Geomorphology of the Malindi Bay coastal sand dunes

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CHAPTER 2

A literature review of the meteorology, oceanography, geology and geomorphology of the study area

SUMMARY OF PREVIOUS WORK

The earliest geological work in the Malindi area involved geological mapping by Thompson (1956). In 1968 the United Nations assigned the Delft Hydraulics Laboratory (Delft Hydraulics, 1970) to investigate the causes of the increased siltation from the Sabaki River in Malindi Bay and on the beaches of Malindi. Their main aim was to propose measures for counteraction and protection of the Malindi beach. They conducted echo sounding to determine reef levels and depth in the offshore area. The data collected were on nearshore currents and wave patterns. This study also included a site investigation for the feasibility of the proposed harbour at Malindi.

Schroeder (1974) conducted reconnaissance fieldwork on the sedimentology of the Malindi coast and shelf environments.

During the survey trips of RV UJUZI, in the period between 1979 and 1981, oceanographic data were collected by the Kenya Marine and Fisheries Research Institute (KMFRI) in the area covering Malindi Bay and Ungwana Bay (Figure 1.1). Extensive data on ocean currents - speed and direction were collected. These data, which are available at the KMFRI library, have been given in project work reports no. 1, 2 and 3, respectively for the survey activities in 1979, 1980 and 1981 (Anonymous, 1981). Besides the data on current movement, climatological data with regard to wind direction and speed are included; part of the data has been published by Johnson et al. (1982).

Hove (1980a) conducted some preliminary studies on sedimentation in the modern depositional environments of Malindi, which included beaches and the Sabaki estuary. A brief description of the submarine geomorphology of the submerged continental margins was also incorporated.

Halse (1980), a consultant geologist, was contracted by the Government of Kenya, Ministry of Environment and Natural Resources to determine the locations of the heavy mineral deposits in the area stretching from Malindi to Lamu, and assess the viability of their exploitation.

During the period ranging from 1974 to 1988, Oosterom (1988) carried out investigations on the soils and geomorphology of the southeastern part of Kenya, including Malindi.

In the 1980's a number of geological investigations were carried out, especially on the southern coast of Kenya. They are mentioned here because similar rock outcrops are present in the Malindi area. The studies mainly involved stratigraphy, paleontology, structural geology and coastal terraces in the context of the geological history of this area starting with the break-up of Gondwanaland to Quaternary events. Notable literature on these topics are Hove (1980b), Cannon et al. (1981), Ase (1981), Braithwaite (1984) and Rais-Assa (1988).
Brakel (1984) presented information on seasonal movement of the suspended sediment plume from the Tana and Sabaki rivers into Malindi Bay and northward to Ungwana Bay. The decline of the Malindi reef complex mainly due to siltation was studied by Blom et al. (1985). This topic has recently been revisited by Obura (pers. commun., 1996) who detected a correlation between the suspended sediment load of the Sabaki and the thickness of silt accumulation on the coral reefs. Abuodha (1989) studied the morphodynamics and sediment dispersion patterns in the nearshore area causing the segregation and deposition of heavy minerals in the beach area between Malindi and Fundisa.

In 1992/1993, during the Kenya-Dutch Expedition aboard the RV TYRO (in which this author participated) in the western Indian Ocean, the physical, chemical, biological and geological aspects of the marine environment were documented. Wave climate characteristics based on information gathered by ships of passage from 1949 can be retrieved from the Meteorological Office & Maritime Data Bank (1990) in London.

Data on the Sabaki river flow discharge rates has been collected by the Ministry of Water Development from the 1960's. More recently, Mwongela (pers. commun., 1996) has done studies on the physical-chemical parameters that control vegetation distribution in the Malindi Bay sand dunes.

Besides the afore-mentioned, some pertinent information on the historical changes of the coastline over the past 40 years can be obtained from a series of aerial photographs dating from 1954 to 1994. In subsequent geological and geomorphological maps, some small coastal locations are not indicated for brevity. These are Robinson Island, 6 km north of Ras Ngomeni (Figure 2.5); Leopard Point, 3 km south of Malindi; Mtwapa and Kikambala, respectively 12 km and 25 km north of Mombasa (Figure 1.1); Shelly Beach and Diani, respectively 2 km and 21 km south of Mombasa Island.

**METEOROLOGICAL AND OCEANOGRAPHIC FACTORS**

The coastal belt of Kenya experiences an equatorial (tropical) monsoon climate with southeast monsoon prevailing from April to October and northeast monsoon from November to March (Kenya Meteorological Department, 1984). The transition period varies considerably in some years, although Johnson et al. (1982) have suggested that the switching takes place within 10 days during which the directions are variable. Anonymous (1981) recorded that wind direction, both in 1979 and 1981 changed in March to a southerly direction while in 1980 this happened in April. In November 1979, 1980 and 1981, at the start of the northeast monsoon period, the wind changed its direction to northeasterly (Anonymous, 1981). The chances of a cyclone passing over Malindi are negligible (Delft Hydraulics, 1970). Findlater (1973) concluded that the winds are controlled in the main by low-level air currents with a well-defined core in the eastern periphery of the East African coast. The author further noted in his jet-stream model that this phenomenon is instrumental in interhemispheric exchange and in the general circulation of the atmosphere. Charts prepared by the Meteorological Office & Maritime Data Bank (1990) based on long-term observations show that the winds blowing from the sea develop dominant components that are mostly oblique to the coastline and that the average strength of the southeast monsoon is greater than the north-east monsoon (Figure 2.1). The coastal wind system is influenced by a land breeze, which develops at night and a moderate sea breeze towards midday.
reaching its maximum during the afternoon. Wind speeds seldom exceed 14 m s\(^{-1}\) during both monsoon seasons. Gusts of 16 m s\(^{-1}\) occur locally and are most frequent in the transition months of March/April and October/November (Mahoney, 1980).

The coastal area has a humid climate with average rainfall of 1058 mm a\(^{-1}\) (Kenya Meteorological Department, 1984). There are two rainy seasons respectively referred to as the long rains and the short rains. The first wet months are April/May with over half the annual precipitation falling between April and June, during the southeast monsoon. This coincides with the penetration of a narrow zone of higher wind speeds across the Kenyan coast (Findlater, 1973). A study of statistical relationships between tropospheric winds and occurrence of rainfall over the western half of the Indian Ocean and East Africa has shown (Parker, 1973) that reduced wind strength due to upward advection is associated with the rainfall during May-October. The precipitation is usually concentrated in showers. The second wet spell occurs during October/November when the air current begins to retract into the southern hemisphere and becomes markedly weaker. The total precipitation during this season is relatively small. There is no real dry season (with zero precipitation as long-term average) due to the effect of the Indian Ocean, although the potential evaporation averages about 1904 mm a\(^{-1}\) which is nearly twice the mean annual precipitation. The driest months according to climatological data (Kenya Meteorological Department, 1984) for the years 1962-1980 are January and February, with an average monthly rainfall of less than 20 mm and number of rainy days averaging 2. The amount of rainfall seems to increase from north to south along the Kenyan coast (Abuodha, 1989).

Monthly variations in air temperature from normal are slight, and closely related to the sea water temperature. From July-September the temperature average is 25°C, while in other months it is from 27-28°C. Diurnal temperature variations are usually within the range of 7-9°C, although the maximum and minimum temperatures recorded at the four coastal stations (Lamu, Malindi, Mombasa and Shimoni) are 36°C and 19°C.

A noteworthy feature of the offshore circulation are the major currents running parallel and close to the Kenyan coast, dominated by a constant northerly flowing (Figure 2.2, Table 2.1) East African Coastal Current (E.A.C.C., Johnson et al., 1982). Charts showing the bathymetry, direction and speed of currents (Anonymous, 1981) apparently suggest that "offshore" means depths greater than 40 m. The southeast monsoon wind regime reinforces the northerly flow of E.A.C.C. which may attain speeds of up to 1-2 m s\(^{-1}\). The northeast winds not only work against the E.A.C.C. direction but also augment a southerly flowing current from the north, called the Somali Current (Johnson et al., 1982). Though frequently strong, these currents are concentrated into narrow flows so that at more than 150 km from the shore, they are often quite weak. The annual variations in the speed and thickness of the coastal currents are only slight to the south of about 2°S. To the north, however, the Somali

Current reverses in direction during the year in accordance with the monsoon wind regime and is therefore an example of a wind-driven western boundary current. In a model of the dynamics of western boundary currents, Johnson et al. (1982) have shown that the Somali Current penetrates some distance south before turning seaward at a zone also characterized by upwelling. During unusually strong northeast monsoon it may penetrate as far south as Mombasa situated at approximate latitude 4°S (Williams, 1970).
Figure 2.1: Wind rose for Kenya based on observations by RV UJUZI (Anonymous, 1981). Wind direction and force were recorded in Beaufort units. Beaufort force has been converted to m s$^{-1}$ using a scale by McIveen (1992).

Figure 2.2: Current 5-100 km off the Kenya based on observations by RV UJUZI (Anonymous, 1981). Current speeds in knots have been converted to m s$^{-1}$.

Figure 2.3: Wave characteristics off the Malindi coast, 1949-89. (Source: Meteorological Office & Maritime Data Bank, 1990).
From where the reversing Somali Current and the northward flowing East African Coastal Current (E.A.C.C.) meet (at approximately 2-3\degree S, and a depth of about 40 m), originates a seaward flowing current called the Equatorial Counter Current (E.C.C.). It has been determined, however, that the switching of winds and currents is not exactly synchronous (Mahoney, 1980; Brakel, 1984). Anonymous (1981) observed that closer to the shore off Malindi Bay, at shallow depths of less than 40 m, the current direction was variable throughout the year, with a dominating southerly flow tendency (Table 2.1). Anonymous (1981) noted that monsoon winds did not seem to affect the current direction at the shallow part of the shelf and concluded that the water movement here is probably a mixture of the "escaping waters" out of Ungwana Bay, tidal currents and the flow of the Sabaki river.

The tides are semi-diurnal, with a mean spring tide range of 2.9 m and a mean neap tide range of 1.0 m (see the annual tide tables for Kenya & Tanzania).

The strong southeast trades generate large waves and swell. During this period (April to October) the coastal zone is also subjected to rare strong winds which induce scarp cutting on the upper shoreface. The dominant direction of waves breaking upon the beach is from the southeast (Figure 2.3), and about 68\% of the deep-water wave height at the breaker point is over 1 m (Bertlin & Partners, 1977). This season is also associated with cloudy and overcast skies. The winds are much weaker during the northeast monsoon (Table 2.1); smooth calm seas and clear skies are representative of the northeast monsoon. Therefore, from November to March, the dominant direction of the breaking waves is from northeast (Figure 2.3) and about 44\% of them attain wave heights higher than 1 m (Bertlin & Partners, 1977). Based on ship data, Turyahikayo (1987) concluded that four wave regimes exist which include the two transition regimes when the wave directions are rather confused. Also important in this observation is that the March/April and November transitions involve a clockwise and anti-clockwise shift respectively with notable reduction in wave strength. The distribution of wave heights averaged between 1949 to 1989 is presented in Figure 2.4 showing that heights above 1 m are the most frequent with an annual average of about 64\%; the log-hyperbolic distribution seems to fit the data well. The waves, carrying the sediment, release their energy at the breaker point and transmit shoaling waves towards the beach; this factor has important implications for the supply of sediment to the beach.

The wind-wave environment and ocean currents are related to the beach-surfzone and dune morphology (Short & Hesp, 1982) and should be regarded as one unit and not in isolation. Short & Hesp (1982) noted that wave energy reaching the shore was determined in the main by the strength, duration and fetch of wind blowing over the sea surface, and further influenced by attenuation and refraction across the continental shelf and nearshore zones.

**CONTINENTAL SHELF**

The continental shelf of East Africa is commonly narrow and its features are scantily documented. While some data on sounding are available on old bathymetric charts and more recently in Anonymous (1981) and Johnson et al. (1982), a detailed description of the shelf features is not yet possible. During the RV TYRO Expedition covering the western Indian Ocean in 1992/1993, the continental shelf topography was determined using seismic profiling and sediment distribution on the ocean floor mapped (Abuodha, 1993). In the northern coast of Kenya the shelf is between 3 and 25 km, attaining its maximum width off Ungwana Bay; at Malindi Bay, the shelf is between 10-15 km wide. The shelf edge lies at comparatively shallow depths, mainly between 60-100 m.
Table 2.1: Surface current movement observed 5-100 km off the coast by means of free drift buoy (diameter = 15 cm) attached to a weight by one meter rope (Anonymous, 1981).

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Date</th>
<th>Start Position</th>
<th>Average Depth (m)</th>
<th>Current Direction From-Toward (°)</th>
<th>Speed (m s⁻¹)</th>
<th>Wind Direction (°)</th>
<th>Speed (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8015</td>
<td>08/02/80</td>
<td>03°09'</td>
<td>40°26'</td>
<td>03°0-210°</td>
<td>0.4</td>
<td>050°</td>
<td>0.8</td>
</tr>
<tr>
<td>8025</td>
<td>06/09/80</td>
<td>03°02'</td>
<td>40°24'</td>
<td>210°-030°</td>
<td>0.9</td>
<td>080°</td>
<td>0.8</td>
</tr>
<tr>
<td>8018</td>
<td>22/03/80</td>
<td>01°42'</td>
<td>41°37'</td>
<td>210°-030°</td>
<td>1.5</td>
<td>180°</td>
<td>0.8</td>
</tr>
<tr>
<td>8022</td>
<td>25/07/80</td>
<td>04°39'</td>
<td>39°47'</td>
<td>210°-030°</td>
<td>1.5</td>
<td>180°</td>
<td>0.8</td>
</tr>
<tr>
<td>8024</td>
<td>23/08/80</td>
<td>01°45'</td>
<td>41°33'</td>
<td>210°-030°</td>
<td>1.5</td>
<td>180°</td>
<td>0.8</td>
</tr>
<tr>
<td>8026</td>
<td>02/10/80</td>
<td>04°37'</td>
<td>39°31'</td>
<td>210°-030°</td>
<td>1.5</td>
<td>180°</td>
<td>0.8</td>
</tr>
<tr>
<td>8028</td>
<td>07/11/80</td>
<td>03°34'</td>
<td>40°10'</td>
<td>210°-030°</td>
<td>1.5</td>
<td>180°</td>
<td>0.8</td>
</tr>
<tr>
<td>8029</td>
<td>28/11/80</td>
<td>02°50'</td>
<td>40°30'</td>
<td>210°-030°</td>
<td>1.5</td>
<td>180°</td>
<td>0.8</td>
</tr>
<tr>
<td>8030</td>
<td>17/12/80</td>
<td>03°08'</td>
<td>40°23'</td>
<td>210°-030°</td>
<td>1.5</td>
<td>180°</td>
<td>0.8</td>
</tr>
</tbody>
</table>
The development of this shelf is connected with glacio-eustatic events and tectonic episodes since Permo-Triassic times (Hove, 1980a). It has been classified as an Afro-trailing edge type by Inman & Nordstrom (1971) and Shepard (1973). Along certain straight segments of the coast, the shelf is markedly absent, suggesting a fault origin. This occurrence is supported by a sudden drop of the sea-floor topography off the Kenyan coast which is attributed to the postulated Ruvu-Mombasa fault (Abuodha, 1989). This fault apparently maintains a NNE-SSW orientation throughout. Examination of bathymetric charts for the Kenyan coast indicate that indentations along the coast such as around the Ungwana Bay area are related to widening of the shelf, whereas narrow zones are generally associated with headlands and islands, for example in the vicinity of Mombasa Island.

The continental slope is generally characterized by gentle gradients of about 1:20 to the shelf edge and shows dissected appearance probably due to previous sub-aerial fluvial action. This means that the continental slope was exposed when the sea level was so low (about 100 m below present) that fluvial action could affect the continental shelf, perhaps during the Mindel glaciation (Oosterom, 1988), i.e. Kamasian Pluvial using the East African pluvial terminology. This, in addition to coral reefs gives it a rugged relief. In the northern sections, offshore sandbars or submerged ridges elongated parallel to the shoreline are superimposed on the continental shelf. The crests of these ridges may be partially exposed during low tide. Also characteristic of the continental slope morphology are the marine terraces at about -8 m, and -35 m (Thompson,
1956) and -5 m and -15 m (Read, 1981) which probably correspond to levels of the shoreline during the various stages of eustatic decline.

Investigation of sediment distribution off the Kenyan coast during the RV TYRO Expedition of 1992/1993 (Abuodha, 1993) showed that in general, sand appears to be the principal constituent of the shelf floor, with mud dominant in the deeper water. In addition to bioclastic and authigenic carbonate accumulation, the Sabaki and Tana rivers also supply terrigenous material to the continental shelf, representing a zone of high sedimentation rates. The bioclastic component is mainly derived from break up of coral reefs. Thus the Malindi shelf with its bioclastic and terrigenous sources could provide a model for sediment mixing on a narrow continental shelf, which in combination with information on wind and wave climate would explain sediment budgets in the littoral and dune systems.

SEDIMENT SOURCES AND SUPPLY

The Sabaki and Tana rivers have a considerable discharge, 1.3x10^9 m^3 a^-1 and 4.7x10^9 m^3 a^-1 (Brakel, 1984) respectively and the terrigenous sediment load has dominated the development of the coast (Delft Hydraulics, 1970; Ojany, 1984; Abuodha, 1989; Arthurton, 1992). Recent reports suggest that the influx of sediment, particularly from the Sabaki river, has been on the increase and that sediment is spreading southward leading to active accumulation (Bird, 1985). The inlet in front of the Sabaki is characterized by the occurrence of spits, bars and offshore plume. In addition, large submarine deltas have been formed which Hove (1980b) believed to be related to the salt-wedge effect.

The Sabaki and Tana rivers approach the coast in a narrow channel and a broad floodplain respectively. The sandy shores near Malindi have their major part of the deposits derived from the Sabaki (Abuodha, 1989; Abuodha & Nyambok, 1991) and resulting from weathering of rocks inland, whereas the Tana River system is connected with widespread deltaic environments dominated by silt/clay deposition (Ojany, 1984).

A recent study by Abuodha (1992) of beach deposits between Malindi and Shimoni in the south revealed that a great deal of carbonate sediments making up the beaches is derived from the adjacent reefs and cliffs. This is particularly so where the shoreline is bordered by fringing reefs. At Kilifi creek (Figure 2.8) and other creeks in the south, the reef is interrupted by the outflow of fresh water and sediments from the local streams, the valleys of which are deeply incised into the coral limestone. The only minimal contribution of terrigenous material into the littoral system is these small streams which originate from the coastal Shimba Hills (Munyao, 1992). In the vicinity of the river mouths and creeks, the beaches consist predominantly of clastic materials but further away, carbonate content increases rapidly (Abuodha, 1992; Munyao, 1992).

The clastic material transported by the Athi-Galana-Sabaki system is entrained by waves and currents which sort the material, mainly according to size and density, such that the beach receives only the sand-size fraction and silt/clay-size fraction is transported offshore to form part of muddy shelf deposits. The sorting action by waves and winds further causes enrichment of heavy minerals on the upper shoreface (Abuodha & Nyambok, 1991). Micas are transported further than are quartz sands. The alternating wave-induced longshore current in combination with tidal streams and ocean currents is the major factor in sand distribution near the Sabaki delta. The contribution of each of these factors is a subject of further research (Munyao, pers.)
commun., 1998), although initial observations show a dominance of wave-induced longshore currents. The winds also effect additional sorting on the berm and dune environments by the selective removal and redeposition of the lighter fraction in the prevailing wind direction.

Observations around Leopard Point reefs near Malindi and Watamu show that terrigenous sediment dispersals in the nearshore area adversely affect coral reef development (Delft Hydraulics, Blom et al., 1985; 1970; Obura, pers. commun., 1996). Hove (1980b) attributed the siltation problem of Malindi Bay to the southward sediment drift during the northeast monsoon coinciding with the main Sabaki floods. Analysis of Landsat imagery to depict seasonal dynamics of suspended sediment plumes from the Tana and Sabaki rivers was carried out by Brakel (1984), who showed that a southward plume from the Sabaki predominated during the northeast monsoons, while a northward plume dominated during the southeast monsoons.

Clusters of heavy mineral placers containing economically valuable minerals are located north of Malindi, in the Sabaki river delta, in the neighbourhood of Ras Ngomeni Peninsula and on the beaches of Ungwana Bay barrier islands (Thompson, 1956; Schroeder, 1974; Halse, 1980; Abudhha & Nyambok, 1991). The detrital heavy minerals of Malindi and Ungwana Bay shores consist predominantly of titaniferous species (hematite, ilmenite and magnetite) with subordinate amounts of garnet, zircon and rutile. Monazite, augite, tourmaline and hornblende are present in trace quantities.

GEOLOGICAL SETTING

The East African coast is an Afro-trailing edge type (Inman & Nordstrom, 1971) which has experienced eustatic sea level oscillations and/or isostatic and differential tectonic movements, which have considerably influenced the coastal configuration.

A number of creeks north of Mombasa would indicate a recent rise in sea level, as would the submerged terraces; while several raised beach terraces now occurring 1-2 km inland indicate a recent sea level drop. The dynamics of the sea level in this area are insufficiently studied to allow any unequivocal statements about trends in sea level fluctuations.

Figure 2.5 shows a wide variety of deposits in the Malindi area, which include Tertiary, Quaternary and Recent deposits; the Taru Grits and the Duruma Sandstone series are not presented on the map because they do not outcrop in this area, but are however believed to form the substrate (Oosterom, 1988).

Palaeozoic, Mesozoic and Tertiary rocks

The Palaeozoic-Mesozoic outcrops, stratigraphy and plate tectonic processes of coastal Kenya have been described by Cannon et al. (1981) and Rais-Assa (1988) in relation to the rifting along the northeastern part of Gondwanaland and the genesis of the proto-Indian Ocean. The vertical and horizontal movements associated with the last breakup of Gondwanaland took place during Permo-Triassic times and the ultimate marine incursion took place during the Jurassic (Kent, 1974).
Figure 2.5: Geological map of the coastal zone in the Malindi area (Re-drawn from Thompson, 1956). The stratigraphical succession is given in the text (scale is in km).

The underlying sedimentary sequence consists of the Upper Carboniferous Taru Grits overlain by the Permo-Triassic Karroo represented by the Duruma Sandstone Series (Caswell, 1956; Thompson, 1956). The Tertiary sediments are represented by the Baratumu Beds (sandstones with subordinate shales and limestones) of the Miocene and the Marafa Beds of the Pliocene (Figure 2.5). The latter comprises sands and sandstones with subordinate shales and marls. Thompson (1956) dated them as Pliocene to Early Pleistocene based on the determination of fossil foraminifera. The Magarini Sands comprise unconsolidated quartzose sands, which locally include gravels or clays and can broadly be subdivided into two different stratigraphic members. The Lower Member is formed by Plio-Pleistocene fluviatile sands (Caswell, 1953; Williams, 1962; Oosterom, 1988). The Upper Member was distinguished in the Malindi area by Thompson (1956) as sands of aeolian origin. Both Caswell (1953) and Thompson (1956) considered them to be of Pleistocene age.

**Pleistocene and Holocene deposits**

During the Pleistocene the Malindi coast was affected by global eustatic sea level oscillations, which are reflected in its geomorphological and sedimentological features. Oosterom (1988) has documented the sequence of events that operated along the Kenyan coast and their equivalents in
the alpine glacial history of Europe. The existing correlations of Pleistocene sediments with particular sea level stands have been neither satisfactory nor have they been unanimously accepted. The following account is based on Caswell (1956), Thompson (1956), Williams (1962), Braithwaite (1984) and Oosterom (1988).

Brief descriptions of the Pleistocene lithological units are given by Oosterom (1988) for the coastal rocks and unconsolidated deposits. In this stratigraphy three main types of Pleistocene formations are identified along the coastal plain from the west to the east. They are known as the Fossil Reef Complex, Lagoonal Sands and Clays and Wind-blown Sands (Figure 2.5). The basement is probably a narrow wave cut platform paved on the underlying Cretaceous and Jurassic formations during the Early Pleistocene.

The **Fossil Reef Complex** consists of an assemblage of coral limestone, calcarenites and intercalations of quartz sands, sandstone pebbles, silt and calcareous algae. Main outcrops of the Fossil Reef Complex formation are found from the Sabaki southward to Shimoni, a coastline distance of approximately 200 km. This reef formation extends 3-5 km from the present shoreline, underlying the coastal plain, and attains elevations of up to 30 m above sea level. However, Caswell (1956) determined from borehole records that the limestone may reach to a depth of 60 m below sea level, so that a maximum thickness of about 90 m may be assumed for their thickness.

The North Mombasa Crag, comprising of calcareous sand, shelly sands and clays (marls) are the sediments which form the foundation of the Fossil Reef Complex. This ‘basal’ unit has been interpreted by Braithwaite (1984), (1) to be a product of mid-Pliocene crustal movements, and (2) to be of sub-aerial origin during a period of low sea level stand. Caswell (1953) recommended a Middle Pleistocene age for the Fossil Reef Complex by connecting the reef build-up with the second interpluvial. In a later study of the Pleistocene limestones of the Kenyan coast, Braithwaite (1984) concluded that these deposits formed about 125 000 years ago when sea level stood 15-20 m above its present position based on radiocarbon dates of the raised coral reef.

The **Lagoonal Sands and Clays** (Figure 2.5) were recognized to be equivalents of the Kilindini Sands by Caswell (1953), the Pleistocene Sands by Thompson (1956) and the red sandy laterite by Braithwaite (1984). The sands comprise mainly quartz sands with subordinate silts and clays. Williams (1962) proposed a lower Upper Pleistocene age based on the presumed age of a terrace he identified at +12 m.

The quartzose Lagoonal Sands and Clays deposits are considered to be contemporaneous with the Fossil Reef Complex, based on their fossil fauna (Caswell, 1953; Thompson, 1956). Due to the small extent of the local drainage basin, only covering the coastal zone, Caswell (1953) concluded that clastic sediments were derived from the nearby Duruma Sandstones of the Permo-Triassic and from the Early Pleistocene Magarini Sands. The fact that the Lagoonal Sands and Clays and coral reef formations are more or less contemporaneous suggests that the rate of clastic sedimentation was rather low since the corals flourished despite the siltation.

The **Wind-blown Sands** were recognized to be equivalents of the Gedi Beacon Sands by Thompson (1956) and Pleistocene Dune Sands by Williams (1962). The latter has differentiated three dune ridges on the basis of platforms on which they accumulated, at 60 m, 36 m and 9 m respectively. The suggested age of Upper Pleistocene for the Gedi Beacon Sands by Thompson...
Thompson (1956) was based on the assumption that the retreat of the sea (which exposed offshore bar deposits to wind activity) from the 36 m terrace took place during that time.

The cocquinas are prominently exposed at Watamu Beach, Vasco da Gama Pillar at Malindi and Ras Ngomeni Peninsula (Figure 2.5) and consist of wind blown, carbonate-rich deposits, derived from beach materials, mainly shells. These aeolian deposits are strongly cross-bedded which led Thompson (1956) to interpret them as offshore bar deposits. A sporadic distribution of related dunes are present along the southern coast of Kenya. Ase (1981) has illustrated that the system continues northward into southern Somalia, a coastline distance of approximately 2,000 km.

Recent deposits comprise Recent Dune Sands, Recent Beach Sands and Tidal-Flat Deposits, and Recent Alluvium.

**GEOMORPHOLOGICAL SETTING**

The work of Ase (1978, 1981), Ojany (1984), Oosterom (1988), Abuodha (1989) and Abuodha (1992) illustrates pertinent geomorphological features of the Kenyan coast. On the basis of their findings, it can be shown that the Kenyan coast shows great diversity in the configuration of the shoreline consisting of sandy beaches, dunes, creeks, muddy tidal flats and rocky shores bordered by cliffs. In the Malindi area, Abuodha (1989) considers the coast presently to be predominantly emergent. In particular, the area has experienced a shoreline progradation of up to 750 m over the last 40 years. At Gilani Beach, in Malindi, Bird (1985) reported beach progradation of up to 150 m between 1975 and 1981 alone, and attributed this to a southward longshore drift from the Sabaki delta.

Further north, Ojany (1984) has reported that the Tana River sediments have resulted in a progradation of the coastline near Kipini (80 km south of Lamu at the mouth of Tana River), and there has been an advance of the mangrove shores in the sheltered bays behind the Lamu archipelago. The north coast is also characterized by a prominence of sand dunes and tombolos, exemplified at Ras Ngomeni, in addition to recognized higher land uplift and arching. Oosterom (1988) has recorded deltaic features in the neighbourhood of the Lamu Archipelago that he interpreted to be evidence for submergence. The Kenyan coast and individual segments may qualify as emergent or submergent coastlines.

Abuodha's (1989) work in the north coast and Abuodha's (1992) results in the south coast demonstrate a remarkable transition in coastal morphology north and south of Malindi. Thompson (1956) and Abuodha (1989) noted that in the northern section, the coastal plain is broad, reaching widths of more than 50 km towards the Tana delta. The foreshore area between Malindi and Mamburi generally consists of wide low-gradient extensive beaches, bordered landward by sub-horizontal berms and seaward by runnel and swash bars. These are succeeded inland by an array of complex dune ridge systems of up to 50 m in height. The dune ridges are particularly prominent between Malindi and Ras Ngomeni; south of the Sabaki mouth the ridges are underlain by the raised reef flat. The youngest dune generation is active, and presently moving over the older dunes. The beach ridges, closely associated with the dunes are of variable Holocene age (Ase, 1981) and altitude. The stabilized foredunes north of Mamburi, which fringe the landward side of the bays invariably show undercutting due to waves/wind erosion at the toe resulting in cliffs measuring about 1-1½ m in height. The modern beach ridges are characterized by sparse vegetation cover and scattered pebble-size pumice particles.
Abuodha's (1989) study included the coastal area of Ras Ngomeni, a peninsula located about 20 km north of the Sabaki delta, and consisting of a small remnant of Pleistocene coral limestone linked by a spit deposit to the mainland. On top of this feature are large dune ridges. In areas north of Ras Ngomeni (Ungwana Bay) different conditions prevail, and Abuodha (1989) considers the low coastal relief here to be associated with Holocene marine transgressions that have largely destroyed the older dune-barrier island systems. The area today is occupied by lagoonal flats subject to spring tide flooding via tidal channels. The low elevation shoreline sand bars or barrier islands constitute the active beach. Mangroves grow in muddy (tidal flat) or lagoon areas behind the dunes and barrier islands. Further inland, to the west of the bay, relict of the Quaternary dune sands occurs as raised scrub covering an environment of low-lying lagoonal sand and clay flats.

Caswell (1953) and Abuodha (1992) observed that in the southern section, the coastal plain is 3-6 km wide and attains elevations of up to 50 m; its landward boundary is marked by the rise of the Foot Plateau, whose elevations range from 60-140 m. Creeks are more common in the Mombasa-Kilifi area than in Malindi. The landscape here is also characterized by a series of fossil dunes and marine platforms (terraces) which occur in decreasing height above MSL, down

Figure 2.6: Geomorphological map showing terraces of the coastal zone between Kilifi and Gongoni (Re-drawn from Hori, 1970).
to the present beach and (even lower) the reef platform (Figure 2.6). The coastal plain is composed of Quaternary coral reef rock, infilling into reef lagoons and channels, and of coastal sand dunes. These rocks form cliffs and an extensive reef platform on their seaward margin, which is a prominent coastal feature from Vasco da Gama Point southwards to Shimoni. The cliff height is generally 10-15 m and is largely associated with elements of wave erosion leading to a slow but significant rate of retreat. However, for most of its extension it is paralleled and protected by a fringing reef which abuts against the seaward edge of the platform. At some portions of the coast, pockets of beaches accumulate behind the fringing reef at the foot of the cliffs; however many beaches are not below cliffs but instead occur as extended beaches separated by rocky headlands. The extended beaches are backed landward by beach ridges or berms of recent origin. All these forms of isolated beaches are narrow and steeply inclined in more protected areas. North of Mombasa, small sand dunes and offshore bars are characteristic features.

Abuodha (1992) further noted that the tidal range and the position of the fringing reef platform concentrate wave action at two different levels. The lower level (reef edge) where waves break, experiences more intense wave abrasion, resulting in a rough surface with numerous small stacks and cavities. The upper level is characterized by weathered undercut cliffs with frequent caves or isolated beaches with beach berms. The distance from the shore to the outer reef edge varies from 1-3 km, although at Mambrui the patchy reef extends seaward for less than ½ km. South of Malindi, reef development is continuous except in the vicinity of creeks and estuaries.
Table 2.2: Correlation of the coastal terraces in southern Kenya according to earlier studies

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<tbody>
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<td>Study Area</td>
<td>Southern Kenya</td>
<td>Mombasa area</td>
<td>Malindi area</td>
<td>Mombasa-Malindi area</td>
<td>Southern Kenya</td>
<td>Southern Kenya</td>
<td>Mombasa area</td>
<td>Mombasa-Miwapa area</td>
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<td>Mombasa area</td>
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<td>Terrace Name And Elevation Above Datum</td>
<td>75 m</td>
<td>Foot Plateau</td>
<td>Foot Plateau</td>
<td>-</td>
<td>Matuga Surface 80-120 m</td>
<td>Marafa Terrace 80-120 m</td>
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<tr>
<td></td>
<td>50 m</td>
<td>Foot Plateau</td>
<td>Foot Plateau</td>
<td>-</td>
<td>Changamwe Surface 45-70 m</td>
<td>Changamwe Terrace 45-70 m</td>
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<td></td>
<td>12 m level</td>
<td>37 m</td>
<td>36 m</td>
<td>18-25 m</td>
<td>Upper Mombasa Terrace 15-37 m</td>
<td>Ganda Terrace 20-37 m</td>
<td>VIII: 20 m</td>
<td>Ganda Terrace 20 m +?</td>
<td>+20 m</td>
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<td></td>
<td>24 m level</td>
<td>37 m</td>
<td>36 m</td>
<td>18-25 m</td>
<td>Upper Mombasa Terrace 15-37 m</td>
<td>Ganda Terrace 20-37 m</td>
<td>VIII: 20 m</td>
<td>Ganda Terrace 20 m +?</td>
<td>+20 m</td>
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<td></td>
<td>9 m old sea beach</td>
<td>7.6 m</td>
<td>7.5 m</td>
<td>7-10 m</td>
<td>Lower Mombasa Terrace 10 m</td>
<td>Malindi Terrace 7-10 m</td>
<td>IV: 12 m</td>
<td>Malindi Terrace 7-10 m</td>
<td>+10 to +12 m</td>
<td>+8 m</td>
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<td>4.5 m</td>
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<td>-</td>
<td>Shelly Beach Terrace 5 m</td>
<td>Shelly Beach Terrace 4.5 m</td>
<td>I: 5 m</td>
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<td>+4 m</td>
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<td>2 m level</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Present-day reef platform</td>
<td>+2 m</td>
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Submarine terraces are present at -8 m and -35 m (Thompson, 1956) and at -5m and -15 m (Read, 1981)