ELSEVIER

Journal of African Earth Sciences 36 (2003) 41–54

Journal of African Earth Sciences

www.elsevier.com/locate/jafrearsci

Grain size distribution and composition of modern dune and beach sediments, Malindi Bay coast, Kenya

J.O.Z. Abuodha *

School of Environmental Studies, Moi University, P.O. Box 3900, Eldoret, Kenya

Received 26 April 2002; accepted 31 January 2003

Abstract

Grain size distribution and heavy mineral content of beach and dune sediments from the Malindi Bay coast, Kenya were determined. Grain sizes were determined by dry sieving sediments; samples represent the upper 5 mm of surficial sediment, collected from the four main geomorphological units (beach, berm zone, foredune and dunefield), during three observation periods, covering the southeast and northeast monsoon seasons. Sediment samples were grouped according to whether they were collected from the northern or southern sector of the Sabaki river. The heavy mineral content of several samples collected from the beach, berm zone and sand dunes was obtained by using separating funnels and tetrabromomethane to gain insight into the mineral distribution, the mineralogy and comment on the economic potential of prospecting for the heavy minerals. The petrographic parameters determined include the heavy mineral weight percentages and the mineral composition of the heavy fractions obtained using a petrographic microscope.

The Malindi Bay shore is dominated by terrigenous deposits brought in by the Sabaki river which consist mainly of fine- to medium-grained quartz sand. The sediments also contain heavy minerals averaging about 15%, with highest concentration being 67% by weight for the samples analyzed. The heavy mineral suite here is dominated by opaque iron–titanium minerals as well as some red garnet and zircon. The results demonstrate a good relationship between the heavy mineral concentrations and the corresponding geomorphological elements.

There are some differences between the various geomorphological units, with a subtle trend from the beach to the dunes. During all three observation periods grain size decreases slightly from the beach to the foredune. The sediment size fraction 0.625∅, present on the beach, was absent in the immediate aeolian environments, except for the steep slopes of sand sheets and interdune valleys. The berm zone rarely has sediments coarser than 1.125∅. The grain size parameters at different beach locations do not suggest a general trend of longshore variations, except on the beach close to the river mouth. The differences between the seasons were larger than those between the geomorphological units. During the northeast monsoon the mean size was coarser, sorting was worse and the distribution was more positively skewed.

Keywords: Grain size distribution; Heavy minerals; Monsoon; Coast; Aeolian sand; Spearman's rank correlation

1. Introduction

Analysis of grain size distribution has been widely used by sedimentologists to classify sedimentary environments and elucidate transport dynamics. Grain size is also an important abiotic component of the dune ecosystem. The grain sizes of sediments provide an indication of the shear stress that must be applied by the medium to initiate and sustain particle movement. Grain size distribution is affected by other factors such as distance from the shoreline, distance from the source (river), source material, topography and transport mechanisms.

Musila (1998) found that the mean particle size of the sand was the most important factor influencing vegetation composition, structure and distribution in the Malindi Bay coastal sand dunes in Kenya. Musila (1998) noted that geomorphological units consisting of fine-grained sand had high species diversity in contrast to those with medium-grained sand which were mostly unvegetated or sparsely vegetated; these differences may be accompanied by differences in chemical composition and/or substrate processes.

---

* Tel.: +254-321-43226/43013; fax: +254-321-43237/43047.
E-mail address: joabuodha@yahoo.com (J.O.Z. Abuodha).

0899-5362/03/$ - see front matter
doi:10.1016/S0899-5362(03)00016-2

1.1. Objectives

This research was conducted in order to determine:

(1) particle size distribution in various geomorphological units;
(2) seasonal variability in grain size characteristics;
(3) heavy mineral concentrations on the beach, berm zone and dunes at Malindi Bay, to gain insight into the mineral distribution, the mineralogy and comment on the economic potential of prospecting for the heavy minerals.

1.2. Systems of grain size classification

A number of analytical and interpretation techniques exist for determination of grain size distributions. Grain sizes are determined either by sieving (wet or dry) or by the settling tube techniques. The sieving method assumes that sediment grains are spherical. The settling tube technique, based on Stoke's law, is used to measure the settling velocity of particles in a medium, and translate this to size scale (Baba and Komar, 1981; Komar and Cui, 1984; Fay, 1989).

The system of size classification is based on the log normal model (Krumbein and Pettijohn, 1938). The log-based Krumbein (1938) phi (ϕ) scale ($\phi = -^{2}\log d$, where d is the diameter of the particle in mm) is preferred. The resulting measures are easily plotted on cumulative frequency curves from which ad hoc graphic measures are determined (Trask, 1932; Inman, 1952; Folk and Ward, 1957; Friedman and Sanders, 1978). Graphic measures derived from the cumulative frequency curve are the mean, sorting, skewness and kurtosis, which provide the descriptive statistics of the particle size distribution. According to Fuechtbauer and Mueller (1977), the Folk and Ward (1957) indices enable a more precise characterization of grain size distributions and also approximate the arithmetic moments.

Wyrwoll and Smyth (1985) suggest the use of the moment measures of the log normal distribution arguing that the graphic measures significantly deviate from the nominal values, especially skewness and kurtosis. In some recent studies, the log–hyperbolic distribution model is used (Barndorff-Nielsen and Christiansen, 1988; Christiansen and Hartmann, 1988; Barndorff-Nielsen et al., 1991; Hartmann, 1991).

2. Study area

The study area is a 10 km coastal strip stretching from Malindi to Mambrui (Fig. 1), and consisting of extensive, low-gradient beaches and active dunefields. It is situated within the latitudes 3°06′S and 3°12′S, and bounded to the west by the transition zone from active to stabilized dune forms. The area is geographically set within a wide open bay near the mouth of the Sabaki river. Beaches along the shore of Malindi Bay consist predominantly of quartzitic sand (Thompson, 1956; Abuodha and Nyambok, 1991). The main source of these terrigenous sandy sediments is the Sabaki river and the provenance includes igneous rocks near Nairobi, Mozambique Belt metamorphic rocks and coastal sedimentary formations (Abuodha, 1998).

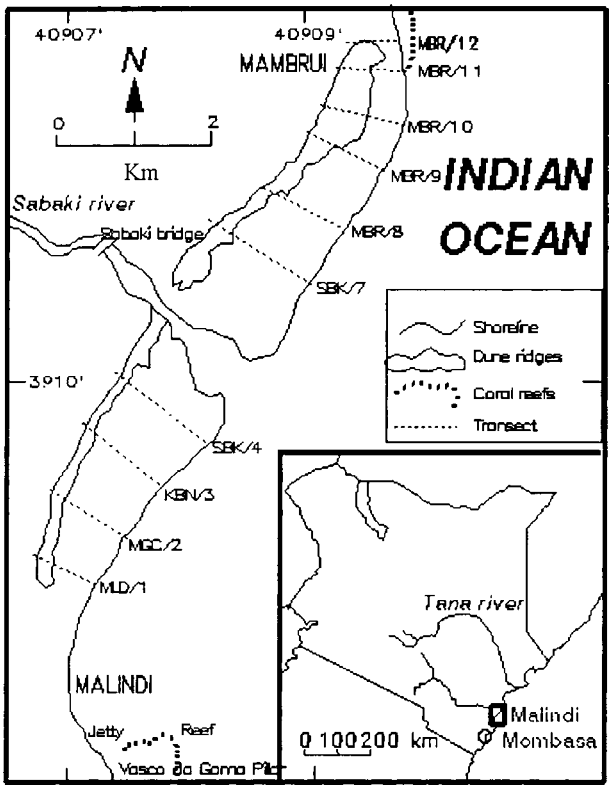


Fig. 1. Map showing location of the study area including transects where sediments were collected for grain size and heavy mineral determination.

The Kenyan coast is influenced by two main monsoon wind regimes and any explanation of the littoral and aeolian processes operating here should be based on this observation. Two distinct wind directions were determined from the wind measurements recorded during 1993 (Abuodha, 2000). One was from SW–S–SE, which prevailed from April–October, during the southeast monsoon season and from N–NE–E, which prevailed from January–February, during the northeast monsoon season. March and November/December were transitional periods. It can also be seen from the 1993 results of wind measurements at Mambrui, that the southerly wind speeds were higher and operated for a much longer duration, when most of the sand transport took place. The contribution of the northeast–east winds to the amounts of sand transported is relatively small. The wind system also showed a diurnal pattern of wind speeds with a land breeze which develops at night and a moderate sea breeze towards midday, reaching its maximum during the afternoon.

The study area is exposed to a mean spring tide range of 2.9 m and a mean neap tide range of 1.0 m (Admiralty Chart, 667; Kenya Ports Authority, Tide tables for Kenya and Tanzania, 1993/1994).

2.1. Previous work on heavy mineral reserves

Previous investigations on these sediments focused on the heavy mineral concentration at the Sabaki river mouth and the Ungwana (Formosa) Bay areas. The first mineralogical examination was made by Pulfrey (1942) on the Sabaki–Mambrui deposits. The results of this investigation showed that although widespread, the deposits are of low grade in comparison to workable occurrences elsewhere in the world. Pulfrey (1942) also reported that only the dune sands found 4 km north of Malindi, containing about 28% ilmenite, may be of economic value. Hornblende and garnet were noted to be present significantly. Further, rutile and zircon occurred in low percentages and monazite was rare. He concluded that further search would probably not yield higher ilmenite amounts. Ryan (1953) then holding an exclusive prospecting licence for an area of approximately 0.8 km of the Silversands beach south of Malindi, noted cemented black sand, but did not carry out any further prospecting.

Extensive prospecting operations and laboratory tests were carried out by McGuinness in 1953 (Thompson, 1956; Williams, 1962). The majority of samples were taken from drill holes made in the berm zone (average depth 3 m) along transect lines at approximately $1\frac{1}{2}$ km intervals. No regular close grid was applied and sampling stopped at water saturation levels. The average ilmenite content was found to be about 2%, which on experimental concentration yielded about 49% TiO_2. A minimum of 50% is normally required to render the concentrate economical for exploitation. McGuinness reported that up to 6% of the iron in the ilmenite can be removed successfully and also suggested that vanadium can be extracted separately as an important by-product, which would then offset the additional concentration costs.

Beinge (1957) examined sands in the Malindi–Fundisa area. His report indicated that the black sands in this area consist essentially of magnetite and ilmenite in approximately equal proportions and concluded that there are no other minerals of economic value. Thompson (1956) and Williams (1962) separately conducted geological reconnaissance surveys along the coast of the same area. They showed that the higher heavy mineral concentrations, found along the northern coast of the Malindi region, consist principally of Ti–Fe particles (ilmenite, hematite and magnetite) with subordinate zircon, rutile and garnet. They further observed that minerals with high TiO_2 content in beach sands from Ras Ngomeni are inhomogeneous. Therefore, composition of individual sand grains is apparently the result of complex intergrowths of ilmenite, hematite and other iron–titanium minerals.

In the 1950s and 1960s the British Standard Cement Company Ltd. sporadically mined the Ras Ngomeni beach sands as raw material for iron in the production of sulphate-resistant cement. The most recent exploration of the Ungwana Bay heavy mineral beach sands was conducted by Halse (1980) in the area between the Tana and Sabaki river mouths. He employed three categories (proven, probable and possible) to evaluate these reserves. For these reserves Schroeder et al. (1980) have described in detail the petrofabric implication of the heavy minerals, when new methods of processing are applied (Gock and Jacob, 1978).

Hove (1980) conducted some preliminary studies of grain size and heavy mineral distribution in the modern depositional environments of Malindi, which included beaches and the Sabaki estuary. The economic potential of beach, berm zone, dune and offshore mining was outlined by Abuodha and Nyambok (1991), who assessed the potential for modern and relict placer concentrations based on the petrographic, textural and geochemical properties of deposits found in these geomorphological units.

3. Field and laboratory methods

3.1. Determination of the grain size distribution

In July 1993, September 1993 and January 1994 a total of 409 sediment spot samples was collected along 10 transects perpendicular to the shore, and spaced at intervals of between $\frac{1}{2}$ and 1 km, from Malindi's Eden Roc Beach to Mambrui (Fig. 1). Along each transect, sediment samples were collected from the beach, berm zone, foredune and dunefield (Fig. 2). The samples were taken from the 'active' layer ranging from 0 to 5 mm. This depth was determined in the field by inserting erosion pins into the sand, in a 1 × 1 m grid, and noting the difference between the maximum and minimum vertical surface change over 24 h (Tole M.P., pers. commun., 1993). Note that 24 h represents both the diurnal pattern of wind system and tides. Sampling from the active layer ensures that only sediments representing the current transport events are considered for analysis. Below this depth, it is assumed that there are mixed sediment populations deposited during previous episodes.

An aluminium sampler was used to collect surface sediments; it was a pan-like device measuring 20 × 10 × 2 cm with a single open edge, which was sharpened to improve its efficiency in sediment retrieval. The

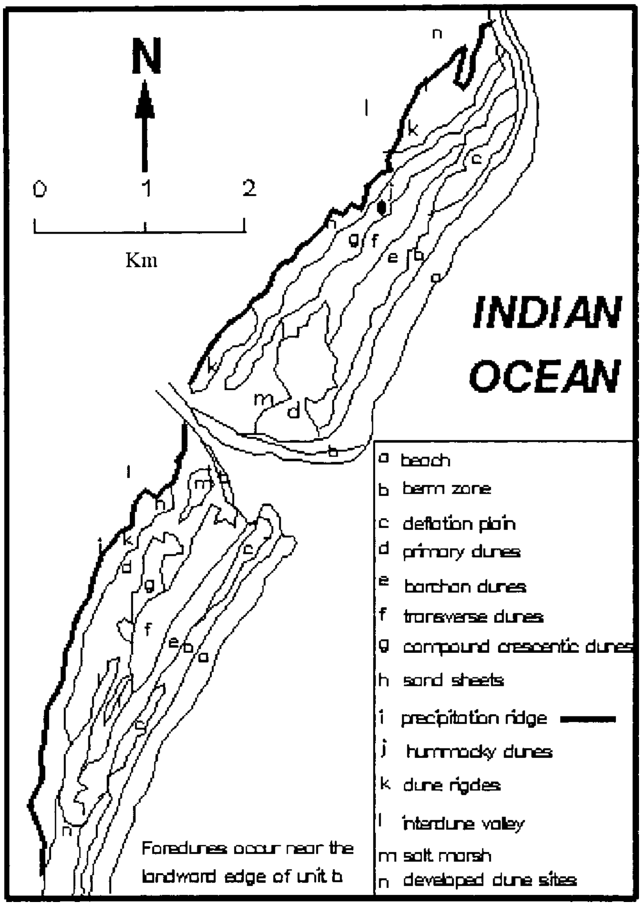


Fig. 2. Map showing major geomorphological units of the Malindi Bay area. Foredunes and sebkha are not indicated due to their sporadic appearance.

samples were labelled by transect, date and the geomorphological unit.

The samples, split into batches of 95–100 g, were repeatedly washed with distilled water in the laboratory in order to remove soluble salts, oven-dried at 60 °C, and sieved at quarter-phi intervals for 10 min using a Retscht mechanical shaker and a nest of 10–15 sieves measuring 50 × 200 mm. The selection of sieves was from apertures ranging between 0.50∅ and 4.00∅ and the weight held in each of these sieves was recorded.

3.2. Analysis of the grain size data

The mass frequency data were subsequently processed using a PC grain size package GAPP (Fay, 1989) which calculates both moment measures and graphical statistical parameters using the Folk and Ward (1957) formulae.

Analysis was done in four stages:

1. Spot samples approach—analysis of all 409 spot samples. These data showed much local variation (noise) probably due to heavy mineral concentrations, terrain configuration and measurement errors, and grain size distributions and derived parameters are difficult to correlate with geomorphological units or seasons. To reduce these effects (noise) partially composite samples (obtained from spot samples taken across the unit) were used. The frequencies (in weight) of each size class (e.g. 0.50–0.75∅) for all the spot samples in a selected group (as explained below) were added to obtain the total weight that would be held in the sieve if it were possible to sieve such a "super sample".
2. Transect approach—spot samples were grouped into the four main geomorphological units, namely the beach, berm zone, foredune and dunefield; the term dunefield encompasses the area between the foredune and the precipitation ridge (Fig. 2). These were grouped into months to generate composite samples for each geomorphological unit, transect and season (Appendix A).
3. Sector approach—very similar to (2) but in this case the grouping in each of the above geomorphological units is done for the northern and southern (of the Sabaki river) sectors (Table 1).
4. Combined north and south—the average for the regions north and south of the Sabaki river was obtained (Table 2).

3.3. Correlations with geomorphological units and seasons

For (3) and (4) above, Spearman's rank correlation coefficients were calculated, to provide a measure of the relationship between grain size parameters and geomorphological units, and with seasons. The choice of Spearman's in this case is justified since (i) there is no reason to expect that the Folk and Ward (1957) measures are normally distributed and (ii) geomorphological zones and date numbers are expressed in ordinal scales (Table 2).

Table 2 gives the seasonal and cross-shore variations in grain size parameters; Spearman's rank correlation coefficients are also provided. The same correlations were tested for significance at $\alpha = 0.05$ to determine whether differences in grain size were significant. Where a trend exists based on these statistical tests and denoted by YES in Table 2, then a significant correlation is detected. Although the number of supersamples (based on sampling periods) appeared to be inadequate, the present correlations are considered statistically sound until studies with more samples contradict them.

3.4. Sample material and analysis of heavy mineral content

In March 1994 and March 1997, sediment samples were collected at six of the transects shown in Fig. 1, i.e. MGC/2, SBK/4, SBK/7, MBR/9, MBR/10 and MBR/12 from the surface of the beach, berm zone and sand

Table 1
Data (weight in grammes and mid-class of sieve aperture) of composite samples from the beach, berm zone, foredune and the dunefield and their statistics based on graphical data; range of graphical parameters of grain size distribution

Sample statistics and sediment description	1 9307 BH-N	2 9309 BH-N	3 9401 BH-N	4 9307 BZ-N	5 9309 BZ-N	6 9401 BZ-N	7 9307 FD-N	8 9309 FD-N	9 9401 FD-N	10 9307 DN-N	11 9309 DN-N	12 9401 DN-N
Composite sample statistics based on graphical data												
Mean size	2.13	2.26	1.94	2.20	2.33	1.98	2.28	2.36	2.03	2.11	2.24	2.00
Sorting	0.35	0.42	0.47	0.35	0.42	0.41	0.33	0.32	0.44	0.36	0.45	0.48
Skewness	0.15	0.16	0.46	0.25	0.14	0.42	0.29	0.09	0.39	0.04	0.13	0.31
Kurtosis	0.96	1.16	0.83	1.02	1.15	0.82	1.18	1.63	0.59	1.04	1.12	0.84
Composite sample description												
Size	fine	fine	medium	fine	fine	medium	fine	fine	fine	fine	fine	medium
Sorting	ws	ws	ws	ws	ws	ws	vws	vws	ws	ws	ws	ws
Skewness	pos	pos	vpos	pos	pos	vpos	pos	near sym	vpos	near sym	pos	vpos
Kurtosis	mes	lept	plat	mes	lept	plat	lept	vlept	vplat	mes	lept	plat
No. of spot samples	21	26	22	4	4	7	8	7	3	43	61	36
Maximum mean size	2.52	2.74	2.69	2.54	2.54	2.21	2.80	2.48	2.46	2.45	2.86	2.37
Minimum mean size	1.90	1.88	1.55	2.07	2.01	1.71	2.07	2.19	1.72	1.89	1.60	1.63
Maximum sorting	0.55	0.68	0.54	0.39	0.44	0.43	0.34	0.46	0.39	0.40	0.54	0.74
Minimum sorting	0.18	0.20	0.16	0.24	0.27	0.27	0.20	0.19	0.23	0.22	0.23	0.16
Maximum skewness	0.63	0.78	0.65	0.50	0.52	0.64	0.31	0.29	0.53	0.52	0.53	0.69
Minimum skewness	−0.06	−0.23	−0.27	0.11	0.15	0.10	−0.04	0.00	−0.29	−0.08	−0.19	−0.36
Maximum kurtosis	2.39	2.34	3.10	1.27	1.52	2.81	1.38	2.13	1.43	1.92	2.95	2.64
Minimum kurtosis	0.86	0.56	0.69	0.85	1.20	0.72	0.87	1.02	1.19	0.84	0.82	0.60
	13 9307 BH-S	14 9309 BH-S	15 9401 BH-S	16 9307 BZ-S	17 9309 BZ-S	18 9401 BZ-S	19 9307 FD-S	20 9309 FD-S	21 9401 FD-S	22 9307 DN-S	23 9309 DN-S	24 9401 DN-S
Composite sample statistics based on graphical data												
Mean size	2.11	2.16	1.77	2.20	2.22	2.07	2.12	2.45	2.17	2.09	1.93	1.91
Sorting	0.29	0.40	0.38	0.32	0.40	0.43	0.29	0.38	0.48	0.35	0.36	0.44
Skewness	0.25	0.23	0.28	0.09	0.32	0.00	0.30	−0.07	−0.26	0.05	0.13	0.50
Kurtosis	0.96	1.00	1.57	0.88	1.13	0.65	0.84	1.27	0.60	1.02	1.43	1.05
Composite sample description												
Size	fine	fine	medium	fine	fine	fine	fine	fine	fine	fine	medium	medium
Sorting	vws	ws	ws	vws	ws	ws	vws	ws	ws	ws	ws	ws
Skewness	pos	pos	pos	near sym	pos	near sym	vpos	near sym	neg	near sym	pos	vpos
Kurtosis	mes	mes	vlept	plat	lept	vplat	plat	lept	vplat	mes	lept	mes
No. of spot samples	12	13	22	6	6	6	8	8	2	21	43	20
Maximum mean size	2.45	2.70	2.22	2.46	2.41	2.41	2.48	2.60	2.50	2.37	2.73	2.27
Minimum mean size	1.92	1.88	1.52	1.96	1.99	1.71	1.96	2.00	1.85	1.87	1.59	1.67
Maximum sorting	0.33	0.47	0.48	0.30	0.48	0.38	0.32	0.42	0.42	0.36	0.55	0.55
Minimum sorting	0.21	0.20	0.16	0.24	0.28	0.29	0.21	0.20	0.32	0.21	0.17	0.29
Maximum skewness	0.45	0.45	0.57	0.42	0.59	0.69	0.52	0.24	0.46	0.41	0.59	0.69
Minimum skewness	0.09	−0.04	−0.30	0.04	0.06	−0.31	0.11	−0.07	−0.47	−0.06	−0.06	−0.13
Maximum kurtosis	1.93	1.57	2.13	1.28	2.01	1.52	1.97	1.54	1.92	1.22	2.86	3.00
Minimum kurtosis	0.93	0.99	0.64	0.89	1.03	0.73	0.84	1.09	1.62	0.93	0.92	0.59

BH = beach, BZ = berm zone, FD = foredune and DN = dunefield.
Scales for mean, sorting, skewness and kurtosis; all figures in phi-units.
Fine = fine-grained sand (2.00–3.00); medium = medium-grained sand (1.00–2.00); vws = very well sorted (<0.35); ws = well sorted (0.35–0.50); – = moderately well sorted (0.50–0.70); pos = positive skewed (+0.10 to +0.29); vpos = very positive skewed (+0.30 to +1.00); near sym = nearly symmetrical (−0.10 to +0.10); lept = leptokurtic (1.11–1.50); vlept = very leptokurtic (1.50–3.00); mes = mesokurtic (0.90–1.11); plat = plarykurtic (0.67–0.90); vplat = very platykurtic (<0.67).

dunes. The materials collected were split into batches of 50 g, washed twice with distilled water in the laboratory in order to remove soluble salts and oven-dried. The heavy mineral separation was carried out by the standard gravity method using tetrabromomethane (sg = 2.8) and separation funnels. The petrographic parameters

Table 2
Seasonal and cross-shore variations in sediment size, sorting, skewness and kurtosis (Folk and Ward, 1957 graphical parameters)

Geomorphological unit	Zone	Date	Num	North of Sabaki river				South of Sabaki river				Combined North and South			
				Mean	Sort	Skew	Kurt	Mean	Sort	Skew	Kurt	Mean	Sort	Skew	Kurt
Beach	1	9307	1	2.13	0.35	0.15	0.96	2.11	0.29	0.25	0.96	2.12	0.32	0.20	0.96
Berm zone	2	9307	1	2.20	0.35	0.25	1.02	2.20	0.32	0.09	0.88	2.20	0.33	0.17	0.95
Foredune	3	9307	1	2.28	0.33	0.29	1.18	2.12	0.29	0.30	0.84	2.20	0.31	0.29	1.01
Dunefield	4	9307	1	2.11	0.36	0.04	1.04	2.09	0.35	0.05	1.02	2.10	0.35	0.04	1.03
Beach	1	9309	2	2.26	0.42	0.16	1.16	2.16	0.40	0.23	1.00	2.21	0.41	0.20	1.08
Berm zone	2	9309	2	2.33	0.42	0.14	1.15	2.22	0.40	0.32	1.13	2.28	0.41	0.23	1.14
Foredune	3	9309	2	2.36	0.32	0.09	1.63	2.45	0.38	−0.07	1.27	2.41	0.35	0.01	1.45
Dunefield	4	9309	2	2.24	0.45	0.13	1.12	1.93	0.36	0.13	1.43	2.08	0.41	0.13	1.27
Beach	1	9401	3	1.94	0.47	0.46	0.83	1.77	0.38	0.28	1.57	1.86	0.42	0.37	1.20
Berm zone	2	9401	3	1.98	0.41	0.42	0.82	2.07	0.43	0.00	0.65	2.02	0.42	0.21	0.73
Foredune	3	9401	3	2.03	0.44	0.39	0.59	2.17	0.48	−0.26	0.60	2.10	0.46	0.07	0.59
Dunefield	4	9401	3	2.00	0.48	0.31	0.84	1.91	0.44	0.50	1.05	1.96	0.46	0.41	0.95
Correlation with geomorphological zone				0.09	0.14	0.31	0.13	−0.1	0.13	−0.1	0.11	−0.14	0.16	−0.24	0.05
Test for significance at $\alpha = 0.05$				NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Correlation with date number				−0.45	0.73	0.64	−0.48	−0.28	0.88	−0.01	0.16	−0.45	0.95	0.35	−0.06
Test for significance at $\alpha = 0.05$				NO	YES	YES	NO	NO	YES	NO	NO	NO	YES	NO	NO
Average per date															
All		9307	1	2.18	0.35	0.18	1.05	2.13	0.31	0.17	0.92	2.15	0.33	0.18	0.99
All		9309	2	2.29	0.40	0.13	1.26	2.19	0.39	0.15	1.21	2.24	0.39	0.14	1.24
All		9401	3	1.99	0.45	0.40	0.77	1.96	0.43	0.13	0.97	1.98	0.44	0.26	0.87
Correlation with date number				−0.50	1.00	0.50	−0.50	−0.50	1.00	1.00	0.50	−0.50	1.00	0.50	−0.50
Test for significance at $\alpha = 0.05$				NO	YES	NO	NO	NO	YES	YES	NO	NO	YES	NO	NO
Average per geomorphological unit															
Beach	1	All		2.11	0.41	0.26	0.98	2.01	0.36	0.25	1.18	2.06	0.39	0.26	1.08
Berm zone	2	All		2.17	0.39	0.27	1.00	2.20	0.38	0.14	0.89	2.17	0.39	0.20	0.94
Foredune	3	All		2.22	0.36	0.26	1.13	2.18	0.38	−0.01	0.90	2.23	0.37	0.12	1.02
Dunefield	4	All		2.12	0.43	0.16	1.00	1.98	0.38	0.23	1.17	2.05	0.41	0.19	1.08
Correlation with geomorphological zone				0.40	0.20	−0.55	0.65	−0.40	−0.40	−0.40	−0.20	−0.20	0.95	−0.80	0.15
Test for significance at $\alpha = 0.05$				NO	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	NO

Spearman's rank correlation coefficients are given and tested for significance at $\alpha = 0.05$.

include the heavy mineral weight percentages, and the mineral composition of the heavy fractions determined using a petrographic microscope.

4. Results

The results of sieve analysis of the 409 spot samples are summarized in Table 1. In Appendix A, statistical parameters are given for each transect to show variation in grain size distribution. The grain size indicates some differences alongshore from the Sabaki river and locally between the various geomorphological units, but no consistent trend is observed in these transport directions. There are no real differences between the areas north and south of the Sabaki river; consequently data for both sectors are averaged and presented as a "combined north and south" column in Table 2.

Table 1 also shows the statistical measures of grain size distribution of the composite samples, calculated using the Folk and Ward (1957) procedure. The month, environmental unit and sector are indicated in the column headings. Grain size and textural descriptions of the Malindi Bay coastal sediments are based on this approach.

Fig. 3a–d show frequency curves of particle size distributions of composite sand samples from various geomorphological units during the southeast monsoon (July and September 1993) and northeast monsoon (January 1994).

From a visual inspection of Fig. 3a–d, it can be seen that the frequency grain size distribution curves taper off at a certain inflection point. A rough estimation of this

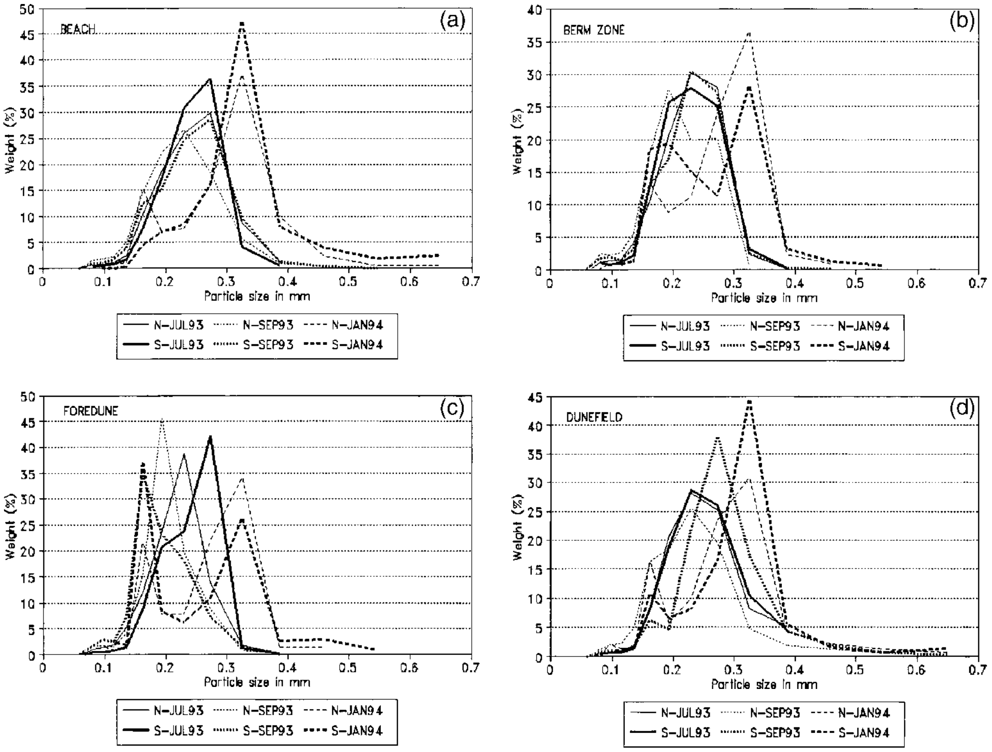


Fig. 3. Percentage of particle size distribution of composite samples for the northern and southern sectors, for two different seasons, southeast monsoon represented by July and September 1993 and northeast monsoon by January 1994: (a) beach, (b) berm zone, (c) foredune and (d) dunefield.

point is taken to be 5%. Hence if a grain size fraction contains more than 5% of the total composite sample then it can be regarded in the dominant size range (group of classes).

A summary of Spearman's rank correlations is presented in Table 2 and plots of mean size, sorting, skewness and kurtosis against geomorphological units for the combined data as shown in Fig. 4a–d.

Longshore variations in sediment size at each transect are shown in Appendix A. In this study area most of sand transport was associated with southerly and northeasterly winds which blew at high oblique angles across the beach. Consequently the change in grain size alongshore through transects appears to be more important than cross-shore through the various geomorphological units. No spectacular changes in the grain size distributions and derived parameters were found alongshore. Only in areas close to the river mouth, about 3 km southward and northward, was a slight decrease in the mean sediment size with distance from the river discernible in the geomorphological units. This tendency decreases further from the river.

During all the three observation periods there was fining of grain size from the beach to the foredune. The grain size trend seems to be consistent with the percentage of the coarse fraction (1.50–1.75∅) in the samples, as shown in Fig. 5. Sorting of sediments on the foredune was better than on the beach and berm zone during the southeast monsoon (9307, 9309), but became less well sorted during the northeast monsoon (9401).

The correlations and significance tests (Table 2) seem to indicate that the differences in grain size distribution between the seasons are much larger than those between the geomorphological units. This might be more clear from the graphs (Figs. 3–5).

During the northeast monsoon, the beach and dune materials were generally coarser, sorting was worse and the distribution was more positively skewed. Except for the beach, the distribution was more platykurtic (smaller kurtosis) and bimodal during the northeast monsoon, compared to the southeast monsoon.

Figs. 4a and 5 show that (i) coarser material arrives on the beach during the northeast monsoon. It is moved mainly southward by the plume, and gets deposited on the beach; material is reflective of a northeast monsoon signature; (ii) during the northeast monsoon, some coarse material moved to the north for reasons that are not as yet clear, though we could invoke some contribution from the Tana river further north of the study area, as mentioned in Abuodha (1998); (iii) the new material influxes on the beach are rapidly reflected in the grain size composition of the berm zone, foredune and the dunefield; this occurs during one season and points to a very active aeolian system.

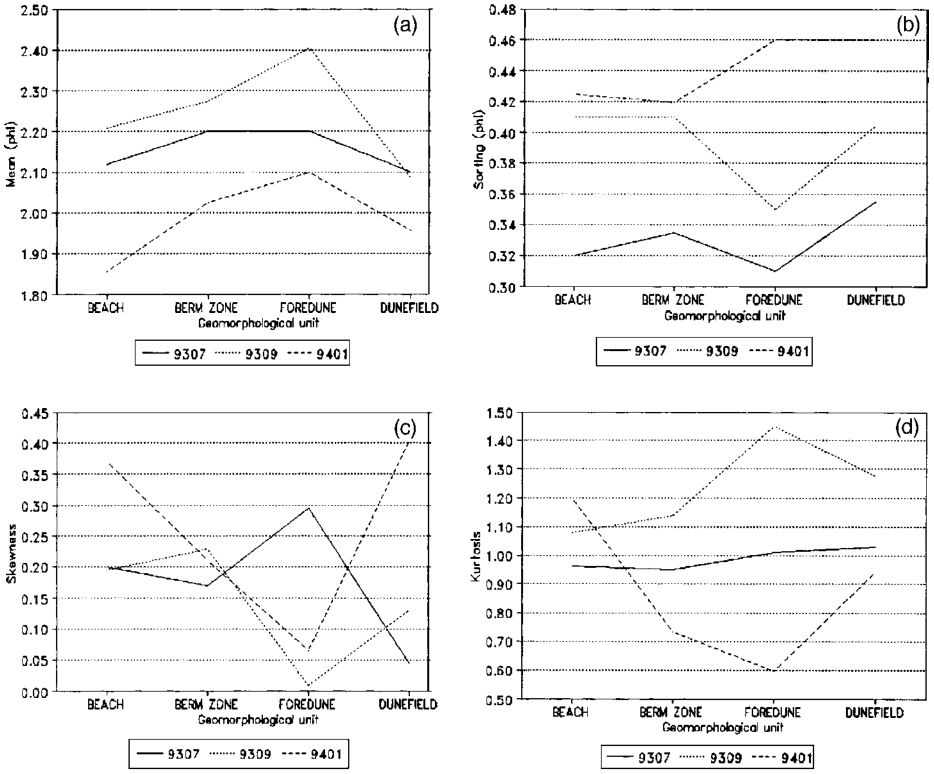


Fig. 4. Cross-shore variations in (a) sediment size, (b) sorting, (c) skewness and (d) kurtosis, calculated by the Folk and Ward (1957) formulae.

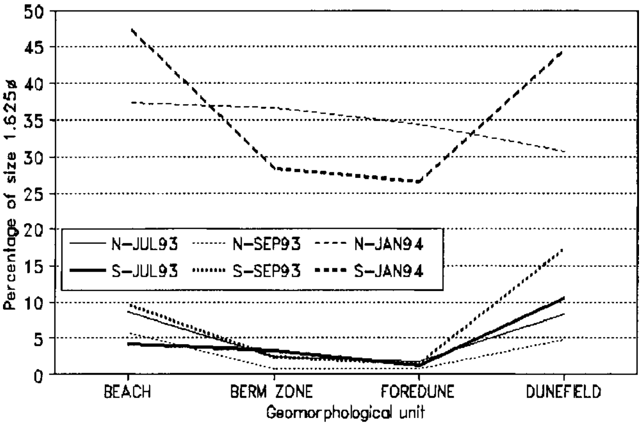


Fig. 5. Weight percentage of particle size 1.625∅ as a function of distance from the beach in July 1993, September 1993 and January 1994.

4.1. Heavy mineral contents

In Table 3 the heavy mineral contents in weight percentages are given. Aside from one exception (MBR/12), a rather subtle decrease of these values with increasing distance from the river is evident in the samples collected (Table 3). Although relative abundance of the heavy mineral component showed general variation along the beach, it was also evident from field observations that the highest concentration was present in the upper shoreface compared to other levels of the beach.

From the samples analyzed, the highest heavy mineral concentration was found to be 67%, on the berm zone close to the river mouth; from visual observations these values may reach as high as 95% near the banks of the Sabaki river. Generally, the heavy mineral concentration in the dunes is higher than on the beach and in the berm zone, except for locations close to the river mouth.

The heavy mineral suite consists largely of opaque iron–titanium minerals (ilmenite, hematite, magnetite) with subordinate red garnet and zircon and other minerals with economic value. Examination of samples from the Malindi Bay dunes yielded the results presented in Table 4.

5. Discussion

Beaches along the shores of Malindi Bay consist predominantly of terrigenous minerals. Quartz is the most abundant in the sands. Dune sediments were piled up by onshore winds transporting wave-reworked sand in the 4.125–0.625∅ (0.06–0.65 mm) size range, which had been supplied to the beaches by the Sabaki river.

Table 3
Weight percentages of the heavy residues of samples collected from the beach, berm zone and sand dunes of the Malindi Bay area

Sample	Unit				
	Month	Beach	Berm zone	Dune	Average
MGC/2	March 1994	5.5	3.4	7.2	5.4
SBK/4	March 1994	26.5	–	31.3	28.9
Sabaki river					
SBK/7	March 1997	7.5	67.0	32.4	35.6
MBR/9	March 1994	6.8	19.7	11.4	12.6
MBR/10-1	March 1994	6.5	5.6	13.4	8.5
MBR/10-2	March 1997	0.2	4.4	10.8	5.1
MBR/12	March 1997	2.5	10.4	16.4	9.8
Average		7.9	18.4	17.6	14.6

Table 4
Grain count analyses (%) of heavy mineral concentrates from the Malindi Bay dunes

Mineral	SBK/4	MBR/7	MBR/9	MBR/10-1
Ilmenite[a]	21.4	35.0	29.0	40.3
Hematite[a]	45.5	47.9	38.7	32.5
Magnetite[a]	0.6	0.5	1.4	0.2
Rutile	4.3	0.3	5.2	1.3
Zircon	9.1	0.2	4.0	1.2
Titanite	1.1	0.1	0.4	0.2
Others[b]	18.0	16.0	21.3	24.3
	100.0	100.0	100.0	100.0
% HM in sample	28.9	35.6	12.6	8.5

[a] Predominant mineral of Fe–TiO_2 intergrowths.
[b] Garnet, Epidote, Hornblende, Tourmaline, Augite, a.o.

Because of the small range in grain size distribution (more than 95% between 1.0$\varnothing$ and 3.0$\varnothing$), distinction in the transported sand was subtle. Beach and dune sediments were mostly characterized by a sorting of less than 0.50$\varnothing$ and a skewness less than 0.40 (rarely greater than 0.40). The beach and dune sediments can generally be classified as well or very well sorted fine- to medium-grained sand. Most of the beach and dune sediments showed near symmetrical distributions or possessed a distinct fine tail and were consequently found to be positively skewed; effect of selective transport by waves and wind reduces the relative proportions of smaller grains. This feature is to some extent demonstrated by a significant Spearman's rank correlation between the mean grain size and skewness (Table 1; $r' = -0.45$, $n = 24$ and $p < 0.05$). Of all 409 samples, 3% were found to be negatively skewed. The data in Table 1 show that there was a significant Spearman's rank correlation ($r' = -0.61$; $n = 24$; $p < 0.05$) between the maximum observed size and sorting; it is apparent that the sorting gets worse with increase in size of the coarsest fraction. Note that coarse grains imply proximity to sediment source and/or high energy transport medium and/or fresh influx of fresh river sediments; under these conditions sorting is poorer.

In the following three sections, longshore, geomorphological (cross-shore) and seasonality in the trends of the grain size distribution are discussed.

5.1. Lateral gradation of sediments

5.1.1. Longshore

Ibe (1988) has similarly noted in beach sediments of the Niger Delta in Nigeria that there are longshore variations only in areas close to the river mouth. This is to be expected; sediments from areas far removed from rivers have undergone a great deal of reworking and hence the loss in the trend of grain size diminution. Sorting, skewness and kurtosis apparently show no longshore trend.

According to accepted sedimentological wisdom, grain size generally decreases in the direction of transport (e.g. Krumbein, 1938; Bird, 1969; Allen, 1970); in the beach, grain size should theoretically decrease parallel to the longshore current. Allen (1970) has distinguished two processes that cause decrease in grain size and improved sorting in the direction of transport: (i) differential entrainment—in which particles of one size and/or density are transported faster than particles of another, and (ii) selective entrainment—in which a decrease in the direction of transport of energy level of the medium, momentum exchange between the grains, bed and fluid, and dependence of threshold speed on grain size, act together to reduce the probability that grains of a given size will continue to be transported.

In the field, the pattern in grain size distribution was complicated by the presence of vegetation, heavy mineral concentrations, bioturbation, surface markings, ripples, swash bars and runnels, each characterized by a change in sediment type. In addition, dilution with freshly transported fluvial and aeolian material could not always be avoided in sampling, resulting in "contamination" of surface material.

Allen (1970) reasoned that if the sediment supply and transport are sustained for long enough, then a steady-state develops and all traces of grain size diminution due to differential transport are lost. This is not easy to determine practically and therefore Allen's (1970) hypothesis is far from conclusive as the processes of sediment entrainment, transport and deposition are still far from being well understood.

5.1.2. Geomorphological units

The use of grain size analysis as a basis for distinguishing beach sands and dune sands has been extensively discussed in the past (e.g. Friedman, 1961; Goldsmith, 1985; Hartmann, 1991; Arens, 1994; Van der Wal, 1999), and in various studies it has been demonstrated that dune sands are better sorted and often finer than beach sands. Pye (1991) observed in northwest England that the grain size distribution in the beach and dune was essentially similar and concluded that aeolian sand is not grain size selective when the source beach sediments are fine-grained and well sorted. According to Leader (1982), lack of size distinction across-shore can be attributed to the short distance that sediments cover during transport across the narrow confines of the beach-dune system.

The present results show that during the southeast monsoon, the finer particles were selectively moved from the beach and berm zone and were deposited together on the foredune, giving rise to the fine grade and the good sorting. Vegetation may also be a factor influencing grain size selection processes in the foredune where the coarser material will move as creep, whereas the finer saltating sand will be trapped, both because of a decreasing wind speed and the physical obstruction.

Comparing only the aeolian geomorphological units at Malindi during the three observation periods, dunefield sediments were on average coarser grained and less well sorted than the berm zone and foredune, indicating an environment that was undergoing active change and that episodic mass movement of sand was more important than the normal sorting processes. Complex topography in the dunefield would augment wind acceleration processes. The more seaward geomorphological units are characterized by lags which result from continuous differential sorting by wind. Arens (1994) suggested that decreased sorting could result from a narrow grain size distribution of source sediments. The combination of various modes of transportation (creep, saltation and suspension) may lead to a sediment with poorer sorting (Visher, 1969). The latter model seems to be more consistent with our field observations. However, it is important to note that all these changes are only relative, and they are not always well marked in this study.

Kurtosis increased (narrower range of grain size) slightly from the beach to the foredune during the southeast monsoon (July and September 1993), but decreased (wider range of grain size) during the northeast monsoon. Only during the northeast monsoon was the skewness found to become less positive from the beach to the foredune (near symmetrical). Skewness showed no trend at all during the southeast monsoon, but it can be noted that the distribution was near symmetrical at the foredune in September 1993.

The beach sediment distribution showed a coarse truncation at the sand size 0.625∅, which was evidently absent on the adjacent berm zone and foredunes, where the coarse truncation occurs at 1.125∅. This implies firstly, that it is only the fraction finer than 0.625∅ that was transported as longshore drift, because the beach material reflects the size grades that are movable by longshore current. Secondly, there was apparent manifestation of only the size fractions finer than 1.125∅ being involved in aeolian transport from the beach into the immediate geomorphological units. However, coarser particles were found in the interdune valleys and steep slopes of sand sheets. It seems that the steep slopes of sand sheets and the interdune valleys provide an environment conducive for the preferential concentration of coarse sand (lag deposits); this fraction enters the system in small concentrations which cannot be detected on the berm zone and the foredune.

5.1.3. Seasonality

According to Fig. 3, some of the supersamples are bimodal—this distribution being a consistent feature of aeolian units during the northeast monsoon. The fine mode occurred at a grain diameter of 2.625∅, while the coarser mode, which was the dominant one, lay at a diameter of about 1.625∅. The problem of bimodal supersamples is noted—this property is particularly inherent in individual spot samples obtained during the northeast monsoon. However, bimodality is unlikely to affect Folk and Ward (1957) graphical parameters as in the case of arithmetic moments. The results seem to indicate an increased influx of coarser and poorer sorted source material from the Sabaki river during the northeast monsoon.

5.2. Heavy mineral lag formation

Differential grain entrainment through size and density has been highlighted by many authors (e.g. Barrie, 1981; Komar and Wang, 1984; Reid and Frostick, 1985). Differential grain entrainment is illustrated by the concentrations of heavy minerals which are left behind as lag deposits.

By comparing sand sizes in the berm zone with those found in the dunefield, the relative importance of grain size in heavy mineral lag formation can be inferred. Light quartz grains are entrained selectively because they are larger (standing proud of the bed) than the coexisting heavy minerals; they are subject therefore, to greater lift and drag. Alternatively, we can base our inference on threshold speeds of the quartz and heavy minerals; where the threshold speed of only the quartz grains is exceeded, a heavy mineral lag is created. Alongshore decrease in heavy mineral concentration can be explained if we assume that the combined wave/current energy decreases in the direction of transport.

Along the Malindi Bay coast concentration of heavy mineral deposits seem to be associated with moderate wave energy and high sediment fluxes, such as are observed in depositional environments. However, studies in North America, and from Dar-es-Salaam, seem to contradict this view. Here, concentration of heavy minerals occur when two conditions are fulfilled: (i) high wave energy and (ii) low sand supply. So the concentration process may also be related to erosion (Fay M.B., pers. commun., 1990).

5.3. Prospecting for heavy minerals

No full-scale mining operations and marketing of the heavy minerals have been conducted because previous investigations based on scanty data suggested that such a venture may not be economical. However, due to the fact that processing technology has been improved since that time and there is increased industrial demand for these raw materials, it is imperative that the reserves be reclassified.

The present study shows that the heavy mineral content ranges between 0.2% and 67.0% with an average grade of the order of about 15%. Especially in the berm zone, it was observed that these values may reach as high as 95%; this was also noted by Abuodha and Nyambok (1991). Under existing conditions, an average grade of at least 5%, but probably higher, would be required for economic operation. The main constituents are iron–titanium minerals as well as some red garnet and zircon.

The present results provide arguments for reconsidering the conclusions from previous studies. However, further investigations are still required to establish the economic feasibility of mining these deposits. The present infrastructure of roads, shipping facilities, bulk loading/or bagging, electrical supply, local product demand, and local fabrication facilities and personnel are suitable for beach mining. On the basis of the present findings, an extensive exploration program seems justified in order to locate old berm deposits covered by wind blown sand.

It will be necessary to use mechanical excavation or more sophisticated deep drilling techniques in the course of a mining development program and consideration could be given to the recovery of heavy minerals by wet concentration and washing. Exploitation in this environment could best be achieved by light mobile mining equipment or manual excavation. However, before actual mining and processing of the economic minerals, an environmental impact assessment of such a mining project is required (Abuodha, 2002) and a pilot plant must be constructed to confirm these methods.

6. Conclusions

1. The Malindi Bay coast is dominated by terrigenous sediments which are mostly composed of fine- to medium-grained quartz sand. In general, the beach and aeolian sands showed near symmetrical distributions or slight positive skewness, or possessed a distinct tail of fine particles and were consequently found to be positive to very positively skewed.

2. Heavy mineral content within the samples analyzed averaged 15%, with the highest concentrations of up to 67% in the berm zone close to the river mouth. Decreasing heavy mineral percentages away from the river mouth was manifest. The heavy mineralogy is dominated by opaque iron–titanium minerals as well as some red garnet and zircon.

3. On the beach and in the aeolian system, there were no spectacular changes in sand size from one end of the study site to the other. Slight longshore variations in sand size in all geomorphological units was only discernible along the stretch close to the river mouth. The pattern in grain size distribution was complicated by the presence of vegetation, heavy mineral concentrations, bioturbation, surface markings, ripples, swash bars and runnels, each characterized by a change in sediment type, and by admixture with freshly transported fluvial and aeolian material resulting in "contamination".

4. Although not always well marked, there were some differences between the various geomorphological units, partly indicating cross-shore variations. During all of

the three observation periods, mean grain size (and percentage of coarse material) decreased slightly from the beach to the foredune. Compared to the beach and berm zone, sorting improved slightly during the southeast monsoon, but became worse during the northeast monsoon.

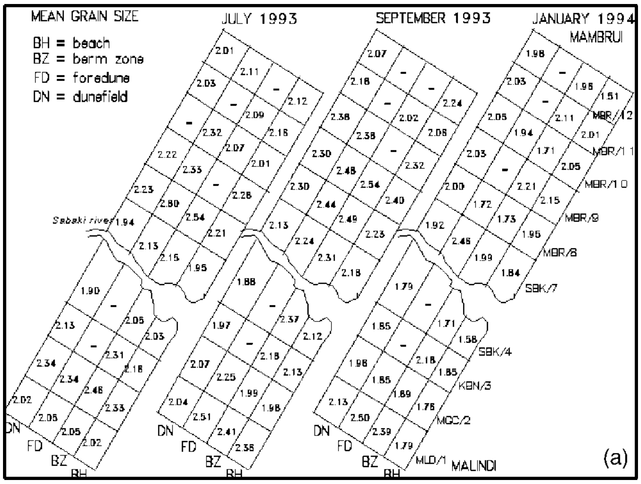
5. Whereas the differences in grain size distribution between the geomorphological units were relatively small, the differences between the southeast and northeast monsoon seasons were much larger. An increase in mean sediment size (smaller phi), worse sorting and more positively skewed distribution were discernible during the northeast monsoon season when compared to the southeast monsoon season. Except for the beach, the distribution is more platykurtic (smaller kurtosis) during the northeast monsoon compared to the southeast monsoon. With increasing sizes, bimodality becomes more manifest. The above effects may be related to the increased contribution to the beach of freshly immature river sands which were generally slightly coarser during the northeast monsoon. The fact that this sediment was found in all geomorphological units indicates that it was transported over the entire system (beach, berm zone, foredune, dunefield) during one season. Thus, this is a very active aeolian system.

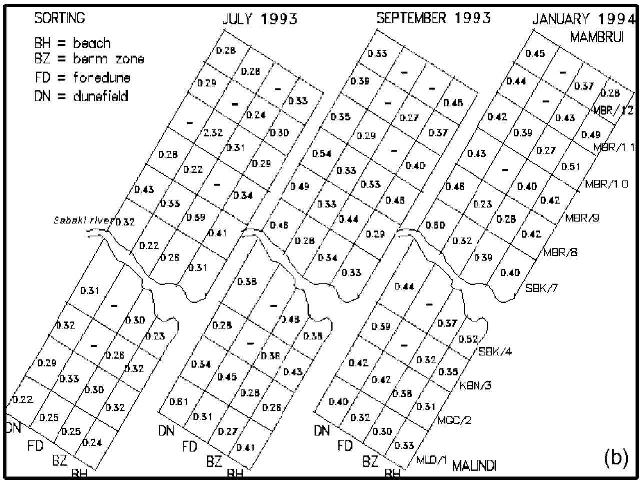
Acknowledgements

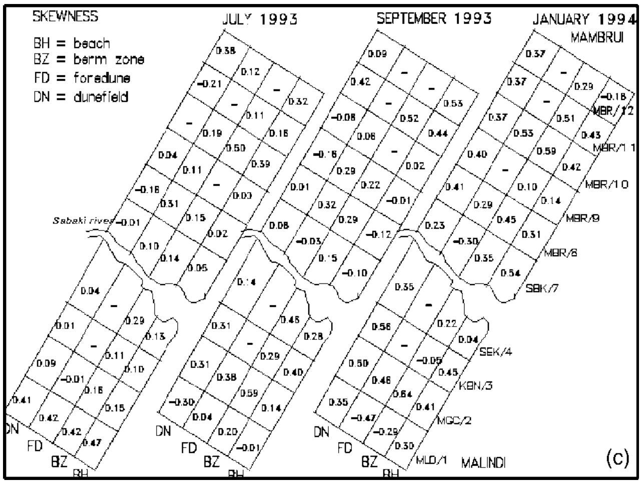
The research was financially supported by the Netherlands University Foundation for International Cooperation (NUFFIC) and the University of Amsterdam. Mr. P.O. Orango, Mr. S.K. Kazungu, Mr. C.H. Mwamtsi and Mr J.C. Mwaduna assisted in the field. Mrs. P.A. Abuodha helped with the sieving. Dr. Ir. J.H. van Boxel, Prof. M.P. Tole and Prof. P.D. Jungerius are acknowledged for their critical comments on the manuscript. Prof. T.C. Davis is thanked for a thorough check of the English structure and grammar. I finally wish to acknowledge invaluable comments from two anonymous reviewers which greatly improved the quality of this paper.

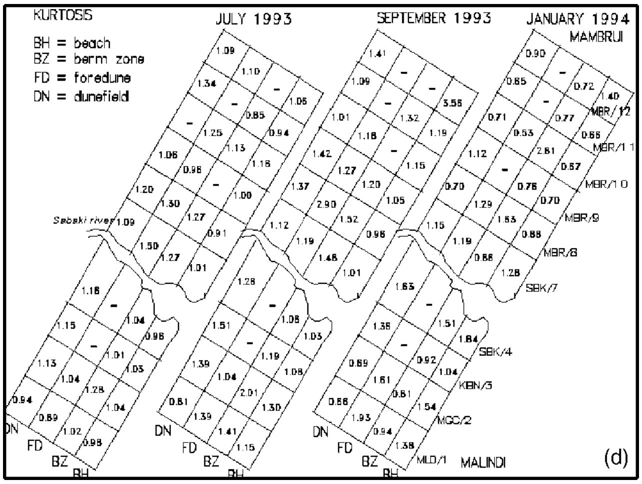
Appendix A

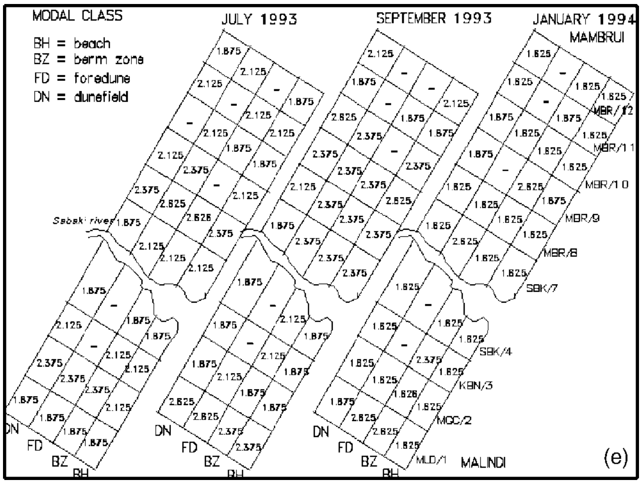
Sketch maps showing cross-shore and longshore variations per transect of (a) mean size, (b) sorting, (c) skewness, (d) kurtosis, (e) modal class, (f) percentage of 1.625∅, (g) percentage of 1.875∅ and (h) percentage of 2.125∅.

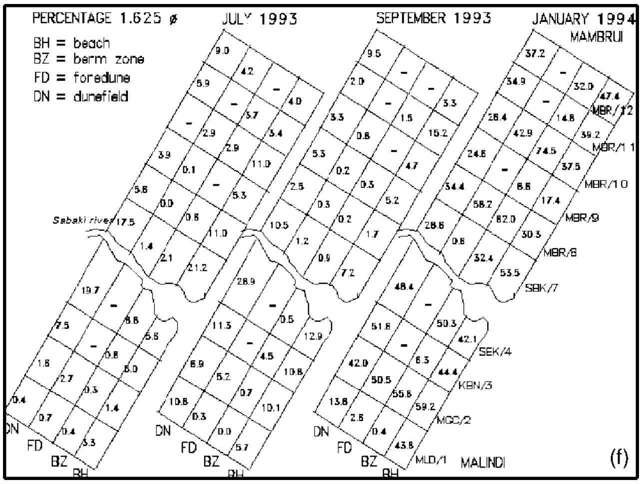


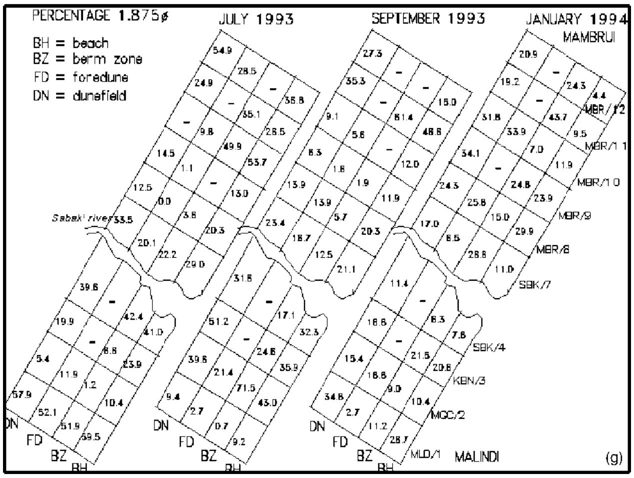


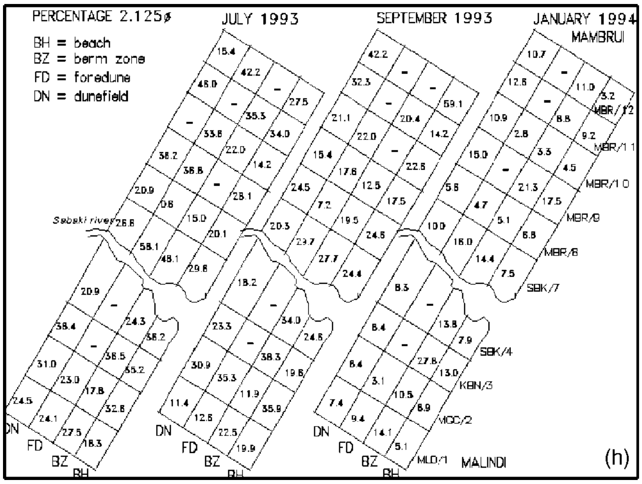












References

Abuodha, J.O.Z., 1998. Geology, geomorphology, oceanography and meteorology of Malindi Bay. In: Hoorweg, J. (Ed.), Coastal Ecology Series, vol. 4. English Press Limited, Nairobi, pp. 17–39.

Abuodha, J.O.Z., 2000. Geomorphology of the Malindi Bay coastal sand dunes. Ph.D dissertation, University of Amsterdam, The Netherlands, 179 p.

Abuodha, J.O.Z., 2002. Environmental impact assessment of the proposed titanium mining project in Kwale District, Kenya. Marine Georesources and Geotechnology 20, 199–207.

Abuodha, J.O.Z., Nyambok, I.O., 1991. Petrology, geochemistry and evaluation of heavy mineral deposits, coastal Malindi and Ungama Bay, Kenya. Marine Mining 10, 337–351.

Allen, J.R.L., 1970. Physical processes of sedimentation: an introduction. In: Sutton, J. (Ed.), Earth Science Series, vol. 1. George Allen and Unwin., 248 p.

Arens, S.M., 1994. Aeolian processes in the Dutch foredunes. Ph.D. dissertation, University of Amsterdam, The Netherlands, 150 p.

Baba, J., Komar, P.D., 1981. Measurements and analysis of settling velocities of natural quartz sand grains. Journal of Sedimentary Petrology 51, 631–640.

Barndorff-Nielsen, O.E., Christiansen, C., 1988. Erosion, deposition and size distributions of sand. Proceedings of the Royal Society of London A 417, 335–352.

Barndorff-Nielsen, O.E., Christiansen, C., Hartmann, D., 1991. Distributional shape triangles with some application in sedimentology. Acta Mechanica 2, 37–47.

Barrie, J.V., 1981. Hydrodynamic factors controlling the distribution of heavy minerals (Bristol Channel). Estuarine and Coastal Marine Science 12, 609–619.

Beinge, F.W., 1957. Report on the Kenya coastal sand—Sabaki river area. Unpublished manuscript, Mines and Geological Department, Nairobi.

Bird, E.C.F., 1969. Coasts: An Introduction to Systematic Geomorphology. The MIT Press, Cambridge, 246 p.

Christiansen, C., Hartmann, D., 1988. On using the log–hyperbolic distribution to describe the textural characteristics of aeolian sediments—a discussion. Journal of Sedimentary Petrology 58, 159–160.

Fay, M.B., 1989. Grain-size analysis program package. Department of Geology, University of Dar es Salaam, Tanzania.

Folk, R.L., Ward, W.C., 1957. Brazos River Bar: a study on the significance of grain size parameters. Journal of Sedimentary Petrology 27, 3–26.

Friedman, G.M., 1961. Distinction between dune, beach and river sands from their textural characteristics. Journal of Sedimentary Petrology 31, 514–529.

Friedman, G.M., Sanders, J.E., 1978. Principles of Sedimentology. Wiley, New York, 792 p.

Fuechtbauer, H., Mueller, G., 1977. Sedimente und sedimentgesteine. Stuttgart, 784 p.

Gock, E., Jacob, K.H., 1978. Method of processing used to obtain synthetic titanium dioxide through the direct dissolution of rutile using sulphuric acid—German patent application. Deutsche Patentanmeldung, No. 2855-4678, pp. 12–19.

Goldsmith, V., 1985. Coastal dunes. In: Davis, R.A. (Ed.), Coastal Sedimentary Environments. Springer-Verlag, New York, pp. 171–236.

Halse, J.E.P., 1980. Formosa Bay heavy mineral beach sand deposits. Initial exploration report. Mines and Geological Department, Ministry of Environment and Natural Resources, Naiorobi, Kenya, 101 p.

Hartmann, D., 1991. Cross-shore selective sorting processes and grain size distributional shape. Acta Mechanica 2, 49–63.

Hove, A.R.T., 1980. Some aspects of current sedimentation, depositional environments and submarine geomorphology of Kenya's submerged continental margins. University of Nairobi, IDS/OP 28, pp. 127–144.

Ibe, A.C., 1988. Coastline Erosion in Nigeria. Ibadan University Press., 217 p.

Inman, D.L., 1952. Measures for describing the size distribution of sediments. Journal of Sedimentary Petrology 22, 125–145.

Kenya Ports Authority 1993/1994. Tide tables for Kenya and Tanzania.

Komar, P.D., Cui, B., 1984. The analysis of grain-size measurements by sieving and settling-tube techniques. Journal of Sedimentary Petrology 54, 603–614.

Komar, P.D., Wang, C., 1984. Processes of selective grain transport and the formation of placers on beaches. Journal of Geology 92, 637–655.

Krumbein, W.C., 1938. The analysis of observational data from natural beaches. Beach Erosion Board, Technical Memo 130, Corps of Engineers, Washington, DC.

Krumbein, W.C., Pettijohn, F.J., 1938. Manual of Sedimentary Petrography. Appleton-Century Crofts, New York, 549 p.

Leader, M.R., 1982. Sedimentology: Process and Product. Allen and Unwin, London, 479 p.

Musila, W.M., 1998. Floristic composition, structure and distribution patterns of coastal sand dune vegetation: a case study of the coastal dunes between Malindi and Mambrui. M.Phil. dissertation, Moi University, Eldoret, Kenya, 160 p.

Pulfrey, W., 1942. Report on alleged Gedi silver-lead deposits. Unpublished manuscript, Mines and Geological Department, Ministry of Environment and Natural Resources, Nairobi, Kenya.

Pye, K., 1991. Beach deflation and backshore dune formation following erosion under surge conditions: an example from Northwest England. Acta Mechanica 2, 171–181.

Reid, I., Frostick, L., 1985. Role of settling, entrainment and dispersive equivalence and of interstice trapping in placer formation. Journal of the Geological Society, London 142, 739–746.

Ryan, W.A., 1953. Report of an investigation of the Silversands beach sands, near Malindi. Unpublished study, Mines and Geological Department, Nairobi, Kenya.

Schroeder, J.H., Jacob, K.H., Gock, E., 1980. Coastal heavy mineral deposits of Kenya: characteristics, new methods of processing, economic potential. The Red Sea and Gulf of Aden Environmental Programme, Jeddah (ALECSO).

Thompson, A.O., 1956. Geology of the Malindi area. Report 36, Mines and Geological Department, Ministry of Environment and Natural Resources, Nairobi, Kenya, 63 p.

Trask, P.D., 1932. Origin and Environment of Source Sediments of Petroleum. Gulf Publishing Company, Houston, 323 p.

Visher, G.S., 1969. Grain-size distributional processes. Journal of Sedimentary Petrology 39, 1074–1106.

Van der Wal, D., 1999. Aeolian transport of nourishment sand in beach-dune environments. Ph.D. dissertation, University of Amsterdam, The Netherlands, 157 p.

Williams, L.A.J., 1962. Geology of the Hadu-Fundisa area, North of Malindi. Report 52, Mines and Geological Department, Ministry of Environment and Natural Resources, Nairobi, Kenya, 59 p.

Wyrwoll, K.H., Smyth, G.K., 1985. On using the log–hyperbolic distribution to describe the textural characteristics of aeolian sediments. Journal of Sedimentary Petrology 55, 471–478.