Depositional environment of sediments along the southern coast of Tamil Nadu, India

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Abstract

Grain size studies of sediments from beaches in the region from Mandapam to Kanyakumari, divided into 5 sectors, indicate that sediments are unimodal to polymodal in nature, coarse to fine grained, moderately to poorly sorted, and positively-negatively skewed in character. The inference to be drawn from these studies is that the variation in sedimentological parameters is governed by fluvial input, wave dynamics, and littoral transport of the sediments. Bivariant plots show that the Mandapam and Kanyakumari sectors can be classified as beach environments, whereas the Tuticorin and Valinokkam sectors come under the influence of riverine environments and the dune environment in the Manappad sector. The CM pattern of all five sectors shows a clustered distribution of sediments in the PQ and QR segments, indicating a graded mode of deposition. Visher diagrams depict a wave shadow environment for the Mandapam sector, whereas the Valinokkam, Tuticorin and Manappad sectors show double saltation populations characteristic of beaches, and the Kanyakumari sector is characterized

by a more truncated population characteristic of a plunge zone, which is a high-energy environment.

1. Introduction

Granulometric studies of beach sediments provide a wealth of information on the intrinsic properties of sediments and their depositional environment. Further, they help to delve into the nature and energy flux of the multifarious agents transporting the sediments. Systematic granulometric studies of the east and west coasts of India have been carried out by Rajamanickam & Gujar (1984, 1985, 1993), Chaudhri et al. (1981) and Rao et al. (2005). Especially along the northern and central Tamil Nadu coast, using textural parameters, Mohan (1990), Chandrasekar (1992) and Udayaganesan (unpublished) have made significant contributions in differentiating the environments of beach and river sediments. However, information is lacking on the grain size characteristics of such sediments and on the processes operating along the southern Tamil Nadu coast. The present study aims to fill this gap.

2. Study area

The study area extends from Mandapam to Kanyakumari on the southern coast of Tamil Nadu (India) (Fig. 1), over a distance of 360 km. It is bound in the north-east by Rameshwaram Island, in the east by the Bay of Bengal, in the west by the Eastern and Western Ghats, and in the south by Kanyakumari, the southernmost tip of India, which is the confluence of the Indian Ocean, Arabian Sea and Bay of Bengal. The drainage pattern of the study area is controlled mainly by perennial rivers like the Vaigai and the Tamiraparani, and non-perennial rivers like the Vaippar, Gundar, Virusuli and Vembar (Fig. 2).

The beaches in the study region are composed of rocky/sandy material. Taking into account the dominance of a particular rock type or lithological presence, the beaches are grouped into beaches of coralline or crystalline rocks. Coralline rocks are exposed in the coastal segment of the Tuticorin – Alantalai region (Fig. 1). At a few places, the calcareous sandstone shows a clear stratification with a seaward dip < 10. The marine calcareous sandstones, rich in quartz and feldspar, with embedded mollusc shells, are exposed in many places like Mandapam, Tiruchendur and Manappad in the high-tide and berm zones. At Tiruchendur, the exposed sandstone stands several metres above the mean tide level, suggesting that the relative Holocene sea level along this region probably stabilized after the cementation of the sand.

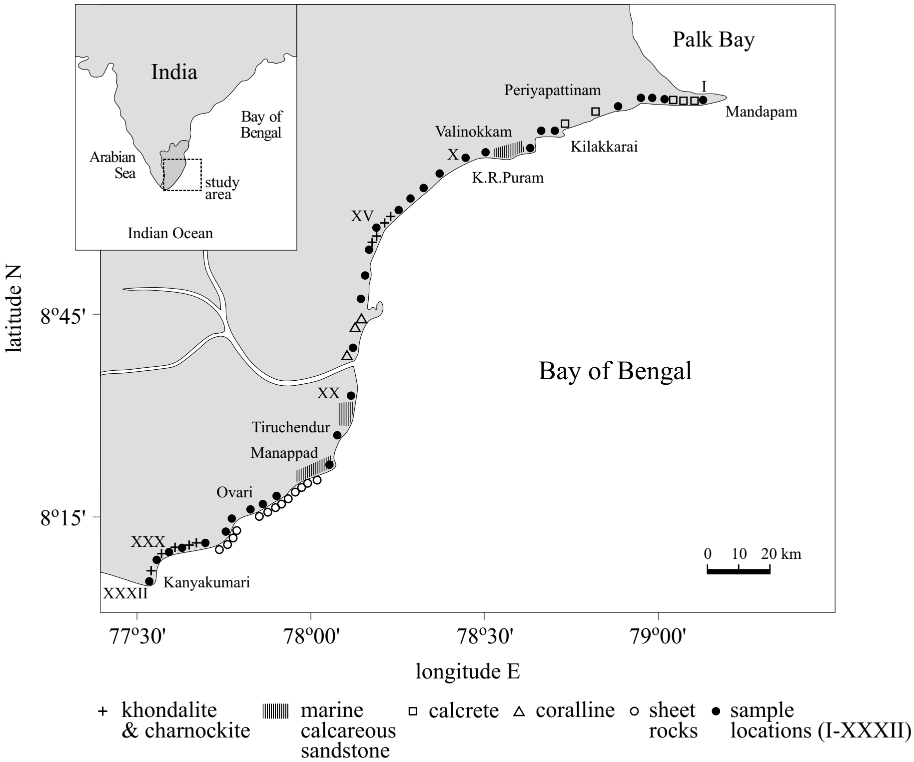

Fig. 1. Location map

Depending upon the nature of the beach sediments and their constituents, sandy beaches are grouped into calcareous, siliceous, algal/seaweed-rich, heavy mineral-rich and muddy beaches. The beaches in the study region consist predominantly of quartz, feldspar and other siliceous minerals. The Mandapam–Valinokkam beaches are awash with considerable quantities of seaweeds in the low-tide region. In the Kallarvaippar region, the entire foreshore and backshore regions are carpeted with rich concentrations of black sands and garnets. Again, from Kuduthalai to Kanyakumari, black sand deposits are widespread. In the Kanyakumari region, the heavy mineral assemblages are represented by monazite, zircon, rutile, garnet, tourmaline, hypersthene, hornblende, apatite, and other flaky minerals like chlorite, as well as trace amounts of glaucophane, whereas in the Mandapam region, flaky minerals like chlorite, biotite and muscovite are dominant, but minerals like ilmenite, magnetite and monazite are completely absent. Muddy shores embrace the mouth of the Tamiraparani River. On the basis of various geomorphological features, drainage and lithology, the study area was divided into five sectors: Mandapam (stations I–VII), Valinokkam (stations VIII–XII), Tuticorin

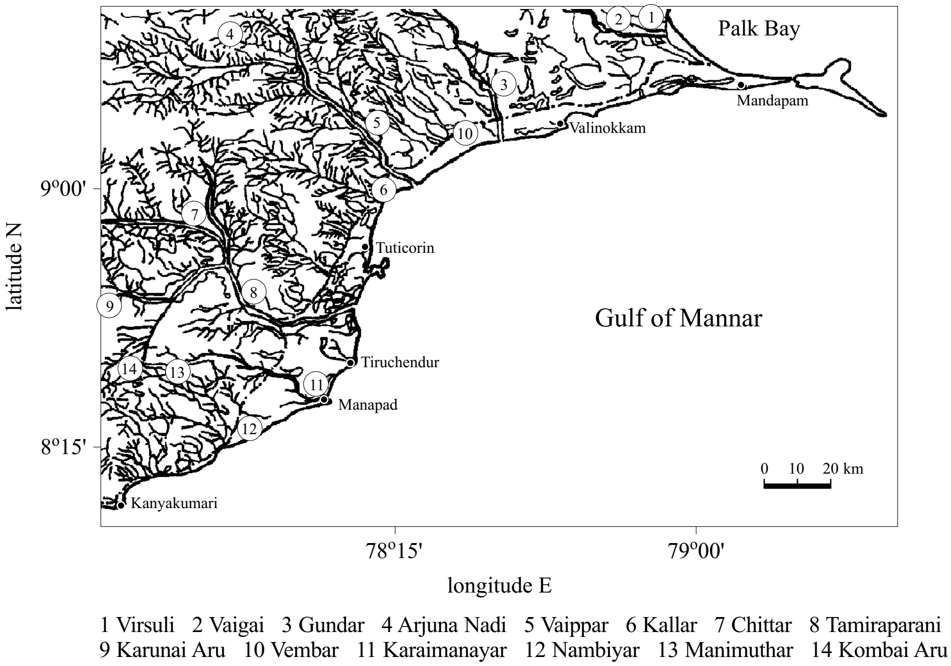

Fig. 2. Drainage pattern of the study area (rivers 1–14)

(stations XIII–XXI), Manappad (stations XXII–XXVI) and Kanyakumari (stations XXVII–XXXII), as shown in Table 1.

3. Methodology

During the month of June, samples were collected with a hand auger from the low-tide, high-tide and berm regions to a depth of 25 cm, while maintaining an interval of approximately 10 km between the sampling stations. In all, 96 samples were collected for detailed sedimentological analysis from 32 stations (Fig. 1). Wherever the beach was wide enough, samples were collected from the low- (LT) and high-tide (HT) zones and the berm regions. Care was taken to prevent contamination or mixing of the sediments. The bulk sample was reduced by coning and quartering, and a 100 gm portion of the sample was selected for laboratory analysis. Organic matter and ferruginous coatings were removed from the samples by treatment with 30% by volume H_2O_2 and $SnCl_2$. After this pre-treatment, the samples were sifted at 0.25 ø intervals through ASTM sieve sets using a Ro-Tap sieve shaker for 15 minutes. The sieved materials were collected and weighed. The carbonates present in the sediments were estimated after sieving by treatment with 1:10 HCl. Weight percentage frequencies and cumulative weight percentage frequencies were computed. The various

Table 1. Classification of the study area into five sectors

	Mandapam (stn. XXVI–XXXII)	Valinokkam (stn. XXIII–XXV)	Tuticorin (stn. XVI–XXII)	Manappad (stn. IX–XV)	Kanyakumari (stn. I–VIII)
type of material	calcrete rocks	calcrete rocks	coralline rocks	marine calcareous sandstone	crystalline rocks
gradient	1–3°	1–5°	1–3°	3–6°	2–4°
nature of the beach	calcareous	siliceous, scattered heavy mineral deposits	heavy mineral-rich calcareous	siliceous calcareous, muddy	heavy mineral-rich
configuration	E–W	NE–SW	NS	NNE–SSW	NE–SW
wave energy	inert zone	predominantly high energy	high energy-low energy	low energy-high energy	high energy
landforms	eight series of beach ridges, dunes, spits, paleochannels, marine terrace (3–5 m height)	cuspate foreland, marine terraces (5.5 m), 2–3 series of beach ridges	disturbed, discontinuous beach ridge one series, spits, mudflats	marine terraces (13.5 m height), wave cut platform, massive dune complex	discontinuous beach ridge, marine terrace (3.5 m height)
breaking wave height	0.10–0.15 m s^{-1}	0.20–0.60 m s^{-1}	0.15–0.60 m s^{-1}	0.28–0.68 m s^{-1}	0.60–1.20 m s^{-1}
current velocity	0.06–0.10 m s^{-1}	0.01–0.39 m s^{-1}	0.02–0.34 m s^{-1}	0.34–0.45 m s^{-1}	0.68–0.75 m s^{-1}
net littoral transport	87.75×10^3 m^3 yr^{-1}	47.26×10^3 m^3 yr^{-1}	243×10^3 m^3 yr^{-1}	2.03×10^3 m^3 yr^{-1}	28.03×10^3 m^3 yr^{-1}

graphic and moment measures were calculated with the formulae of Folk & Ward (1957). In accordance with the weight percentage data of the sediments, granulometric studies were undertaken using the modified programme of Schlee & Webster (1967).

4. Results and Discussion

At most of the stations in the Mandapam sector, the frequency curves are bimodal to polymodal in character, with peaks at 2.0, 3.0 and 3.25 ø (Fig. 3). The presence of finer populations at these stations, where there is

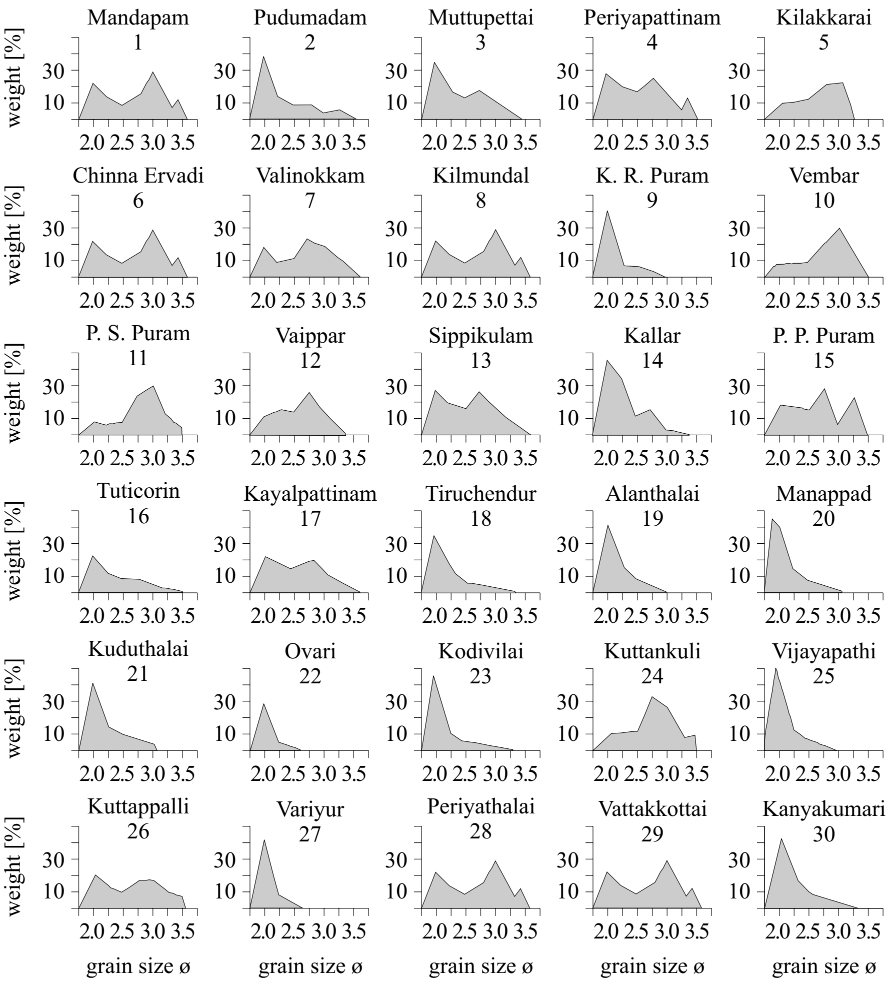

Fig. 3. Frequency distribution of sediments in different sizes in sectors: Mandapam 1–6, Valinokkam 7–10, Tuticorin 11–19, Manappad 20–23, Kanyakumari 24–30

no river inflow, is attributable to the deposition of sediments primarily by waves and currents. The greater influence of sea currents is corroborated by the findings of Loveson & Rajamanickam (1988), who, in the absence of any drainage pattern, have attributed spit growth at Periyapattinam to northward-flowing littoral currents. From the distribution of heavy minerals, Angusamy & Rajamanickam (2000) also confirmed the role played here by the littoral transportation of sediments.

In the Valinokkam sector, all the sediments are bimodal, except for the sample from K. R. Puram. Peaks were recorded for the 2.5 and 3.0 ø sizes, the 3.0 ø peak being the primary one. This bimodality is ascribable to the discharge of fine sediments from smaller rivers like the Vembar, Vaippar and Kallar (Fig. 2). The unimodality at K. R. Puram reflects the lack of sediment deposition from these rivers.

In the Tuticorin sector, the samples are also all bimodal, except for the one from P. P. Puram, where sediment is additionally deposited by the Tamiraparani River (Fig. 2). At P. P. Puram, the polymodal nature of the sediment, with a secondary peak at 3.25 ø, can be put down to the deposition of material from coralline rocks, in addition to the contribution from waves and currents.

In the Manappad sector, the sediments are unimodal with a dominant peak at 2.0 ø; the sediment here is supplied from a single, probably offshore, source.

The Kanyakumari samples are unimodal to bimodal. The bimodality at Kuttankuli (stn. XXXI) and Kuttappalli (stn. XXIX) is due to the additional sediments from the Hanuman Nadhi and Uppanar Rivers. The unimodal nature at the remaining stations reflects the deposition of sediments primarily by waves and currents.

4.1. Mean

In the Mandapam sector, the sediments are finer in the LT, HT and berm zones at stn. I–IV. A gradual southward coarsening of the sediments was observed at LT from stn. I (3.11) to stn. V (1.53). Agarwal (1988) reported the circulation of a clockwise current between Mandapam and Sethukkarai, leading to erosion at Sethukkarai (stn. V) and deposition at Mandapam (stn. I). As a result, finer sediments are deposited in the Mandapam area, and medium ones at Sethukkarai. From Kilakkarai to Ervadi (stn. VII), the presence of fine sediments is a reflection of the depositional environment; this is corroborated by the strong wave divergence prevailing in this region.

In the Valinokkam sector, the distribution of coarser sediments at K. R. Puram (av. 0.79), medium sediments at P. P. Puram (av. 1.38), Kallar (av. 1.55) and Vaippar (av. 1.43) is due to the prevailing high-energy environment, where wave orthogonals converge. At K. R. Puram, evidence for the presence of molluscan shells is provided by the 30 to 40% loss in residue from the total sediments when these were treated with HCl; as a result, the sediments are coarser.

In the Tuticorin sector, the sediments from Tuticorin itself (stn. XVIII) are very fine (2.90). This is due to the strong wave divergence or low-energy conditions in that region; the fact that a spit is growing at Tuticorin provides further confirmation. The fine sandy nature of the sediments at the remaining stations (stn. XIX–XXI) can be attributed to the low-energy conditions prevailing throughout the year, which help to deposit the fine sediments.

At stn. XXII in the Manappad sector, sediments are medium-grained at LT and HT, but finer in the berm zone. This is due to the high wave energy conditions, causing the finer sediments to be winnowed away offshore. The finer sediments in the berm zone supplement the deposition of sediments from the adjacent dunes and beach ridges by aeolian processes. At stn. XXIV, the distribution of coarser sediments at LT (0.78 ø) and HT (0.91 ø) indicates that beaches are exposed to open-sea conditions without any protection from promontories. However, the distribution of finer sediments (2.30 ø) in the berm zone suggests the influence of aeolian processes, which must have transported sediments in suspension as well as by traction.

In the Kanyakumari sector, sediments are fine-grained on both the fore- and backshore. Examination of the beach sediment composition reveals that from 70 to 80% of the finer sediments consist of heavy minerals. This indicates that under the prevailing high-energy conditions, the coarser but lighter materials must have been winnowed away, leading to the accumulation of heavy minerals of a finer size grade.

4.2. Standard Deviation

In the Mandapam sector, the fine sediments of both foreshore and backshore are moderately to better sorted, except at Periyapattinam (stn. V), where the sediments are poorly sorted. This corresponds well with the observations of Griffith (1951) and Inman & Chamberlain (1955) that fine sediments are better sorted than coarser to medium sediments.

In the Valinokkam sector at K. R. Puram (stn. XI), the poor sorting in the berm, HT and LT sediments is due to the presence of large amounts of shell fragments in the sands. This corroborates with Friedman & Sanders' (1978) observation that the presence of skeletal remains adversely affects the sorting of sediments. The better sorting at the other stations in this sector is due to the prevalence of wave convergence throughout the year.

In the Tuticorin sector (stn. XIII–XVI) the sediments are medium-grained; nevertheless, they are better sorted as a result of the prevailing high wave energy conditions there. At Tuticorin itself, however, the sediments are poorly sorted, even though their mean size is finer (stn. XVIII). The growth of the spit at Tuticorin impedes the movement of sediment-laden littoral currents; as a result, lateral updrift causes sediment deposition, especially in the northern part of the Tuticorin sector. In this process, the materials removed from the Tamiraparani River mouth are immediately deposited in the Tuticorin region, and no further sorting is possible. Besides the above, the deposition of fine sediments from the adjacent reefs may be a further factor causing the poor sorting of sediments. The better sorting at the remaining stations is probably due to the prevalence of wave convergence throughout the year and the finer size of the sediments.

At stn. XXII in the Manappad sector, the backshore sediments are poorly sorted, unlike the earlier stations mentioned. This can be explained by the presence of sand dunes known as 'teri' sands in the backshore region. Sediments blown away from the backshore by the wind may well have become mixed with the berm sediments; hence, sorting there is poor. However, LT and HT sediments are moderately well sorted because of the prolonged winnowing action of the waves. At Ovari (stn. XXV), the coarser sediments are poorly sorted. The Ovari beach is fringed by sheet rocks, and the coarser materials released from these rocks must have been mixed with the fine sediments brought by littoral currents, which has led to their poor sorting.

In the Kanyakumari sector, the berm, LT and HT sediments are well to moderately well sorted owing to the prevailing high-energy environment; the exception is the HT sample from stn. XXIX, where the poorer sorting is probably due to the coarser nature of the sediments.

4.3. Skewness

The sediments in the Mandapam sector are positively skewed. The unchanging skewness values from Mandapam to Chinna Ervadi indicate, except at Sethukkarai, that fine sediments are deposited by waves and currents under the prevailing low energy conditions. Duane (1964) observed that positive skewness characterizes the area of deposition. Evidence for such a mode of deposition is the Manappad-Danushkodi spit and the hook-shaped sandbar at Periyappattinam (stn. IV). Loveson & Rajamanickam (1988) have discussed the process of spit formation and progradation taking place at Periyapattinam. The disposition of four series of beach ridges alternating with swales supplies further evidence of the prograding nature of the coastline. However, at Sethukkarai, the sediments are negatively skewed owing to the influence of the cyclic current pattern, indicative of the high-energy environment prevailing there. The change in the skewness values is in line with the change in the energy conditions in this sector.

At K. R. Puram (stn. XI) in the Valinokkam sector, sediments are negatively skewed, indicating the higher-energy conditions obtaining there. Similarly, Chaudhri et al. (1981) have attributed the coarser sediments of Dwaraka beach to high-energy wave conditions.

At Kallar (stn. XVI) and Vaippar (XIV) in the Tuticorin sector, the sediments display a negative skewness, which points to higher-energy conditions. At Tuticorin, the sediments are uniquely positively skewed, which further reinforces the hypothesis regarding the depositional conditions prevalent there. The development of a spit at Tuticorin, primarily because sediments are being deposited there by northward-flowing currents, also attests to the progradational activity predominant there. At other stations in the Manappad and Kanyakumari sectors, the sediments are negatively skewed, which is indicative of the higher-energy conditions in these regions. This accords with Friedman's (1967) observation that the distributions of present-day beach sands are negatively skewed or symmetrical.

4.4. Binary Plots

The binary plots of mean vs standard deviation (Fig. 4a), skewness vs mean (Figs 4b and 4f), skewness vs standard deviation (Figs 4c and 4d), skewness vs kurtosis (Fig. 4e), reveal the dominant influence of the beach environment in the Mandapam, Manappad and Kanyakumari sectors. 30% of the samples from the Tuticorin and Valinokkam sectors are derived from riverine environments, probably due to the influence of the Tamiraparani River in the Tuticorin sector, and the Kallar and Vaippar Rivers in the Valinokkam sector. In the plot of mean vs standard deviation, the sediments display a better sorting, as the mean size of almost all the samples increases. The plots are broadly similar to those of Friedman (1967). However, in the skewness vs kurtosis plot, the influence of the coastal dune is manifested in the samples from the Manappad sector, where huge dune complexes adjoin the backshore region.

In the binary plots of first percentile vs standard deviation (Fig. 5a), the samples are typical of beach environments, except those from the Tuticorin and Valinokkam sectors. The distribution of a few samples from the Mandapam sector in the river environment could be due to the influence of littoral drift, by which process the sediments discharged by the nearby rivers in Valinokkam are carried away and deposited in the Mandapam region. The mean vs standard deviation plot (Fig. 5b) demonstrates the influence of the dune environment in the Manappad and Kanyakumari sectors. The

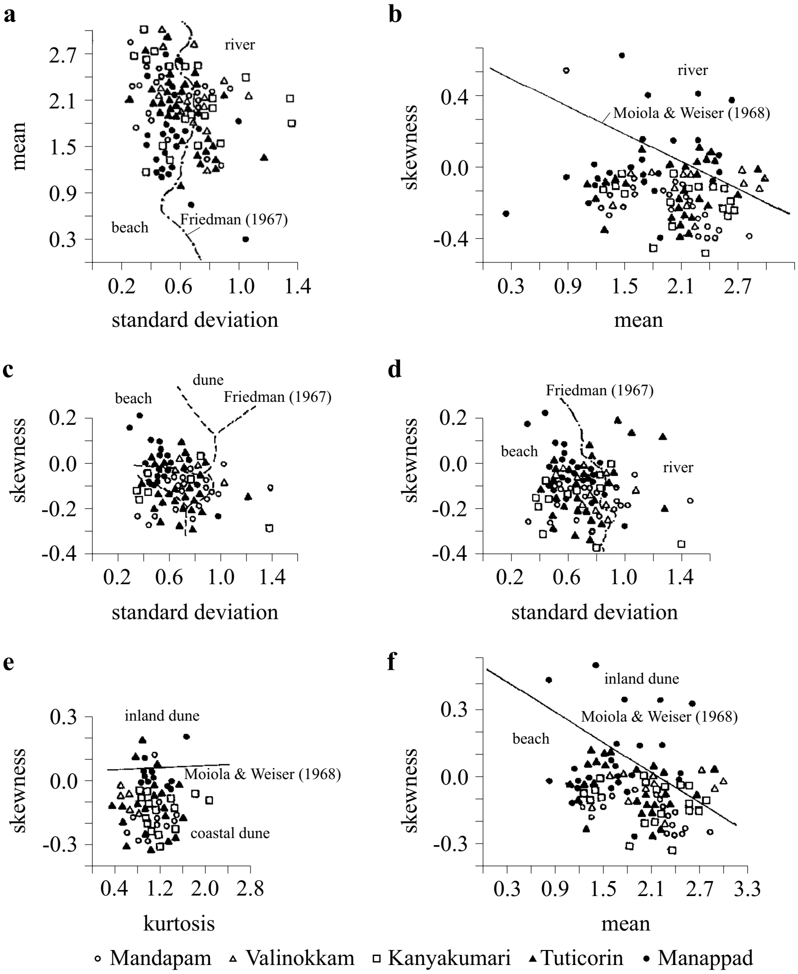

Fig. 4. Binary plots

effect of a riverine environment is characteristically brought to the fore in the Valinokkam and Tuticorin sectors in the plots of third moment vs first moment (Fig. 5c), moment mean vs moment standard deviation (Fig. 5d), skewness vs kurtosis (Fig. 5e), simple skewness measure vs simple sorting measure (Fig. 5f).

4.5. CM Pattern

The CM pattern (Passega 1964) of the study area shows an overall distribution of samples in the PQ and QR (Fig. 6) segments between C = 100 and 900 microns and between M = 100 and 600 microns. The position of the dividing line 300 microns away from the normal pattern suggests

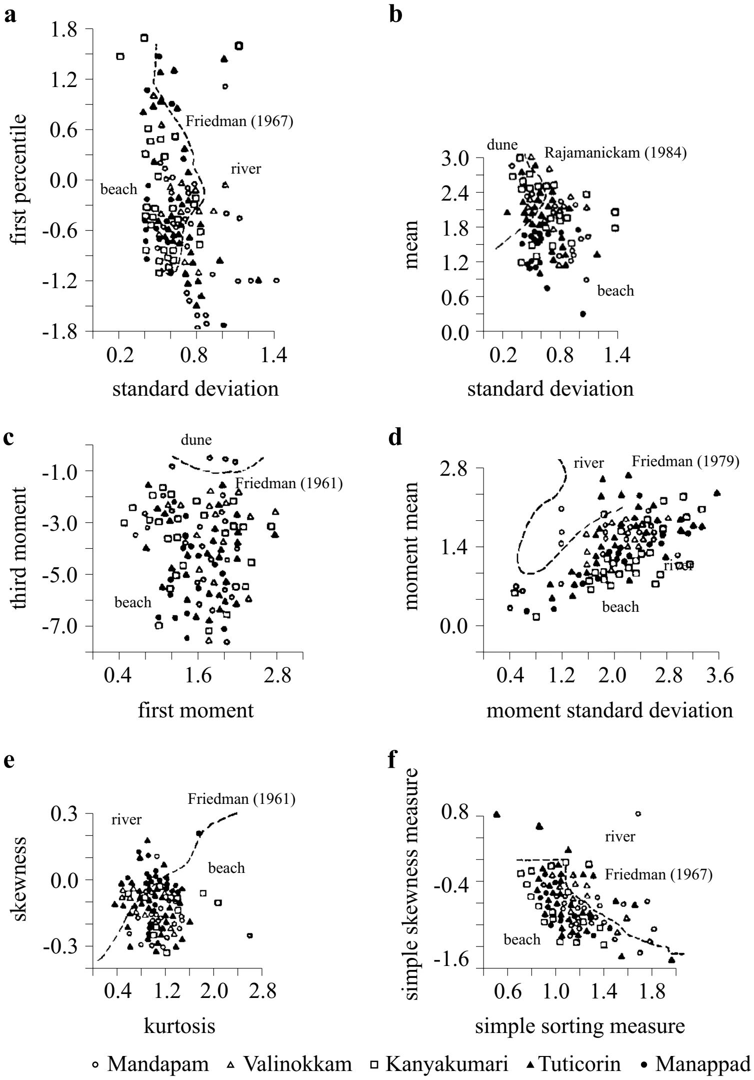

Fig. 5. Binary plots

the distribution of finer sediments. The absence of sediment distribution in the NO and OP sectors discounts the dominant influence of the riverine environment in the study region. However, a minor amount of bottom suspension and rolling is present in the PQ segment in the Tuticorin sector; this is quite possible, owing to the confluence of the major River Tamiraparani. Most of the sediments are segregated close to the M = C line and parallel to the QR segment, indicating that sediments are deposited by graded suspension. The existence of a clear gap from 300 to 400 microns denotes a specific distributional gap attributable to the removal of that size fraction by tractive currents, or else the non-availability of materials from the source itself.

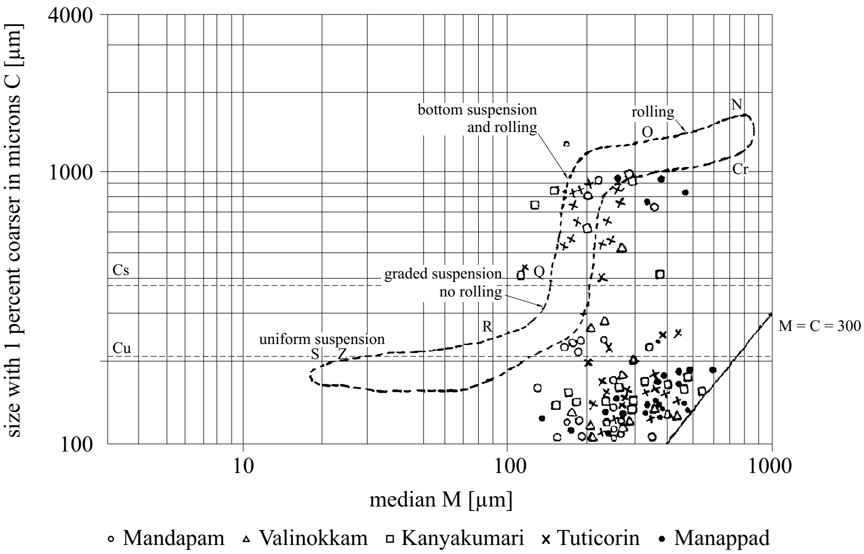

Fig. 6. CM Pattern

4.6. Visher Diagram

The Visher diagram of the Mandapam sector (Fig. 7a) samples clearly shows the presence of a dominant single saltation population with a minor amount or lack of suspension and no surface creep population. The truncation points of the different populations of stn. I to III establish a close similarity to the characteristics of a shoal area, a calm depositional environment, as indicated by Visher (1969). The fine-grained polymodal nature of the sediments clearly attests to the prevalence of a calm, undisturbed environment. The presence of a series of islands – typical progradation activities in the Mandapam and Sethukkarai regions – endorses the prevalence of low-energy conditions, leading to shoal formation.

The Visher plots of the Valinokkam (Fig. 7b) and the Tuticorin and Manappad (Figs 7c,d) sectors show the presence of a double saltation population with a difference in the surface creep population and suspension characteristic of a beach environment. Though the influence of the fluvial environment is manifested in frequency curves, sorting and skewness values, the probability curves broadly reflect the influence of the beach environment.

In the Kanyakumari sector, the presence of a double saltation population helps to infer the prevalence of the beach environment as corroborated in

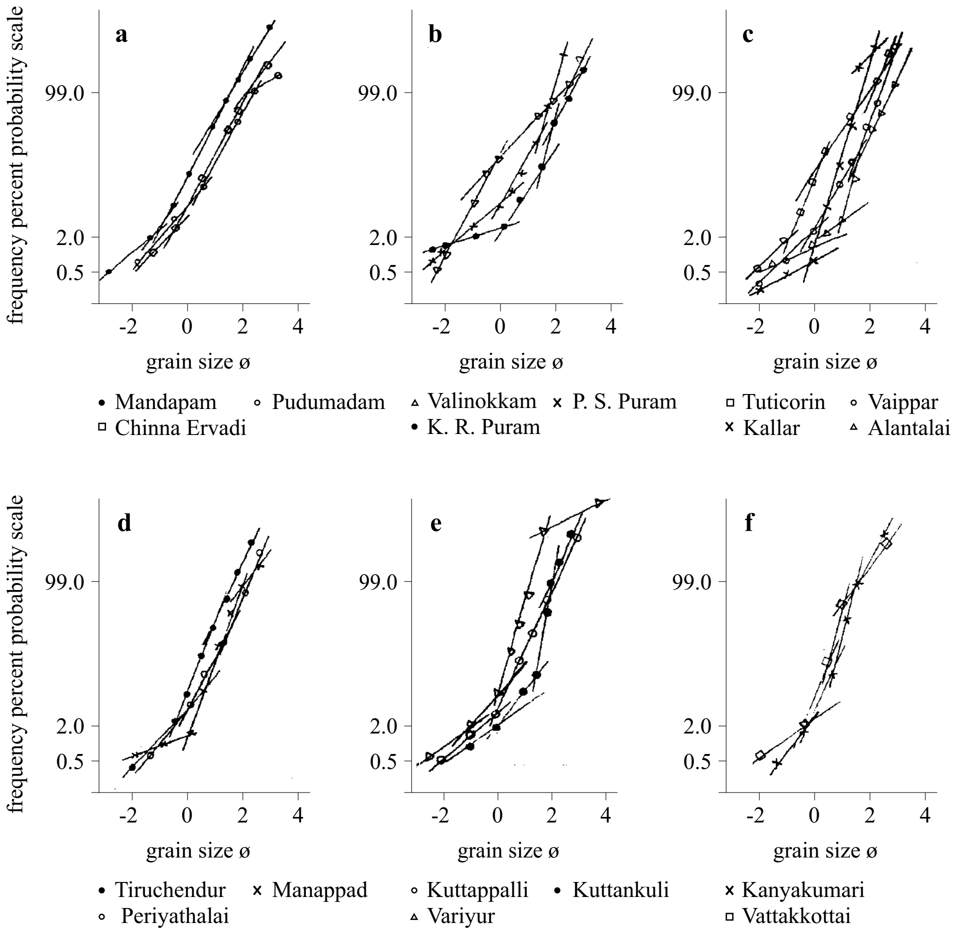

Fig. 7. Log probability plots

bivariant plots (Figs 7e and 7f). However, at stn. XXVII, the presence of a poorly sorted surface creep population and suspension population resembles Visher's plunge zone. Strong wave convergence and a rocky coastline with promontories are further high-energy factors.

5. Conclusions

The frequency curves vary from unimodal to bimodal in places of river discharge from the Vembar, Kallar, Vaippar and Tamiraparani, as a result of which an additional sub-population is deposited. Otherwise, the nature of the frequency curve is controlled primarily by wave dynamics and littoral currents. The mean size of the sediments is finer in the Mandapam sector, where low-energy conditions prevail and accretionary processes are taking place; this is corroborated by the positive skewness of the sediments. In the Kallar and Vaippar Rivers and at the stations in the Kanyakumari sector, the sediments are medium to coarser where high-energy wave conditions prevail. The skewness values characteristically discriminate the energy conditions obtaining in the study region: low energy in the Mandapam sector, higher energy in the Valinokkam, Manappad and Kanyakumari sectors, and a mixture of high and low energy in the Tuticorin sector. The CM pattern indicates the deposition of sediments in graded suspension. The binary plots help to discriminate the different environmental conditions prevailing in the study region. The Visher plots emphasize the low-energy conditions of the shoaling environment in the Mandapam sector, the high-energy beach environment in the Valinokkam and Tuticorin sectors, and the high-energy plunge environment in the Kanyakumari sector.

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