CHAPTER-4
SEDIMENTOLOGY

4.1 INTRODUCTION

The study area is situated on the mouth of the Gulf of Kachchh along the Kachchh coastline, influenced by the open sea-sandy environment in the western side, while muddy setting dominates the eastern side. Kachchh coast from Bhada to Mundra is marked by admixture of sandy and muddy sediments forming crescentic coastal landforms and ridges that intermingle with the fine grained, muddy, tidal flats. On account of various settings the intertidal zone shows wide range in textural characteristics, bedforms, sediment facies, physical and biogenic sedimentary structures. These are direct indicatives of changing balance of the physical, sedimentological and biological forces. In this chapter attempts have been made to analyze sediment characteristics and physical structures.

As for exposure index, tidal amplitudes, the intertidal zone of the study area can be separated into three distinct zones similar to those proposed by Klein, (1985) and Dyer et al, (2000) for intertidal mudflats. The subtidal region lie between mean low water neap to mean low water spring tide level; the intertidal zone is located between mean high water neap and mean low water neap; the supratidal region lie between the mean high water neap and mean high water springs. Moreover the intertidal zone is further divided into various zones based on the degree of exposures. Exposure time is an important parameter influencing faunal zonation in intertidal zone. The exposure verus elevation function has both continuous and discrete properties and is time dependant (Swinbanks and Murray, 1981). The region of high and low intertidal regions experiences tremendous ranges in daily exposures. At the levels of high and low waters duration of continuous exposures or submergence increases abruptly by a discrete interval, the magnitude of which is determine by tidal cycle period. Doty (1946) and Swinbanks and Murray (1981) have proposed to subdivide the intertidal zone into discrete exposure zones and termed them as critical tide levels (CTL's). In Mandvi region the tides are of semi-diurnal type, which means that there are two high and two low waters a day but successive high and low waters are of different height. Thus on any day there are four CTL's defined by higher high water (HHW), lower high water (LHW), higher low water (HLW), and lower low water (LLW), which subdivide the intertidal region on that day into five discrete levels (Figure 10). Level-1= above HHW; Level-2= between HHW and LHW; Level -3= between LHW and HLW; Level-4= between HLW and LLW and Level-5= below LLW.

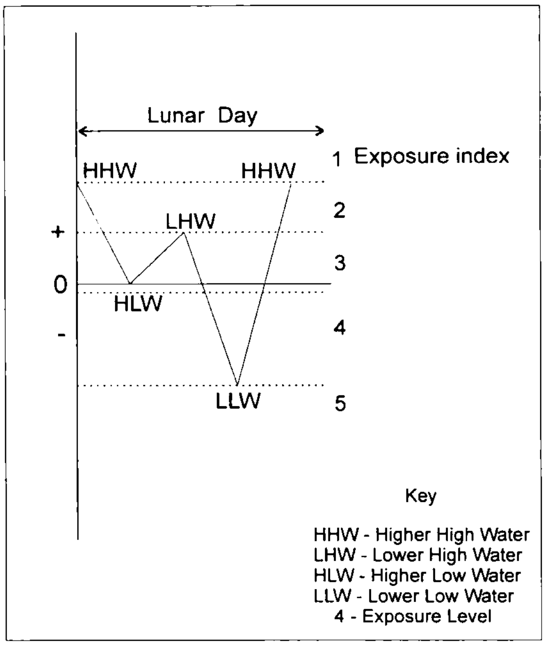

Figure-10: Five levels of exposure possible for semi-diurnal tides (after Swinbanks and Murray, 1981)

These zones effect the distribution of the fauna, flora, and sediments in the intertidal zone along with resultant geomorphology. The Rawal Pir lagoon is situated above HHW i.e. Level-1 and is flooded once in a tidal cycle, during spring tides and during remaining tides the filled water drains out with falling tides, thus creating various ebb and tide oriented bedforms. Ridges and runnels are characteristic of Level-2, 3, and 4 in the study area and based on exposures of various levels, lower sets of ridges and runnels are exposed.

4.2 GRAIN SIZE VARIATIONS

The main objective was to describe the physical structures and textural variations in the different sedimentary facies. The samples were collected using grid pattern for textural analysis. All the facies showed striking differences in grain sizes across the coast, however it displayed uniformity along the coast. The lateral continuity of the textures in the ridge and runnel systems is lacking compared to the beach. Geomorphologically the intertidal zone is characterized by ridge-runnel systems, grain size variation along and across the intertidal zone show marked differences and control of various physical parameters. Grain size variation across the intertidal zone from beach to lowest exposed ridge (bar-e) in the CTL's level-5 show decrease in sediment size (Figure-11). The beach

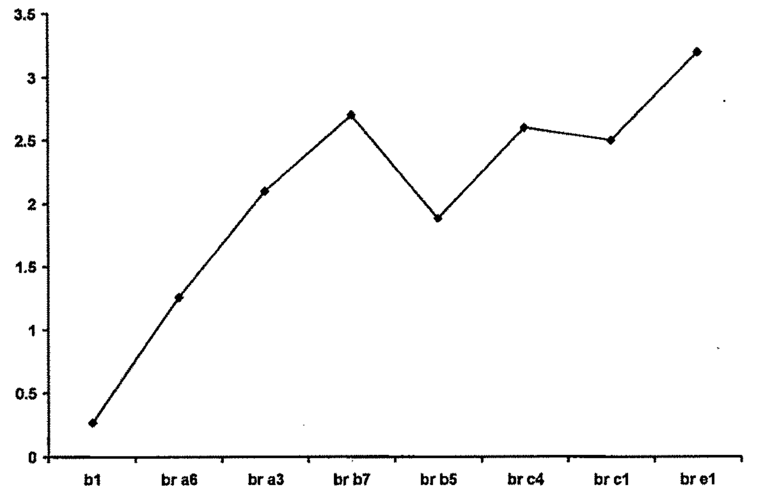

Figure-11: Grain size variation in ridge across intertidal zone at Rawal Pir site (b-beach, br-ridge).

samples shows coarse to medium sand size and decreases to fine sand to coarse silt. Sediment variation along the coast from Mandvi to Modwa Spit (Figure-12) do not shows any differences. Some coarse sand dominates along the Mandvi side, but as observed in

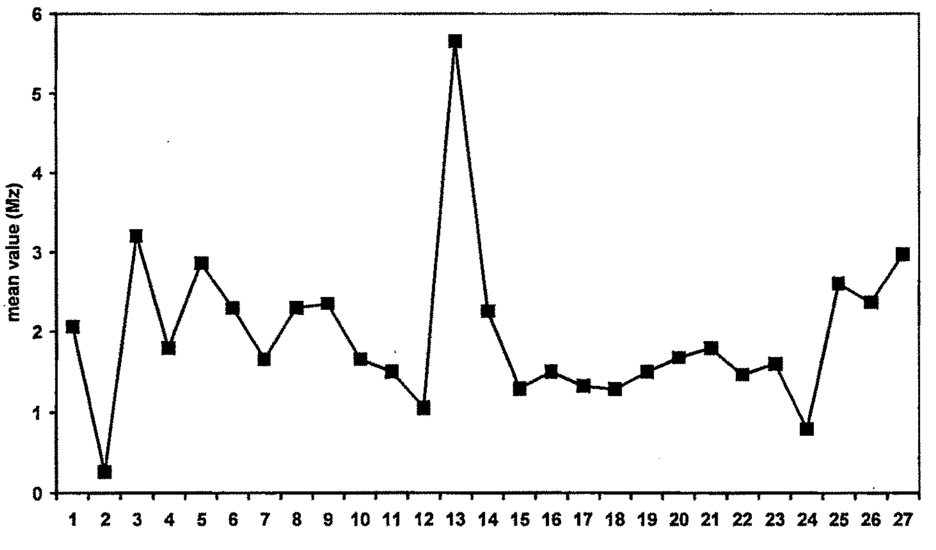

Figure-12: Grain size variation from Mandvi to Modwa Spit sites.

field this coarsening was due to accumulation of coarse sand near the man made barriers, along the mouth of Rukhmavati River and welding of the ridges to the beach. Like ways the spike in the graph, as observed in the field was due to exposure of paleo mud in the runnels of the intertidal zone, thus the overall sediment distribution pattern do not change but dominated by fine sands. There is also marked difference in the grain size of the ridge and runnels. Though the ridges show decrease in sediment size across the intertidal zone

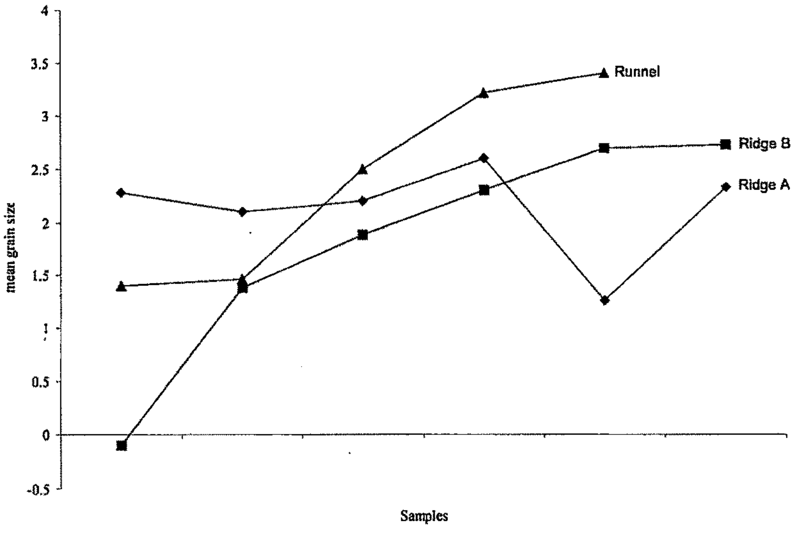

Figure-13 Mean grain size variation in ridge and runnel system of the Rawal Pir site.

and are well to moderately sorted, the runnels are on the contrary poorly sorted and show wide range of sediment types from gritty material to, fine silt (Figure-13). This is probably due to runnels actively erodes the underlying sediments, and during low tide level it also acts as unidirectional channel in between the ridges. Overall, the sediment texture in intertidal zone shows some differences in which fine sands dominate the sediments.

4.3 SEDIMENT TRIGONS

Sediment trigons were prepared to classify the sediments into general substrate conditions, based on varying percentage of fractions of the Gravels, Sand and Silt + Mud.

In a triangular plot each corner of a triangle was assigned to sand, gravel and silt + mud. These were further classified based on varying proportion of the three individuals. On sand- silt + mud axis, boundary for pure sandy substrate was divided at 70% of sand, for pure silt + mud substrate the boundary was assigned at 70% of silt + mud. The values between 70% sand to 30% of the sand, or 70 % to 30% of the silt +mud were assigned to the silty sand substrate. Similarly, on silt + mud and gravel axis upto 70% silt + mud and gravel was assigned to substrate of silty/muddy and gravelly nature respectively. The mix proportion of silt + mud and gravel were termed as muddy gravels. The mixture of sand and gravel from 70% to 30% on either side was called sandy gravel. The mixture of all the components almost in equal ratio was called gravelly silty sand.

Percentage of grain size of all fractions from the three different sites was plotted

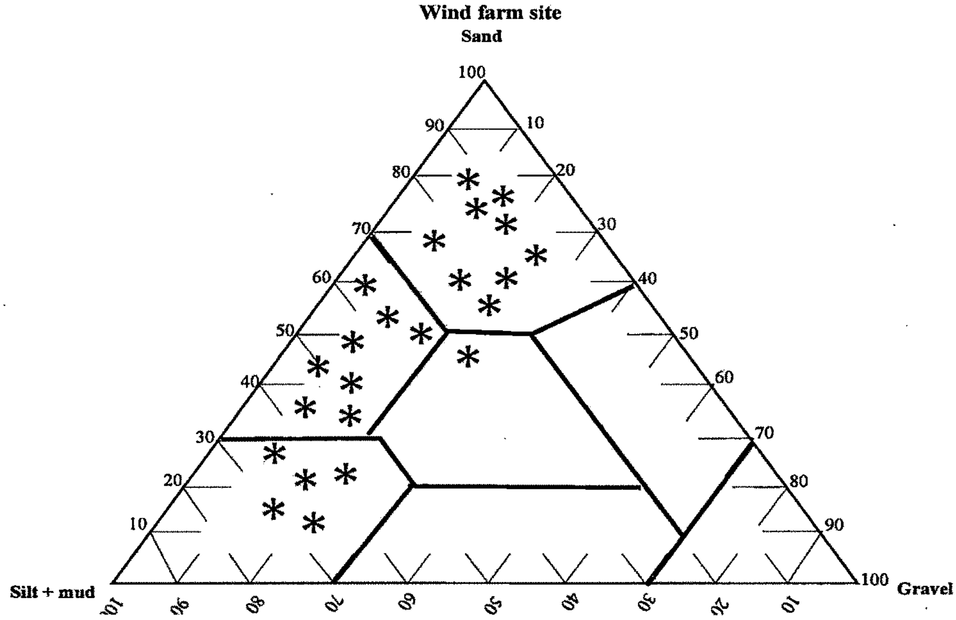

Figure-14: Sediment trigon of Wind Farm site showing nature of the sediments.

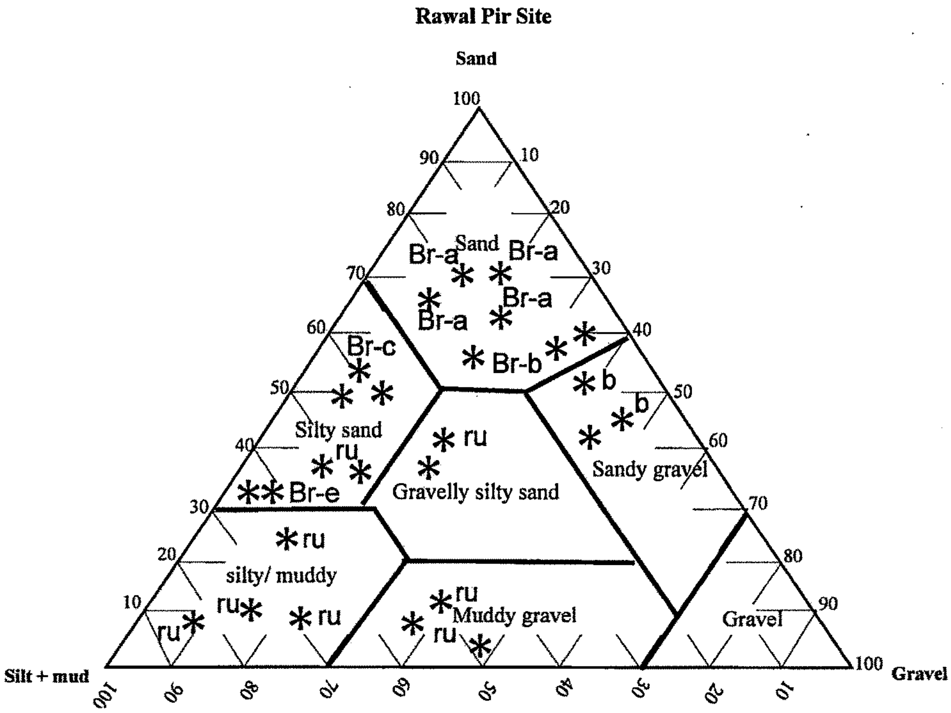

Figure-15: Sediment trigon of Rawal Pir site showing nature of the sediments. (b-beach, br-ridge, ru-runnel)

on the trigons (Figure-14, 15, 16). In the Rawal Pir site the ridge-A and ridge-B fall into the pure sandy substrates, the ridge-C and ridge-E showed fine-grained sediments and

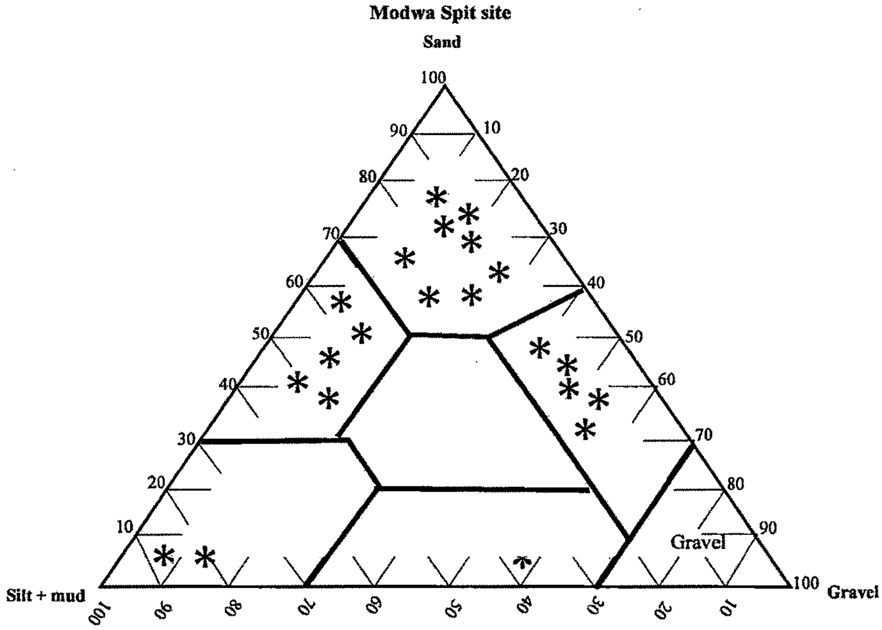

Figure: 16 Sediment trigon of Modwa Spit site showing sediment characteristics

were confined in the silty sand category. This is also confirmed by the grain size analysis shown in (figure-11), which shows fining towards the last bar from the beach. The beach samples were confined to sandy gravel. The runnels showed wide range of substrates ranging from sandy silt to silt/mud to muddy gravel and gravelly silty sand. The Modwa Spit site plots showed variation from sandy substrates to silty sand, and sandy gravel but few samples showed silt/muddy nature of substrate. The Wind Farm site showed same trend but the gravelly fractions were absent.

4.4 PRIMARY SEDIMENTARY STRUCTURES

4.4.1 Plane Bed Laminations

Parallel laminations are the prominent and common features of the beaches and ridges of the intertidal zone. It comprises of alternating coarse and fine sand size grains, deposited as a part of upper flow regime plane beds (Alexander et al, 2001). Generally, each lamination is found to be varying from 2 mm to 8mm in thickness and are bundled in sets generally ranging from 25 per unit to more than 500 per unit. The Relief peels show plane laminae of 2 mm to 7 mm thick and the total number of the laminae preserved in the peels may depend on the degree of bioturbation (Plate-4). In many X-radiograph of

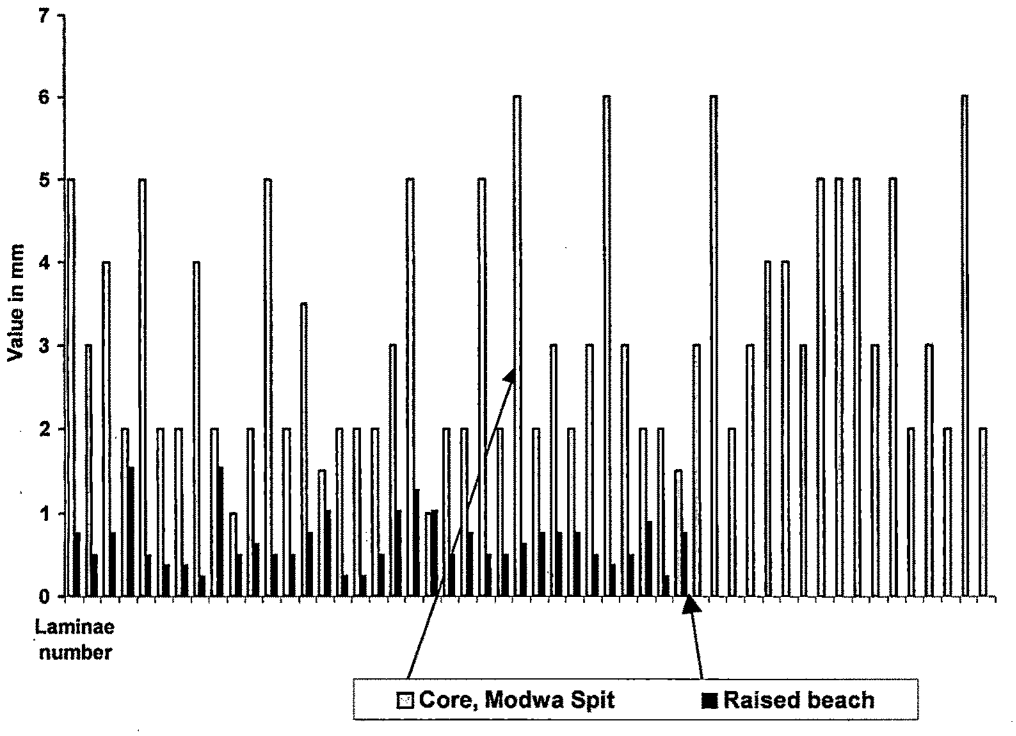

Figure-17: Variation of thickness in plane bed lamination.

the core samples from Modwa Spit area, it shows distinct laminae ranging from 1 to 8 mm in 1.5 ft of core. Nearly 50 laminae are well recognized, showing alternate and sequential variation in thickness. It can also be very well observed in the raised beach sections. In relief peels these plane laminae units are found to be alternating with small-scale ripples, occasionally bioturbated (Plate-4 b &c). Very often on the plane laminae, crude laminations of alternating coarse and fine grained sand laminae are preserved. According to Myrow and Southard (1991) the plane beds are the result of upper flow regime. These are very common bedform features found on the top of the ridges in the ridge-runnel system. The plain bed laminations of raised beach sections

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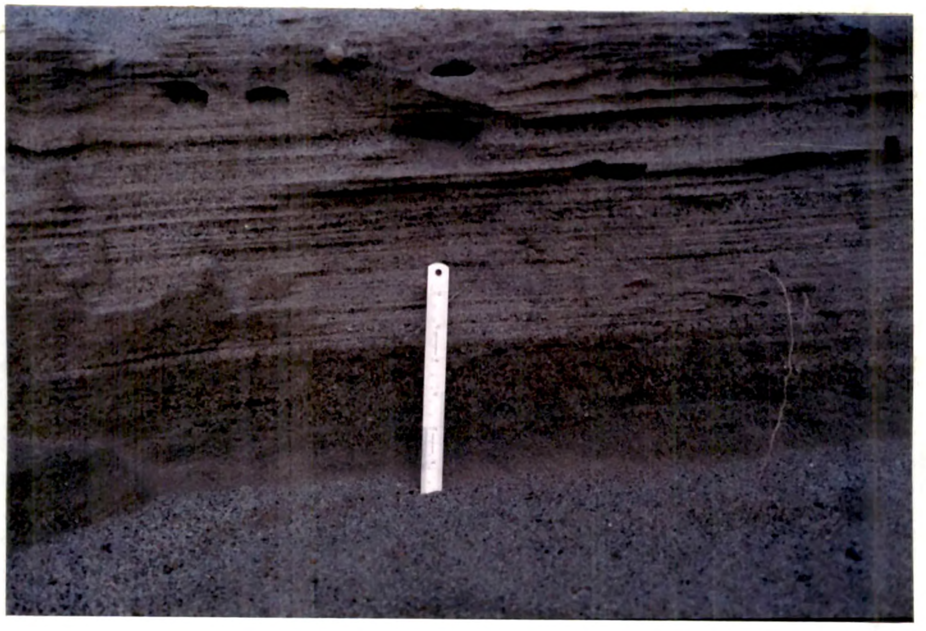
Plate 4 Beach laminations, (a) Plane bed laminations, showing centimeter scale alternation of fine and coarse grained sand layers intervened by *Thalassinoides* burrows. (b) Relief peel of the raised beach section showing plane bed laminated sequence (Pb) along with bioturbated rippled (Br) sequence. (c) Relief peel of the raised beach showing bioturbated layers (Bl) intervened by low angle cross stratification attributed to antidunes (An).

PLATE-4



(a)

(b)

(c)

along the Rawal Pir area also shows similar type of structures in the core samples from modern beach and ridge, indicating that there was not much difference in the tidal amplitude in recent past.

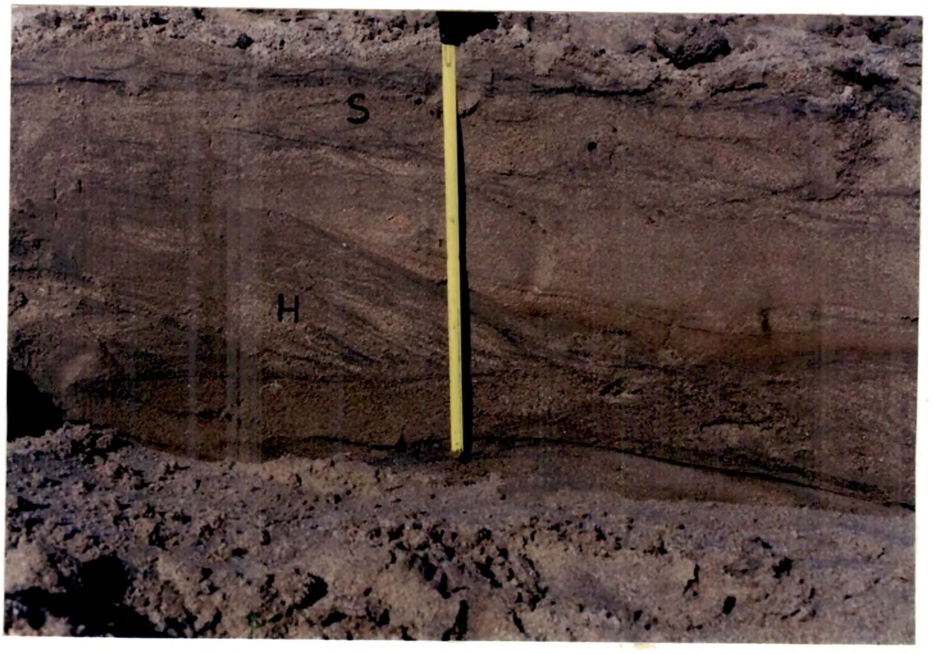
4.4.2 Hummocky and Swaley Cross-stratification

Hummocky and swaley cross-stratification were observed in the trench of the Rawal Pir lagoonal sediments. The lagoon, as stated earlier, experiences diurnal inequality in tidal conditions, and hence wide range in flow condition. During neap tide, it experiences low velocity tidal flow with less run-off from the lagoon during the low tide times. During the spring tides, it experiences high velocity tidal flow, with high run-off and high water conditions. The formation of hummocky and swaley cross-stratification is controlled by the changing tidal regimes.

The trenches made normal to the flow of lagoon are upto 6 ft in length and 1.5 ft deep. Some of the hummocks were found to be crosscutting the previously formed hummocks. The top few cm showed swaley cross stratification (Plate-5a) formed during the neap tide cycle. Such types of the swaley cross stratifications were formed due to formation and migration of low amplitude linguiodal ripples. Underlying, these are lenticular sets of laminae, which made up of fine-grained sand size sediments. The laminae are upto few millimeters thick, and can be distinguished by slight variation in grain size accompanied by dark coloured sand size particles. Some of the lenticular sets also contained structureless material. The laminae were found to be dipping at 20^0 and decrease in the dip angle was observed at top and base of the bedforms. They either flattened out upward or were eroded by the overlying trough-shaped surface of overriding bedforms. The trough height was less than trough length. The cross stratification showed numerous intraset discontinuities or "pause planes". Two type of discontinuities (Plate-5)

Plate 5: Hummocky and swaley cross stratification, (a) nature of the hummocky cross stratification in a trench near Rawal Pir lagoon. Hummocks formed on account of migration of 3D dunes indicated by various ebb oriented stratification (H) during strong tidal current, The top portion shows Swaley (S) stratification formed on account of weak tidal current. (b) Trench showing hummocky and swaley cross-stratification. (c) Close up of 5b, showing intraset discontinuities Type -A (i) and erosional contact discontinuity Type -B (ii).

PLATE-5



(a)

(b)

(c)

were observed, Type-A and Type-B of Allen et al, (1994). The Type-A discontinuities are in the form of erosional surfaces, which truncate the bedding below and are buried by overlying sediments (Plate-5c). The Type-B discontinuities are restricted to the lower part of the laminae set. In both the type of discontinuities a considerable change in lithology and grain size change were observed.

Down stream dipping laminae, numerous cross cutting trough with less trough height and multi pause planes indicates, that these bedforms were formed on account of the migration of the asymmetrical bedwaves with a steep leading edge (Alexander et al, 2001), generally it is characteristics of 3-D subaqueous dunes and antidunes.

The high amplitude cross stratified units indicates the result of the most energetic spring tides (Allen et al, 1994) and discontinuities that cut across below were formed by falling tides or tidal reversal, or through wave action during bedform ebb exposure. The hummocky and swaley cross stratification and its bedforms change due to their adaptation to changing tidal flow, because in a field of mobile bedforms, there is continuous creation, change, and vanishing of individual bedforms (Allen, 1968; Terwindth and Brouwer, 1986).

4.4.3 3-D Subaqueous Dunes

Subaqueous mature dunes (Allen, 1982) were observed in the runnels and lagoon of the Rawal Pir site (Plate-6). These are three-dimensional asymmetrical sand ridges characterized by (i) comparatively long transverse crest, (ii) wavelength measured in meter, generally 1-1.5 m and (iii) height in decimeter, 20-30cm. The dunes were developed in medium to coarse sediments, and had mean ripple index of about 9.5 to 10 cm, with mean distance between the two crest about 100 cm and the deepest portion of trough of about 10cm. According to Allen et al, (1994), the bedform to be called as subaqueous dunes must last at least one tidal cycle. The sediments comprised of medium to coarse-grained sand size particles but very often, coarse grains were accumulated in the

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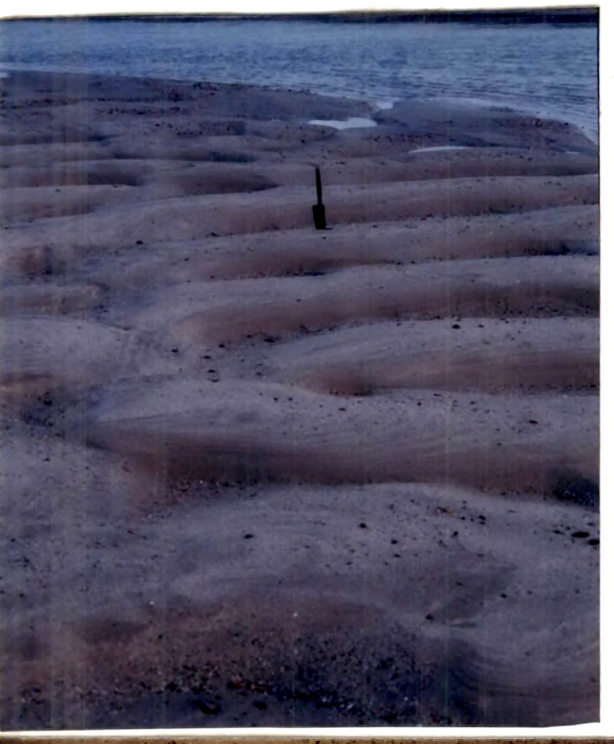
Plate-6: Intertidal subaqueous dunes, (a) 3-D subaqueous dunes developed in the lagoon tidal inlet channel. Note the accumulatiom of coarse grains in the lee side (trough) of the dunes. (b) Nascent dune consisting, fan of ripples in the lee side of the dune along with falling water marks and coarse grain accumulations. The height of the plastic pipe is 15 inch. (c) Small scale nascent dune in lee side of a larger nascent dune.

PLATE-6



(a)

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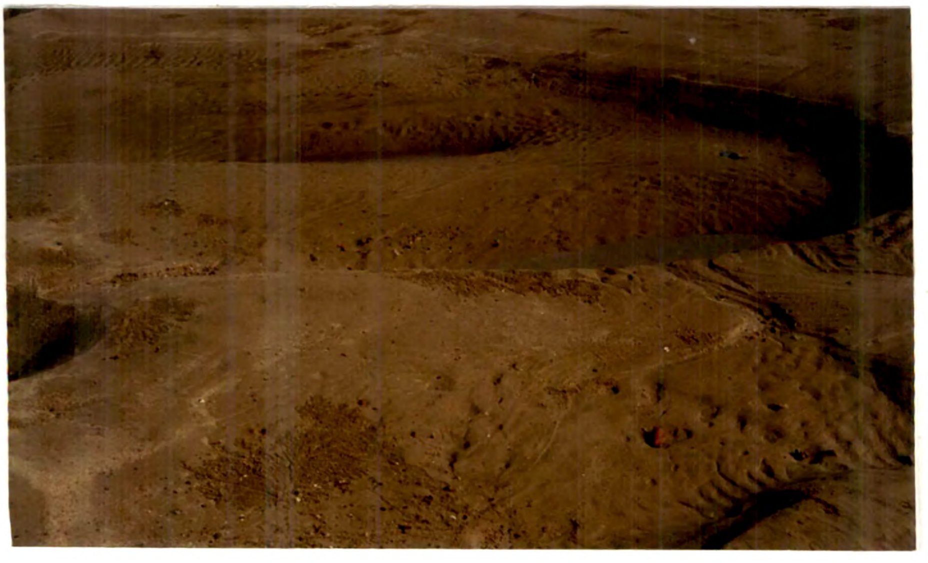


(c)

trough of the dune. During a tidal cycle, in September 1999, it was observed that with the changing tidal conditions, 3-D dunes undergo processes of flattening and negative transformation to the nascent dune. In the same dune field, falling stage of the spring tide the high amplitude dunes flattened out with their constant wavelength, but height decreases. Their troughs are filled by coarse sediments, as a result of the advancement of the dune crest unable to accommodate more sediment and hence coarser grains avalanche in to the trough. The coarse grain particle were accumulated on the lee side of the dune would be as a result of turbulent nature of the current. Some of the dunes also display bifurcation of the crests, with supplementary crest, shorter than the dune itself. These are perched high on the bedforms with comparatively straight and lie not far from the main leading crest. The dunes in the lagoonal area showed two kinds of terminations similar to those reported by Allen (1968), i.e. with the leeward face gradually dies out along the stoss of the neighboring dune and joining of the crests and leeward slopes to form Y-shaped junction. According to Allen et al (1994) "With continuing sediment transport, each supplementary crest in turn advances forward to degrade and replace previously leading crest". There was difference in dunes form of the upstream and downstream areas. Smaller dunes were observed in the downstream direction and can be attributed to the slightly non-uniform flow and transport activity (Allen et al., 1994).

4.4.4 Nascent dunes

Nascent dunes are intermediate in size between current ripples and mature dunes (Allen et al., 1994). They occur in Wind Farm and Rawal Pir site of the study area, corresponding to "minor dunes" of Allen and Friend (1976) and the smaller-scale isolated megaripples of Elliott and Gardiner (1981). These are mainly negative features superimposed on mature dunes but restricted to the downstream two-thirds to one-half of their stoss slope (Plate-6 b & c). In the Wind Farm site the observed nascent dunes are of large, isolated, symmetrical, oval to cresentic pits, 2-3 m across and upto about 0.5 m deep. The grain size indicated mix influence, with dominance of medium to coarse-grained fractions. The crescentic pits contain asymmetrical small ripple fans of low amplitude. The upstream side is a steep, ebb-facing avalanche slope, and the downstream surface a gentler, larger convex-up slope carrying a fan of current ripples (Allen, 1968; Allen et al., 1994). The rims of the crescentic pits have accumulations of the coarse grained sediments, generally accumulated due to the avalanche along the steep upstream face. Associated with these are falling watermarks and late stage modified planed ripples on its horns, indicating mature stages of the nascent dunes. These features were seen to be cannibalizing and growing, laterally fusing into other smaller nascent dunes. As indicated by Allen et al., (1994) nascent dunes are triggered by tides rising higher that those driving mature dunes. The presence of the ripple fans and falling water marks are indicative of late stage run-off or falling state conditions (Elliot and Gardiner, 1981).

4.4.5 Antidunes

Antidunes are the trains of ripple-like bedforms produced by the free surface flow in or near the super-critical flows, when bedforms are in phase with the water surface. Antidunes developed on the top of the ridges only in the Rawal Pir and Modwa Spit areas. These are long crested and of low relief. Internally they contained laminae that were concave upward and more or less parallel to the trough shaped base of the sets, they flattened out upward thus forming filled troughs. The sediments of the antidunes were very fine to fine grained sand size particles. In relief peels of the raised beach, antidunes were determined as sets of low angle laminations, with slightly convexity, sandwiched between the plane bed laminations (Plate-4c). Experimental studies of supercritical water flow over a sand bed under aggrading and non-aggrading conditions by Alexander et al., (2001) indicated that the internal structures of the antidunes were made up of laminae sets, in which laminae dip upstream are associated with surface-wave breaking and filling of the antidunes.

4.4.6 Ripples Marks

Ripple marks (Plate-7) are present as undulations on a non-cohesive surface, though they may also be found infrequently in muddy sediments. They are developed as a result of interaction of waves or currents on a sediment surface. Many types of ripples are found in the intertidal zone, especially restricted to the runnels and lagoons of the Rawal Pir and Modwa Spit sites. The varieties that can be studied are symmetrical ripples, asymmetrical flat topped ripples, rhomboidal ripples, linguoidal ripples, complex ripples, etc. (Plate-7). The symmetrical straight crested ripples were studied in the Rawal Pir site at the junction of the beach and runnel. The grain size was characteristically coarse to very coarse grained, the ripple index (RI) of the straight crested ripples falls into the range of 6-8, indicating effect of both wave and current on the ripples, the mean ripple length is about 40 cm (N= 12) and mean ripple height is 5.5cm (N=12). Similarly the flat-toped asymmetrical ripples were developed in coarse grains, with very coarse sand/gravel size material accumulating in the trough of the ripples. The ripples have wavelength of about 30 cm and ripple crest height upto 5cm, the flat top of the crest was of average 20cm broad. The rhomboidal ripples were abundant on the lower end of the ridge and flat intertidal zone of the Wind Farm and Rawal Pir sites, they formed in fine to medium sand size particles, with slope less the 3^0, the mean angle between the rhomb is approximately 60^0. Linguoidal ripples (Plate-7) were formed at the center of the runnels in Rawal Pir sites and consist of fine to medium sand size particles. It formed due to changing flow conditions either during high tides, when the water column height is about 6ft in the runnels, or during late stages, when falling water level is about less than 1m.

A slow longshore movement of currents in runnels produced small linear to sinuous crested ripples (Plate-7) transverse to shoreline. Under these conditions the ridge-runnel systems shows several bedforms depending on the flow regime. With decreasing depth, the following sequences of bedforms are observed in runnels. The landward side of runnels are bounded by straight crested, followed by asymmetrical wave ripple with undulatory crests and asymmetrical wave ripple with discontinuous crest and at the end, i.e. towards the steep face of the ridge, there is development of lunate and interference ripples (Plate-7d) at late stage.

4.4.7 Rill marks

Rill marks are observed on the ridge and especially on the junction of the beach and runnel and are formed by the residual flow. They are generally formed on smooth and gentle surfaces of the beach. Two types of rill marks (Plate-8a) are observed the tooth shaped and the dendritic. The dendritic rill marks are composed of small rills which meet together to form broad channels. Rills may show extreme bifurcation similar to dendritic pattern. In some cases gentle slopes of the beach are characterized by toothed shaped rill marks and it may show extreme bifurcation forming dendritic pattern. Forming of the rills causes water to drain out and erode the sediment, which are deposited into runnels and forms Micro-deltas (Plate-8b).

4.4.8 Air trap structures

The air trap structures occur all along the coast on the non-rippled, flat, gently inclined surface and particularly on the high micro-relief of the beach-bar complex (Patel et al, 2002). These are essentially made up of coarse to fine-grained sand size sediments with graded layers. The surfacial expressions of air trap structures occur as domes conical and hemispherical mounds with or without pit and as cylindrical holes of varying dimensions. The subsurface structures are represented as bubble sand/cavernous sand layers, forming spherical to elliptical cavities. These occur under the sand domes and their surfacial expressions on the beach can be easily recognized as compressible sediments, while walking. The gentle slope ($2-10^0$) of the beach contains sand domes and conical mounds, while the moderate slopes ($>15^0$) are characterized by sand holes; the intermediary slope ($8-16^0$) contains sand mounds and pits (Figure-18).

Subaerially exposed cross-stratified sand layers are filled with air and are modified forming new air trap structures during the flood tides. These modified structures are described as under.

4.4.8.1 Sand domes

These occur as convex, vault like conical mounds with circular outline, varying dimensions and uniform morphology with similar domal angle. Occasionally the domes are fractured. The roofs of the domes are hemispherical with circular to elliptical base. The air cavities generally form due to upheaval of the upper fine-grained layer and appear as laccolith shape. These cavities have greater equatorial axis than vertical axis with constant height/ basal length ratio (0.21). The observed height of the dome is upto 15 mm with maximum diameter of 70 mm.

Plate-7: Different type of ripples in intertidal zone, (a) Late stage development of linguoidal ripples on top of megaripples in runnel at Rawal Pir site. (b) Straight crested symmetrical ripples in runnels. (c) Sinuous, flat topped ripples near the beach-runnel junction. (d) Interference ripples showing bifurcation of curved crests in the middle part of runnel.

Plate-8: Rill Marks, (a) Two types of rill marks, tooth shaped rill marks (i) formed at the slope break of the beach in coarse sand, and dendritic rill marks (ii) in fine grained sediments (Wind Farm). (b) Lobate shaped micro-delta formed in the runnel due to cannibalization of various earlier formed rills, comb shaped rill marks present on the left side of the delta. Note the remnant of early stage flattened ripples surrounding the distal part of the delta (Rawal Pir).

PLATE-7

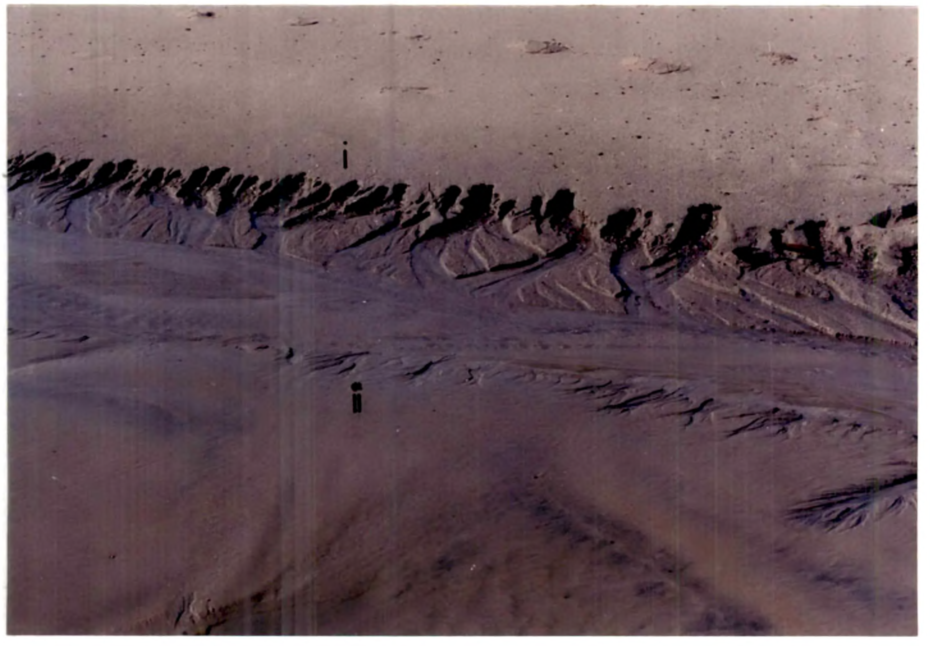
(b)

(c)

(a)

(d)

PLATE-8



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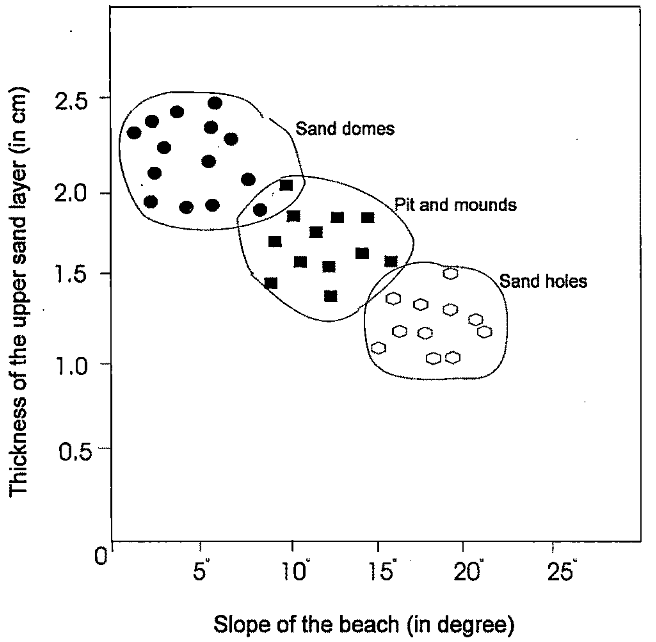

Figure-18: Graph showing relation between thickness of upper sand layer and slope on beach on development of various air trap structures.

4.4.8.2 Mound and pits

These structures are similar to sand domes but usually show a pit at the center. In addition, the upper fine-grained sand layer is relatively thin compared to sediments of sand domes. The pits are cylindrical to conical in shape and developed at the center of the mound and the depth of the pit depends upon the thickness of upper layer.

4.4.8.3 Sand holes

These are linearly arranged and occur as small, cylindrical to conical and steeply inclined to vertical holes with circular opening. They are developed on steep slopes of the medium to fine grained sediments surface of beach near high water lines and occur in a row indicating continuation of the laminae. The depth and diameter of the holes are variable. The depth of the holes increases with an increase in the peripheral area. The maximum observed depth and diameter are of 50mm and 15 mm respectively.

4.4.8.4 Bubble sand/Cavernous sand

They occur under the sand domes and are identified on the surface based on the compressible nature of the sediment. These show a "sponge like" texture formed in different fine-grained sediment layers. The vesicles are rounded to elliptical in cross-section and their density, dimension and abundance decreases with increasing depth. In the vertical section the upper part of the sand layer produces rounded bubbles while the lower portion produces elliptical bubbles with larger equatorial axis. The bubble sand layers are also found at a depth of 45 cm from the surface.

Interpretation: The above described air trap structures are formed by three phase (water/air/sediment) dynamic systems (Figure-19). In given condition, Subaerially exposed beach-bar complex acts as two phases active, water saturated or air saturated

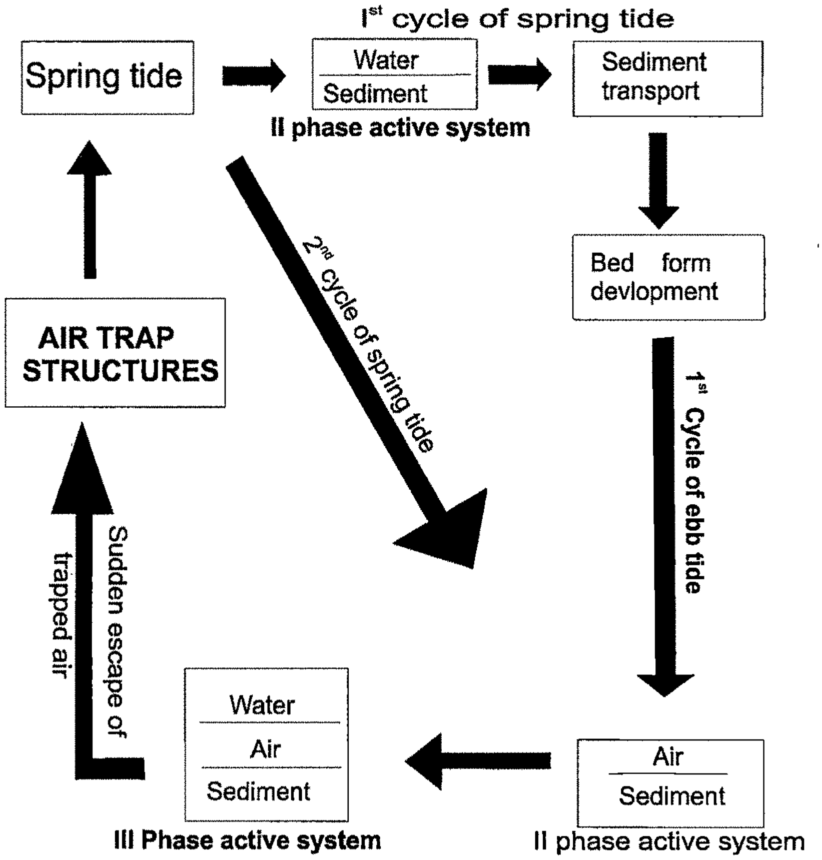

Figure-19: Flow chart depicting stages in formation of air trap structures.

system. Trapped air is the driving force behind the process leading to formation of different types of structures. It was observed in beach-bar complex along Mandvi coast, where the process of formation of air trap structures appear to be due to sudden escape of the entrapped air through different sediment layers to reach equilibrium state. Sand domes, fractured domes, pit and mound structures are very well controlled by the thickness of the upper fine to medium grain sand layers and gentle slope of the ground (Figure-18). The repetitive formation of the sand domes and other related structures can destroy the depositional fabrics and sometimes leads to convolute laminations (De Boers, 1979). Mass escapes of air through conduits on the slope break are responsible for development of sand holes on extreme reaches of flood tide level. The continuation of the alternating coarse and fine-grained layers along the beach slope is responsible for linear arrangement of the sand holes. Lateral movement of water in coarse-grained sediment layer is faster than the fine-grained sediment layer that causes trapping of air in the fine-grained layers. Thus, local fluidization causes finer grains to displace easily and to get reoriented forming cavernous structures/bubble sand layers.

4.4.9 Dune cross stratification

Well-developed cross-laminations are produced along a slip face during the migration of the sand avalanches in the aeolian sand dunes. The aeolian cross-beddings are distinguished by its large-scale cross-foresets that are steeply dipping. The aeolian cross-stratification was observed in the Rawal Pir section, which are at an angle of 25^0 to 30^0. McKee (1953) experimentally suggested angle of repose of about 30^0 to 40^0. There is a mark difference in thickness of cross-bedded units, the planar types of the cross bedding are usually very common, but sometimes festoon shaped cross- bedding were also observed.

4.4.10 Soft sediment deformation structures

The soft sedimentary deformation structures described here were studied on 26th January 2001, soon after the earthquake. These are farthest reported liquefaction structures (Desai and Patel, *in press*). The Kachchh earthquake produced very strong ground motion in the coastal zone of Mandvi area that was responsible for the development of ground fissures, cracks and landslides. The deformational structures described below were found in the planar and cross laminated layers of the backshore lagoon and adjoining beach sediments of Mandvi area (Rawal Pir site) that is about 150 km SW from the epicenter. The lateral extent of an individual deformation is variable, while in vertical sections they are found upto 70 cm. The photos were taken soon after the earthquake of 26th January 2001. The tidal condition was low tide of the neap tide cycle. The shape of the structure is either as simple as "Cycloid" of Hempton and Dewey (1983) or a more angular variety in which the layers have been projected to brittle deformation. Sometimes plastic deformation can also be seen. The types of co-seismic surface structures observed are collapsed raised beach, criss-cross cracks and aligned sand blows.

Trenching across of the sand blows shows the presence of micro-faulting, deformed sand layer and laminae, flame structure, plumose pattern, and mud and sand intrusion structures. The effect of the earthquake shocks was also seen on *Oratosquilla striata,* which practically never leaves burrow but changed its habit from dwelling (Hamano et al. 1994) to crawling in embicile condition (Patel and Desai 2001). The intimate associations of physical and biogenic structures are the result of extensional stress along Mandvi coast. Details of various structures noted are given below.

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Criss-crossed cracks (Figure-20-3) are numerous and have developed on the wet clastic sediments of the beach, primary cracks are oriented at 125^0 (NW-SE main mode) and width of upto 20 cm, which tapers downward and disappears at different levels. Associated secondary cracks (NE-SW subordinate mode) are less prominent and are perpendicular or inclined to at various angles. Criss-crossed cracks help to lateral spreading of the blocks and are also responsible for forming horst and graben structures.

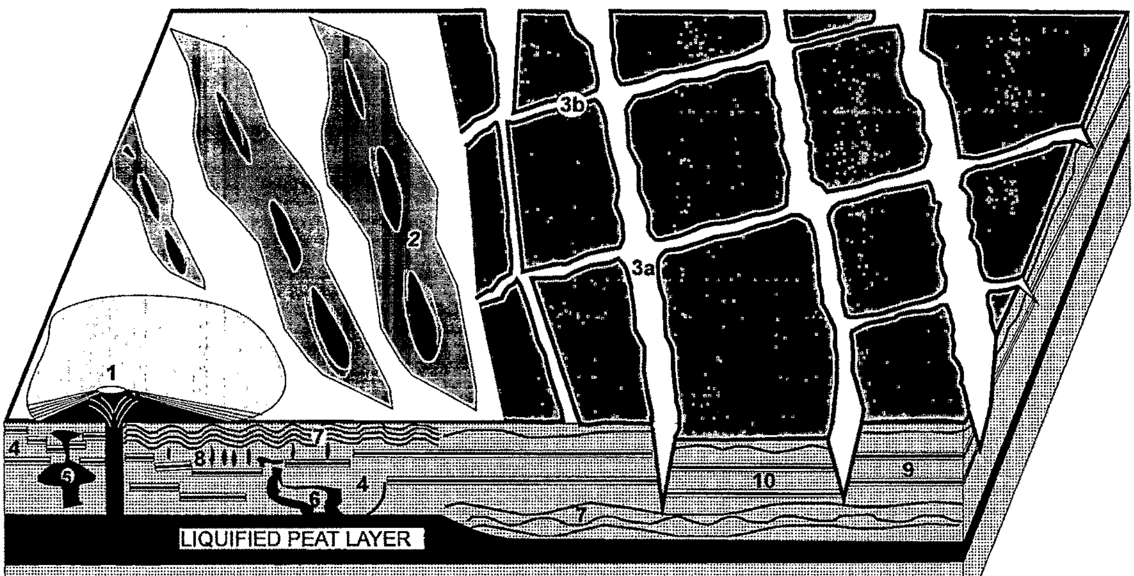

Figure-20: Three dimensional figure showing various seismically deformed structures (1) Sand blow, (2) linearly arranged sand blows, (3) criss crossed cracks (a) major cracks (b) minor cracks, (4) micro faults showing graben like structures. (5) sand intrusion (6) mud intrusion, (7) plumose pattern (8) flame structure, (9) horst, (10) graben.

The block within these two cracks is cut by several parallel fractures with little of no vertical displacement. Some of the larger cracks extend to a reasonable distance and die out under the dunal area. It also shows vertical offsets of upto 10cm.

The large injection structures typically restricted to the backshore lagoonal zone show internal homogenized texture and vary from 0.5 cm to 30/40 cm in diameter. The series of sand blows (Figure-20-1&2) are aligned in the major crack direction i.e. N125^0, which is also, a major lineament direction. The conduits of the sand blows and fissures are vertical to sub-vertical and their planner development is visible throughout the coast in varying dimension as well as in density. Black peaty sediments were thrown out and spread for 60 to 90cm around the vent of the sand blows.

Series of microfaults are observed around the vicinity of vents of the sand blows and fissures. Laminae are intensively faulted as horsts, grabens and antithetic normal faults giving step like appearance. In Figure-20-4, the graben is bounded by a normal fault in which displacement increases down the dip of the fault and three distinct disturbed laminae are observed, which shows 12, 6 and 2-cm displacement in the upward direction. The top layer shows displacement is less than the thickness of the layer while in second layer displacement increases in dip direction (left side of the graben displacement) and shows complete separation of the layers and third layer shows maximum displacement.

Mud and sand intrusions (Figure-20-5&6) are very common structures found to be associated with the micro faulting. These are irregular injected bodies in the sandy layer and are distinguished by the injection material. Usually these are found within the subsurface sediment layer.

Flow line pattern indicating plumose deformation styles are found in the area at the depth upto 6-8 cm, and are found continuous up to 45-50 cm from the vent of sand blow (Figure-20-7). The patterns show slightly downward-convex flowline repeatedly dragging the lower sediment. Folding was also developed on account of propagation of normal growth faults.

Flame structures (Figure-20-8) are seen as upward injection formed between intrusion of the upper, higher density sediments. Deformation is also represented by large vertical conduits that starts from the underlying homogenized bed, which cut and fold the surrounding, cross lamination of the beach sediment.

4.5 INTERTIDAL FACIES

A particular suite of sediment textures along with physical sedimentary structures and geomorphic settings distinguish intertidal facies. Across the intertidal zone, the waves and currents play an important role for transporting and redistributing of the sediments along the coast and help in forming distinct boundary between the facies. Depending upon the wave and current energy regimes and sediment supply, intertidal/supratidal facies range upto +17m thick, with varying proportion of the sand, silt and clay.

The intertidal zone of the Mandvi (Plate-9a) region is dominated by presence of the ridge- runnel systems (King and Williams, 1949), which are bars parallel to the coast, intersected by drainage channels at right angles to the waterline (Plate-1a). In the study area the well-developed ridges-runnel systems are observed in the Rawal Pir and Modwa Spit area. They are oriented at N 140^0 and vary in length from nearly 50m to more than 800m and in width from 10-30m. Their one end remains attached to the shoreface at an angle of nearly 15^0-20^0 with its height up to 3 ft, with sediments ranging from coarse sand to gravel. The formation of ridge-runnel systems along the coast is thought to be local construction of a slope in equilibrium with the incident waves and sand size sediments (Hayes, 1969). These ridges are exposed during low tide with their seaward surface gently sloping (5-10^0), while the stoss side of the ridge facing the landward is steep (20-25^0). In all there are two to three sets of the ridges intervened by runnels. It has been commonly observed that they are builds after storms and migrate towards the land until weld onto backshore to form a beach/berm.

The grain size distribution shows variation from the high tide to low tide, and in all ridge sediments shows decline in the mean grain size (Figure-11 &13). Similar variation is also observed along the ridge. The Graphic Mean size of the ridge sand ranges

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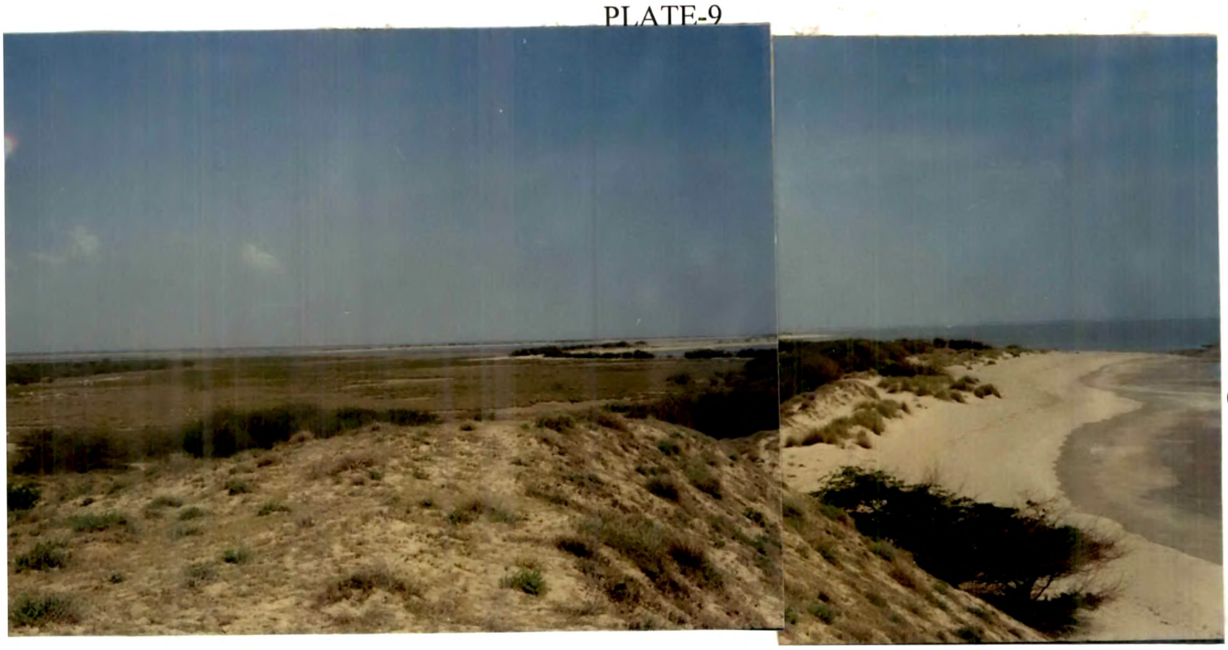
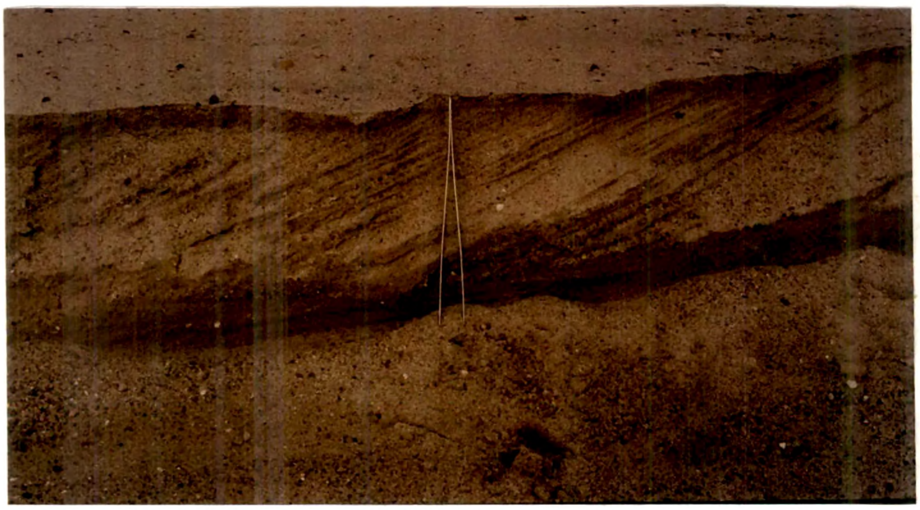
Plate-9: (a) Panaromic view of the Modwa Spit site showing complete landform sequences, from tidal flat to dune/raised beach and intertidal zone. (b) Planar cross stratification in the beach sediments exposed in the tidal channel, (forcep = 45 cm). (c) Armoured mud balls on the beach surfaces, which are eroded from the exposed paleo-mud in runnels of Rawal Pir site. Irregular shape of the mud balls indicates less transportation.

PLATE-9



(a)



(b)

(c)

from coarse to fine sand (-0.1 Mz to 2.2 Mz). Inclusive Graphic Standard Deviation of the beach sand varies from poorly sorted (-0.394) to well sorted (-0.6) in ridge. The study area comprises the beach facies, ridge facies, runnel facies, berm facies, lagoonal facies and aeolian facies

4.5.1 Beach Sub-Facies

Beach environment corresponds to the CLT's exposure level 1 & 2, with sediments ranging from sandy gravel to gravel substrate. The dominant structures are planar laminations dipping gently seaward, with low-angle discordance representing adjustment of the beach to changes in wave regimes or sediment supply. In high wave energy regimes, parallel laminated sand is deposited under intense bottom shear (Kumar and Sanders, 1976). Heavy minerals tend to be concentrated in discrete laminae, often alternating with other sand layers. Sea ward imbricate discoidal and blade shaped clast of bivalve shells like *Arca*, *Cardium*, *Solen*, *Murex*, *Oysters*, coral fragments, etc, tend to be particularly abundant near the high-tide line on the beach, with a greater proportion of subspherical clasts near lower level. Beach facies are characteristically exposed in all the sites of the study area, especially between foredune and flat intertidal zone in Wind Farm site and, foredune and ridge-runnel system in Rawal Pir site to berm and ridge-runnel system at Modwa Spit. The raised beaches, exposed all along the study area also corresponds to the beach facies, characterized by medium to poorly sorted, coarse grained sands, sedimentary structures, as revealed by relief peels shows development of plane bed laminations, low angle cross sections (antidunes) and ripple marks. Cores taken from the recent beach at Modwa Spit site shows development of crude laminations, with 55-65% moderately sorted coarse sand. The graphic mean size of the beach sand ranges from fine sand to coarse sand 0.27 Mz to 2.5 Mz. Inclusive graphic standard deviation of the beach sands varies from very poorly sorted 0.202 to moderately well sorted -0.6. There is a significant variation in the textural characters along the beach from west to east. Clean coarse and medium grained sands are essential components of the sediments and their proportion decreases towards the east. The coarse sands are deposited due to the breaking of the swash on the beach face and its deposition as mega ripples with planner cross stratification (Plate-9b). Trenching across a beach at Rawal Pir sites showed top fine layer of fine sands are underlying by coarse to gravelly sands, which are plane laminated but some times display well-developed planar cross stratification but lacking intense bioturbation, though, larger scattered burrows of the beach dwelling adult crustacean are found. Other minor structures like development of air-trap structures are also essential indicators of the beach facies, in which their development is related to the beach slope and thickness of upper sand layer.

4.5.2 Ridge Sub-Facies

Ridge environment is very similar to the beach environment, except in CTL's exposure index they correspond to the level 2,3,4, according to the nearness to the low water line. In the sediment trigon plots, the substrate conditions falls into the pure sand assemblage in contrast to the beach sediments, which falls into sandy gravel zone. The sediments of this facies are variable according to the variation in high water level and low water level. The ridge sub facies are found where fine clastic sediment influx into the littoral zone is high and occurs as linear mound shaped ridges roughly paralleling the coast (Stapor, 1975). In study area, such conditions are met at Rawal Pir site, where there is sudden decrease of the flow conditions, as compared to the Wind Farm sites, resulting into high sediment influx of sediments. According to Carter (1986) nearshore bedforms "feed" intertidal beach ridges by sediment transport through the surf and swash zone. In the ridge facies planar laminations are essential component, formed as a result of upper flow regime or lower flow regime conditions depending upon the water depth and wave conditions with fluctuating tidal cycles. Such plane bed discrete laminae of coarse and fine sand layers are seen in relief peels and X-radiograph of the long cylindrical and plate cores. The bioclast accumulation is similar to the processes as observed in the beach environment. In Rawal Pir and Modwa Spit sites ridge facies are observed in the couplet with the runnel facies. The ridge shows considerable variations in grain size, proportion of fine grain sand and silts increase in ridges of seaward direction, occasionally it also consists of armoured mud balls (Plate-9c). Clean, medium grained sands are the essential component for the ridge; the graphic mean size ranges from coarse to fine sand (-0.1 Mz to 2.2 Mz); inclusive graphic standard deviation varies from -0.394 (poorly sorted) to -0.6 (well sorted). Ridge in three dimension is a triangular body with one side gentle, characterized by plane bed deposition and antidune development, while other side steep, with slope upto 40-45^0 these are marked by falling water marks. Sometimes sediment avalanche from this slope to fill the runnels, causing migration of the ridge over the runnel. X-radiograph and relief peels shows planar cross laminations, due to the deposition of the plane laminations on the gentle slope, these are made up of coarse to medium grained sands. In some cases, the physical structures of the ridge lack clear laminations because sediments are intensely bioturbated by crustaceans, polychaetes bivalves, gastropods, etc.

4.5.3 Runnel facies

Runnel system is unique in the intertidal setting, inter-fringing with the ridges in Rawal Pir and Modwa Spit sites. The runnels often behaves as unidirectional flow system, during the low tide conditions, while during high tide conditions, dominated by bi-directional and oscillatory flow conditions. The first runnels of the Rawal Pir area are

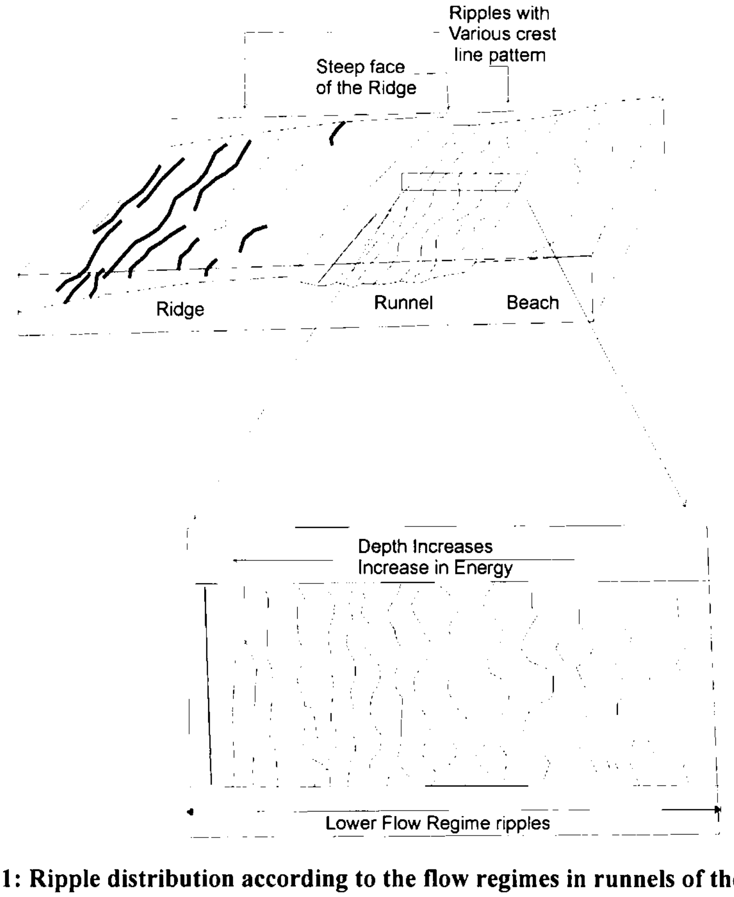


Figure-21: Ripple distribution according to the flow regimes in runnels of the Rawal Pir area.

situated between the beach facies towards the landward side and ridge facies on seaward side. Rests of the runnels are between the ridges. The runnel facies can be delineated by poorly sorted grain (-0.053 to 0.16) size often ranging from muddy sediments to gravelly sediments, this is on account of the fines settling during the draining of the runnels during the low tides, and coarser accumulating during the high tides, and by rill erosion of the beach. The runnels drain out from the runnel channel, often at right angle to the beach or cutting the ridge at right angle. It is characterized by accumulation of the pebble lag deposit in the neck of the channel and is assumed to be the result of strong current velocity, enough to plane off the bottom (Carter, 1986). When runnel turns to meet an outlet channel, a triangular zone can occur in which a sequence of seaward asymmetric oscillatory ripples have formed. Some times due to saturation of the grains of the ridges, the steep side collapse and forms a micro-delta (Plate-8b), which also contributes sediments to the runnels. Runnels also display various types of ripple marks in the form of stratification like S2D, S3Ds, L3Dsa, S3Dsa, (abbreviations from Mayrow and Southard, 1991) and also large scale, ebb oriented, megaripples. Similar, bedforms and morphodynamic observations were also made by Moore et al (1984); Owens and Frobles, (1977); Carter, (1986); Dabrio and Polo, (1981) from various parts of the world. The bedform sequence found in the runnels of the study area shows variation and gradations of various types of ripples according to their increasing water depth. With decreasing water depth (increasing flow regime) the bedforms sequence are developed in the runnels are (i) straight crested asymmetrical wave ripples, (ii) undulatory crested wave ripples (iii) lunate ripples towards the center of the runnels. Dabrio and Polo (1981) while describing the flow regime and bedforms in a ridge and runnel system also described such kind of gradation of ripple forms in runnels, but observations made by author is in contrast to their study. In X-radiograph of plate cores show distinct ripple-laminations of fine sand layers which can be preserved as flaser bedding. Suspension and deposit feeding organisms make bioturbational structures in the runnel, and tubicular animals often aligned themselves to the flow directions.

4.5.4 Supratidal Subfacies:

Supratidal facies (Plate-9a) is separated from the intertidal environment by a subtle break in slope of beach or by a berm. In the study area, this zone is very well developed and corresponds to the CTL's exposure level-1, which is rarely submerged, or is exposed for more than 5 continuos days in a tidal cycle. The sediments are composed of fine to medium sand size, with good sorting, generally because of saltation process in dunes. This facies is very well developed all along the seacoast of the study area, dominated by dune accumulations. In the Wind Farm site fore-dunes have developed in the backshore zone. They attain a height of about 10-12 m and show multi-stage accumulations. They consist of very well sorted fine-grained sediments. In the Rawal Pir site, backside of the lagoon, this facies is well exposed in the form of vertical sections (Plate-3a). The dunes developed on the tidal plains, show large-scale cross- laminations. On lee-ward side, cross-laminations dip 20^0-30^0 due south. In the Modwa Spit site, vegetated dunes attain heights of +17 m along with small dunes are developed on the backshore area. Small dunes are composed of essentially unabraided shells of bivalve. The shells deposited in convex up fashion, suggest role of taphonomic processes in the form of post-mortem transport during high storm conditions. Small dunes sediments are moderately to well sorted and consisting of two grain size populations, fine sand size grains and bivalve shells.

The supratidal facies characteristically displays three distinct dune stages,

(i) Shadow dunes, which are small isolated, initial dunes formed by sediment trapping around any stable material, either, drift wood, or grass, or, any anthropogenic material like bottle, can etc. This zone is extensively developed in the Modwa Spit site.

(ii) Foredunes, which are intermediary dunes built by accretion of shadow dunes, well developed in Wind Farm, Rawal Pir, and Modwa Spit sites.

(iii) Last stage of dune formation, which show full development of dunes.

In Wind Farm sites the dunes are not stabilized, or poorly stabilized, but in Rawal Pir and Modwa Spit sites the dunes are stabilized, and two generations of the stabilized dunes can be distinguished. The older one is more stabilized and is about +17m high at Modwa Spit site, while at Rawal Pir sites, the older dunes are incised and reveals the internal sedimentary structures. Low coppice dunes, bare foredunes and vast supratidal salt marsh (Plate-3b) is the characteristic of the Modwa Spit site. The sedimentary structures present in these facies are characterized by medium to fine grained sand size particles, well sorted nature, low dipping, parallel, or aeolian type cross bedding, variation of physical structures characterizes these facies, (Frey and Howard, 1988; Howard, 1972). During some seasonal change the facies are generally influenced by storm surge that tops the berm crest as sheet-flow and by adhesion of wind blown grains on to the damp surface. Bioturbation is rare and comprises of large diameter burrows of crustaceans.

4.5.5 Lagoonal facies

Coastal lagoons are the common features of the Kachchh coast, which occur as shallow bodies parallel to the coast. They are separated from the open sea by sandbars. According to Reinick and Singh (1973) the lagoons in the tidal region develop more or less like tidal flats, and suggest that in tidal region only those shallow depression that remain water filled even at low tide be considered as lagoons. Two lagoons present in the study area are, one at Rawal Pir consisting of coarse to fine grained sands and other at Modwa Spit, which is characterize by medium to fine grained sands with muddy sediments. Black peaty layers, overlain by a sandy layer are varying in thickness indicating reducing environmental conditions, characteristics of the lagoonal sediments. In absence of any inflow of the rivers into the lagoons, the development of the peat layers can be attributed to the development of the algae, and cynobactrial growth (V. Prasad, *Personal communication*). Since the distribution of sediments and sedimentary structures within a lagoon is controlled mainly by hydrographic conditions and availability of sediments (Singh, 1980). The lagoons of the study area characterized by medium to very fine-grained sediment with good sorting. The sedimentary structures comprise of sand/mud interlayered along with sequences of wavy bedding and ripple marks, deformation structures were also observed during the recent earthquake, which is a significant feature of lagoonal deposits, (Singh, 1980; VanStraaten, 1954). The sedimentary structures shows presence of hummocky and swaley cross stratification, which can be attributed to the peak high tidal flow conditions, interrupted by layer of algal deposit, indicating the low tide current energy. Thick algal mats, attracts various algal-symbiotic organisms like *Turritella*, *Cerithium* and *Telescopium*. They give refuge to many reducing environments loving organisms like nemertea, bivalves, crustaceans and polychaetes.

4.6 SUBSTRATE CONSISTANCY

A sediment substrate is an unconsolidated surface that allows the organisms to live in or on the surface. Many of the biologic attributes of the sediments are related to the depositional environments. The distribution of the aquatic benthos are usually correlated to the texture, more specifically to the sand, silt and clay contents of the sediments rather than its mineral composition (Purdy, 1971). The current velocity determines the proportion of silt and clay in sediments, as well as the ecologically important variables of substrate. The sediment texture and its structures of the Wind Farm area indicate its deposition under relatively high current velocities and characterize the shifting bottom sediments containing small amount of mud and organic matter. Thus sandy and silty sand types characterize its substrate. This is in contrast to its adjoining (Rawal Pir and Modwa Spit) area where the current velocities decreases and more amount of organic rich mud is deposited, along with it ridge-runnel systems also develop, giving the area a wide range of substrate characteristics, ranging from pure sand to muddy gravel, silty sand and sandy gravel. The Modwa Spit is characterized by sandy to sandy gravel types. All this substrates, excersies a major control over distribution and activity of crustaceans and polychaetes. Mechanical properties of sediments also govern the distribution of these communities and their behavioral pattern. Chapman and Newell (1947) and Chapman (1949) emphasis significance of the mechanical properties of the sediments for the burrowing animals along with functional grain size and its relation to the size of burrowers (Bromley 1996). The juveniles, young and adult species of the crustaceans share the same sediment but apparent grain size of the substrate found is different for each of them. Their burrowing strategies are modified in order to cope with the different sediments of different substrate conditions and thus resulting into biogenic structures. Along with the grain-size, water content in the sediments is also important when organisms use it as a substrate.

Endobenthos like crustaceans and polychaetes are influenced directly by the firmness of the substrate. Four different types of substrate Viz., soupground; softground; firm ground; and hardground characterize the study area. Highly watery sediment is referred to as a soupground. This substrate has a fluid consistency; the grains are hardly in contact or are separated by mucoid substances, and the animals may 'swim' through the substrate. Nevertheless, mucus and other organic-walled tubes may be constructed by sedentary endobenthos, in some cases as upward extension of burrows constructed in more dewatered sediment lower down. Softground, consist of watery sediment where the grains are in contact. Softground suggests mud or silty mud and includes thixotropic sediment and the soft dilatant sediments. The initial establishment of a permanent burrow in a softground requires some wall support mechanism, either through compression alone or together with mucus impregnation. Advance dewatering and compaction produces firm ground. Such sediment characteristically is exposed at the sea floor after erosion of upper layers to expose stiffer, deeper levels. Relic sediment of this kind is typically reworked by excavation, the compact form of the fabric precluding the use of compressive processes. Introduction of cement in the pore spaces and the concomitants rigidifying of the substrate creates hardground; bioturbational processes cease and are replaced by bioerosional processes. The suffix-ground implies that the substrate is exposed at depositional interface.

Substrate as a medium excersies major control over the structure of the benthic communities. This is also a limiting factor to the animals and their behavioral ability. There are numerous physical properties of the substrate that governs the nature of the behavior and resultant activity. Amongst them are the nature of consolidation, grain size, sorting, porosity, water content etc.

4.6.1 Soup Ground Substrate and Feeding Type

"Soup grounds" are a type of substrate, in which the sediments are water laden and appear soupy and incompetent. The sediment grains are hardly in contact with each other and has fluid consistency. Such types of substrates are encountered in the lagoons of Rawal Pir and Modwa Spit sites. Some times, due to excessive force over the soft ground of the Wind Farm site the sediment change its characteristics, and attracts small *Ocypodes*, which build small pouch like colonies. Polychaetes usually may 'swim' through the substrate, but due to the fluidity their structures are generally unidentifiable. The animals dwelling in soup ground substrates have tendency to plough through the sediment for feeding purposes (Ekdale, 1985). The feeding activities in this substrate were not noticed, on account of poor preservability.

4.6.2 Soft Ground Substrate and Feeding Types

This is the most abundant substrate, exposed in all sites, and characteristic of ridge, runnel, lagoon and beach units. The sediments are watery but firm as compared to soupy ground. The grains are in contact with each other and the sediments may be thixotropic or dilatant. The sediment can be easily burrowed and do not collapse behind the animal. Due to this reason the substrate was burrowers paradise for young and juvenile *Ocypode* crustaceans. Small crustaceans of *Ocypode, Matuta* and *Uca* often feed on such substrates and produce feeding and fecal pellets, which are distributed in the form of various designs on the surface. Polychaetes were seen feeding by diverse types of feedings strategies included are filter, suspension, deposit and interface feeding. The structures are generally mucus binded grains and includes excavation and backfill structures.

4.6.3 Firm Ground Substrate and Feeding Type

The partially dewatered muddy sediments are observed in patches on the Rawal Pir site. Such sediments are firm but unlithified exposed at the seafloor only after erosion of upper layer to expose stiffer, deeper levels. They are typically known as relic sediments and usually suspension feeders are sole inhabitants of these sediments, generally develop *Glossifunguites* ichnofacies (Pemberton and Frey, 1985).

4.6.4 Hard Ground Substrate and Feeding Type

The nature of the hard substrate attracts numerous sessile organisms. Substratum surface area is an important limiting resource at some time during the life of most sessile organisms. In the present study area such type substrates are provided by various agencies, like inshore platform, wood pieces, piers, oyster reefs, and even dead shells. These special groups provide a special insight to the *opportunistic* nature of this animal. They are ready to get attached the almost anything. The inshore platform is quiet extensive, but in patches and support colonies of *serpulid, Oysters,* barnacles gastropods etc.