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Late Quaternary Coastal Stratigraphy on a Platform-Fringed Tropical Coast—a Case Study from Zanzibar, Tanzania

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ABSTRACT

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The coasts of Zanzibar's islands, in common with those of the adjacent African mainland coast, are formed largely of Stage 5e Pleistocene limestones of back-reef facies. The limestones form typically undercut cliffs and associated wave-cut platforms, commonly more than 1km wide. Where not masked by the deposits of beach ridge plains, the platforms coincide with the contemporary intertidal zone. This coincidence might suggest that the platforms are mid-late Holocene products, formed since the post-late-Weichselian glacial sea level attained its current highstand position. However, the present extremely slow rates of limestone cliff recession due to marine erosion, together with the existence, at the landward margin of the platform, of well lithified beach rocks of lithologies markedly different to those of the contemporary beach sands, indicate that most of the platform erosion occurred pre-Holocene. A sea-level stillstand period, following the peak of the Stage 5e highstand, is suggested. The overwashing of a pre-existing platform as a consequence of Holocene sea-level rise would have significantly and abruptly increased the area of intertidal to shallow subtidal habitats and thus the potential for the increased production of calcium carbonate sediment derived from that biota. The impact on the platform environment of predicted sea-level rise over the next century would be to create an extensive shallow subtidal environment promoting the growth of the calcareous green alga, *Halimeda,* coral mounds and small patch reefs. The beach ridge plains would become increasingly vulnerable to erosion.

ADDITIONAL INDEX WORDS: *Climate change, shoreline change, sea level, wave-cut platform, coral reef, beach rock, beach ridge plain, longshore drift.*

INTRODUCTION

Beach erosion and consequent shoreline recession are matters of concern to the coastal communities of the eastern African mainland and its associated islands because of the threat that they pose to property, notably investment in tourism development. The coastal geomorphology of the islands of Zanzibar (Figure 1) is typical of the region. The shores of the two largest islands, Pemba and Unguja, are characterised by largely intertidal fringing platforms (Figure 2) commonly extending more than one kilometre, and locally as much as 3km, seawards from the shore. The fringing platforms are of considerable socio-economic importance, with large numbers of people involved in coir (coconut fibre) production, seaweed farming, shellfish gathering and fishing. They are also of great ecological value, supporting corals, turtles and wading birds. Hence, the platforms are prime assets for eco-tourism as well.

The edge of a platform forms a breaker zone for ocean swell at most stages of the tide, with the platform giving way, in places abruptly, to deep oceanic waters beyond. The platforms are defined to landward by rock cliffs up to about 10m, or by beach ridge plains 2–3m above mean high water (MHW) (Figures 2 and 7). Such plains provide attractive locations for tourism development. In sheltered embayments and creeks the platforms usually support mangrove. At the mouths of the more extensive creek systems, the platforms are incised by deep water channels. The surrounding waters have a tidal range during Spring Tides of some 4 metres. The region is affected by the Northeast Monsoon from December until March and for the remainder of the year the prevailing winds blow less strongly from a southerly quarter (ASE, 1987).

Concerns over beach erosion prompted the Department of Environment in Zanzibar to carry out a comprehensive survey of shoreline changes in recent years, based on field study and aerial photo interpretation (MOHAMED and BETLEM, 1996a). The present paper arises from a follow-up study of coastal erosion on Zanzibar's islands (MOHAMED and BETLEM, 1996b). The study was of a reconnaissance nature and did not include systematic monitoring and sediment sampling. The paper describes the stratigraphic evidence of past coastal change affecting the islands in geological, historical and contemporary perspectives, and, in particular, describes and interprets the geological context and geomorphology of the platforms and their associated shoreline types. It reviews

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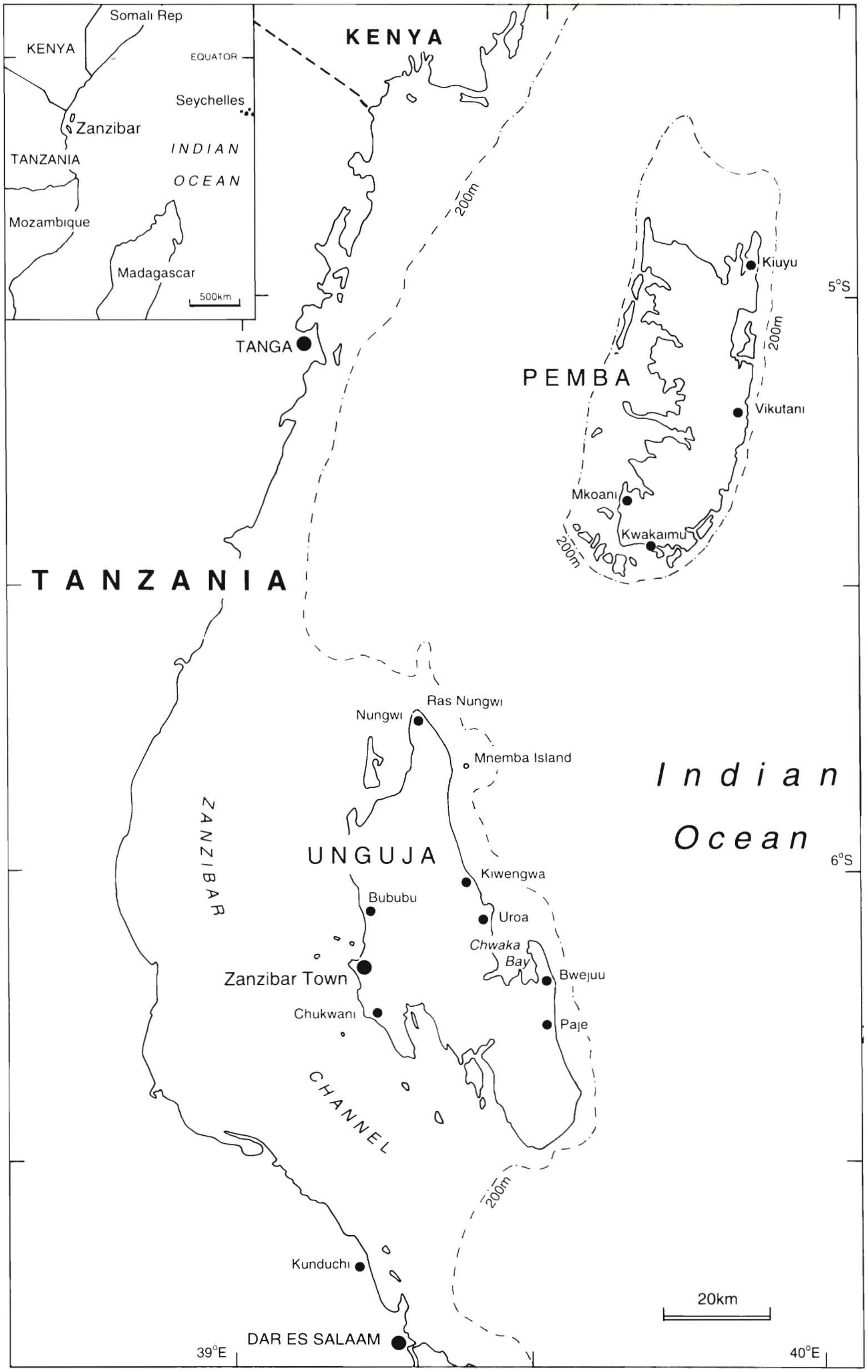

Figure 1. Zanzibar's main islands, Pemba and Unguja, and their regional setting. The 200m isobath is indicated.

Figure 2. Cliffs and platform cut in Pleistocene limestone, Ras Nungwi, Unguja.

the sources of sediment that contribute, and formerly contributed, to the beaches. Finally, the paper discusses the implications of climatic change on the coastal geomorphology in general and on the stability on the islands' beaches and vulnerable hinterland.

COASTAL GEOLOGY AND GEOMORPHOLOGY

Much of the coastal land of Zanzibar's main islands comprises coral-rich limestone of Pleistocene age. These are the Azanian Series of STOCKLEY (1928), informally referred to by that author as 'Coral Rag'. Stratigraphically analogous limestones on the adjacent Kenyan coast (Figure 1) were assigned by CRAME (1980) to a complex depositional event which took place during the last interglacial, *c.* 120ka Before Present (B.P.), a date compatible with the last interglacial highstand (Stage 5e) in the Caribbean (GALLUP *et al.,* 1994); and by BRAITHWAITE (1984) to depositional episodes *c.* 240ka and *c.* 125ka B.P. respectively, with sea levels up to 20m higher than at present. The limestone terrain has a karstic plateau form with sub-surface drainage. It supports only scrub vegetation and is generally sparsely populated. Elsewhere the coastal formations comprise older (Neogene), mainly siliciclastic, sedimentary rocks. These provide fertile land with a varied topography, are relatively densely populated and drained by surface streams.

The Pleistocene limestone forms cliffed shorelines, with cliffs typically 5–10m high and conspicuously and raggedly undercut (Figure 2) with a notch within 2–3m above the contemporary MHW. In places the cliffs are demonstrably relict features, defining the landward limits of beach sand plains (Figure 4). While much of the intertidal platform usually supports a cover of unconsolidated sediments that form the substrate of seagrass meadows, Pleistocene limestone is exposed, particularly on the inshore parts of the platform adjoining the limestone cliffs, where freshwater springs or seepages are common. Where the limestone is exposed on the platform, it often contains potholes to depths of a metre or so, or partially obscured by sediment and plant growth, and represented by polygonally patterned ridges (Figure 3). The limestone was also observed at the platform edge off northeast Unguja (Figure 1) as a cavernous submarine cliff 2–3m high. The cliff was overlapped at its base by an apron of carbonate sand with a variety of living coral mounds (Figure 4). Scattered living coral colonies encrusted the cliff, though these were sparse towards its top.

The fringing platforms and associated coral reefs of Unguja

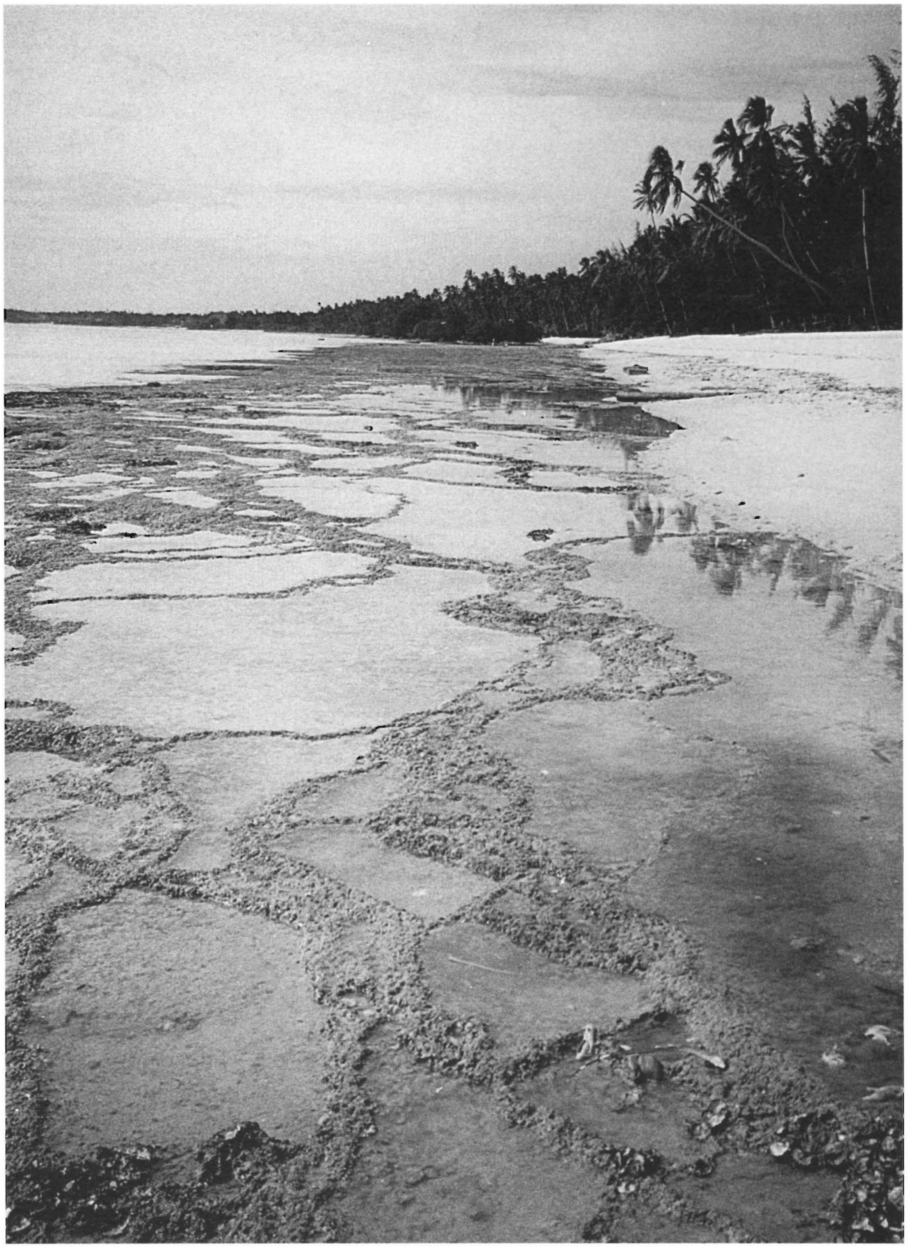

Figure 3. Beach sand overlapping platform of Pleistocene limestone showing polygonally patterned ribs, Bububu, western Unguja.

and Pemba were described by CROSSLAND (1902, 1903). Analogous platforms on the neighbouring Kenya coast, described as being composed of bare rock, sand patches, marine grasses and algae, have been taken by many authorities to be entirely erosional in origin (CRAME, 1986). The present intertidal positions of the Zanzibar platforms are compatible with a wave-cut origin in the late Holocene, when the present (post late-Weichselian glacial) eustatic sea-level highstand was attained (FAIRBANKS, 1989; BLANCHON and SHAW, 1995). CRAME (1986), however, observed living corals on well washed parts of the Kenyan platform surface and suggested the possibility that the reef (platform) there may be partly constructional in origin, built up from an antecedent reefal foundation. However, it is very unlikely that the extensive wave-cutting of the Pleistocene limestone in its present, well-lithified state could have been achieved during the five thousand years or so of the late Holocene. Such erosion would imply rates of extensive cliff recession averaging at least 20m every 100 years, but there are few indications of talus or collapse debris as would be expected from such recession rates. The present rate of limestone cliff recession around the islands is scarcely detectable within the timescale of contemporary monitoring, as evidence by historical and modern charts and topographic maps.

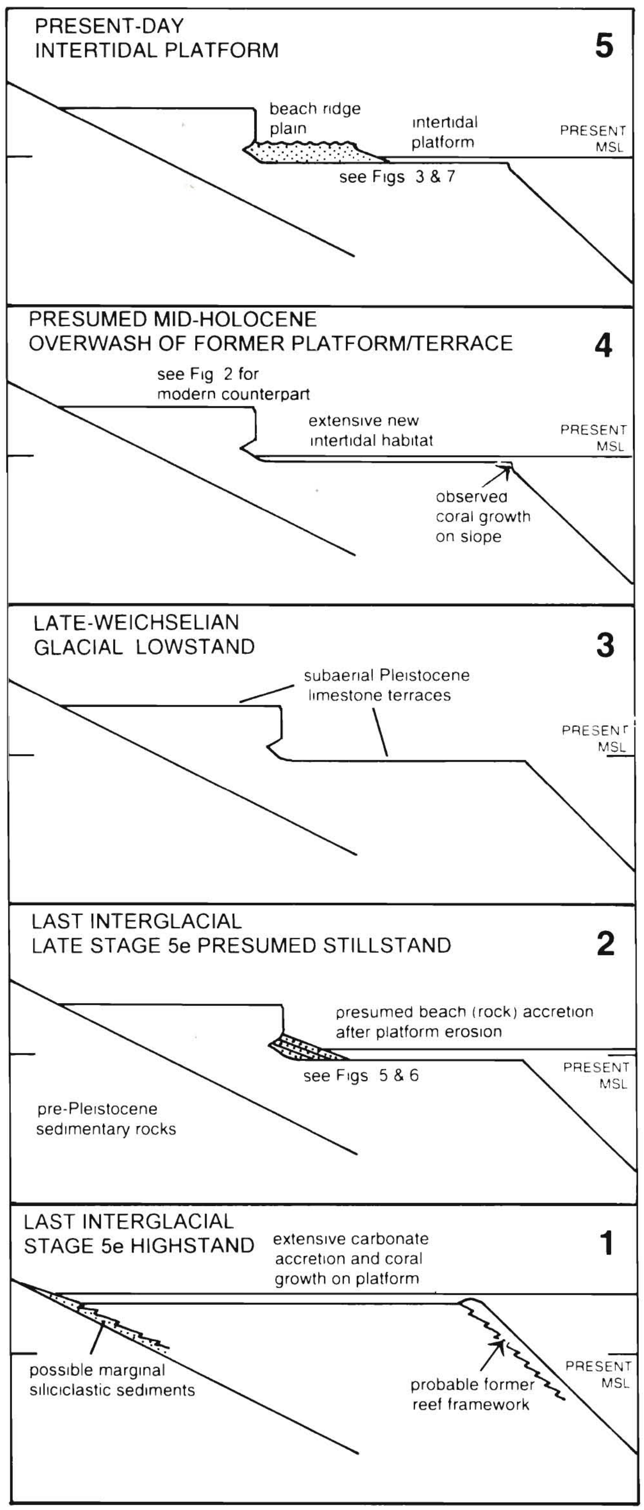

Figure 4. Coast-normal sections showing an interpretation of successive stages in Zanzibar's coastal evolution during the late Quaternary: (1) Stage 5e reconstruction based on Crame (1980, 1981, 1986) and Braithwaite (1984); (2) Stage 5e age of beach rock is unproven; (3) presumed karst development of depositional terraces and erosional platforms during lowstands; (4) transgression to presumed pre-existing palaeocliff; (5) present situation where beach ridge plain is developed.

If the present erosional regime is taken as indicative of the rate of cliff recession over the long term, then much of the platform morphology must have been cut during one (or more) previous sustained, coincident sea-level episode. While parts of the platform may have been raised as a result of coral reef growth and sediment accretion during the Holocene, the general platform morphology in Zanzibar is provisionally interpreted as formed, as on the Kenya coast (Figure 1; CRAME, 1980), by the wave-cutting of Stage 5e limestone during a stillstand which postdated the peak of the last interglacial sea-level maximum (Figure 4; see STODDART, 1973).

Stratigraphic evidence from outcrops of beach rock of yet unproven age may hold the key to an improved understanding the sequence of events shaping this distinctive coastal morphology. At several localities in the region there are outcrops of well lithified beach rock in the present high intertidal zone. These are mostly of medium- to coarse-grained quartzose sandstone occuring as inclined slabs mimicking the present (unlithified) beach face (Figure 5). The early development of Zanzibar Town (Figure 1) exploited these natural coastal defences. The beach rock on Unguja, termed Beach Sandstone by STOCKLEY (1928) and mapped by him (despite its marked lithological contrast) with the Raised Sands (the 'beach ridge plain sands' of this paper), consists of partly pebbly, medium to coarse quartzose sandstone, which is well lithified and jointed. Its coarse, terrigenous components must have been derived from the hinterland under conditions of weathering quite different to those of today, and their lithification, a product of a groundwater regime unrecognised in the present littoral environment. Similar well-jointed beach rocks in a contemporary high intertidal to backshore position have been noted on the adjacent Tanzanian mainland shore at Kunduchi, near Dar es Salaam (Figure 1; FAY, 1987; ARTHURTON, 1992).

At two localities on the eastern coast of Pemba, well lithified beach rock forms the present backshore ramp, resting on the Pleistocene limestone platform and banked against undercut but contiguous limestone cliffs (Figures 4, 6). If this beach rock itself proves to belong to the last interglacial, as the limestone forming the cliffs against which it is banked, then the history of platform development can be more confidently constrained. If, however, this beach rock proves to be Holocene, then the question of the age of extensive platform formation remains open. If a last interglacial age for the erosion becomes established, the platform surface would mark a previous sustained period of stable sea level almost coincident with that of the present. The rates of cliff recession during such a Stage 5e stillstand episode might have been somewhat faster than those of the present considering that the deposits had probably not by then attained their present state of lithification.

The regional landscape that was transgressed by the sea as a consequence of the rapid post-late-Weichselian glacial eustatic sea-level rise would have comprised gently to steeply sloping ground rising to the extensive limestone shelves or terraces which form today's fringing platforms. A land bridge in the position of the present Zanzibar Channel (Figure 1) would have connected Unguja with the mainland at the maximum late-Weichselian sea-level lowstand, but Pemba would

Figure 5. Inclined slabs of beach rock of unproven age mimicking a contemporary beach at Chukwani, western Unguja.

have remained isolated, surrounded by deep water. Except over the Unguja land bridge, the transgression would have created little shallow coastal water until the platforms became overwashed. This overwashing event, here estimated at 5–6ka BP when the present-day sea-level had been attained (FAIRBANKS, 1989), may have been a critical episode in the recent biogeomorphological evolution of the islands' platform-fringed coasts (Figure 4). In terms of their areas, the habitats suitable for colonisation by the intertidal to shallow subtidal biota, and thus the potential for the production of calcium carbonate sediment derived from that biota, would have expanded significantly over perhaps only a few decades. This reasoning follows SCHAAF (1996), who took a theoretical approach to the ecological implications of sea-level changes affecting continental shelf morphology since the last glacial maximum lowstand. In the case of the eastern African continental margin, the area of intertidal to shallow subtidal sea bed habitat in the present highstand conditions is many times greater than at the preceding lowstand.

Evidence that sea level during the latter part of the Holocene ever significantly exceeded today's level has not been identified by the authors on Zanzibar. The level represented by the maximum erosion notch on the undercut limestone cliffs is estimated to approximate to that of contemporary high water (Spring Tides). However, a maximum level of some 3m above sea level (undefined, but presumed MSL), radiocarbon dated at *c.* 6ka BP was recognised on the Mozambique shore (Figure 1) by JARITZ *et al.* (1977). An interpretation of the sequence of Zanzibar's late Quaternary coastal evolution from the last interglacial to the present-day, based on the stratigraphic evidence and interpretation described above, is shown in Figure 4.

HISTORY OF HOLOCENE BEACH ACCRETION AND SOURCES OF SEDIMENT

On the beaches of western Unguja (but not on the outlying islands) and on many of Pemba's beaches, field examination showed that quartz sand is the dominant component, with varying proportions of dark minerals and calcium carbonate clasts. The latter usually occupy the lower parts of beach profiles and comprise mainly mollusc fragments. The beaches at Bububu, on the western side of Unguja (Figure 1), are typical. The quartz sand is generally, though not exclusively, fine grained and derived mostly by stream discharge from the hinterland catchment though, in a few places, notably at Kwa-

Figure 6. Eroded inclined beach rock of unproven age banked against undercut Pleistocene limestone cliffs near Vikutani, eastern Pemba.

kaimu on southern Pemba (Figure 1), by the marine erosion of soft cliffs in Neogene sediments. Contemporary erosion of the Pleistocene limestone cliffs occurs mainly by solution within 2–3m above MHW, giving characteristic, rough, pitted surfaces, with varying amounts of undercutting. Where undercutting is pronounced, a very few instances of collapse have been noted, with massive blocks of limestone tumbled on the backshore.

Inspection of the beaches of eastern Pemba and Unguja, and those around the northern shore of Unguja at Nungwi (Figure 1), showed that these are formed of calcium carbonate sand derived from the fragmentation of carbonate-fixing biota that colonises the platform and its reefal front. The proportions of the various biogenic components vary from place to place. Many of the sands examined in the field comprise mostly platy fragments derived from the green calcareous alga, *Halimeda,* which grows on the platform in extreme low intertidal to shallow subtidal conditions. In the lower beach deposits, mollusc and coral debris may dominate locally as a coarse sand to pebble fraction. No sign of lithification of recent beach sediments has been noted.

On the eastern coasts of Unguja and, to a lesser extent, Pemba, the platforms and their fringing beaches are flanked by sandy beach ridge plains (the Raised Sands of STOCKLEY, 1928), 2–3m above MSL and extending up to some 500m inland from the backshore (Figure 4). The shores formed by these plains are subject to erosion and accretion on annual to decadal timescales (Figure 7). The plains that flank the extensive eastern beaches, such as at Paje and Kiwengwa on Unguja (Figure 1), are characterised by shore-parallel ridges with amplitudes of up to about one metre, interpreted as degraded beach ridges. Convex-seaward concentric patterns of ridges at Bwejuu on Unguja and Kiuyu on Pemba (Figure 1) are replicated in the forms of the contemporary beaches on those shores. At some sites on the more landward parts of the plains there are indications from inspection of aerial photographs of a hummocky relief, interpreted as relict sand dunes. The seaward edge of each plain is generally marked by a prominent storm ridge, littered with coconut trash as well as ocean-derived flotsam, including abundant pebbles and small boulders of pale grey pumice.

The age range of these plain-forming sediments is unproven. At their seaward edges they appear to be stratigraphically contiguous with the beach sediments of the present-day, but the age of the oldest parts of the beach plains is constrained only by the assumed date of platform overwashing during the mid-Holocene (Figure 4). If the deposits were a product of a previous highstand, then some lithification might be expected. No sign of lithification of the sands forming these plains has been observed, though its possible occurrence would merit investigation, particularly near to limestone palaeocliffs where groundwater springs might occur. There is no indication of contemporaneity between these sands and the well lithified beach rocks described in the preceding section.

In a long-term perspective, and assuming a mid-Holocene

Figure 7. Backshore erosion of sands forming a Holocene beach ridge plain at Kiwengwa, eastern Unguja.

to recent age for the beach ridge plain deposits, there has been substantial net accretion of beach sediments. One of the widest plains, extending some 500m inland from the backshore to a palaeocliff of Pleistocene limestone, is that at Paje in southeast Unguja (Figure 1). Sediment movements around parts of the coastline are also affected by tidal currents, with the large tidal inlets such as Chwaka Bay on Unguja (Figure 1) acting as sinks for sandy to muddy sediments. The Jozani Forest area, south of Chwaka Bay, has developed from such natural tidal silting of a former channel system during the late Holocene.

On Zanzibar's islands there appears to be a present underlying trend for backshore erosion of the beach plains (MOHAMED and BETLEM, 1996a). This trend may be a consequence of particular weather conditions over the last few years, or an expression of a longer-term climatic variation. Along much of their length the sand plains are subject to periodic erosion as a consequence of beach sediment wasting, mostly through wave action, though also by deflation on the backshore. On shores protected by a fringing platform, long wave-length, ocean-derived waves are transmitted to the beach only at times of high tidal levels. In extreme conditions, e.g., storm events coinciding with Spring High Tide, the incidence of these waves may lead to significant beach erosion with the creation of an erosional backscar. Smaller waves, including those generated over the platform at mid- to high tidal stages, favour the reinstatement of a steeper beach profile along with the burial of any existing backscar.

There is little evidence to suggest that local human agency has contributed to present erosion problems, except where jetties have interrupted natural sediment transport, as at Mkoani on Pemba (Figure 1), or where beach sand has been extracted for construction purposes.

IMPLICATIONS OF CLIMATIC CHANGES ON COASTAL GEOMORPHOLOGY

It is not clear whether present conditions on the platforms where the beach ridge plains have developed are representative of the period since the mid-Holocene overwashing event. Neither is it assumed that the regimes of sediment transport and rates of biogenic carbonate sediment production and supply have remained constant during this period. Indeed, if the Holocene history of sea level change in Zanzibar followed a pattern similar to that described from Mozambique by JARITZ *et al.* (1977), with a fall of 3m since 6ka B.P., then the accretion of beach plain sand could be interpreted as a product of a regressive regime.

Climatic changes on a range of timescales are likely to affect the geomorphology of these island shores both directly, due to regional variations, and indirectly, due to sea level change at a global scale. The present regional climate regime of the western Indian Ocean is characterised by a seasonal alternation of Northeast and Southeast monsoons (ASE, 1987). As well as affecting the aeolian transport of backshore sands, the monsoonal alternation produces marked seasonal changes in the regional and local wave climates, and thus in the directions and rates of wave-induced sediment transport alongshore. Observations by BRAMPTON (1996) on a number of Zanzibar's beaches where this pattern of alongshore drift reversal occurs describe how fine sand moves along the coast in a wave-like form, the beach plan shape having a series of humps and hollows which retain their character as they progress. As the respective impacts of the two monsoon sets vary from year to year, so some beaches may become either over-endowed with, or starved of, sand. An example of this is recorded at Nungwi on Unguja (Figure 1), where in 1992 the beach ridge plain hinterland was being rapidly eroded (ARTHURTON, 1992), while, four years later, the beach along the same shore had accreted seawards by some 40 metres (ARTHURTON, 1996). The changing shape of the island of Mnemba, a sand bank resting on an isolated platform off northeast Unguja (Figure 1), provides evidence of the variations in the balance between (seasonal) waves from the northeast and south respectively. The monsoon winds are not invariable from year to year. There may also be longer-term climatic fluctuations producing trends in shoreline evolution over decadal, or longer, timescales.

The effects on the platform sedimentary environment of rising sea level over the long term are speculative. However, the consequences may be important in the planning and management of these shores. Three questions are relevant. One is whether the seaward margin of the platform would become a more prolific coral growth zone, with a coral framework and its associated back-reef debris zone maintaining its position relative to a rising sea level. Another is whether deeper or more sustained submergence of the back-reef platform would promote widespread accretion of carbonate sediments and associated coral patches. A third question is whether an increase of mean water depth over the platform would affect the stability of the beach environment. This would allow larger waves to travel over it and impact the beach ridge plains.

The environment created over the platforms in this higher sea level scenario might be similar to that of the contemporary intra-platform lagoons and the extreme low intertidal zone, with scattered corals flourishing in water with minimum depths of perhaps 1–5 metres. Similar conditions were considered by CRAME (1980, 1981) to have existed during the accumulation of the Pleistocene limestone on the nearby Kenya coast (Figure 1). According to CRAME (*op. cit.*), the limestone in the vast majority of present-day exposures there formed in what was an extensive back-reef environment, with small reef clumps and isolated coral mounds. He interpreted the small size of so many of these fossil reef patches as suggesting that comparatively shallow water conditions prevailed over much of this back-reef region; any organised reefal framework that existed at the seaward margin of the contemporaneous reef flat having since been removed by erosion (Figure 4). CRAME (1986) described another distinctive rock type of the late Pleistocene back-reef as being composed almost entirely of whole plates and fragments of the calcareous alga *Halimeda*. He noted that *Halimeda* thickets must have been extensive in both space and time, covering many square kilometres and forming layers in excess of 5m thick. In the case of the contemporary platform environment, a rise in MSL of a metre or so could be expected to favour the growth of *Halimeda* more extensively than at present, with a consequent increase in the production of the derived carbonate sediment.

SUMMARY OF CONCLUSIONS

- The fringing platforms and associated cliffs of Zanzibar's main islands are formed of Pleistocene coral limestone, stratigraphically analogous to the documented Stage 5e back-reef limestones of the adjacent African mainland.
- The extremely slow modern cliff recession rates suggest that Zanzibar's platform morphology is unlikely have been formed solely since sea level attained its present highstand position in the mid-Holocene. Instead, the platforms are likely to have formed largely during a sustained Pleistocene period of stable sea level, postdating the preceding (Stage 5e) highstand peak.
- The well lithified beach rocks of Zanzibar differ markedly in composition from modern beach sediments and may be late Pleistocene (Stage 5e), rather than Holocene, as their present high intertidal position might suggest.
- The overwashing of the pre-existing platforms as a consequence of sea-level rise during the mid-Holocene would have greatly increased the intertidal and shallow subtidal habitats around the islands, with a consequent increase in the production of calcium carbonate sediment from e.g. the calcareous green alga, *Halimeda*.
- The accretion of sands on the platforms as beach ridge plains at 2–3m above MHW post-dates the mid-Holocene overwashing event. The plains are characterised by extensive, shore-parallel ridges and the deposits are vulnerable to marine erosion especially in storm conditions coincident with Spring High Tide.
- Longshore beach sediment transport, controlled by the alternating wave climates of the Northeast and Southeast monsoons, is a major factor controlling beach erosion and the erosion of vulnerable hinterland shores, and, conversely, beach sand accretion.
- Predicted global sea-level rise would create an extensive shallow subtidal environment over the platform promoting the growth of *Halimeda,* coral mounds and small patch reefs; this would recreate the environment in which the exposed Pleistocene back-reef limestones were formed. Holocene beach sand plains would become increasingly vulnerable to marine erosion.

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