Western Indian Ocean J. Mar. Sci. Vol. 2, No. 1, pp. 1–13, 2003

The Fringing Reef Coasts of Eastern Africa—Present Processes in Their Long-term Context

Russell Arthurton
5A Church Lane, Grimston, Melton Mowbray, Leicestershire LE14 3BY, UK

Key words: Kenya, Tanzania, fringing reef, reef platform, sediment, sea-level change, climate variability, shoreline change, Late Pleistocene, Holocene

***Abstract*—**Sea-level changes through the Quaternary era have provided recurrent opportunities for the biosphere to significantly shape the coastal geomorphology of eastern Africa. Key agents in this shaping have been the calcium carbonate-fixing biota that have constructed the ocean-facing fringing reefs and produced the extensive backreef sediments that form the limestone platforms, cliffs and terraces that characterise these coasts. Today's reefs comprise tough, algal-clad intertidal bars composed largely of coral rubble derived from their ocean front. They provide protection from wave attack to the inshore platforms with their sediment veneers and their beach and beach plain sands that are susceptible to erosion. If the eastern African coasts are subjected to the rise of sea-level that is predicted at the global scale during the coming century, the protective role of the reef bars will be diminished if their upward growth fails to keep pace. Favourable ocean temperatures and restraint in the destructive human pressures impacting the reef ecosystems will facilitate such growth.

INTRODUCTION

Today's eastern coast of Africa from Egypt to northern Mozambique is a reef coast, mostly without a significant continental shelf. Where a shelf is present, as off much of the Tanzanian mainland, the coast is characterised by patch reefs. Where there is no shelf, as along most of Kenya's shore, fringing reefs predominate, facing the deep ocean and fronting lagoonal platforms. Reefs of either type tend to be absent around the outflows of major rivers.

The fringing reefs and platforms, and their associated coastal landforms including terraces, are the products of a complex Quaternary sequence of accretion and erosion of biogenic reef and backreef sediments composed of calcium carbonate, in response to sea-level variation. These processes have produced terraced, landward-tapering wedges of carbonate sediments (now mostly lithified as limestones). The wedges lap onto the much older rocks that form the continental margin and are probably more than 100 m thick at their steep ocean-facing edges (Fig. 6).

The constructive, or accretionary, elements of this limestone geomorphology reflect the capacity of certain animals and plants to extract calcium carbonate from seawater in the specific conditions of the coastal waters of the western Indian Ocean during the latter part (at least) of the Quaternary era (Arthurton, 2001). Of particular importance are the biota that have contributed to the building of rigid fringing reefs at the ocean margin, thriving in the turbulent conditions of breaking ocean swell. It is this defensive bulwark, produced by the upward accretion of these fringing reefs in response to episodic rises of sea-level, that has provided the backreef, lagoonal protection for the biogenic production of carbonate sediments as well as the accommodation necessary for the long-term

E-mail: r.arthurton@btinternet.com

accumulation of those sediments. Such backreef sediments, occurring now as limestones, constitute the bulk of the existing accretionary wedges. They are extensively exposed on intertidal platforms and in coastal cliff sections.

Carbonate-producing biota have been the key agents in the formation of the Quaternary coastal limestones (Crame, 1980). However, episodic marine erosion of these limestones (including their unlithified precursors), has led to the creation of, *inter alia*, the coastal platforms and notched cliffs that are so characteristic of these shores (Fig. 4). Huge volumes of former backreef sediments appear to have been removed by one or more episodes of such erosion.

This paper examines the contemporary coastal processes and ecosystems on the fringing reef coasts of Kenya and Tanzania in the context of their geological history. It considers particularly the pressures affecting those processes and ecosystems due to natural marine forcing and climate variability, and briefly reviews the impacts due to human activities. The paper incorporates field observations made by the author on the coasts of Kenya and Tanzania during the period 1991–2002.

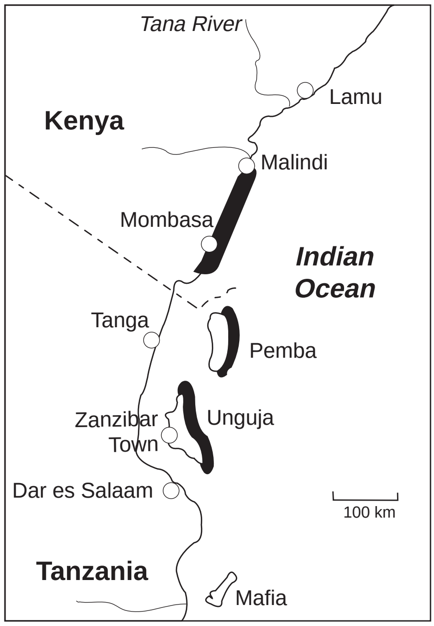

Fig. 1. Sketch-map of the coastal districts of Kenya and Tanzania with the described fringing reef coasts indicated in heavy line

THE FRINGING REEFS THROUGH QUATERNARY TIME

The prime fringing reefs of Kenya and Tanzania are situated on coasts that are exposed to the open ocean, and where there is an insignificant discharge of terrigenous sediment from the hinterland (Fig. 1). Such reefs dominate the Kenyan coast over some 150 km between Watamu and Chale Point (Fig. 1). In Tanzania, fringing reefs feature particularly on the eastern shores of the Zanzibar islands. The present-day geomorphology of these reef coasts has been inherited from a long history of carbonate sedimentary development and degradation at the land-ocean boundary.

In terms of crustal plate tectonics, the coasts of Kenya and Tanzania are part of a passive continental margin flanking the Indian oceanic crustal plate, which is moving very gradually eastwards in relation to the African continental plate. They have no significant promontories or gulfs over hundreds of kilometres. Only around the fragmented continental-crust islands of Zanzibar in Tanzania, is this morphological simplicity disrupted.

The stratigraphic record—the known sequence of preserved sedimentary rocks—provides evidence of the occurrence of major environmental changes affecting this continental margin over geological time. Such changes have affected the physical nature of the shoreline through the Quaternary era (the last two million years) at least, and particularly during the last part of that era—the Late Pleistocene and the Holocene (the last 10 ka). Fluctuations in global sea-level ranging over more than 100 m have been a particular feature of the Quaternary (e.g. Gallup et al., 1994), reflecting major cycles of warm and cold periods, including glacial episodes when much of the global water budget has been stored as continental ice cover.

The construction of the fringing reef coasts

Little is known of the earliest development of fringing reefs on the eastern African continental margin—neither the sea-levels at which they formed, nor the extent to which they have been subsequently destroyed by erosion. The onshore record of preserved reef-related rocks extends back no further than the Late Pleistocene, and knowledge of the chronology of reef development offshore to depths of more than a few metres below present mean sea-level (MSL) is sketchy at best. The record shows, however, that at least from the Late Pleistocene, Kenya's and Tanzania's ambient ocean waters have provided conditions favourable to the reef-building biota. The temperature and nutrient levels, and the generally low levels of land-sourced sediment delivery to the coastal waters, have all been conducive to reef growth. These conditions contrast with those of western Africa, where the coastal waters have been generally colder with a higher nutrient level and have tended to be dominated by land-sourced sediments discharged from rivers or blown by desert winds.

Despite the latency of reef growth in eastern Africa during this period, the actual periods of reef growth and backreef sediment accretion have depended on the complex relationship between sea-level and the contemporaneous coastal geomorphology. During lowstands, when levels were perhaps more than 100 m below the present position, it is conjectured that the shoreline terrain shelved steeply towards the ocean (the continental slope), giving a restricted intertidal to shallow sub-tidal zone with little or no scope for upward reef growth. As sea-level rose, however, the reefs would have grown from their vestigial foundations, with the creation of increasingly extensive accommodation for backreef sediments (Fig. 2).

During the highstands of the Late Pleistocene Interglacial periods, the fringing reefs appear to have grown to levels several metres above the present MSL along much of the ocean margin. The stratigraphic record, as evidenced in cliffs and terraces, shows that the sea lapped over the continental margin during these episodes, creating extensive, protected, intertidal and lagoonal tracts with coral mounds and prolific biogenic carbonate sediment accumulation (Fig. 2). On the Kenyan coast such sediments, now forming the lowest suite of limestone terraces (typically 5–10 m above MSL) and their adjoining cliffs and platforms, were considered by Crame (1980) to date from Pleistocene Stage 5e, about 120 ka B.P. (Before Present) and by Braithwaite (1984) from about 125 ka B.P.

Where the upward growth of fringing reef was not achieved in response to rising sea-level, a different type of coastal geomorphology has developed—the patch reef coast. Without the protection against wave energy afforded by the continuity of fringing reefs, extensive lagoonal conditions were seemingly never established when the sea overlapped the continental margin. Instead these coasts are characterised by inshore waters typically some 40 m deep (e.g. Tanzania's Zanzibar Channel) (Shaghude et al., 2002) with reefs forming irregular intertidal or shallow subtidal patches and fringes—some with cliffed, limestone terraces and associated platforms, as on Wasini Island in southern Kenya.

The erosional history of the fringing reef coasts

Coastal erosion due to wave energy has been a recurrent process on the fringing reef coasts of Kenya and Tanzania, but in different modes at different times, depending, like reef growth, upon the relationship between sea-level and shoreline morphology. As with the constructional phases of development, stratigraphic evidence of the erosional events affecting the foundations of what is now the ocean-facing reef apron is scarce.

During sea-level lowstands, with sea-levels as much as 100 m or more below present levels, it is conjectured that wave abrasion would have cut cliff-notches on the contemporaneous steeply shelving shores (Fig. 2). With subsequent rises in sea-level, such erosion may have recurred, though perhaps impeded by the upward growth of fringing reef, the latter reducing the wave energy impacting the shore. More significantly, it is likely that there would have been recurrent erosion of the live and dead coral and associated carbonate-skeletal biota on the ocean flank of the fringing reef, similar to that occurring on contemporary reefs during severe wave events.

By far the most widespread erosional event in the evolution of the present-day coastal geomorphology has been the removal of huge amounts of the Late Pleistocene mainly backreef limestones (or their precursive carbonate sediments) to form the coastal platforms and their adjoining cliffs that characterise these coasts (Figs

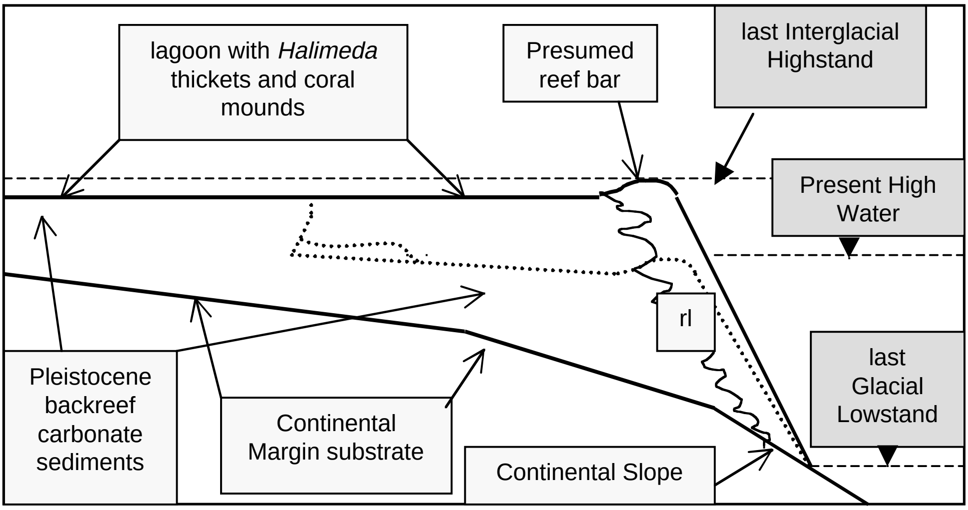

Fig. 2. Schematic section showing a reconstruction of the coastal geology and geomorphology during the last Interglacial sea-level highstand. Present geomorphological profile shown by dotted line. rl = reef limestone.

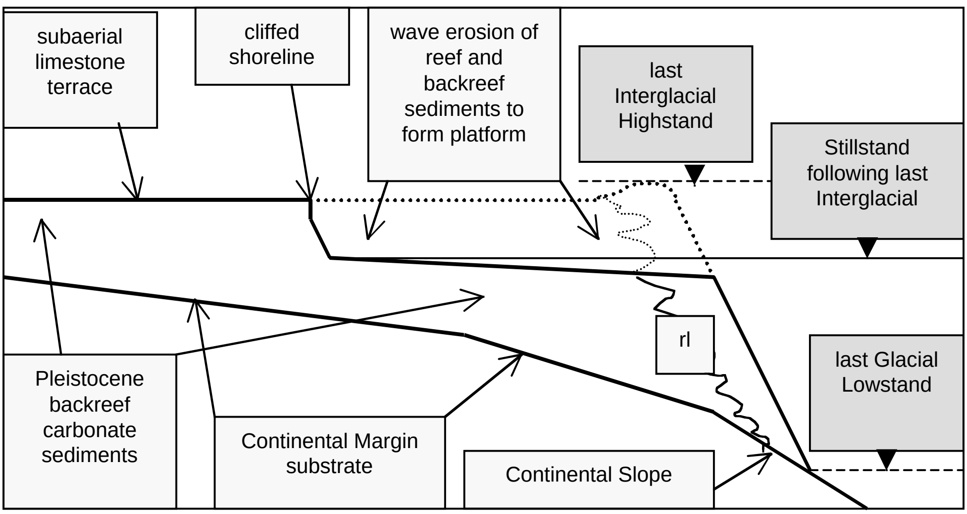

Fig. 3. Schematic section showing a reconstruction of the coastal geology and geomorphology following the erosion of the platforms. Geomorphological profile at the last Interglacial highstand shown by dotted line. rl = reef limestone

3 and 4). Evidence for the timing of this event is controversial. From the general coincidence of the platforms with today's intertidal zone, their surfaces might at first sight appear to be wave-cut erosion products of the Holocene transgression, formed, say, within the last 5–6 k years. However, the necessary rate of removal by wave erosion of so much well lithified limestone to form the present platforms since the mid-Holocene is not considered plausible. Contemporary erosion of the limestone cliffs at the shoreline by wave attack is scarcely perceptible, other than the formation of a characteristic undercut notch at about the high water swash line (Fig. 4).

An alternative explanation is that the erosion occurred during the Late Pleistocene before the carbonate sediments were fully lithified, largely protected from groundwater percolation by the maintenance of high sea-levels. In such circumstances, it is argued, erosion would have pre-dated the major fall in global sea-level following the last Interglacial period. It would have

Fig. 4. Late Pleistocene limestone cliffs and platform at Ras Nungwi at the northern end of Unguja island, Tanzania. View to North

occurred probably late in Pleistocene Stage 5e times, during an episode of stillstand that broadly coincided with today's sea-level (Arthurton et al., 1999; Fig. 3). The recognition in limestones exposed at the platform surface of polygonal patterning resembling desiccation shrinkage cracks (Arthurton et al., 1999, Fig. 3) lends weight to the suggestion that these sediments may have remained essentially unlithified until after the erosional event and subsequent sea-level fall.

During the low sea-level states of the last Glacial period, which peaked some 18 ka B.P. (Gallup et al., 1994), the platforms would have been sub-aerial landforms, their 'former fringing reef' fronts presenting steep banks more than 100 m high above the ocean shore during the lowstand. On the platforms, the shallow valleys that are now occupied by lagoon channels may have been formed during this sub-aerial phase.

The enigma of beach rocks

In many places on both the fringing and the patch reef coasts there are outcrops of older beach sediments—mostly medium- to coarse-grained, calcareous sandstones—which rest directly on platform limestone in contemporary high intertidal to supratidal positions. Some are strongly lithified while others are only weakly cemented and friable. These deposits may be pebbly and shelly, and may mimic the bedforms of their contemporary beach counterparts. They contrast markedly with modern beach sands in the coarseness of their component grains. In the vicinity of Zanzibar Town, on the western coast of Unguja, they are especially well lithified and jointed, and have been quarried for the construction of sea-walls. Near Vikutani, on the eastern coast of Pemba, similarly lithified beach rocks are banked against an undercut notch in a Pleistocene limestone cliff (Arthurton et al., 1999; Fig. 6). By contrast, the beach rocks that crop out on the platforms on the Nyali and Diani shores near Mombasa (Fig. 5), where they rest on the wave-cut surfaces of Late Pleistocene limestone, are only weakly lithified.

Fig. 5. Beach rock of probable Holocene age cropping out on the shore at Diani Beach, south of Mombasa, Kenya. View to North at Low Water. Copious freshwater springs issue on the landward side of this ridge.

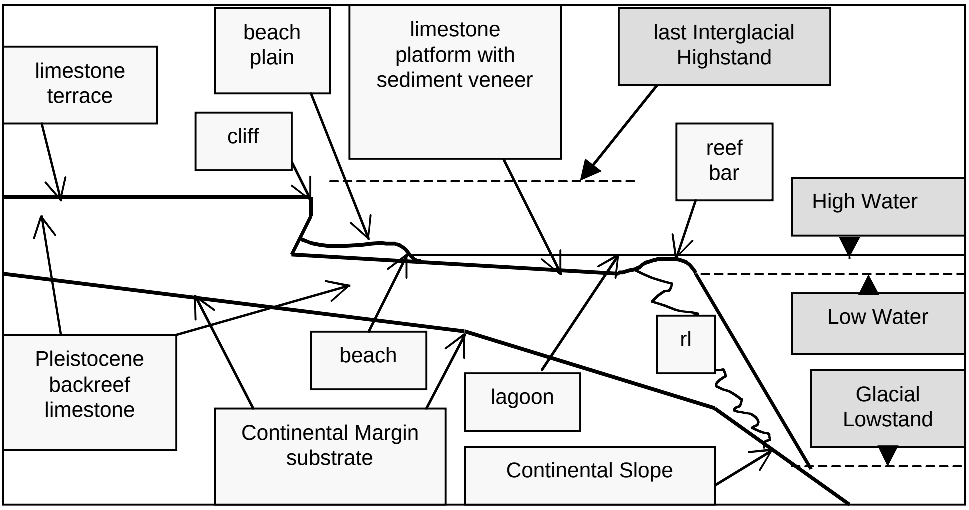

Fig. 6. Schematic section showing the present coastal geological and geomorphological components. Former highstand and lowstand sea-levels are indicated. rl = reef limestone.

The chronology of beach rock accumulation is unclear. The weakly lithified rocks of the Mombasa shores are here regarded as having formed soon after the Holocene marine transgression of the limestone platforms. The strongly lithified, fissured rocks, e.g. of western Unguja and eastern Pemba, and the Kunduchi shore north of Dar es Salaam, are more problematic. A Late Pleistocene, Stage 5e, age has been suggested (Arthurton et al., 1999)—relics of an episode of beach formation following the wave-cut erosion of the limestone platforms—but their history remains enigmatic. Whatever their ages, the compositions of all the beach rocks indicate that they accumulated in conditions, and from sources, quite different from those of their contemporary beach sediment counterparts.

CONTEMPORARY PROCESSES AND ECOSYSTEMS

The sea-level change event that set the stage for the present-day coastal processes and ecosystems was the rise of more than 100 m associated with the global warming that has occurred since the last Glacial maximum about 18 ka B.P. By the mid-Holocene (5–6 ka B.P.) the rising ocean waters would have overtopped the ocean-facing fringing reef aprons and flooded the (previously sub-aerial) limestone platforms. Conditions for a renaissance of fringing reef construction at the platform's rim would have been established (Fig. 6). Importantly at this time there would have been regional step increases both in the development of the reefal ecosystems and in the opportunities for intertidal colonisation.

The contemporary fringing reef coasts comprise a range of geomorphological components (Table 1; see Kairu & Nyandwi, 2000). Of key importance are the (inherited) limestone platforms and their ocean-fronting aprons. These foundations may be partially masked by veneers of sediment and, at the ocean front, reef growth. Typically the platforms range from a few hundred metres to more than three kilometres wide (Figs 4 and 8). They may be fully emergent at low spring tides, sloping gently seawards, or carry lagoons with coral gardens or lagoon channels up to several metres deep. The present-day tidal regime on these coasts has a maximum vertical excursion of about 4 m at spring tides.

Issues of fresh groundwater from the platform limestones have been noted at several localities in the upper intertidal zone, particularly in proximity to extensive coastal limestone terraces. At Diani, south of Mombasa, vigorous springs issue during mid- to low tidal states directly from the rock or penetrating a veneer of beach sand (Arthurton, 1998; Fig. 5).

Table 1. Components of eastern African fringing reefs and their relation to resources and susceptibility to physical change (adapted from Kairu & Nyandwi, 2000)

Geomorphological components	Resources (in addition to fisheries)	Susceptibility to physical change
Forereefs and reef aprons	Reef ecosystem, eco-tourism	Dynamite fishing, bleaching, pollution and siltation affecting coral growth, storm damage
Reef bars	Reef ecosystem and coastal defence	Tourism-related damage, sea-level rise
Backreef lagoons	Reef ecosystem	Tourism-related damage, sea-level rise
Backreef platforms with sediment veneer	*Halimeda* thickets, seagrass meadows, seaweed culture	Sediments may be ephemeral, especially in landward parts; pollution, eutrophication
Backreef rock platforms		Resistant to erosion
Beach-rocks	Coastal defence	May be resistant to erosion
Sand beaches	Tourism, recreation, coastal defence	Shoreface erosion and accretion
Sand dunes	Coastal defence, groundwater	Beach-head erosion and accretion, aeolian deflation and accretion
Beach plains	Agriculture, settlements, tourism	Beach-head erosion and accretion
Rock cliffs	Coastal defence	Resistant except where soft or weathered
Hinterland, limestone terraces	Groundwater, tourism infrastructure	Resistant except where soft or weathered

The reef bars

Typically the fringing reefs form bars a metre or so above the general level of the adjoining part of the platform. During mid- to high tidal states the bulk of water transfer between ocean and platform takes place across the (then submerged) bar. At low to mid-tidal states, with the bar emergent, the platforms may flood and flush via lagoon channels, flowing to and from the open ocean through low points (passes) in the reef. During neap tidal states the reef bar may remain submerged throughout the tidal cycle.

The reef bars are typically several hundred metres wide. Their surface is rather flat overall, though interrupted by pools and gullies (Fig. 7). They are composed of largely algal-bound carbonate sand and rubble, including fragmental coral and, locally, limestone blocks dislodged from the reef's ocean front by extreme wave impact. Debris is swept landwards onto the bars, where the ocean swell breaks during much of the tidal cycle. There, rubble and associated finer sediment becomes entrapped and enveloped by tough, algal growths (including coralline algae), thus raising the level of the bars (Arthurton, 2001). Some detrital carbonate material may be carried across the bars, making a contribution to the sediment veneer of the backreef platform. Hard coral growth occurs mostly on the submerged substrates on the ocean side of the bars (or, in the absence of a bar, on the platform's ocean front) and, to a small extent, in intra-bar pools.

The platform sediments

In addition to reef-derived rubble, the sediment veneers on the backreef platforms commonly include abundant lobate carbonate flakes, 3–4 mm across, produced from the withered thalli of the calcareous alga *Halimeda opuntia*, which thrives in low intertidal to shallow subtidal conditions (UNEP, 1998). Such flakes may form the dominant component, contributing to the substrate for low- to mid-intertidal seagrass meadows (Arthurton et al., 1999; Arthurton, 2001). Fossil *Halimeda* flakes are also reported as abundant in some of the Pleistocene limestone cliffs that bound the platforms (Crame, 1980). Other platform contributors to the carbonate sediment budget include foraminifera, a rich variety of shelled molluscs and hard corals that form scattered

Fig. 7. The reef bar at Low Water Spring tide off Nyali Beach, north of Mombasa, Kenya. View to North

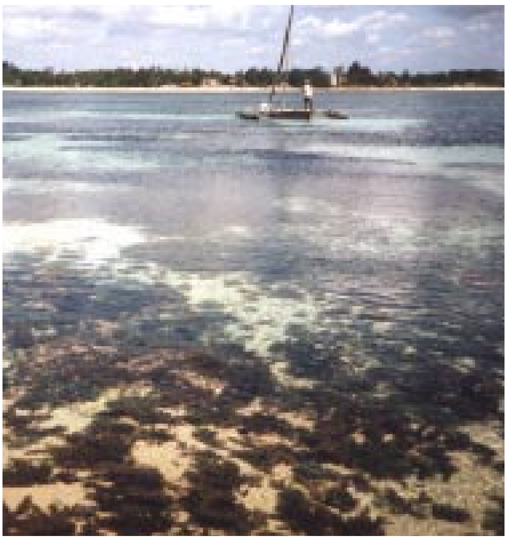

Fig. 8. The backreef platform near Nyali, north of Mombasa, Kenya. View from the reef bar towards the beach and low limestone cliffs at Low Water Spring tide

Fig. 9. Quartz beach sand rests on platform limestone at Tiwi Beach, south of Mombasa, Kenya. View to Southwest

mounds associated with *Halimeda* thickets, as seen, for example, on Diani Beach.

Beach deposits and associated intertidal sandbanks usually cover the landward parts of the limestone platforms (Fig. 9). In many places, e.g. southeastern Unguja, beach sands have prograded (seawards) from pockets in their backing cliffs to form extensive beach plains, 2–3 m above MSL with a storm-beach morphology of shore-parallel ridges and furrows. Volcanic pumice pebbles feature amongst the marine-derived flotsam washed by extreme waves onto the crests of the contemporary storm beaches. It is suggested that beach plain progradation may have occurred in response to a 1–1.5-m fall in sea-level during the mid- to late Holocene—evidence for a stepped or fluctuating fall of this magnitude in the late Holocene has been documented in the southern hemisphere (Baker & Haworth, 2000).

The beach sands are of two contrasting types, depending on their location. On mainland shores that receive sediment discharge from the hinterland, the sands consist predominately of fine-grained quartz (Fig. 9). On Zanzibar's islands, similar quartz sands feature on shores fed by surface streams, e.g. in the vicinity of Zanzibar Town in western Unguja (Shaghude et al., 2002). However, where surface discharge is distant or absent, the sands consist mostly of fine-grained calcium carbonate (Arthurton et al., 1999). Examples occur on the eastern shores of Pemba and Unguja where there is no surface drainage to the sea due to extensive coastal outcrops there of internally draining Pleistocene limestone (Mohamed & Betlem, 1996), also around patch-reef islands.

The beach sands, whether of quartz or carbonate, are naturally ephemeral deposits—subject to erosion, transportation and accretion by waves and, in the generally dry backshore environment, by wind (see Kairu & Nyandwi, 2000). Their morphology is altered to some extent by the passage of every tide, notably during the upper part of the tidal cycle, when ocean waves are translated across the lagoons. The higher the tidal level, the greater the susceptibility of beaches to the impact of ocean derived waves. The major changes occur during extreme wave and climatic surge events, especially when these coincide with spring tides. These tend to result in the drawdown of beach sand onto the platform, perhaps rendering the hinterland prone to erosion at the backshore. A return to less extreme wave conditions promotes the restoration of steeper beach profiles. The net accretion of beach sands results in the shoreline prograding over the platform. The long-term trends of shoreline change, both rates and directions, may be difficult to assess by short-term monitoring.

Reports of backshore erosion threatening coastal infrastructure on these coasts are common (Arthurton, 1992; IOC, 1994), but there are also instances of sites previously reported as suffering erosion that have since become sites of accretion (Arthurton et al., 1999). Reported instances of shoreline change commonly relate to situations where the hinterland is formed of a beach plain, the beach plain sands being particularly susceptible to backshore erosion. Beach plains are particularly favoured for hotel developments, thus investment in these situations may be particularly vulnerable to shoreline change.

Despite the continuing supply of carbonate sediment from the erosion of the reef front and from the productivity of the carbonate-fixing biota on the platform, the net accumulation of carbonate sediment on the platforms since the mid-Holocene transgression is somewhat insubstantial. Many inshore areas of the platform remain free of sediment, particularly in the vicinity of beach toes (Figs 4 and 9). Compared with the Late Pleistocene Interglacial episodes, when sea-levels were comparable and higher, the accommodation for backreef sediment accumulation on the contemporary platforms appears to be restricted. Some of the largest stored banks of carbonate sand are those that form the beach plains on the eastern sides of Zanzibar's islands, Pemba and Unguja. However, these are vulnerable to backshore erosion and their existence may be only short-term in nature.

PRESSURES AFFECTING PROCESSES AND ECOSYSTEMS

The fringing reef coasts are vulnerable to natural and human-related pressures in a complex biophysical relationship. As described above, they are products of the interplay of biological (reef growth and carbonate sediment production) and physical (sediment transport and erosion) processes. Any pressures that alter those processes may produce changes in the system.

From a coastal management perspective, there is a need to identify those pressures that are contributing, or likely to contribute, to significant impacts on the coastal environment and/or threaten the welfare of coastal communities. Two of the issues that are especially relevant to the fringing reef coasts are the health and biodiversity of the reef and platform habitats, and the incidence of shoreline change, especially coastal erosion. The pressures that bear on these issues include natural forces as well as human activities. A challenge for management is to recognise, on the one hand, which of those pressures might be reduced by an effective intervention strategy, and, on the other, which are beyond the capacity of management to control and thus require a policy of adaptation within the coastal planning process.

Natural pressures

Global average sea-level is predicted to rise by up to 0.88 m between 1990 and 2100 (with a central value of 0.48 m) as a result of global warming due to increasing levels of 'greenhouse gases' in the atmosphere (IPCC, 2001). If a change of this order occurs in the western Indian Ocean, it will have a progressive impact on these coasts. Although such a rise might be reduced to some extent by an immediate reduction in the global production of greenhouse gases, this is a pressure that is beyond the control of coastal managers. Thus, its potential impacts need to be addressed by adaptive planning measures including relocation and set-back policies.

The effects on the reef-related ecosystems are speculative. A fundamental question is whether the upward growth of the reef bars—the principal first line of sea defence—could keep pace with the predicted rate of sea-level rise. Assuming such a capability, there would be a prospect of increased accommodation for backreef sediment accumulation on the platforms. Any deepening of the waters over the platforms would favour the translation of ocean swell and lagoon-generated waves to the beaches, a condition that would be exacerbated if upward reef growth fails to keep pace with sea-level rise. Existing beach and beach plain deposits would become increasingly vulnerable to wave erosion.

Climatic variability and extreme climatic events at the global to local scale are uncontrollable pressures with two types of impact. A direct impact of temperature rise is the catastrophic effect of warmer ocean waters on coral health. The phenomenon of coral bleaching—the expulsion of the coral's symbiotic algae—has been widespread around the coasts of Kenya and Tanzania, a consequence of abnormally high sea surface temperatures in 1998 (Obura et al., 2000; UNEP, 2001). The long-term impact of such widespread coral death episodes on the continuity of the supply of detrital coral rubble to fringing reef bars and platforms is yet unclear. Additional stress on the health of the carbonate-fixing biota of the reefs and their platforms may arise over the long term from another consequence of global climate change—the increased levels of atmospheric carbon dioxide. The resulting acidification of ocean waters through increased dissolved CO_2 may impede biogenic calcification (Elderfield, 2002).

Climatic conditions are important in determining the nature of wave impacts responsible for the erosion of reefs and beaches, and sediment transport. The monsoon winds that prevail on these coasts, and their consequent wave climate, alternate seasonally between north-easterly and south-easterly, resulting in switches in the regimes of longshore sediment transport on some beaches (Arthurton, 1992). The balance between these opposing forces changes from year to year and may lead to situations of 'feast or famine' in respect of beach sands, giving protection or vulnerability to susceptible backshores. While extreme wave events are uncommon, their incidence is evident from the widespread distribution of reef-derived rubble on platforms such as at Kenyatta Beach, north of Mombasa.

Turbidity in coastal waters produced by high levels of suspended sediment discharged by rivers is another pressure of natural, often seasonal occurrence, usually related to monsoonal flooding. The health of the various reef-related, carbonate-producing biota is impaired by such turbidity. In the coastal zone turbidity and salinity vary both spatially and over time scales ranging from extreme event to geological. The variation is due largely to differences in the amounts of sediment discharged by rivers from the hinterland and in the delivery of freshwater either by surface drainage or through aquifers into the coastal waters. Thus some parts of the coast provide, and, geologically, have long provided, conditions more favourable to the support of the carbonate-fixing biota, and thus the construction of fringing reef coasts, than others.

Recurrent episodes of turbid sediment discharge from the Tana River's outlets into Ungwana Bay, between Malindi and Lamu, through the Quaternary are a likely cause of the absence of fringing reefs across almost the entire mouth of the bay—about 50 km (Fig. 1). Further south, sediment discharge from the Sabaki River periodically impinges upon the reefs of the Malindi Marine Park, and, over geological time, has probably been a major factor in determining the northern limit of the Mombasa fringing reef coast (Obura & McClanahan, 1994).

Human-related pressures

Human activities in the region's catchments and coastal zone increasingly impact on the health and biodiversity of the reef and platform habitats, and contribute to physical shoreline change. These include:

- industrial, agricultural and domestic discharges leading to the eutrophication and pollution of the coastal environment,
- physical interventions such as water impoundment and abstraction in catchments, sand mining and coastal engineering affecting the supply and transport of sediment both to and within the coastal zone, and
- the physical disruption of the ecosystem by insensitive fishery and recreational practices.

Much has been written about these human activities in the context of coastal management in Africa (e.g. Hatziolos, 1994; Coughanowr et al., 1995; UNEP, 1998; 2001). Unlike natural pressures, these human pressures are to some extent controllable by coastal and catchment management responses through legislation, regulation or incentive.

As described above, the reef bars form the key ocean defences for the fringing reef coasts. Given the forecast global average sea-level rise (see above), the long-term protection of the reef-front, sediment-producing biota (especially the hard corals) from degradation by pollution (both marine- and land-sourced) and eutrophication, as well as human-inflicted physical damage must be a management priority. Similar protection is also relevant to the platform ecosystems, so that the biogenic production of carbonate sediment—the substrate of the backreef seagrass nurseries—is maintained. Because of their mesotidal condition, the fringing platforms are well flushed, generally with little scope for a build-up of contaminants. However in Kenya, all the reefs outside the marine parks are considered to be degraded to some extent (UNEP, 1998). Industrial pollutants have been recorded on a platform in the vicinity of the Mombasa creeks (Rees et al., 1996). Because of the groundwater regime in the coastal limestones, there is potential for sewage-contaminated and swimming pool effluent discharge to the intertidal zone.

While essentially a natural process, the discharge of suspended sediment to the coastal sea may be aggravated or in some instances reduced by human agencies. Intensive agriculture in catchments leads to a higher run-off of sediment fines. Conversely, damming schemes impound sediments that would otherwise have discharged to the sea. The fringing reef coasts are mostly exclusive of river outflows, an exception being the northern end of the marine park at Malindi (Fig. 1).

The reduction in beach sediment budgets caused or compounded by human activities is an issue familiar to coastal managers (CIRIA, 1996). The maintenance of beach sands is of crucial importance where hinterlands are susceptible to backshore erosion, notably the beach plains. Besides their defensive role, these beach sands are key regional asset in tourism and recreation—a resource to be valued and conserved. Sand mining is a clear case for regulation. Another is the construction of engineered sea defences. There are many instances on these coasts where the loss of beach sand and consequent backshore erosion has been aggravated by hard coastal defence structures that reflect wave impacts rather than dissipating them (Kairu & Nyandwi, 2000).

CONCLUDING SUMMARY

- The fringing reef coasts of Kenya and Tanzania, comprising platforms with bars at their ocean margins, are modifications of a geomorphology created during the Pleistocene period by the extensive coastal accretion and partial erosion of calcium carbonate sediments occurring now as limestones.

- The reef bars are constructed largely of coral rubble derived from the ocean-front bound by a tough algal cladding. The platforms carry patchy veneers of similar rubble as well as carbonate sediment derived from the platform biota; they also carry beach and beach plain deposits.
- Beaches protected from the influx of terrigenous sediment consist of calcium carbonate sand; elsewhere they consist of quartz sand.
- The reef bars provide the primary defence for hinterlands susceptible to erosion from ocean-derived waves; their capacity for upward growth in response to predicted sea-level rise may depend upon the health of the rubble-supplying biota being maintained.
- Sea-level rise would promote the accumulation of carbonate sediments on the platform, though it would endanger susceptible shores, notably the sandy beach plains so favoured by hotel developers.
- Beach sand budgets are at the mercy of climatic variations, especially shifts in the balance of monsoonal sets. They are also vulnerable to human activities including sand mining and the construction of unsuitable sea defences.
- There is potential for contamination of the fringing reef ecosystems by industrial pollutants, domestic sewage and swimming pool effluents. Smothering by suspended sediments occurs at the local scale.

REFERENCES

Arthurton, R.S. (1992) Beach erosion: case studies on the East African coast. *In:* Proceedings of Bordomer 92, International convention on rational use of coastal zone. Intergovernmental Oceanographic Commission, Bordeaux. pp. 91-95.

Arthurton, R.S. (1998) The societal value of geoscience information in less developed countries —the coastal zone of eastern Africa. Technical Report WC/98/60. British Geological Survey, Keyworth. 17 pp.

Arthurton, R.S. (2001) Interaction of natural beach formation and degradation through human activity: implications for coastal zone management. *In:* Wittmer, H. & Hassan, Z.-E. (eds), Proceedings of the INCO-DEV International workshop on policy options for the sustainable use of coral reefs and associated ecosystems, Mombasa, Kenya, 19–22 June 2000. ACP-EU Fisheries Research Report No. 10, Brussels. pp. 115–120.

Arthurton, R.S., Brampton, A.H., Kaaya, C.Z. & Mohamed, S.K. (1999) Late Quaternary coastal stratigraphy on a platform-fringed tropical coast—a case study from Zanzibar, Tanzania. *J. Coastal Res.* **15:** 635–644.

Baker, R.G.V. & Haworth, R.J. (2000) Smooth or oscillating late Holocene sea-level curve? Evidence from the palaeo-zoology of fixed biological indicators in east Australia and beyond. *Mar. Geol.* **163:** 367–386.

Braithwaite, C.J.R. (1984) Depositional history of the late Pleistocene limestones of the Kenya coast. *J. Geol. Soc. Lond.* **141:** 685–699.

CIRIA (1996) Beach management manual. Report 153, 1996, CIRIA (London). 448 pp.

Coughanowr, C.A., Ngoile, M.N. & Linden, O. (1995) Coastal zone management in eastern Africa including the island states: A review of the issues and initiatives. *Ambio* **24:** 448–457.

Crame, J.A. (1980) Succession and diversity in the Pleistocene coral reefs of the Kenya coast. *Palaeontology* **23:** 1–37.

Elderfield, H. (2000) Carbonate mysteries. *Science,* **296:** 1618–1621.

Gallup, C.D., Edwards, R.L. & Johnson, R.G. (1994) The timing of high sea levels over the past 200,000 years. *Science* **263:** 796–800.

Hatziolos, M., Lundin, C.G. & Alm, A. (1994) (Second Edition 1996). Africa: a framework for integrated coastal zone management. The World Bank, Washington. 150 pp.

IOC (1994) *IOC-UNEP-WMO-SAREC* planning workshop on an integrated approach to coastal erosion, sea level changes and their impacts. Submitted Papers, 1. Coastal Erosion. IOC Workshop Report No. 96 – Supplement 1. UNESCO. 173 pp.

IPCC (2001) Climate change 2001: the scientific basis. Third assessment. Report of Working Group 1. IPCC, Geneva.

Kairu, K. & Nyandwi, N. (eds) (2000) *G*uidelines for the study of shoreline change in the western Indian Ocean region. IOC Manuals and Guides No. 40. UNESCO 2000 (English), vii + 55 pp.

Mohamed, S.K. & Betlem, J. (eds) (1996) Proceedings of the national workshop on coastal erosion. Zanzibar Environmental Study Series, 20. Commission for Lands and Environment, Zanzibar.

Obura, D. & McClanahan, T.R. (1994) Status of Malindi Marine Park—Study of the 1991 and 1992 Sabaki River sediment discharge on the Park's coral community. Unpublished report prepared for the Kenya Wildlife Service. Kenya Marine and Fisheries Research Institute and Kenya Fisheries Department. The Wildlife Conservation Society, Nairobi.

Obura, D., Suleiman, M., Motta, H. & Schleyer, M. (2000) Status of coral reefs in East Africa: Kenya, Mozambique, South Africa and Tanzania. *In:* Wilkinson, C. Status of coral reefs of the world: 2000. Australian Institute of Marine Science and Global Coral Reef Monitoring Network, Townsville. pp. 65–76.

Rees, J.G., Williams, T.M., Nguli, M.M., Kairu, K.K. & Yobe, A.C. (1996) Contaminant transport and storage in the estuarine creek systems of Mombasa, Kenya. Technical Report WC/96/42. British Geological Survey, Keyworth. 67 pp.

Shaghude, Y.W., Wannäs, K.O. & Mahongo, S.B. (2002) Biogenic assemblage and hydrodynamic settings of the tidally dominated reef platform sediments of the Zanzibar Channel. *Western Indian Ocean J. Mar. Sci.* **1:** 107–116.

UNEP (1998) *Eastern Africa Atlas of Coastal Resources, 1: Kenya*. UNEP, Nairobi. 119 pp.

UNEP (2001) *Eastern Africa Atlas of Coastal Resources – Tanzania.* UNEP, Nairobi. 111 pp.