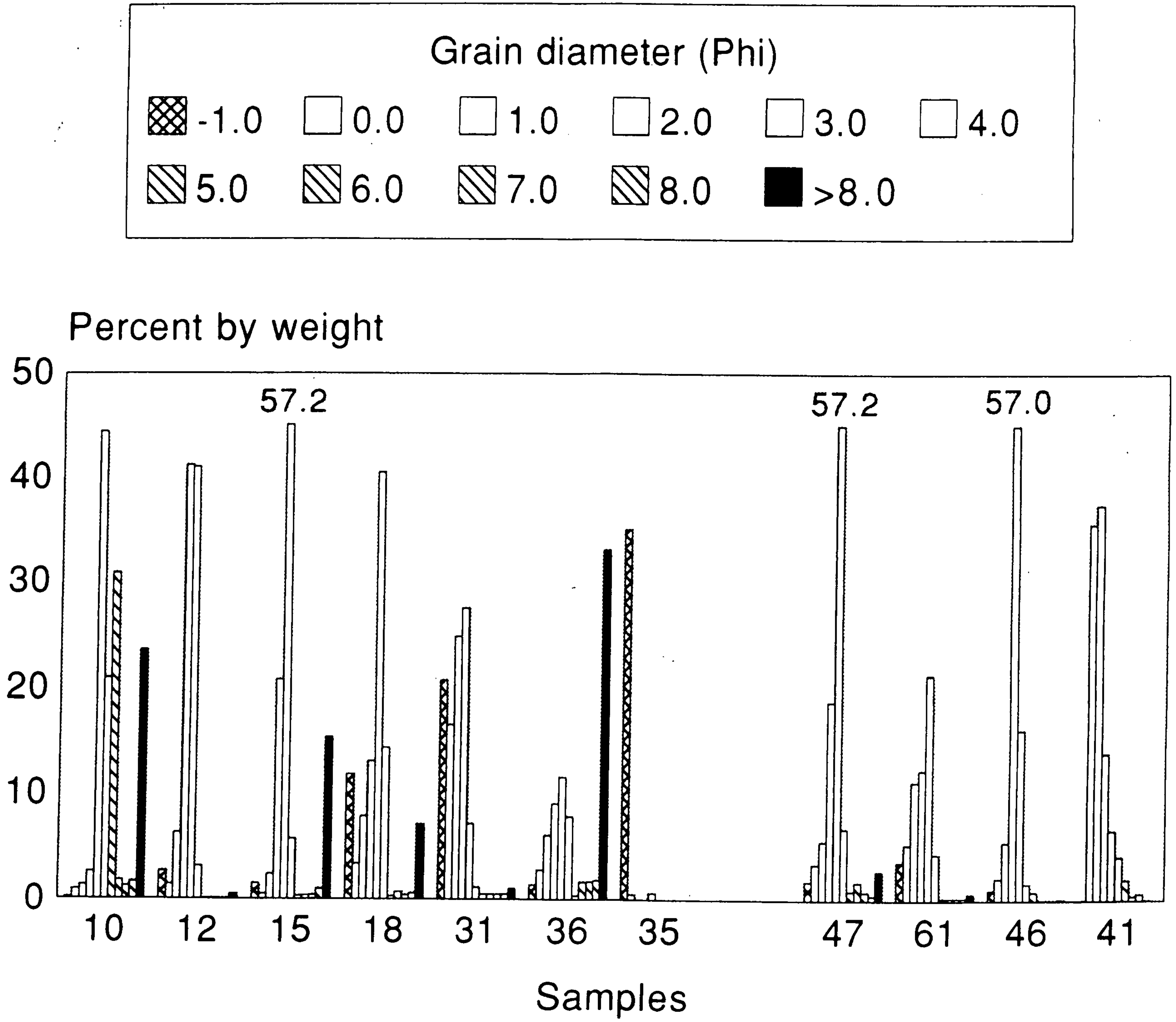

PORT TUDOR underlain by Jurassic shales
PORT MOMBASA flanked by Pleistocene limestone
INDIAN OCEAN
100%
75%
50%
25%
0%
No Sediment Recovered (bedrock)
10
12
16
18
31
36
35
47
61
46
41
Mouth R.Tsalu
Nyali bridge Ras Kisauni
Nyali Lagoon
Foraminifera
Coralline Algae
Resistate aggregates
Corals
Pleistocene
Other
Gastropods
Bivalves
Resistates
Lithics
Sample Identifier

restricted to the upper reaches of the distributary channels during the dry season. At such times low discharge may allow limited bedload transport, and insufficient flow rates to prevent buildup of muds; during periods of high discharge the reverse may be true. Few primary sedimentary structures have been observed in the distributary channel muds, probably largely because of bioturbation.

The **peripheral lagoon** in Port Reitz is floored by sandy muds; gravity cores prove that these coarsen upwards. Locally the muds are shelly, and contain many intact, though disarticulated, bivalve valves. The sandy muds differ from those of the adjacent mangrove swamps, being dark grey in colour, though they also appear to be structureless. Towards the west of the peripheral lagoon the sandy muds pass into the muddy sands of the distributary channel mouth bars (see below). The existence of the peripheral lagoon is somewhat puzzling, and is discussed below. The present rate of sediment accumulation is likely to be higher in the peripheral lagoon than on the flanks of the main lagoon as the distributary channels of the Mwachi and Mteza pass into it, and, during the wet season, the turbidity maximum may span it. The maximum rate of deposition will be directly related to the suspended load of the Mwachi and Mteza, and thereby to peak discharge events.

The **distributary channel mouth bars** consist of muddy fine-grained sands that overlie finer grained sediments, interpreted to have been deposited in the main lagoon. This trend, is shown in the particle size analyses of samples from Auger core 4, from the mouth bar in Port Reitz which remains subaerially exposed, except at HWS (Figures 1, 15 and 16). The upper two samples comprise muddy sands of the mouth bar, and the lower two samples, sandy muds of the underlying lagoonal sediments. The sand, dominated by lithic and quartz grains, with few carbonate grains, is a pale grey (N4) underneath the mangrove vegetation, though is a darker hue elsewhere.

Figure 14 **(Overleaf). Particle size distributions of sediment samples taken on the transect from the mouth of the River Tsalu through Port Mombasa to the sea at Nyali (see Figures 1 and 13) See Figure 12 for a description of Phi classes.**


Grain diameter (Phi)
-1.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
>8.0
Percent by weight
50
40
30
20
10
0
57.2
57.2
57.0
10
12
15
18
31
36
35
47
61
46
41
Samples

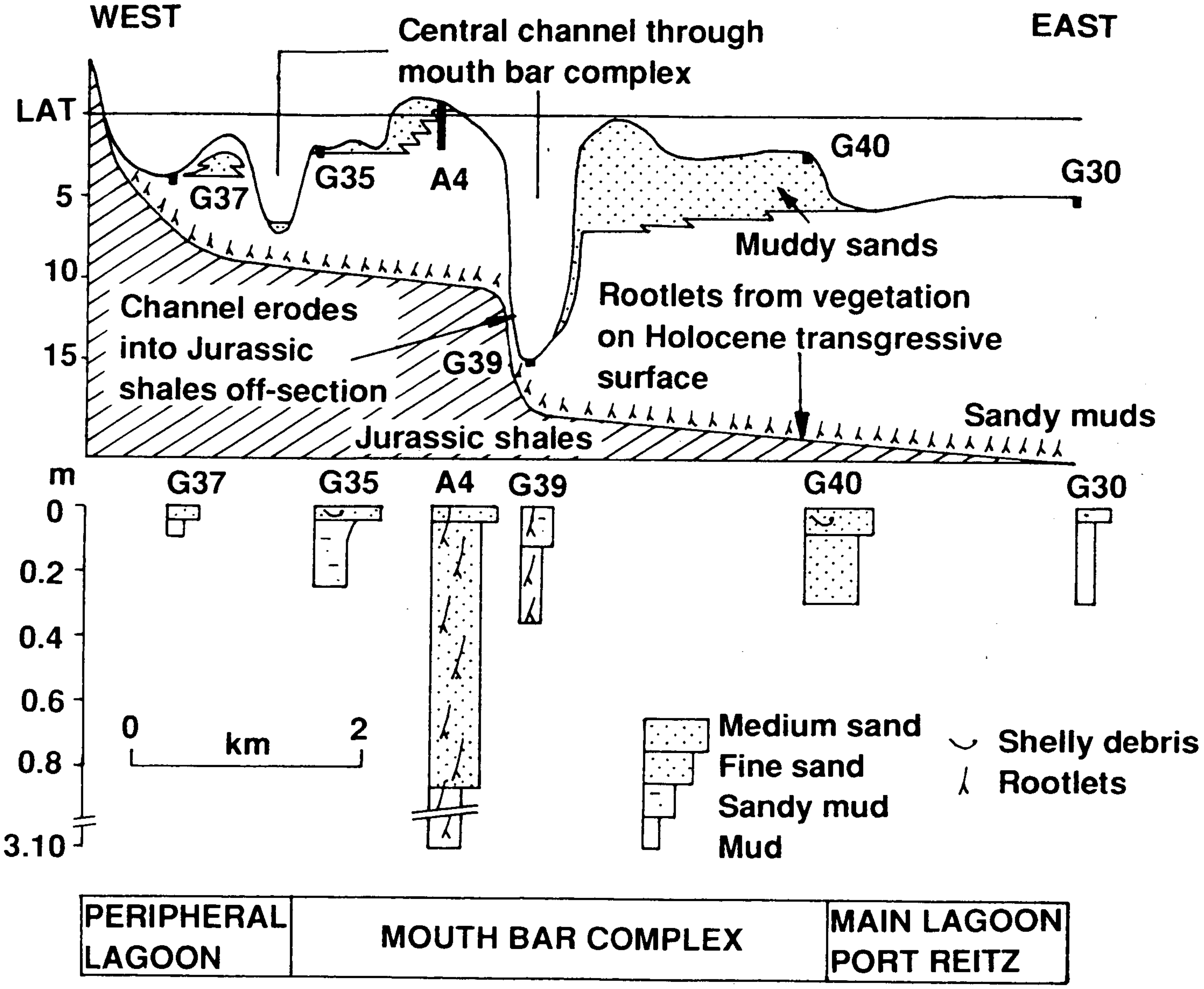
The limited number of cores taken through the sands suggest that the latter are structureless. Under the mangrove canopy this may be attributed to extensive bioturbation; indeed active bioturbation, largely by crustaceans, and soldier crabs in particular, can be readily observed today. Elsewhere, however, bioturbation may have played a more limited role in sediment mixing. The sands beneath the mangrove canopy have also been disturbed by the root fabric, the density of which decreases with depth (as is indicated by the organic fraction of the sand component of Auger core 4 in Table 7). The density of roots in the underlying muds seems to be higher than the overlying sands, though also appears to decrease with depth (this is also reflected in Table 7).

Auger core	Depth (m) (downhole)	Sand weight% loss on ignition	Lithology	Interpretation
4	0.52-0.62	2.54	Muddy sand	Mouth Bar
4	0.75-0.85	0.75	Muddy sand	Mouth Bar
4	2.28-2.38	2.66	Sandy mud	Lagoonal mud
4	3.00-3.10	1.75	Sandy mud	Lagoonal mud
3	0.00-0.12	8.86	Sandy mud	Mangrove swamp
3	4.66-4.80	5.27	Sandy mud	Mangrove swamp
3	5.50-5.60	4.59	Sandy mud	Mangrove swamp

Table 7 **Description and interpretation of sediment samples from auger holes 3 (Port Tudor) and 4 (Port Reitz)**

The interpretation of the distributary channel mouth bars as such is supported by their position on the seaward side of the distributary channels entering the lagoons, and their apparent lack of internal structure. The bars are interpreted to have formed by dumping of sand-grade sediment at the mouths of the channels by rapid deceleration of waters as they entered the lagoon during periods of high discharge.

Figure 15 **(Overleaf). Cross section across the Holocene sequence of Port Reitz based on gravity cores (G) and auger cores (A). Details of the cores are shown below the main section. For line of section see Figure 1.**


WEST
Central channel through mouth bar complex
EAST
LAT
5
10
15
G37
G35
A4
G40
G30
Muddy sands
Rootlets from vegetation on Holocene transgressive surface
Channel erodes into Jurassic shales off-section
G39
Sandy muds
Jurassic shales
m
0
0.2
0.4
0.6
0.8
3.10
G37
G35
A4
G39
G40
G30
0
km
2
Medium sand
Fine sand
Sandy mud
Mud
Shelly debris
Rootlets
PERIPHERAL LAGOON
MOUTH BAR COMPLEX
MAIN LAGOON PORT REITZ

It is probable that the since relative sea-level stabilised within the Holocene (see Section 4.5) lack of accommodation space towards the peripheries of the lagoon caused the mouth bar complexes to prograde seawards over older lagoonal muds. This is reflected, not only by coarsening-upwards of cores of the mouth bars themselves, but also by muds within the main body of the lagoons of Port Tudor and Port Reitz, as is illustrated in the western part of Port Reitz in Figure 15.

Given the above interpretation, the existence of the peripheral lagoon, on the landward side of the mouth bars, at the western end of Port Reitz requires some explanation. It may be expected that when sediment supply exceeds accommodation space in a depositional system, all bathymetric depressions in the proximity of the sediment supply, such as the peripheral lagoon in Port Reitz, would be infilled prior to seawards progradation of the system. It would appear then, that in this case the peripheral lagoon developed after the progradation of the mouth bar complex into the central part of Port Reitz. As an explanation for this, it is suggested that the peripheral lagoon has been caused by channel switching within the mouth bar complex, and that the distributary channel of the Mwachi previously occupied the position of the present position of the peripheral lagoon at the western most limit of Port Reitz. The present channel probably developed as a lateral tidal channel and eventually captured the Mwachi, as a short-cut. This explains the existence of the right-angle bend of the Mwachi channel on the western side of the main sand bank complex of Port Reitz, as well as the steep-sided (?oversteepened) margin of the western end of Port Reitz that has the appearance of having been cut in the relatively recent past by a channel. The evidence for on-going rapid morphological change in the sand bank complex, including channel switching, is supported by the changing distribution of intertidal areas as depicted on various versions of Admiralty and Kenya Survey maps.

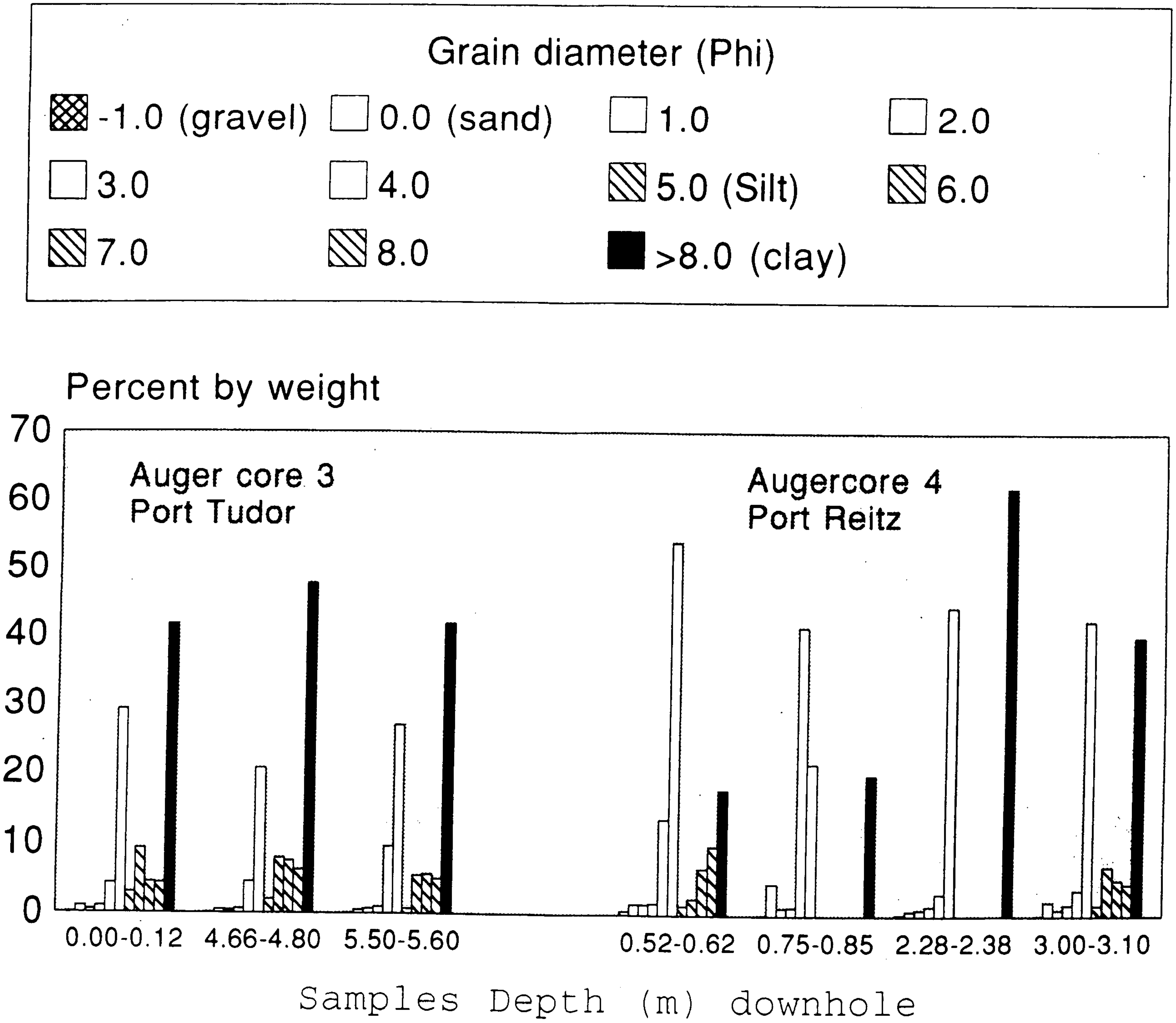
Several of the distributary channel mouth bars are orientated parallel to the main lagoonal channel where they are proximal to it, because of redistribution of sands by tidal currents in periods of lower river discharge. Such processes are suggested by the growth of a (thickly vegetated) spit of sand from northwest to southeast across the mouth of Junda Creek (Figure 1); the growth of this spit was facilitated by the residual ebb-tidal current in the main channel of Port Tudor. The sandy muds underneath the spit were sampled in an auger hole (3) on its lagoon side, and are typical of sandy muds of the mangrove swamps, being pale grey (N4) in hue, well-mixed, and having an organic content decreasing with depth (Figure 16, Table 7)

The **main lagoon** (channel flanks) are floored by gravelly sandy muds and sandy muds. The sand and mud fractions of these generally coarsen slightly upwards, though the gravel component, consisting almost exclusively of modern or Pleistocene carbonate detritus, is more evenly distributed vertically. Shelly fragments also form most of the medium- to coarse-grained fraction of the sediments. The mean grain-size of sediments appears to decrease with distance from the central channel of the lagoons. This is illustrated by grab samples 21 and 37, which were taken from distal and proximal sites respectively relative to the central channel in Port Tudor (Figures 1 and 12). Muds towards the margins of the lagoons, particularly near Makupa causeway in Port Tudor, are dark grey in hue and have a "soupy" character. The few measurements made of organic content in the lagoon sandy muds show no clear distribution pattern. The muds, dark grey in colour, locally show crude bedding, though contacts are gradational; no sharply defined laminae have been noted.

The sediment samples taken from the **marginal embayments** all are characterised by homogenous dark grey gravelly sandy mud which display no stratification or lamination. In the case of samples taken from Liwatini and Mbaraki creeks, this may be due to churning of sediments by ships anchoring. As over most of the lagoons, the cores taken appear to increase in sand content upwards.

The **lagoon channel** is floored by sediments ranging from dark sandy muds to gravels. The sandy muds and gravelly sandy muds probably represent older (Holocene) sediments that have been incised by the channel (where the Port Reitz lagoon channel traverses the distributary channel mouth bars in Figures 11 and 15).

Figure 16 **(Overleaf). Particle size distributions of samples taken from Auger core 3 (mangrove swamp) and Auger core 4 (mouth bar [top 2 samples] and main lagoon). See Figure 1 for location of Auger holes and Figure 12 for a description of Phi classes.**


Grain diameter (Phi)
-1.0 (gravel)
0.0 (sand)
1.0
2.0
3.0
4.0
5.0 (Silt)
6.0
7.0
8.0
>8.0 (clay)
Percent by weight
70
60
50
40
30
20
10
0
Auger core 3
Port Tudor
Augercore 4
Port Reitz
0.00-0.12
4.66-4.80
5.50-5.60
0.52-0.62
0.75-0.85
2.28-2.38
3.00-3.10
Samples Depth (m) downhole

Locally, where gravels occur on the lagoon channel floor, it appears that the channel has cut through the Holocene estuarine fill into Jurassic rock; evidence from the lagoons and confined-channel suggest that the gravels are basal lag deposits consisting of fragments of shale. It is notable that the only gravity core (39) in the floor of either of the lagoon channels to contain roots was one occurring in the vicinity of such gravels in Port Reitz (Figures1 and 15); the roots may be the remains of vegetation that first colonised the transgressive surface of the creek earlier in the Holocene (see Section 4.5). Most sands flooring the channels were probably transported into them as bedload during periods of high discharge; the clays and silts within these have largely been winnowed away. However, it is notable that sand bodies on the channel floor appear to be most common in the vicinity of the entrances to the distributary channels. Such sand bodies may be considered to be low discharge mouth bars, which would suggest that relatively little sand is transported into the lagoon channel from the distributary channels during such periods. The limited transport capacity of the lagoon channel during periods of low discharge would also appear to be supported by the occurrence of fluid muds in the centre of the channel in Port Tudor in several gravity cores (8, 20 and 29, Figure 1) and the predominance of muddy sediments within them as a whole.

The **upper confined-channel** in both creek systems is dominated by gravelly sandy muds and that of Port Mombasa, almost exclusively so. As in the lagoon channels, sands and shale-gravel lags occur locally, and coincide with the main tidal stream indicated by drogue studies (Norconsult 1975), and beaches (not depicted in Figure 11). Where sampled, the gravels consist, almost totally, of either shale or shell detritus. The sands are a mixture of lithic and resistate grains with a notable carbonate fraction (reflected by a 3-8% CaO content: Williams et al. 1996[a]), probably derived mainly from the Pleistocene limestones. The predominance of muddy sediments in the upper confined-channels suggests that average tidal currents are insufficient to mobilise the sediment, thus it would appear that most sediment transport occurs infrequently, probably during high discharge events.

The few samples of gravelly sandy mud that have been taken, for instance grab sample 36 (Figures 1 and 14), suggest that the muddiest sediments occur within the probable tidal scour cauldrons. These sediments have a lot of sand-grade plant material; the loss of weight on ignition of grab sample 36 was 10.78 weight per cent.

The **lower confined-channels** are filled mainly by sand, though sandy muds and gravelly sandy muds occur on the channel margins. The sand is mostly fine- to medium-grained and well-sorted. Compositionally it is distinctive, largely being composed of resistates (quartz and feldspar grains), as well as very characteristic resistate-aggregate grains. The latter, which have not been recognised elsewhere in the creek systems, are aggregates of quartz and feldspar that have a weak calcareous cement; they bear no similarity to the lithic aggregate grains found in the distributary channels feeding Port Tudor and Port Reitz (grains of which also have been recognised here). Another large component of the sand consists of grains of coralline algae, unrecorded elsewhere in the creek systems. This component accounts for the relatively high CaO levels of sediments (>8%) recorded in the lower confined channels by Williams et al. (1996[a]).

The sands identified on the side-scan sonar records of Port Kilindini were scrutinised for bedforms, but these are rare. Straight-crested ripples occur in Port Kilindini, their crests lying orthogonally to the confined channel and the direction of rectilinear currents identified by the Admiralty and drogue studies. No sand waves have been identified, despite the fact that such bedforms would be expected to start forming in currents of between 0.7-0.8m/s in water depths between 20 and 60m water depth (Rubin and McCulloch 1980), conditions which undoubtedly occur in Port Kilindini according to current measurements (Figure 9). The apparent absence of such bedforms on the side-scan sonar records is not a function of poor record quality; many other features such as buoy chains, anchor drag marks and dredging marks are clearly discernible on the records. The preservation of such 'anthropogenic' features adds further weight to the argument that sand transport in the creek systems is negligible, or very spasmodic.

The sand which blankets the floor of the lower confined-channels is clearly derived from two sources. Much of it, consisting mostly of coralline algae, has been transported into the creeks from the lagoons behind the modern reef and coast to the north and south of Mombasa. Most is likely to be carried when ebb tides are weakest and when the waves are most powerful; probably during neap tides in August and September (see Section 2.4). The considerable component of sand comprising resistate grains and grain aggregates is likely to be derived from the catchments feeding the creek systems as no sand sources of this character have been recognised along the coast. The partially cemented nature of the resistate aggregates suggests that resistates deposited in the confined-channel have been resident there for some time. They may have been deposited in the mid-Holocene, possibly as part of an ebb-tidal delta which has since lost its morphological character (Section 4.5).

It is likely that resistate rich sediments, such as those identified in the lower confined-channel, in the **open sea** only occur in the entrance to the creek systems, immediately off Mombasa. However, even here they are probably swamped volumetrically by carbonate sands, composed largely of corraline algae, but also containing significant quantities of foraminifera, especially nummulitic taxa. These carbonate sands are mostly coarse-grained, well sorted and in the lagoons separating the modern reef and the wave-cut platforms comprise 100% of the sediment (e.g. grab sample 41 in Figures 13 and 14). These sands are indigenous, having been generated behind the modern reef. Chemically, their high carbonate content is reflected by high CaO and only trace concentrations of SiO_2 and Al_2O_3 (Williams et al. 1996 [a]).

4.4: Morphodynamics of the creek systems

The sediment distributions described strongly suggest that sediments from the fluvial distributaries move through the creek systems to the sea, whilst marine-derived sediments generally do not move landward of the outermost (lower confined-channel) parts of creek systems. This is illustrated by the samples taken in the transect from one of the distributary channels to the open sea in Port Tudor (Figure 13). Grain types typical of the distributary channels (such as lithoclasts) are found throughout the system, but grains derived from the open sea (e.g. corals, coralline algae) extend landwards only as far as the lower confined-channel. This trend it so be expected as the net long-term movement of sediments in any tidal channel system connecting a coastal basin (such as the lagoons described here) and the sea will be largely a function of the ebb and flood velocity and discharge in the system. The tidal measurements of Norconsult (1975) and Nguli (1994) clearly indicate that, in the creek systems of Mombasa, the ebb currents are stronger than the flood currents. As ebb-dominant systems have shorter, higher velocity, ebbs they tend to flush bed-load sediment seaward (conversely, flood-dominant estuaries have shorter duration, higher velocity floods, and tend to fill their channels with coarse sediment).

Such ebb-dominance is caused by the effect of the hypsometry of the creek system on the propagation of the tidal wave. As the latter is depth-dependant, the hypsometry affects the overall tidal characteristics (time lag, phase lag, range, asymmetry) and direction of net sediment transport (Boon and Byrne 1981, Dronkers 1986, Friedrichs and Aubrey 1988, Lessa and Masselink 1995). The shape of the tidal wave changes as it decelerates whilst entering the mangrove swamps and at high water, water is still flowing into the creek system to raise the water levels upstream. This results in high water slack current being delayed after high water and low water slack being similarly delayed after low water. To ensure that the accumulated water is removed, the peak velocity of the ebb is increased, and that of the flood tide decreased (Dyer 1986). Several researchers investigating the geometry and distortion of the vertical tide (Aubrey and Speer 1985, Friedrich and Aubrey 1988, Lessa and Masselink 1995) have shown that ebb-dominance occurs when intertidal storage is large, as is the case with the Mombasa creek systems. Importantly, the flushing of ebb-dominant systems inhibits the long-term build-up of sediments within them. Consequently ebb-dominant systems may have more stable geometries than flood dominant systems (Speer and Aubrey 1985, Aubrey 1986).

4.5: Evolution of the creek systems

Although gross seaward transport of sediments has been established, the timing of the transport processes is poorly understood. Many lines of evidence suggest that bedload transport, at least, has been very limited in the period preceding the recent surveys. For instance, the muds in the distributary channels, the lagoon channels, the confined-channels (including the tidal scour cauldrons) and the preservation of 'anthropogenic' features in the confined-channels, would all be removed during a high energy event. In the creek systems such events must equate with high discharge events, caused by heavy rainfall during short periods, probably towards the start of the wet seasons. How frequently such events occur is unclear. Whether the channel muds get flushed out of the system, and sands re-mobilised with each wet season, or annually is not known, but the density of the muds, and the variety of 'anthropogenic' features in the sands would appear to argue against this. Clearly it is important to know more about the periodicity of sediment flushing if we are to understand better the residence time of contaminanted sediments within the creek systems.

Some features of the creek systems, including the partially-cemented ebb-tidal delta in Port Mombasa, and the extensive mouth bar complexes in Port Tudor and Port Reitz, suggest that much larger fluxes of sandy sediments must have occurred in the creek in the past. Given the lack of evidence for transport of great volumes of sand today (in fact, as already discussed, the existence of the peripheral lagoon may suggest that the mouth bar complexes have been recently subject to erosion), when did the sediment fluxes responsible for these sand bodies occur? The problem may be partially addressed by referring to the likely post-glacial sedimentation history of the area.

The rise in sea-level, following the Weichselian glaciation, from over 100m below MSL, was not gradual, but stepped (because of periodic ice-sheet collapse) as shown by Blanchon and Shaw (1985). Their work demonstrated that coral reefs which developed during periods of relative sea-level stability, were drowned during periods of rapid sea level rise. A similar scenario may be expected on the continental slope off

Mombasa, indeed slope-parallel ridges may be identified on the bathymetric charts that may equate with earlier Holocene reef development. Global sea level curves (including Blanchon and Shaw's) from tectonically stable areas outside the limits of glacial influence (see Pirazzoli 1991) would suggest that marine waters first inundated the confined channels of the Mombasa creek systems about 9000 years ago, their level remaining relatively stable, probably at about 18m below chart datum, until about 7500 years ago. It is during this period that it is most likely that the tidal scour cauldrons in the confined channels began to be cut, as most bathymetric ridges separating paired cauldrons have surfaces at about 20m below chart datum. The shallow waters of the confined channels at that time would have had high tidal velocities with considerable power, not only to erode, but also to carry sediments trapped in newly flooded valley systems on the Pleistocene surface out of the creek system. The fate of these sediments is uncertain, but it may be that these are the partially-cemented sands which occur at the seaward end of the confined channels (as found in Port Mombasa) that probably formed as ebb-tidal deltas.

From about 7500 years sea level rose rapidly. Coastal vegetation (represented by rootlets at the base of the Holocene sequence; Figure 15) would have been rapidly inundated during the transgression, and swamped by fast-accumulating lagoonal muds. By about 6000 years ago the entire creek systems are likely to have been inundated by marine waters.

Subsequent stabilising sea levels would have decreased accommodation space for sedimentation in the lagoons, and started the progradation of the distributary channel mouth-bars bar complexes over the lagoonal muds (Figure 15). The mouth bar complexes in Port Reitz and Port Tudor are, however, too large to have been created by such stabilisation alone, as the flux of sediment during periods of sea-level stability are too low (as may be seen today). It is more likely that the progradation resulted also from a period of high sediment flux.

The period of high sediment flux is tentatively attributed to a mid-Holocene sea-level *fall*, in which the supply of sediments to the creek systems would have been increased by rejuvenation of the drainage systems. This setting is supported by the incised nature of the lagoon channels in Port Reitz and Port Tudor which have both cut through the distributary channel mouth bar complexes into older Holocene sediments and locally into Jurassic rocks.

When did this sea-level fall occur? Globally, sea-level reached a high between 5000 and 6000 years ago (see review by Pirazzoli 1991). Jaritz et al. (1977) suggest that sea level on the coast of Mozambique during this period reached up to 3.0m above MSL. A distinct notch at about this height in the cliff behind the present day (and ?Pleistocene) wave-cut platform at Nyali may have been cut at this time. On the basis of the sea-level curve of Jaritz et al. (1977), the fall which accounts for the growth of the ebb tidal delta and distributary channel mouth bars occurred after this, probably between 5000 and 2000 years ago.

The progradation of the distributary channel mouth bar complex now appears to have ceased, or be limited, today, indeed the component sediments are mostly being eroded by channels, or being entrained by tidal currents. (The main processes affecting sediment redistribution are tidal winnowing, and shifting of intertidal sediments on bars or beaches.) The paucity of sand in several of the rock-floored tidal scour cauldrons would also suggest that the period of high sand flux has ended; any sands resident in the scour cauldrons from this period having been removed by (?sporadic) high energy events since then.

4.6: Residence of sediment-hosted contaminants

Although levels of pollution in the Mombasa creek systems are presently low (Williams et al. 1996[a]), it is useful to try and predict which intra-creek environmental zones are most liable to store pollutants from contamination events in the future. From our understanding of the morphology and evolution of the creek systems (above) it is possible to make some predictions about which zones will be sinks of contaminated sediment in the long-term, and which zones will have the highest uptake of contaminants by sediments.

Some parts of the creek systems have probably reached a dynamic equilibrium with respect to present day sea-level. The long-term balance (over several years) between deposition and erosion in the mangrove swamps, distributary channels, distributary channel mouth bars, lagoon channels, and confined-channels has probably been acheived. Accommodation space for sedimentation in these zones has been fully utilised and may only be increased only by compaction (very slowly) or by a rise in sea-level (more rapidly). Sediment which accumulates within these on a short-term basis (for instance during the dry season) is likely to become eroded during high energy events (such as higher discharge in the wet season).

Other areas, however, including the peripheral lagoon, main lagoon (channel flanks), and the marginal embayments probably have capacity for sediment storage. These are generally removed from the areas of strongest tidal currents, and so are subject to lesser amounts of erosion; they are liable to be storage areas, or sinks for contaminated sediments in the future. Some zones, such as the peripheral lagoon, Makupa Creek, and the main lagoon in Port Tudor (especially near Makupa Causeway) are liable to have higher rates of sedimentation either because they are fed directly by distributary channels, or because they occur in (man-made) 'backwaters'. (No sediments within these areas have been dated, so it is not possible to calculate rates of sedimentation.) Accumulation of contaminants in such areas is also likely to be higher than average (on a long-term basis) because they are liable to contain a greater proportion of clays, onto which pollutants are preferentially adsorbed.

Whilst the mangrove swamps and mouth bars may not be areas in which sediments may accrete most rapidly, their near-surface sediments (particularly the uppermost 0.5 m) are particularly liable to pollution. There are three reasons for this. Firstly, as noted in Section 3, the residence time of (contaminated) waters is likely to be greatest within these zones, because of entrapment by roots. Secondly, the flocculation of clays (onto which contaminants get adsorbed) is likely to be greatest in these zones because the flux of Fe and dissolved humic organic matter in terrestrial runoff is highest in these areas (Williams et al. 1996[a]). Thirdly, and perhaps most importantly, these zones are particularly susceptible to extensive bioturbation (see below). Although sediments throughout the creek systems are heavily bioturbated (causing destruction of most primary sedimentary features), active bioturbation is most extensive, and deepest, under the mangrove canopy. In similar intertidal environments in Thailand soldier crabs, such as those that frequent the intertidal areas in the Mombasa creek systems) burrow to an average depth of 8cm, and, in conjunction with wave action, turn over sediment at the rate of $0.5m^3$ per year (Bradshaw 1996).

Given the likely infrequency of high energy events that may flush muds out of the creek systems, all of the intra-creek zones may be susceptible to short-term build-ups of contaminants in surficial sediments. These contaminants are also likely to be incorporated into sediments below the sediment water interface by (very active) burrowing animals in all zones. These sediments are likely to escape erosion, even during high-energy events. The extent of bioturbation, vertically, in sediment cores (almost total), and areally over the intra-creek zones, would suggest that bioturbation affects all parts of the creek systems, especially in the vicinity of the lagoons; consequently it is likely that sub-surface patterns of sediment contamination will quickly reflect distributions at the sediment-water interface. Thus *all* zones of the creek systems should be considered as potential contaminant sinks. A detailed knowledge of the rates at which contaminants in surficial sediments become incorporated into the sub-surface (which are likely to greatly exceed those of erosion during high-energy events) of the different environmental zones of the creek systems is thus essential in understanding the storage of sediment-hosted contaminants of the systems. Future research into bioturbation rates is thus very important in planning contaminant amelioration programmes.

5: CONCLUSIONS AND RECOMMENDATIONS

5.1: Hydrodynamics: conclusions

1 The *average* residence time of dissolved and suspended contaminants in Port Tudor or Port Reitz, taking all assumptions in modelling into consideration, is likely to be less than a week. This time will be shorter (probably less than 3 days) for any contaminant in the lagoon channel, and considerably longer (over 2 weeks) for contaminants within the mangrove swamps.

2 Equivalent residence times in ports Mombasa and Kilindini are likely to be less than 2 days, and will vary little between different parts of these confined-channels.

3 During spring tides residence times are likely to be much less than these, except in the mangrove swamps where contaminants may become trapped. During neap tides average residence times will be longer; inundation of the mangrove swamps during such periods is, however, likely to be minimal.

4 During the wet season residence times may be considerably reduced, because of higher discharges.

5.2: Sediment dynamics: conclusions

1 The sedimentary analysis suggests that the distribution of the sediment within the creek systems reflects their ebb dominance.

2 The sediment flux within the creek systems is extremely periodic. Large bedload transport events are very infrequent (?most occurring only during high discharge events). In between high energy events sedimentation from the suspended load takes place. This is suggested by the presence of fluid muds in

the distributary channel, the lagoon channel and the upper confined channel, and the preservation of man-made features in the sands on the floor of the Lower confined-channel. Most contaminants adsorbed by muds in the creek systems will reside within the systems between high discharge events.

3 The periodicity of high discharge events capable of transporting bedload is unknown, as is the rate of deposition of suspended sediment between such events.

4 The parts of the system that are likely to have above average long-term sedimentation rates are the channel flanks of the main lagoon, and the peripheral lagoon of Port Reitz. These zones are potential contaminated sediment sinks.

5 The rates of incorporation of contaminants in surficial sediments into the sub-surface by bioturbation is likely to far exceed the rate at which the surficial sediments are likely to get eroded by high-energy events. All parts of the creek systems may therefore be considered to be potential contaminant sinks.

5.3: Recommendations

1 More detailed estimates of water-borne contaminant residence times will be possible only after the basin hypsometry is surveyed in detail and after long time-series data covering salinity, discharge and evapo-transpiration become available.

2 A better understanding of the periodicity and nature of high-discharge events, of rates of sedimentation, and of bioturbation is essential for improved predictions of the storage of sediment-borne contaminants in the creek system to be made.

3 The longer residence times of waters, the greater susceptibility to flocculation of clays (onto which pollutants get adsorbed), and the rapid incorporation of surficial sediments into the sub-surface by bioturbation, in the mangrove swamps, distributary channels, distributary channel mouth bars, the lagoons and marginal embayments, make these zones particularly susceptible to pollution. Consequently the development of industrial activities in these zones, or areas which discharge directly into them, ought to be restricted, and carefully planned. High-contamination risk industries should be sited adjacent to the confined-channels, though discharge of heavy metals into the creek systems should be avoided at all times.

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textures observed in the records, in conjunction with data based on sampling using a wax charged lead line (Admiralty 1990). Sediment distributions in parts of Admiralty sheet 666 not covered by side-scan sonar were interpreted on the basis of samples collected during former Admiralty surveys.

4.3: Sediment distribution

Each of the intra-creek environmental zones (outlined in Section 3.2) have characteristic facies associations; these are defined below.

The **mangrove swamps** are underlain by a distinctive suite of remarkably homogeneous and sandy muds which have a notable pale grey (N4) hue. The muds show little or no textural variation within a few metres of the sediment surface. Most shelly grains comprise crustacean fragments. Mangrove roots extend as a matted fabric throughout the sediments, though decrease in density with depth. The predominance of clay minerals in the mangrove muds is illustrated by the proportion of Al_2O_3 (up to 15%) and K_2O (up to 2.5%) within them (Williams et al. 1996[a]).

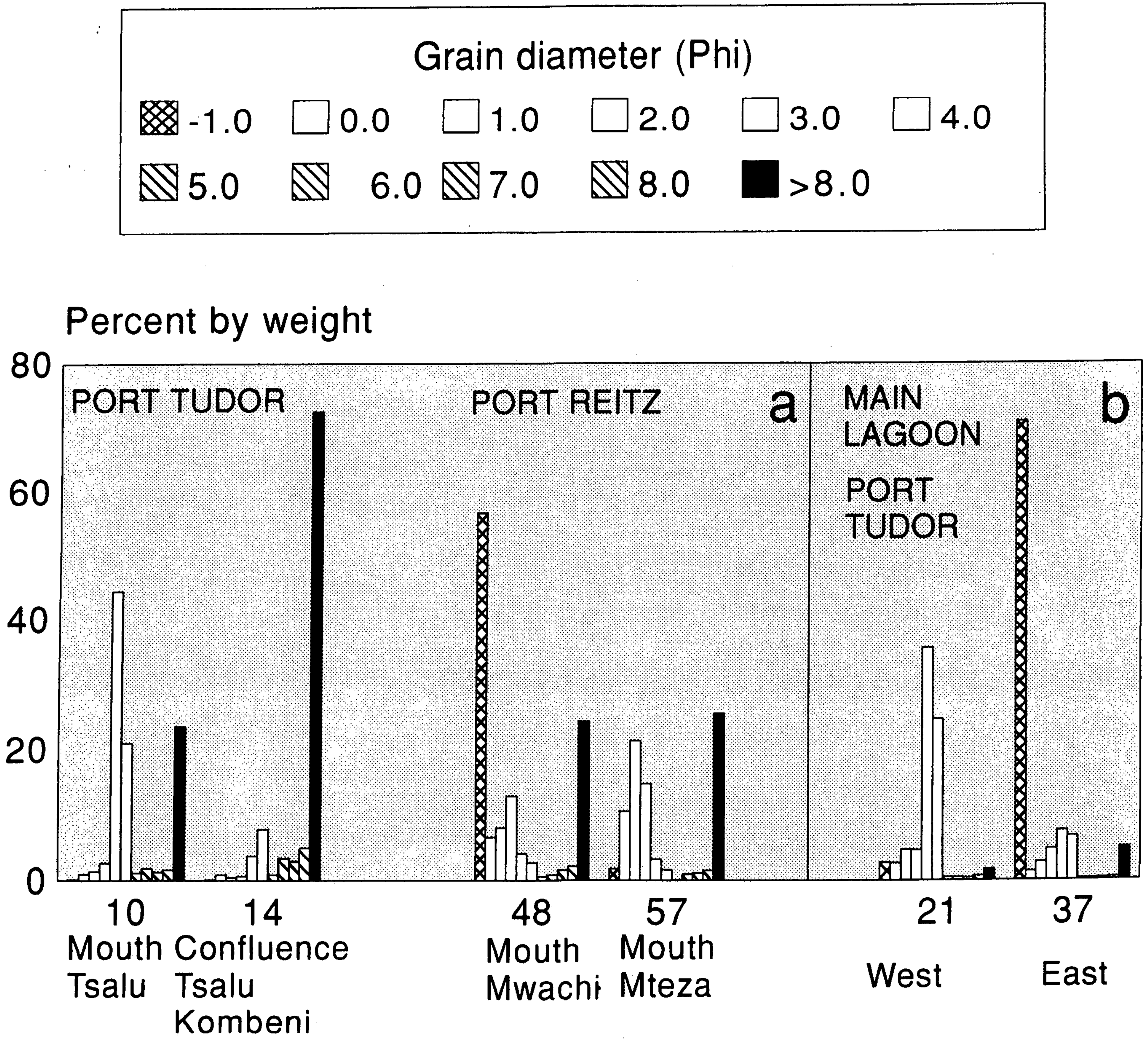
The limited resources of the recent surveys prevented detailed examination of the extensive mangrove swamps at the western and northern ends of the creek systems so little is known of the sediment textural variations within these areas. Although the mapped sediments (Figure 11) are shown as sandy mud, it is probable that they pass into muddy sands, laterally, on the margins of channels, and with depth, into moribund mouth bars (see below) that have been carpeted by finer-grained sediments as the depositional system prograded towards the main lagoon (Section 4.5).

The **distributary channels** are floored mostly by sands or gravels consisting of resistates (quartz, feldspar) and lithic grains or aggregates that appear to originate from the catchments of the main rivers flowing into the creek systems (see below). The high proportion of resistates in the channels (relative to the adjacent mangrove swamps) is indicated by an enhanced SiO_2 content (>60%), detailed by Williams et al. (1996[a]). Limited sampling suggests that the grade of sand entering Port Reitz and Port

Tudor (Figure 12) may differ; the sands from the floors of the Mwachi and Mteza being coarser than those of the Tsalu and Kombeni. The proportion of lithic grains in the coarser component in all the mouths of the channels (the Mwachi and Mteza where they discharge into the peripheral lagoon at the western end of Port Reitz and the Tsalu and Kombeni where they flow into the main lagoon of Port Tudor) is substantial (e.g. Grab sample 10, Figures 1 and 13; for grain size, also see Figure 14). These grains consist mainly of sandstone fragments, largely of litharenite, but also comprise silty shale. A significant part of some samples of distributary channel sand consists of plant debris; such sands from the mouth of the Tsalu and Kombeni (Grab sample 14, Figure 1) lost 5.16 weight percent upon ignition. The gravel component of the tidal reaches of both distributary channel systems consists largely of bored and abraded shelly detritus. Although most of this is modern, and probably derived from fauna living in the adjacent mangrove swamps, a small fraction of it appears to have been derived from the Pleistocene limestones.

The siliciclastic grains in the distributary channels appear to be characteristic of those of the creek systems as a whole (see below). We wanted to confirm that all the grain types (identified in a limited study by binocular microscope) recorded in the distributary channels have equivalents in the formations of the watersheds draining into the creek systems (establishing that they are the likely sources of sand and gravels in the distributary channels, and elsewhere in the creek systems). Consequently a traverse was undertaken across the supra-Karoo Series formations between the Miritini and Mazeras areas to the north of Port Reitz and west of Port Tudor (Figure 1). The aim of this survey was to observe the range of lithologies present in the parts of the drainage systems nearest to the coastal lagoons, and characterise the sandstones at seven key localities. The nature of the sandstones at each of these is outlined in Table 6.

Figure 12 **(Overleaf). Particle size distributions a) of sediments in the channels entering Port Tudor and Port Reitz, and b) of sediments on the flanks of the lagoon channel in Port Tudor. Phi classes and equivalent grain types are: -1, Granules; 0, Very coarse sand; 1, Coarse sand; 2, Medium sand; 3, Fine sand; 4, Very fine sand; 5-8, Silt; >8, Clay (after Wentworth (1922).**


Grain diameter (Phi)
▩ -1.0
☐ 0.0
☐ 1.0
☐ 2.0
☐ 3.0
☐ 4.0
▧ 5.0
▧ 6.0
▧ 7.0
▧ 8.0
■ >8.0
Percent by weight
80
60
40
20
0
PORT TUDOR
PORT REITZ
a
MAIN LAGOON
PORT TUDOR
b
10
Mouth Tsalu
14
Confluence Tsalu Kombeni
48
Mouth Mwachi
57
Mouth Mteza
21
West
37
East

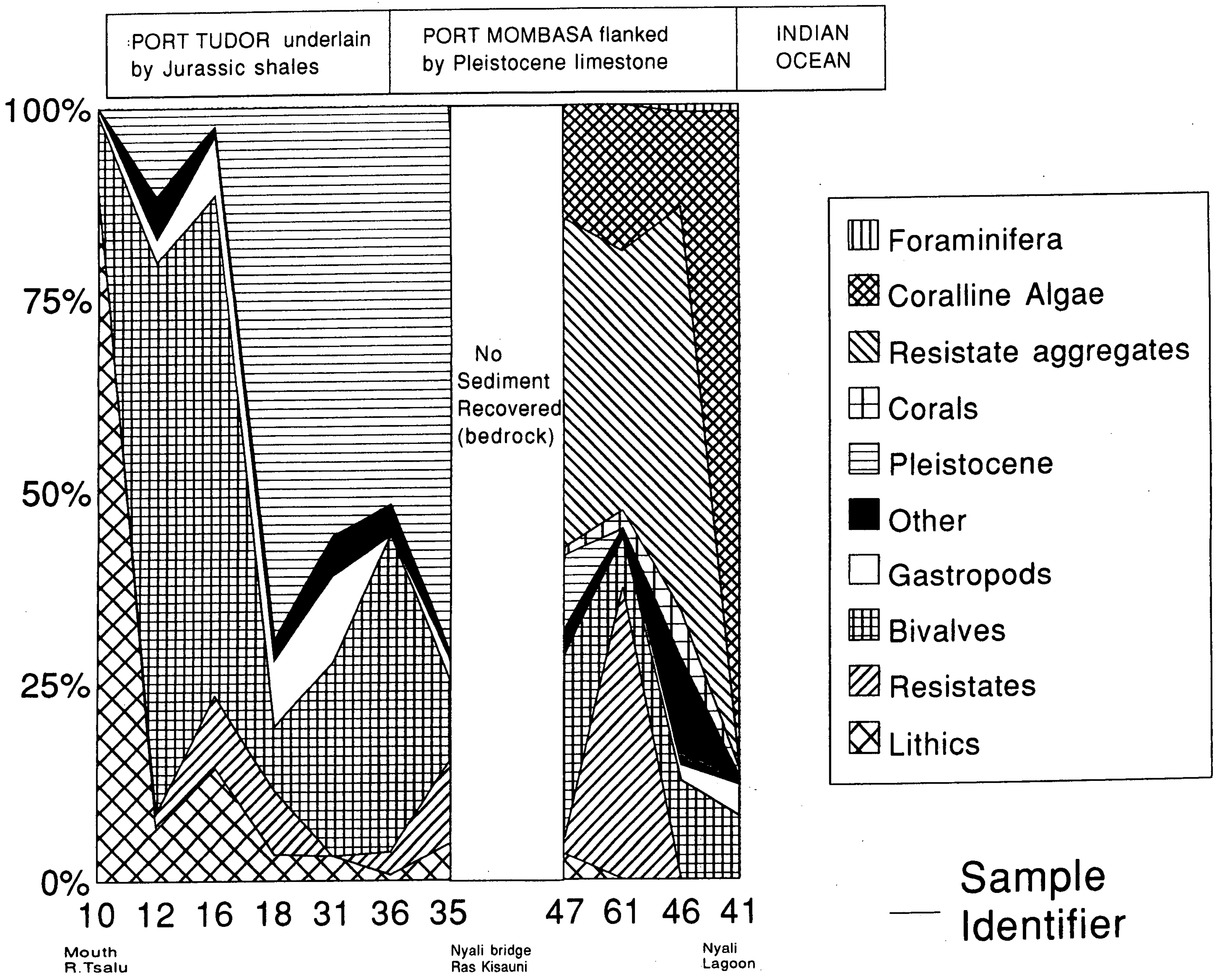
Rock sample	Grid Reference	Formation (Rais-Assa 1988)	Description
1	634 579	Mtokmkuu Formation	Very fine-grained sandstone, yellowish grey (5Y7-2) weathering greyish orange (10YR7-4). Poorly sorted, silty and micaceous litharenite.
2	632 578	Mtokmkuu Formation	Very fine-grained sandstone, light olive grey (5Y5-2) weathering moderate yellowish brown (10YR5-4). Poorly sorted, silty and micaceous litharenite.
3	601 579	Kambe Formation	Medium-grained sandstone, yellowish grey (5Y7-2). Well sorted arkosic arenite, grains angular to sub-angular.
4	618 583	Mtokmkuu Formation	Very fine-grained sandstone, light olive grey (5Y5-2). Moderately well sorted litharenite.
5	619 575	Mtokmkuu Formation	Fine-grained sandstone, light olive grey (5Y5-2) weathering moderate yellowish brown (10YR5-4). Poorly sorted arkosic sublitharenite.
6	623 575	Mtokmkuu Formation	Gravelly very coarse-grained sand, yellowish grey (5Y7-2). Moderately well sorted subarkose, grains angular.
7	641 576	Magarini Sands	Fine grained sands (friable and poorly-cemented) light brown (5YR5-6). Well sorted arenite, grains sub-angular.

Table 6 **Lithological samples of supra-Karoo System formations taken from an inland traverse between and Mazeras and Miritini areas to the northwest of Mombasa. Colours are from the Munsell Colour Chart.**

The traverse established that there is substantial lithological variation in the Supra-Karoo Series rocks, but that all of the common lithic, aggregate and mineral grains identified in the sediments of the distributary channels in this limited study may have been derived from these rocks.

Muds on the margins of the mangrove swamps most commonly grade laterally into sands of the distributary channels, but locally also extend across most of the width of the channel, restricting the sands to the channel axis. Near the (unsampled) tidal limits of the channels it is possible that the entire channel width may consist of muds. Such muds are likely to have been deposited in the turbidity maximum which would be

Figure 13 **(Overleaf). Grain type analysis performed on medium, coarse and very coarse sand and granules from samples taken on the transect from the mouth of the River Tsalu through Port Mombasa to the sea at Nyali (see Figures 1 and 14). Counts based on miniumum of 100 grains.**



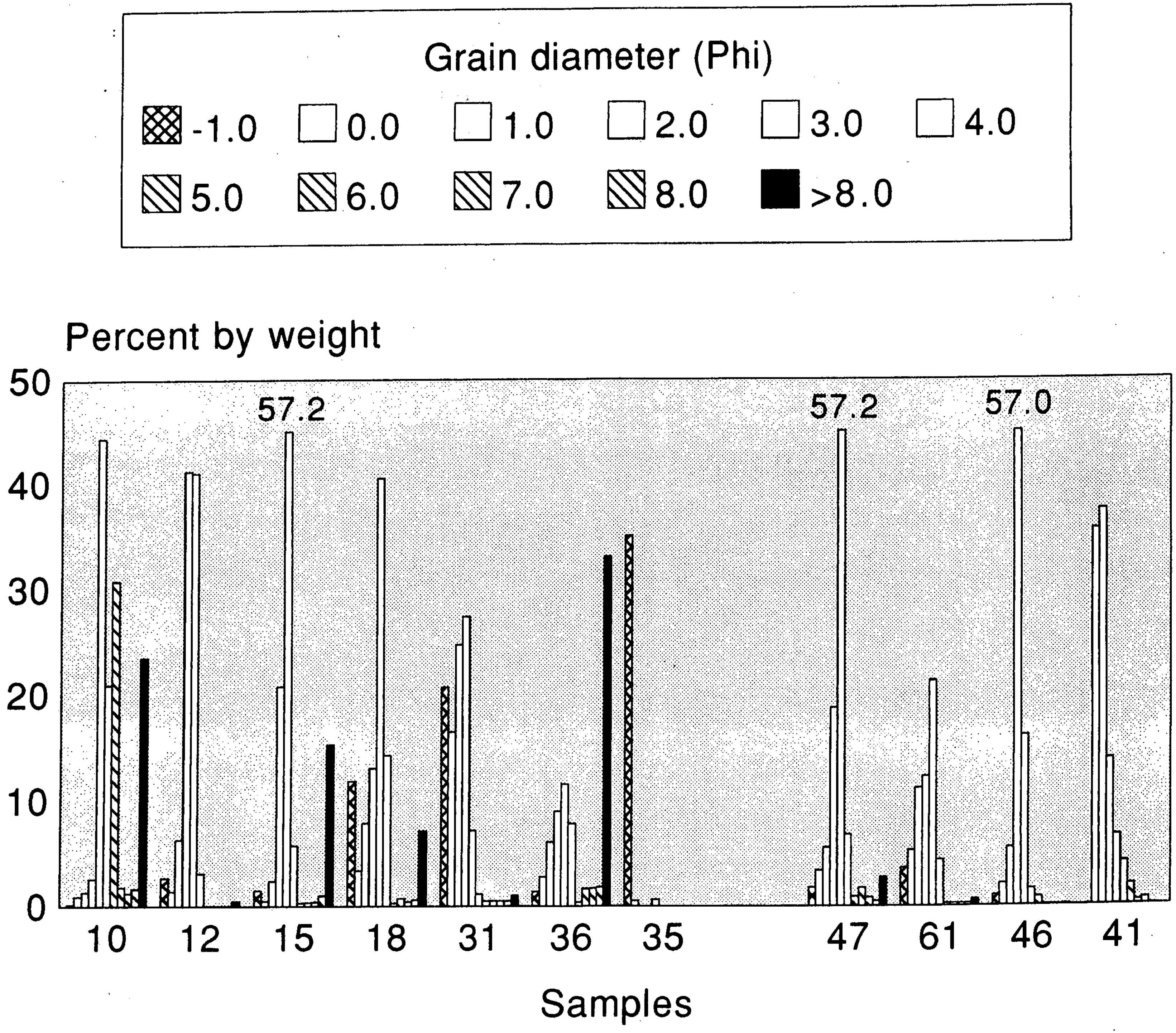
PORT TUDOR underlain by Jurassic shales
PORT MOMBASA flanked by Pleistocene limestone
INDIAN OCEAN
100%
75%
50%
25%
0%
No Sediment Recovered (bedrock)
10
12
16
18
31
36
35
47
61
46
41
Mouth R.Tsalu
Nyali bridge Ras Kisauni
Nyali Lagoon
Foraminifera
Coralline Algae
Resistate aggregates
Corals
Pleistocene
Other
Gastropods
Bivalves
Resistates
Lithics
Sample Identifier

restricted to the upper reaches of the distributary channels during the dry season. At such times low discharge may allow limited bedload transport, and insufficient flow rates to prevent buildup of muds; during periods of high discharge the reverse may be true. Few primary sedimentary structures have been observed in the distributary channel muds, probably largely because of bioturbation.

The **peripheral lagoon** in Port Reitz is floored by sandy muds; gravity cores prove that these coarsen upwards. Locally the muds are shelly, and contain many intact, though disarticulated, bivalve valves. The sandy muds differ from those of the adjacent mangrove swamps, being dark grey in colour, though they also appear to be structureless. Towards the west of the peripheral lagoon the sandy muds pass into the muddy sands of the distributary channel mouth bars (see below). The existence of the peripheral lagoon is somewhat puzzling, and is discussed below. The present rate of sediment accumulation is likely to be higher in the peripheral lagoon than on the flanks of the main lagoon as the distributary channels of the Mwachi and Mteza pass into it, and, during the wet season, the turbidity maximum may span it. The maximum rate of deposition will be directly related to the suspended load of the Mwachi and Mteza, and thereby to peak discharge events.

The **distributary channel mouth bars** consist of muddy fine-grained sands that overlie finer grained sediments, interpreted to have been deposited in the main lagoon. This trend, is shown in the particle size analyses of samples from Auger core 4, from the mouth bar in Port Reitz which remains subaerially exposed, except at HWS (Figures 1, 15 and 16). The upper two samples comprise muddy sands of the mouth bar, and the lower two samples, sandy muds of the underlying lagoonal sediments. The sand, dominated by lithic and quartz grains, with few carbonate grains, is a pale grey (N4) underneath the mangrove vegetation, though is a darker hue elsewhere.

Figure 14 **(Overleaf). Particle size distributions of sediment samples taken on the transect from the mouth of the River Tsalu through Port Mombasa to the sea at Nyali (see Figures 1 and 13) See Figure 12 for a description of Phi classes.**


Grain diameter (Phi)
▩ -1.0
☐ 0.0
☐ 1.0
☐ 2.0
☐ 3.0
☐ 4.0
▧ 5.0
▧ 6.0
▧ 7.0
▧ 8.0
■ >8.0
Percent by weight
50
40
30
20
10
0
57.2
57.2
57.0
10
12
15
18
31
36
35
47
61
46
41
Samples

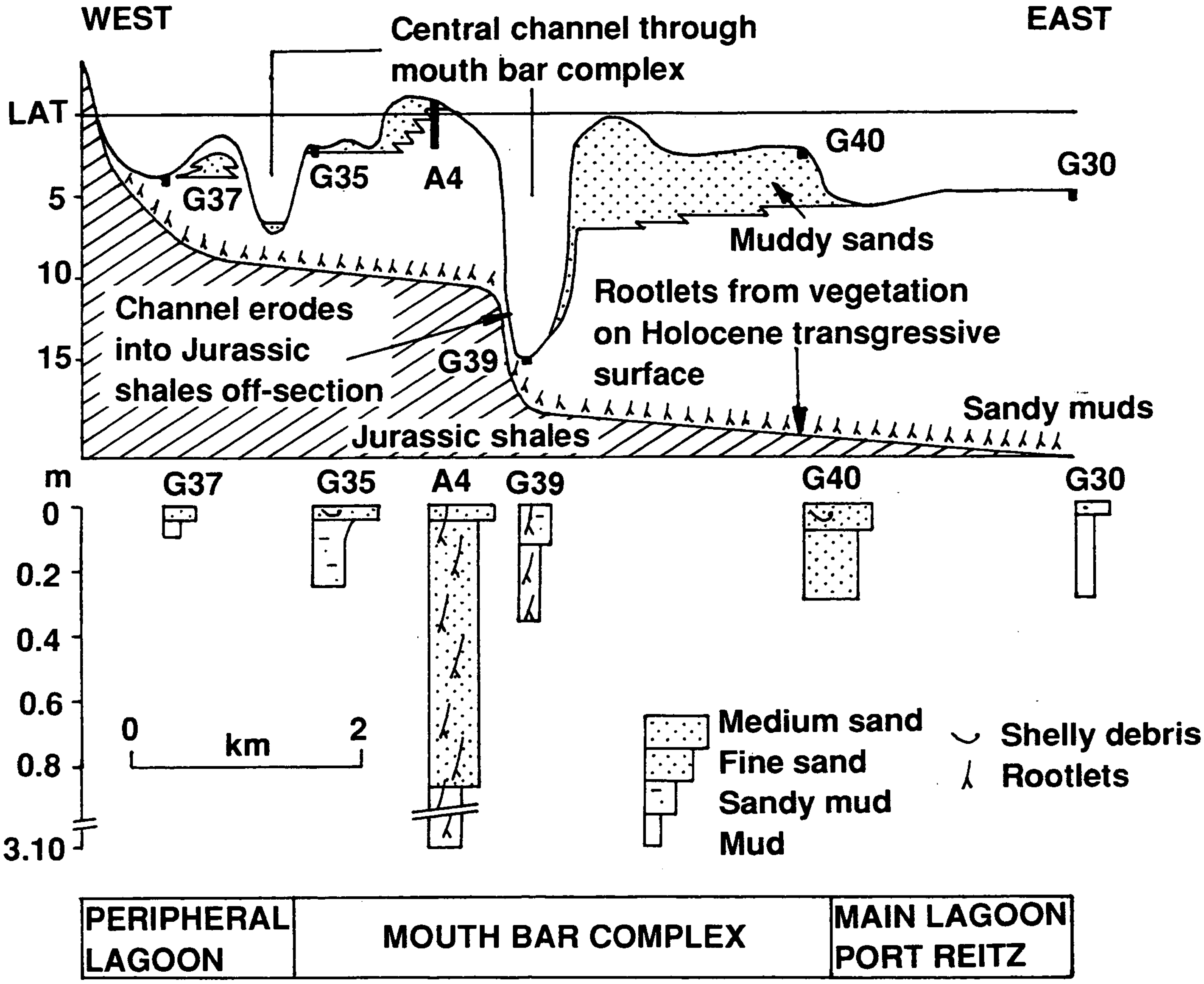
The limited number of cores taken through the sands suggest that the latter are structureless. Under the mangrove canopy this may be attributed to extensive bioturbation; indeed active bioturbation, largely by crustaceans, and soldier crabs in particular, can be readily observed today. Elsewhere, however, bioturbation may have played a more limited role in sediment mixing. The sands beneath the mangrove canopy have also been disturbed by the root fabric, the density of which decreases with depth (as is indicated by the organic fraction of the sand component of Auger core 4 in Table 7). The density of roots in the underlying muds seems to be higher than the overlying sands, though also appears to decrease with depth (this is also reflected in Table 7).

Auger core	Depth (m) (downhole)	Sand weight% loss on ignition	Lithology	Interpretation
4	0.52-0.62	2.54	Muddy sand	Mouth Bar
4	0.75-0.85	0.75	Muddy sand	Mouth Bar
4	2.28-2.38	2.66	Sandy mud	Lagoonal mud
4	3.00-3.10	1.75	Sandy mud	Lagoonal mud
3	0.00-0.12	8.86	Sandy mud	Mangrove swamp
3	4.66-4.80	5.27	Sandy mud	Mangrove swamp
3	5.50-5.60	4.59	Sandy mud	Mangrove swamp

Table 7 **Description and interpretation of sediment samples from auger holes 3 (Port Tudor) and 4 (Port Reitz)**

The interpretation of the distributary channel mouth bars as such is supported by their position on the seaward side of the distributary channels entering the lagoons, and their apparent lack of internal structure. The bars are interpreted to have formed by dumping of sand-grade sediment at the mouths of the channels by rapid deceleration of waters as they entered the lagoon during periods of high discharge.

Figure 15 **(Overleaf). Cross section across the Holocene sequence of Port Reitz based on gravity cores (G) and auger cores (A). Details of the cores are shown below the main section. For line of section see Figure 1.**


WEST
EAST
Central channel through mouth bar complex
LAT
5
10
15
G37
G35
A4
G39
G40
G30
Muddy sands
Rootlets from vegetation on Holocene transgressive surface
Sandy muds
Channel erodes into Jurassic shales off-section
Jurassic shales
m
0
0.2
0.4
0.6
0.8
3.10
0
km
2
Medium sand
Fine sand
Sandy mud
Mud
Shelly debris
Rootlets
PERIPHERAL LAGOON
MOUTH BAR COMPLEX
MAIN LAGOON PORT REITZ

It is probable that the since relative sea-level stabilised within the Holocene (see Section 4.5) lack of accommodation space towards the peripheries of the lagoon caused the mouth bar complexes to prograde seawards over older lagoonal muds. This is reflected, not only by coarsening-upwards of cores of the mouth bars themselves, but also by muds within the main body of the lagoons of Port Tudor and Port Reitz, as is illustrated in the western part of Port Reitz in Figure 15.

Given the above interpretation, the existence of the peripheral lagoon, on the landward side of the mouth bars, at the western end of Port Reitz requires some explanation. It may be expected that when sediment supply exceeds accommodation space in a depositional system, all bathymetric depressions in the proximity of the sediment supply, such as the peripheral lagoon in Port Reitz, would be infilled prior to seawards progradation of the system. It would appear then, that in this case the peripheral lagoon developed after the progradation of the mouth bar complex into the central part of Port Reitz. As an explanation for this, it is suggested that the peripheral lagoon has been caused by channel switching within the mouth bar complex, and that the distributary channel of the Mwachi previously occupied the position of the present position of the peripheral lagoon at the western most limit of Port Reitz. The present channel probably developed as a lateral tidal channel and eventually captured the Mwachi, as a short-cut. This explains the existence of the right-angle bend of the Mwachi channel on the western side of the main sand bank complex of Port Reitz, as well as the steep-sided (?oversteepened) margin of the western end of Port Reitz that has the appearance of having been cut in the relatively recent past by a channel. The evidence for on-going rapid morphological change in the sand bank complex, including channel switching, is supported by the changing distribution of intertidal areas as depicted on various versions of Admiralty and Kenya Survey maps.

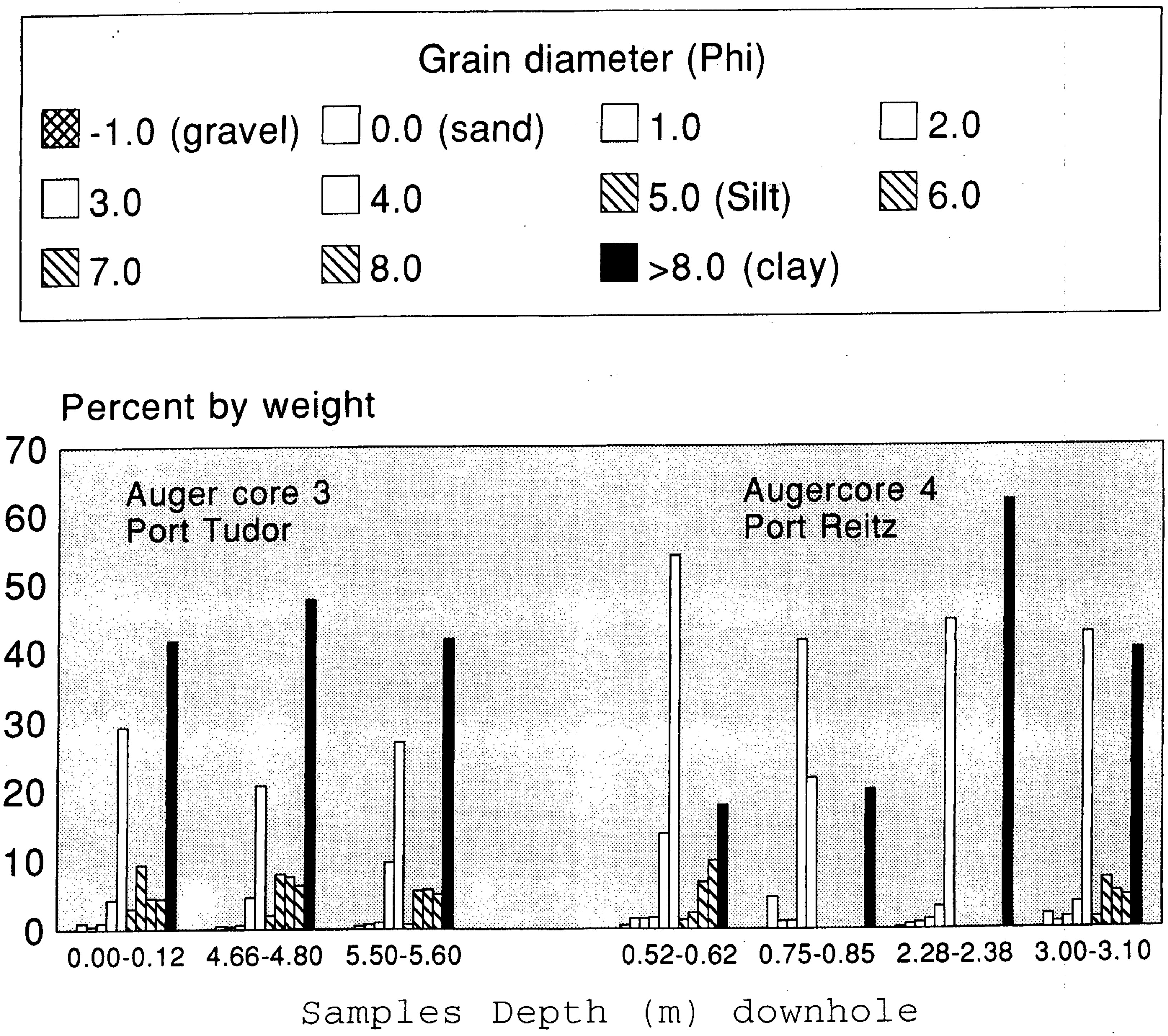
Several of the distributary channel mouth bars are orientated parallel to the main lagoonal channel where they are proximal to it, because of redistribution of sands by tidal currents in periods of lower river discharge. Such processes are suggested by the growth of a (thickly vegetated) spit of sand from northwest to southeast across the mouth of Junda Creek (Figure 1); the growth of this spit was facilitated by the residual ebb-tidal current in the main channel of Port Tudor. The sandy muds underneath the spit were sampled in an auger hole (3) on its lagoon side, and are typical of sandy muds of the mangrove swamps, being pale grey (N4) in hue, well-mixed, and having an organic content decreasing with depth (Figure 16, Table 7)

The **main lagoon** (channel flanks) are floored by gravelly sandy muds and sandy muds. The sand and mud fractions of these generally coarsen slightly upwards, though the gravel component, consisting almost exclusively of modern or Pleistocene carbonate detritus, is more evenly distributed vertically. Shelly fragments also form most of the medium- to coarse-grained fraction of the sediments. The mean grain-size of sediments appears to decrease with distance from the central channel of the lagoons. This is illustrated by grab samples 21 and 37, which were taken from distal and proximal sites respectively relative to the central channel in Port Tudor (Figures 1 and 12). Muds towards the margins of the lagoons, particularly near Makupa causeway in Port Tudor, are dark grey in hue and have a "soupy" character. The few measurements made of organic content in the lagoon sandy muds show no clear distribution pattern. The muds, dark grey in colour, locally show crude bedding, though contacts are gradational; no sharply defined laminae have been noted.

The sediment samples taken from the **marginal embayments** all are characterised by homogenous dark grey gravelly sandy mud which display no stratification or lamination. In the case of samples taken from Liwatini and Mbaraki creeks, this may be due to churning of sediments by ships anchoring. As over most of the lagoons, the cores taken appear to increase in sand content upwards.

The **lagoon channel** is floored by sediments ranging from dark sandy muds to gravels. The sandy muds and gravelly sandy muds probably represent older (Holocene) sediments that have been incised by the channel (where the Port Reitz lagoon channel traverses the distributary channel mouth bars in Figures 11 and 15).

Figure 16 **(Overleaf). Particle size distributions of samples taken from Auger core 3 (mangrove swamp) and Auger core 4 (mouth bar [top 2 samples] and main lagoon). See Figure 1 for location of Auger holes and Figure 12 for a description of Phi classes.**


Grain diameter (Phi)
▩ -1.0 (gravel)
☐ 0.0 (sand)
☐ 1.0
☐ 2.0
☐ 3.0
☐ 4.0
▨ 5.0 (Silt)
▨ 6.0
▨ 7.0
▨ 8.0
■ >8.0 (clay)
Percent by weight
70
60
50
40
30
20
10
0
Auger core 3
Port Tudor
Augercore 4
Port Reitz
0.00-0.12
4.66-4.80
5.50-5.60
0.52-0.62
0.75-0.85
2.28-2.38
3.00-3.10
Samples Depth (m) downhole

Locally, where gravels occur on the lagoon channel floor, it appears that the channel has cut through the Holocene estuarine fill into Jurassic rock; evidence from the lagoons and confined-channel suggest that the gravels are basal lag deposits consisting of fragments of shale. It is notable that the only gravity core (39) in the floor of either of the lagoon channels to contain roots was one occurring in the vicinity of such gravels in Port Reitz (Figures1 and 15); the roots may be the remains of vegetation that first colonised the transgressive surface of the creek earlier in the Holocene (see Section 4.5). Most sands flooring the channels were probably transported into them as bedload during periods of high discharge; the clays and silts within these have largely been winnowed away. However, it is notable that sand bodies on the channel floor appear to be most common in the vicinity of the entrances to the distributary channels. Such sand bodies may be considered to be low discharge mouth bars, which would suggest that relatively little sand is transported into the lagoon channel from the distributary channels during such periods. The limited transport capacity of the lagoon channel during periods of low discharge would also appear to be supported by the occurrence of fluid muds in the centre of the channel in Port Tudor in several gravity cores (8, 20 and 29, Figure 1) and the predominance of muddy sediments within them as a whole.

The **upper confined-channel** in both creek systems is dominated by gravelly sandy muds and that of Port Mombasa, almost exclusively so. As in the lagoon channels, sands and shale-gravel lags occur locally, and coincide with the main tidal stream indicated by drogue studies (Norconsult 1975), and beaches (not depicted in Figure 11). Where sampled, the gravels consist, almost totally, of either shale or shell detritus. The sands are a mixture of lithic and resistate grains with a notable carbonate fraction (reflected by a 3-8% CaO content: Williams et al. 1996 [a]), probably derived mainly from the Pleistocene limestones. The predominance of muddy sediments in the upper confined-channels suggests that average tidal currents are insufficient to mobilise the sediment, thus it would appear that most sediment transport occurs infrequently, probably during high discharge events.

The few samples of gravelly sandy mud that have been taken, for instance grab sample 36 (Figures 1 and 14), suggest that the muddiest sediments occur within the probable tidal scour cauldrons. These sediments have a lot of sand-grade plant material; the loss of weight on ignition of grab sample 36 was 10.78 weight per cent.

The **lower confined-channels** are filled mainly by sand, though sandy muds and gravelly sandy muds occur on the channel margins. The sand is mostly fine- to medium-grained and well-sorted. Compositionally it is distinctive, largely being composed of resistates (quartz and feldspar grains), as well as very characteristic resistate-aggregate grains. The latter, which have not been recognised elsewhere in the creek systems, are aggregates of quartz and feldspar that have a weak calcareous cement; they bear no similarity to the lithic aggregate grains found in the distributary channels feeding Port Tudor and Port Reitz (grains of which also have been recognised here). Another large component of the sand consists of grains of coralline algae, unrecorded elsewhere in the creek systems. This component accounts for the relatively high CaO levels of sediments (>8%) recorded in the lower confined channels by Williams et al. (1996[a]).

The sands identified on the side-scan sonar records of Port Kilindini were scrutinised for bedforms, but these are rare. Straight-crested ripples occur in Port Kilindini, their crests lying orthogonally to the confined channel and the direction of rectilinear currents identified by the Admiralty and drogue studies. No sand waves have been identified, despite the fact that such bedforms would be expected to start forming in currents of between 0.7-0.8m/s in water depths between 20 and 60m water depth (Rubin and McCulloch 1980), conditions which undoubtedly occur in Port Kilindini according to current measurements (Figure 9). The apparent absence of such bedforms on the side-scan sonar records is not a function of poor record quality; many other features such as buoy chains, anchor drag marks and dredging marks are clearly discernible on the records. The preservation of such 'anthropogenic' features adds further weight to the argument that sand transport in the creek systems is negligible, or very spasmodic.

The sand which blankets the floor of the lower confined-channels is clearly derived from two sources. Much of it, consisting mostly of coralline algae, has been transported into the creeks from the lagoons behind the modern reef and coast to the north and south of Mombasa. Most is likely to be carried when ebb tides are weakest and when the waves are most powerful; probably during neap tides in August and September (see Section 2.4). The considerable component of sand comprising resistate grains and grain aggregates is likely to be derived from the catchments feeding the creek systems as no sand sources of this character have been recognised along the coast. The partially cemented nature of the resistate aggregates suggests that resistates deposited in the confined-channel have been resident there for some time. They may have been deposited in the mid-Holocene, possibly as part of an ebb-tidal delta which has since lost its morphological character (Section 4.5).

It is likely that resistate rich sediments, such as those identified in the lower confined-channel, in the **open sea** only occur in the entrance to the creek systems, immediately off Mombasa. However, even here they are probably swamped volumetrically by carbonate sands, composed largely of corraline algae, but also containing significant quantities of foraminifera, especially nummulitic taxa. These carbonate sands are mostly coarse-grained, well sorted and in the lagoons separating the modern reef and the wave-cut platforms comprise 100% of the sediment (e.g. grab sample 41 in Figures 13 and 14). These sands are indigenous, having been generated behind the modern reef. Chemically, their high carbonate content is reflected by high CaO and only trace concentrations of SiO_2 and Al_2O_3 (Williams et al. 1996[a]).

4.4: Morphodynamics of the creek systems

The sediment distributions described strongly suggest that sediments from the fluvial distributaries move through the creek systems to the sea, whilst marine-derived sediments generally do not move landward of the outermost (lower confined-channel) parts of creek systems. This is illustrated by the samples taken in the transect from one of the distributary channels to the open sea in Port Tudor (Figure 13). Grain types typical of the distributary channels (such as lithoclasts) are found throughout the system, but grains derived from the open sea (e.g. corals, coralline algae) extend landwards only as far as the lower confined-channel. This trend it so be expected as the net long-term movement of sediments in any tidal channel system connecting a coastal basin (such as the lagoons described here) and the sea will be largely a function of the ebb and flood velocity and discharge in the system. The tidal measurements of Norconsult (1975) and Nguli (1994) clearly indicate that, in the creek systems of Mombasa, the ebb currents are stronger than the flood currents. As ebb-dominant systems have shorter, higher velocity, ebbs they tend to flush bed-load sediment seaward (conversely, flood-dominant estuaries have shorter duration, higher velocity floods, and tend to fill their channels with coarse sediment).

Such ebb-dominance is caused by the effect of the hypsometry of the creek system on the propagation of the tidal wave. As the latter is depth-dependant, the hypsometry affects the overall tidal characteristics (time lag, phase lag, range, asymmetry) and direction of net sediment transport (Boon and Byrne 1981, Dronkers 1986, Friedrichs and Aubrey 1988, Lessa and Masselink 1995). The shape of the tidal wave changes as it decelerates whilst entering the mangrove swamps and at high water, water is still flowing into the creek system to raise the water levels upstream. This results in high water slack current being delayed after high water and low water slack being similarly delayed after low water. To ensure that the accumulated water is removed, the peak velocity of the ebb is increased, and that of the flood tide decreased (Dyer 1986). Several researchers investigating the geometry and distortion of the vertical tide (Aubrey and Speer 1985, Friedrich and Aubrey 1988, Lessa and Masselink 1995) have shown that ebb-dominance occurs when intertidal storage is large, as is the case with the Mombasa creek systems. Importantly, the flushing of ebb-dominant systems inhibits the long-term build-up of sediments within them. Consequently ebb-dominant systems may have more stable geometries than flood dominant systems (Speer and Aubrey 1985, Aubrey 1986).

4.5: Evolution of the creek systems

Although gross seaward transport of sediments has been established, the timing of the transport processes is poorly understood. Many lines of evidence suggest that bedload transport, at least, has been very limited in the period preceding the recent surveys. For instance, the muds in the distributary channels, the lagoon channels, the confined-channels (including the tidal scour cauldrons) and the preservation of 'anthropogenic' features in the confined-channels, would all be removed during a high energy event. In the creek systems such events must equate with high discharge events, caused by heavy rainfall during short periods, probably towards the start of the wet seasons. How frequently such events occur is unclear. Whether the channel muds get flushed out of the system, and sands re-mobilised with each wet season, or annually is not known, but the density of the muds, and the variety of 'anthropogenic' features in the sands would appear to argue against this. Clearly it is important to know more about the periodicity of sediment flushing if we are to understand better the residence time of contaminanted sediments within the creek systems.

Some features of the creek systems, including the partially-cemented ebb-tidal delta in Port Mombasa, and the extensive mouth bar complexes in Port Tudor and Port Reitz, suggest that much larger fluxes of sandy sediments must have occurred in the creek in the past. Given the lack of evidence for transport of great volumes of sand today (in fact, as already discussed, the existence of the peripheral lagoon may suggest that the mouth bar complexes have been recently subject to erosion), when did the sediment fluxes responsible for these sand bodies occur? The problem may be partially addressed by referring to the likely post-glacial sedimentation history of the area.

The rise in sea-level, following the Weichselian glaciation, from over 100m below MSL, was not gradual, but stepped (because of periodic ice-sheet collapse) as shown by Blanchon and Shaw (1985). Their work demonstrated that coral reefs which developed during periods of relative sea-level stability, were drowned during periods of rapid sea level rise. A similar scenario may be expected on the continental slope off

Mombasa, indeed slope-parallel ridges may be identified on the bathymetric charts that may equate with earlier Holocene reef development. Global sea level curves (including Blanchon and Shaw's) from tectonically stable areas outside the limits of glacial influence (see Pirazzoli 1991) would suggest that marine waters first inundated the confined channels of the Mombasa creek systems about 9000 years ago, their level remaining relatively stable, probably at about 18m below chart datum, until about 7500 years ago. It is during this period that it is most likely that the tidal scour cauldrons in the confined channels began to be cut, as most bathymetric ridges separating paired cauldrons have surfaces at about 20m below chart datum. The shallow waters of the confined channels at that time would have had high tidal velocities with considerable power, not only to erode, but also to carry sediments trapped in newly flooded valley systems on the Pleistocene surface out of the creek system. The fate of these sediments is uncertain, but it may be that these are the partially-cemented sands which occur at the seaward end of the confined channels (as found in Port Mombasa) that probably formed as ebb-tidal deltas.

From about 7500 years sea level rose rapidly. Coastal vegetation (represented by rootlets at the base of the Holocene sequence; Figure 15) would have been rapidly inundated during the transgression, and swamped by fast-accumulating lagoonal muds. By about 6000 years ago the entire creek systems are likely to have been inundated by marine waters.

Subsequent stabilising sea levels would have decreased accommodation space for sedimentation in the lagoons, and started the progradation of the distributary channel mouth-bars bar complexes over the lagoonal muds (Figure 15). The mouth bar complexes in Port Reitz and Port Tudor are, however, too large to have been created by such stabilisation alone, as the flux of sediment during periods of sea-level stability are too low (as may be seen today). It is more likely that the progradation resulted also from a period of high sediment flux.

The period of high sediment flux is tentatively attributed to a mid-Holocene sea-level *fall*, in which the supply of sediments to the creek systems would have been increased by rejuvenation of the drainage systems. This setting is supported by the incised nature of the lagoon channels in Port Reitz and Port Tudor which have both cut through the distributary channel mouth bar complexes into older Holocene sediments and locally into Jurassic rocks.

When did this sea-level fall occur? Globally, sea-level reached a high between 5000 and 6000 years ago (see review by Pirazzoli 1991). Jaritz et al. (1977) suggest that sea level on the coast of Mozambique during this period reached up to 3.0m above MSL. A distinct notch at about this height in the cliff behind the present day (and ?Pleistocene) wave-cut platform at Nyali may have been cut at this time. On the basis of the sea-level curve of Jaritz et al. (1977), the fall which accounts for the growth of the ebb tidal delta and distributary channel mouth bars occurred after this, probably between 5000 and 2000 years ago.

The progradation of the distributary channel mouth bar complex now appears to have ceased, or be limited, today, indeed the component sediments are mostly being eroded by channels, or being entrained by tidal currents. (The main processes affecting sediment redistribution are tidal winnowing, and shifting of intertidal sediments on bars or beaches.) The paucity of sand in several of the rock-floored tidal scour cauldrons would also suggest that the period of high sand flux has ended; any sands resident in the scour cauldrons from this period having been removed by (?sporadic) high energy events since then.

4.6: Residence of sediment-hosted contaminants

Although levels of pollution in the Mombasa creek systems are presently low (Williams et al. 1996[a]), it is useful to try and predict which intra-creek environmental zones are most liable to store pollutants from contamination events in the future. From our understanding of the morphology and evolution of the creek systems (above) it is possible to make some predictions about which zones will be sinks of contaminated sediment in the long-term, and which zones will have the highest uptake of contaminants by sediments.

Some parts of the creek systems have probably reached a dynamic equilibrium with respect to present day sea-level. The long-term balance (over several years) between deposition and erosion in the mangrove swamps, distributary channels, distributary channel mouth bars, lagoon channels, and confined-channels has probably been acheived. Accommodation space for sedimentation in these zones has been fully utilised and may only be increased only by compaction (very slowly) or by a rise in sea-level (more rapidly). Sediment which accumulates within these on a short-term basis (for instance during the dry season) is likely to become eroded during high energy events (such as higher discharge in the wet season).

Other areas, however, including the peripheral lagoon, main lagoon (channel flanks), and the marginal embayments probably have capacity for sediment storage. These are generally removed from the areas of strongest tidal currents, and so are subject to lesser amounts of erosion; they are liable to be storage areas, or sinks for contaminated sediments in the future. Some zones, such as the peripheral lagoon, Makupa Creek, and the main lagoon in Port Tudor (especially near Makupa Causeway) are liable to have higher rates of sedimentation either because they are fed directly by distributary channels, or because they occur in (man-made) 'backwaters'. (No sediments within these areas have been dated, so it is not possible to calculate rates of sedimentation.) Accumulation of contaminants in such areas is also likely to be higher than average (on a long-term basis) because they are liable to contain a greater proportion of clays, onto which pollutants are preferentially adsorbed.

Whilst the mangrove swamps and mouth bars may not be areas in which sediments may accrete most rapidly, their near-surface sediments (particularly the uppermost 0.5 m) are particularly liable to pollution. There are three reasons for this. Firstly, as noted in Section 3, the residence time of (contaminated) waters is likely to be greatest within these zones, because of entrapment by roots. Secondly, the flocculation of clays (onto which contaminants get adsorbed) is likely to be greatest in these zones because the flux of Fe and dissolved humic organic matter in terrestrial runoff is highest in these areas (Williams et al. 1996 [a]). Thirdly, and perhaps most importantly, these zones are particularly susceptible to extensive bioturbation (see below). Although sediments throughout the creek systems are heavily bioturbated (causing destruction of most primary sedimentary features), active bioturbation is most extensive, and deepest, under the mangrove canopy. In similar intertidal environments in Thailand soldier crabs, such as those that frequent the intertidal areas in the Mombasa creek systems) burrow to an average depth of 8cm, and, in conjunction with wave action, turn over sediment at the rate of 0.5m^3 per year (Bradshaw 1996).

Given the likely infrequency of high energy events that may flush muds out of the creek systems, all of the intra-creek zones may be susceptible to short-term build-ups of contaminants in surficial sediments. These contaminants are also likely to be incorporated into sediments below the sediment water interface by (very active) burrowing animals in all zones. These sediments are likely to escape erosion, even during high-energy events. The extent of bioturbation, vertically, in sediment cores (almost total), and areally over the intra-creek zones, would suggest that bioturbation affects all parts of the creek systems, especially in the vicinity of the lagoons; consequently it is likely that sub-surface patterns of sediment contamination will quickly reflect distributions at the sediment-water interface. Thus *all* zones of the creek systems should be considered as potential contaminant sinks. A detailed knowledge of the rates at which contaminants in surficial sediments become incorporated into the sub-surface (which are likely to greatly exceed those of erosion during high-energy events) of the different environmental zones of the creek systems is thus essential in understanding the storage of sediment-hosted contaminants of the systems. Future research into bioturbation rates is thus very important in planning contaminant amelioration programmes.

5: CONCLUSIONS AND RECOMMENDATIONS

5.1: Hydrodynamics: conclusions

1 The *average* residence time of dissolved and suspended contaminants in Port Tudor or Port Reitz, taking all assumptions in modelling into consideration, is likely to be less than a week. This time will be shorter (probably less than 3 days) for any contaminant in the lagoon channel, and considerably longer (over 2 weeks) for contaminants within the mangrove swamps.

2 Equivalent residence times in ports Mombasa and Kilindini are likely to be less than 2 days, and will vary little between different parts of these confined-channels.

3 During spring tides residence times are likely to be much less than these, except in the mangrove swamps where contaminants may become trapped. During neap tides average residence times will be longer; inundation of the mangrove swamps during such periods is, however, likely to be minimal.

4 During the wet season residence times may be considerably reduced, because of higher discharges.

5.2: Sediment dynamics: conclusions

1 The sedimentary analysis suggests that the distribution of the sediment within the creek systems reflects their ebb dominance.

2 The sediment flux within the creek systems is extremely periodic. Large bedload transport events are very infrequent (?most occurring only during high discharge events). In between high energy events sedimentation from the suspended load takes place. This is suggested by the presence of fluid muds in

the distributary channel, the lagoon channel and the upper confined channel, and the preservation of man-made features in the sands on the floor of the Lower confined-channel. Most contaminants adsorbed by muds in the creek systems will reside within the systems between high discharge events.

3 The periodicity of high discharge events capable of transporting bedload is unknown, as is the rate of deposition of suspended sediment between such events.

4 The parts of the system that are likely to have above average long-term sedimentation rates are the channel flanks of the main lagoon, and the peripheral lagoon of Port Reitz. These zones are potential contaminated sediment sinks.

5 The rates of incorporation of contaminants in surficial sediments into the sub-surface by bioturbation is likely to far exceed the rate at which the surficial sediments are likely to get eroded by high-energy events. All parts of the creek systems may therefore be considered to be potential contaminant sinks.

5.3: Recommendations

1 More detailed estimates of water-borne contaminant residence times will be possible only after the basin hypsometry is surveyed in detail and after long time-series data covering salinity, discharge and evapo-transpiration become available.

2 A better understanding of the periodicity and nature of high-discharge events, of rates of sedimentation, and of bioturbation is essential for improved predictions of the storage of sediment-borne contaminants in the creek system to be made.

3 The longer residence times of waters, the greater susceptibility to flocculation of clays (onto which pollutants get adsorbed), and the rapid incorporation of surficial sediments into the sub-surface by bioturbation, in the mangrove swamps, distributary channels, distributary channel mouth bars, the lagoons and marginal embayments, make these zones particularly susceptible to pollution. Consequently the development of industrial activities in these zones, or areas which discharge directly into them, ought to be restricted, and carefully planned. High-contamination risk industries should be sited adjacent to the confined-channels, though discharge of heavy metals into the creek systems should be avoided at all times.

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