CHAPTER-3
GEOMORPHOLOGY

Kachchh, is an ancient rift, incepted during the counter clockwise rotation of the Indian Plate in the Early Jurassic period. Since then, Kachchh basin has experienced various phases of tectonic movements giving shape to the present day landforms. These landforms have resulted due to tectonic activity along the E-W and N-S oriented master faults and transverse faults respectively (Biswas, 1971; 1974; 1980; Kar, 1988; 1993; Patel et al., 2001). These structures have not only affected the Kachchh Mainland but have also shaped the coastal Kachchh region, in which N-S oriented Median High has also played a significant role (Patel et al. 2001; Kar 1993).

3.1 KACHCHH COASTAL PLAINS

The Kachchh coastal plain is a flat, even, low lying surface from Sir Creek to Little Rann and have a height of ~20 m. The rivers of the Mainland Kachchh, after entering the coastal plains suddenly change their morphology, by either changing their direction, or by widening of the channel. Geomorphologically, extensive sand flats characterize the area between Sir Creek to Jakhau; while the NW-SE oriented coastline from Jakhau to Bhada villages is straight and consists of sealed river mouths. The NW-SE oriented trend takes an eastward turn (23^0) after Bhada village and becomes crescent shaped coastline (Figure- 4), consisting of cuspate and spits along the sea ward margin of the beach between Bhada and Mundra. While area beyond the Mundra is again composed of tidal flats of inner gulf.

The study area falls in the crescent shaped coastline, in which, variety of coastal landforms are developed in the study area, Viz., tidal mudflats, raised beaches, sealed river mouth, spits, ridge-runnel systems, stabilized and non-stabilized dunal area, lagoons and alluvial plains. The coastline consist of minor cusplates, along the seaward margin of the beach and beach cusps features which are produced by superposition of the processes operating in the intertidal zone with different scale of motions (Dolan et al. 1974). The landforms developed along the coastline are the result of changing morphological processes across the coastline. The developed features are governed by the reactivation of the E-W regional fault in the Gulf of Kachchh and reflect the regional trend of the shelf edge (Chauhan et al. 1992). Other factors that are responsible for the development of the crescent coastal landforms are the waves, which are normal to the straight coast and make impact against the curved coast. Between Mandvi and Modwa Spit, coastline is oriented in WNW-ESE direction where this wave refraction angle coupled with incoming tide impinge against the inner curved coast in the Gulf of Kachchh.

Coastal configuration from Bhada to Modwa Spit is characterised by crescent shaped coastline (cuspate foreland), consisting of minor cusplates, cusps and sand waves. Landforms observed from low tide region to the coastal plains are ridge and runnel systems, shore platforms, beaches, berm, raised beach, foredunes, tidal mudflats, saline sandflats and alluvial plains.

3.1.1 Cuspate foreland

This is a large triangular area, dominated by three sets of ridges and is often terminated landward by poorly drained terrain. It forms as a result of a long episode of local marine aggradation under wave advance from two dominant directions.

Cusplates are observed on the beach step of Wind Farm and Rawal Pir sites. They are rhythmic in the longshore direction, consisting of small, erosional channels or grooves formed by swash and backwash flow and their temporal span ranges from minutes to hours (Dolan et al., 1974). These are found on beaches with grain size ranging from fine sand to gravel with spacing upto 3m. In general they tend to form under low-energy conditions and once formed remain in place. Rarely do they last longer than one tidal cycle.

Cusps are also observed on beach face (berm) of Wind Farm, Rawal Pir and Modwa Spit sites. These constitute of rhythmic, small shallow sloped bays in the berm, separated by more steeply sloped horns. They are formed by swash action and currents of a newly deposited berm. Cusps range in length from 1-10m, width from 1-3m, and height upto 1/2 m. They have been observed on beaches with grain size varying from fine to coarse sand to pebbles and are believed to have formed when there is a drop in current energy levels.

Sand waves are part of beach-ridge-runnel systems of the Rawal Pir and Modwa Spit area consisting of a gentle cresentic or wave like shape of the shoreline. Sand waves are associated with the dynamics of the eastward-directed longshore currents.

3.1.2 Beach

Beaches (Plate-1a) are developed all along the coast consisting of different size of the sand grains and varying slope. The maximum slope of the beach is about 20^0 at Wind Farm site that decreases gradually and becomes $4\text{-}6^0$ towards the Modwa Spit. The Wind Farm consists of fine to coarse sand with gravel and flat pebbles along with fragments of invertebrates. The Rawal Pir area consists of series of regularly spaced crescentic shaped structures formed on local relief along a beach. The horns of beach cusps are composed of coarse sand-gravel and point down the beach. The intervening troughs are made up of finer sand. The width of the beach is more compared to Wind Farm sites. The beaches of Modwa Spit are relatively flat or gentle sloping in seaward direction with width of 100m. They consist of mainly fine sand with subordinate amount of coarse-grained sand. In the study area beaches are very well developed and are backed by either dunes or by berms.

3.1.3 Ridge-Runnel Systems

The term "Ridges and Runnels" was first used by King and Williams (1949) to describe multiple swash bars on tidal coast. These bars are parallel to the coast and are intersected by drainage channels at right angles to the waterline. According to Hayes (1969) ridges and runnels are defined as combination of swash bar and a trough that develops between the landward dipping slip face of the bar and beach face. Ridge (Plate-1a) is a tabular body of the sand that develops on the low tide terrace during constructional phase. In the study area the formation of the ridges are observed in the Rawal Pir and Modwa Spit sites. They are oriented at N 140^0, varying in length from nearly 50m to more than 800m and in width from 10-30m. One end of these ridges is attached to the shoreface at an angle of nearly $15^0\text{-}20^0$. The formation of ridge-runnel systems along the coast is thought to be local construction of a slope in equilibrium with

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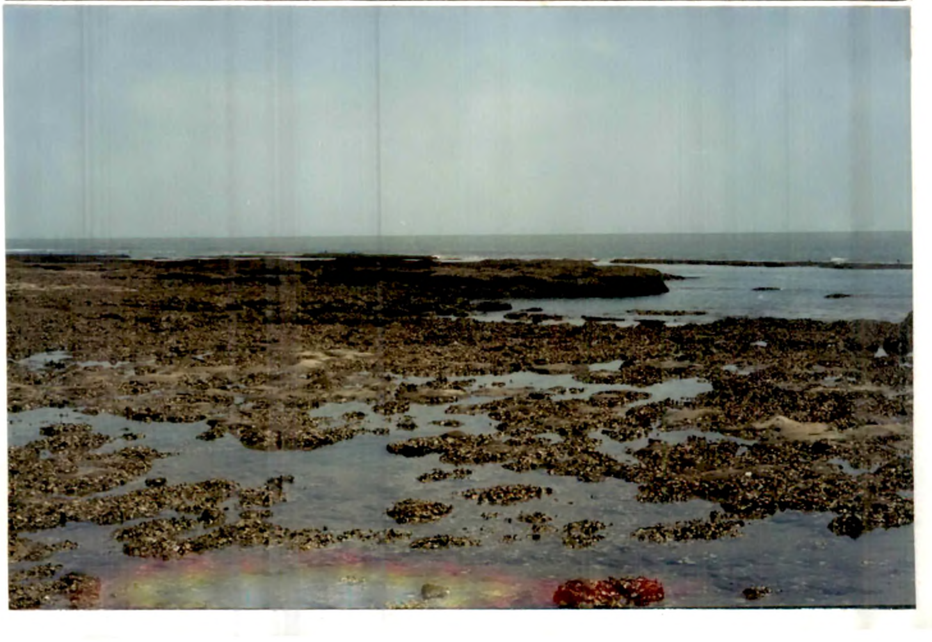
Plate-1: Nature of the intertidal zone, (a) General view of the intertidal zone showing beach and two sets of ridge-runnel systems. Arrow indicates occurrence of Paleomud flats in the runnel. (b) Patchy exposure of the Rawal Pir shore platform covered by sessile encrusters like *Barnacle, Oysters,* and *Serpulids*. (c) Extensive development of Modwa Spit, biogenic shore platform covered with different generation of the *Oyster, Barnacles* and *Serpulids*.

PLATE-1

(a)

(b)



(c)

the incident waves and sand size sediments. The surface of the ridge is gently sloping (5-10^0) seaward, while the stoss side of the ridge facing the landward is steep (30-60^0). In all there are three to four sets of the ridges intervened by runnels. It has been commonly observed that they builds after storms and migrate towards the land until they weld onto backshore to form a beach/berm.

3.1.4 Flat intertidal

Flat intertidal zone is developed on the tip of the Modwa Spit area. The surface of tidal flats sloping gently towards sea. It is primarily made up of muddy sediments and attributed as a result of the gentle bathymetry and low energy conditions of the turbidites. Their width increases towards the Mundra side, and is characterised by fine sticky tidal mud. They are interfringed by shore platform near Modwa Spit while tidal channels in the eastward direction. Tidal flats are characterised by tidal rhythms, where sediment is sticky and not eroded by normal wave and current energy. The paleo-tidal mud flat is occasionally occurring as exhumed patches in runnels.

3.1.5 Shore platforms

Shore platforms are the occasional pop-ups in the beach and ridge-runnel system. Geologically, these are of Pleistocene in age and have varied dimensions and their exposure increases in the eastward direction. In Wind Farm area, the shore platforms are totally absent while they are developed in the Rawal Pir and Modwa Spit area. In the Rawal Pir area they are exposed in patches, having a length of 20-30m, width 10-20m and are sometimes about 0.5 m in height, occasionally covered by beach sediments. Various types of encrusters like oysters, barnacles and serpula tubes (Plate-1b) colonise on shore platform. In the Modwa Spit area, the shore platform becomes more wide and about 1 km in length and more than 500m wide and having thickness of about 1-1.5m above the surrounding sediments. Various types of encrusters like oysters, barnacles and serpula tubes covers the surfaces along with abundant wandering invertebrates like gastropods, crustaceans and bivalves which further adds material to the shore platform. Surfaces are completely encrusted by the different generation of the oyster shells and form the modern the incident waves and sand size sediments. The surface of the ridge is gently sloping (5-10^0) seaward, while the stoss side of the ridge facing the landward is steep (30-60^0). In all there are three to four sets of the ridges intervened by runnels. It has been commonly observed that they builds after storms and migrate towards the land until they weld onto backshore to form a beach/berm.

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3.1.6 Spits

The Modwa Spit (Figure-4) is the only prominent spit in the study area, which is about 9 km in length and 50m to 800m in width. It starts from Rawal Pir and further extended over the Modwa village in the east. After the Modwa village, width of the spit decreases and tapers down to eastward direction. The overall shape of the spit is linear with sinuous nature fronted by wide berm. The other spits observed in the eastward direction around Mundra are probably the remnant of the past ridge-runnel systems. It is backed by wide supra tidal mud flats and fan deltas (Figure 5). Dhoa and Sirtar are ESE-WNW oriented major spits and have ~ 20m height. The other ones are smaller and are

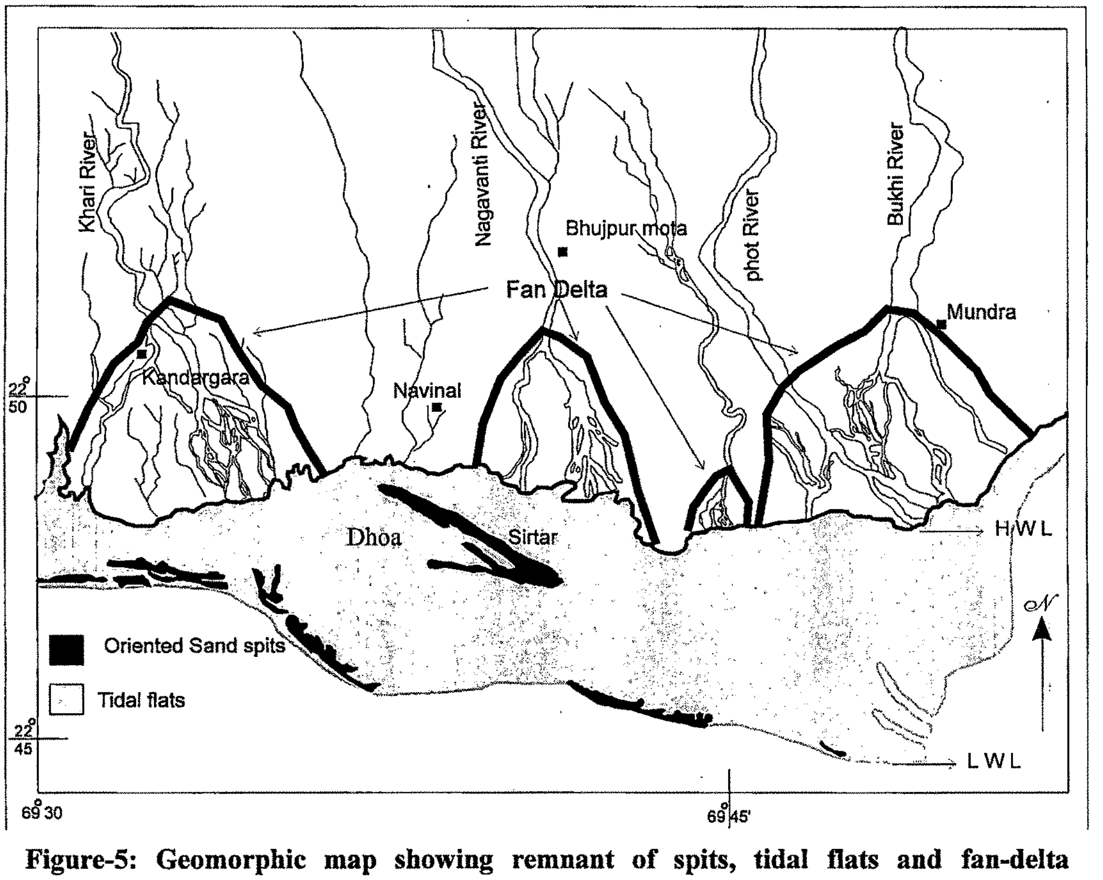

Figure-5: Geomorphic map showing remnant of spits, tidal flats and fan-delta complex.

similar to the spit and hooks. The cycle of the spit development is complete with the severance of its connection with the mainland in the west.

3.1.7 Berm

The berm is very well developed in the Modwa Spit area and backed by the beach and frontal by the dunes and marked break of slope at the seaward edge. It is a flat, broad and slightly higher relief than the beach and even remains open during the spring tide. The finer particles are lifted by the wind, so it is made up of medium to coarse-grained clastic unconsolidated sediments and to be merged into Modwa Spit. The maximum width (~1.5km) of the berm is observed near Modwa and again decreases further eastward and cut by the tidal channel.

3.1.8 Intertidal Lagoons

Two intertidal lagoons are present in Rawal Pir and Modwa Spit area. The Rawal Pir lagoon is situated at high tide level, originated due to shutting off the stream mouth near the Rawal Pir coupled by a small tectonic uplift of the coastal tract. During spring tide, the water gets filled up in the shallow depression dammed by bar. The presence of peat layer and algal mats in the sediments is the characteristics of the Rawal Pir lagoon. The second lagoon is situated near the Modwa village, formed by the cutting of a berm by tidal channel. Alternately filled by water during the spring tide, moreover depict similar characters in the sediments. It is formed due to depression created on dune face side on account of tectonic movement.

3.1.9 Raised beaches

The coastal plains are made up of tidal laminates along with well-defined sections of the raised beaches. These raised beaches show physical laminae (Plate-2a&b) of beach

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Plate-2: (a) Rawal Pir raised beach section capped by recent dune sediments and vegetation. (b) Trench made for relief peels showing physical sedimentary structures along with *Psilonichnus* burrow opening.

PLATE-2

(a)

(b)

origin and can be distinguished from the dunes, moreover characterised by marine bioturbated structures. Near Rawal Pir, flat pebble-gravel and stratified conglomerate are exposed, which are characteristic indicators of the wave-dominated settings (Nemec and Steel, 1984; Clifton, 1973). This size sorted, disc shaped conglomerate dipping in the seaward direction is often documented as gravely beaches (Bluck, 1967a; Dobkin and Folk, 1970). Vegetated stabilised dunes (Plate-2a) are overlying the raised beaches.

3.1.10 Dunes

Dunes are present all along the coast, on the supratidal zone as well as on coastal plains. These are stabilised and unstabilised forms, which are made up of very fine-grained sands, indicating various stages of dune accumulation (Plate-3). In the Modwa Spit area two types of dunes are present, the older mature dunes and the younger immature dunes (Plate-3b). The older dunes are stabilised, densely vegetated by babul trees and grass and are at higher elevation of about +17m above MSL. The younger immature dunes are very conspicuous, consisting of unabraided bivalve shell debris deposited by older storms, later, they were probably sorted by powerful wind blows.

3.2 TECTONIC GEOMORPHOLOGY

3.2.1 Holocene Tectonics

Kachchh an intracratonic basin, have received recurrent seismic shocks of varying magnitude, since the time of its formation to the present day which resulted in upliftment of the Kachchh basin (Biswas and Khatri, 2002). Holocene uplift of the Kachchh peninsula noticed, since historic times indicates the Rann was inundated by water and probably due to seismic shaking, it was turned into a arid waste land (MacMurdo, 1839; Nelson, 1845; Lyell, 1853; Wynne, 1872; Sivewright, 1907; Kar, 1988). The coastal area has also received continuos seismic shocks since historic times (Malik et al 1999) and have effect on substantial upliftment in the Gulf of Kachchh along the Kachchh coastline (Kar, 1993;

Plate-3: Nature of the dunal accumulation, (a) Large scale cross stratification of the stabilised, incised dunes (i) overlying tidal flats sediments (ii) at Rawal Pir site. (b) Two generations of the dunes, older, stabilised dunes (i) with high relief and bivalve shell dominated younger copice dunes (ii) at Modwa Spit site.

PLATE-3

(a)

(b)

Patel et al, 2001). The area is seismically active, bordered in the north by active Katrol Hill Fault (Sohoni et al 1999) and Median High, which is a zone of fractures and igneous activity (Biswas and Deshpande, 1982) in the west. While east is marked by North Kathiawar and Bhujpur faults and also comprises Anjar nose, Vira nose, Mathak syncline and E-W oriented minor fault systems (Figure-6). The area has also experienced repeated, clustering of low level seismicity of 3-5 magnitude (Malik et al, 1999) and high magnitude Anjar Earthquake of 1956 and Bhuj earthquake of 2001 (Patel and Desai, 2001; Desai and Patel, *in press*). The different types of soft-sediment deformational structures formed and preserved in the raised beach sections of the Mandvi, indicates that the area is affected by >5 seismic magnitude earthquake (Ambraseys, 1988). The

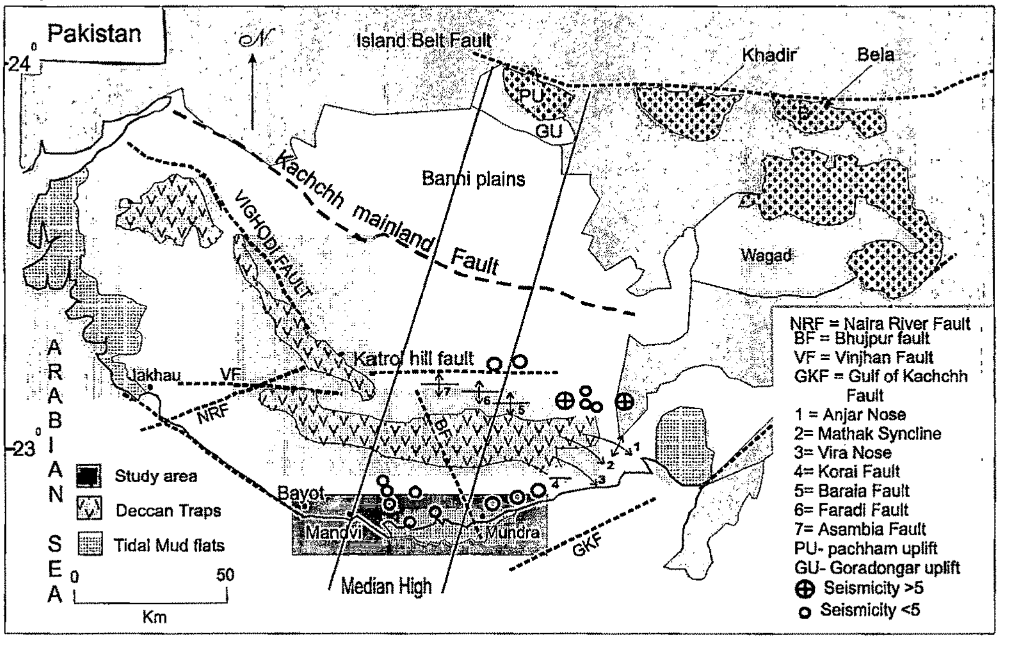


Figure-6: Tectonic map of Kachchh (Biswas and Deshpande, 1972; Seismicity data after Malik et al, 1999)

seismicity in this pre-existing zone of weakness (Median High) has given rise to the development of ambient stress field, inferred to be in compressive stress regimes based on the local various tectonic features. Moreover, these stresses accumulating in the E-W directed major faults, are transmitted to the transverse faults during the late Quaternary times due to locking of the Indian plate in NE direction (Thakkar et al 1999). This has caused upliftment of the beaches and tidal mud flats (Patel et al, 2001) along the Kachchh coastline in the Gulf of Kachchh and, swampy and poorly developed tidal creeks that could be related to slow regional (cymatogenetic) uplift (Kar, 1988; Biswas, 1974). The stress locking and slow cymatogenetic uplift have contributed to the upliftment of the

Mainland Kachchh along the axis of the Median High which resulted in the differential blocks movement in coastal region of Kachchh (Kar, 1993; Patel et al., 2001).

3.2.2 Coastal Upliftment

The coastal landforms are the result of tectonic activities that took place along the E-W directed major faults and N-S directed transverse fault systems (Figure-6). These

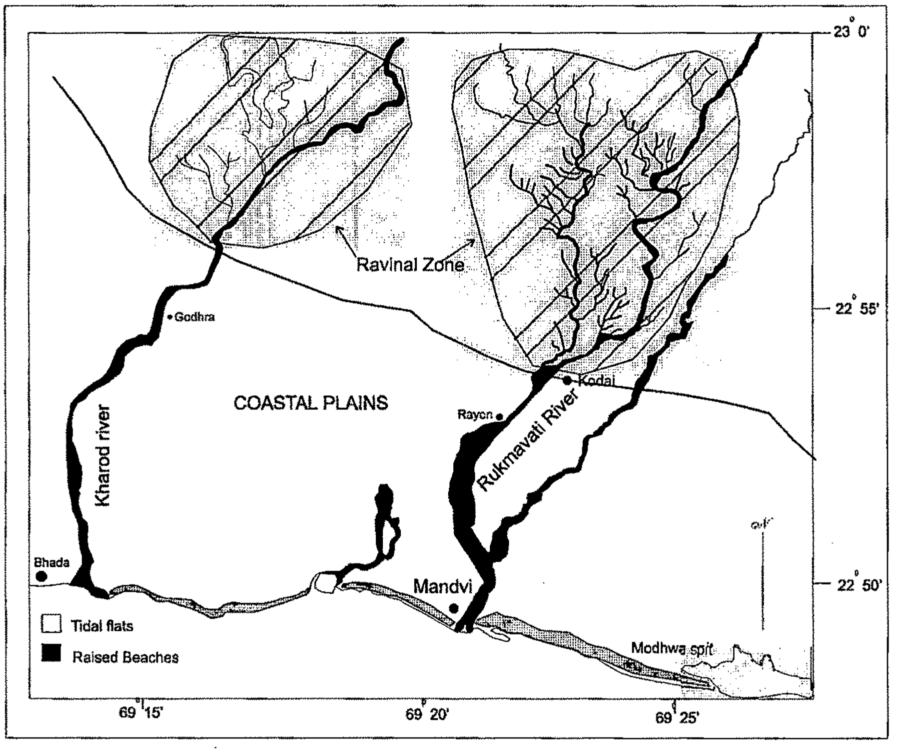


Figure-7: Geomorphic map showing drainage patterns and coastal configuration around the Mandvi.

two structural trends have considerable influence in shaping of the coastal landforms and their distribution. The study area bears symptoms of these activities, exhibiting cuspate foreland with wave cut terraces, sealed river mouths and raised beach with relict paleo-tidal mud flats, representing varied coastal geomorphic features indicating tectonic activities of Holocene time. These paleo-tidal mud flats (Plate-1a) consist of soft, sticky, partly dewatered muddy sediments, consisting of dead *in situ* bivalve shells of *Bernea, Macoma* and *Solen* at different levels in the sediments and polychaetes tubes. The well developed raised beaches consists of cross laminations and mud flats along the coast indicating movement along E-W directed major faults, while coastal plains and other associated features indicate movements along N-S directed faults.

Rukmavati and Kharod rivers flow along the N-S directed lineaments of Median High and its effect is reflected by the sudden ENE-WSW turn and widening of the river channels after entering the coastal plains (Figure-7). The long profile of the river Rukmavati (Figure-8) shows number of nick points and change in the slope gradient. Phi values of River Kharod and Rukmavati are 23.35 and 39.25 respectively, indicating major evidences for the role of neotectonic activity, which is still continued across the coastal plains. The area exhibits erosional surfaces in the upland zone (Figure 7) characterised by

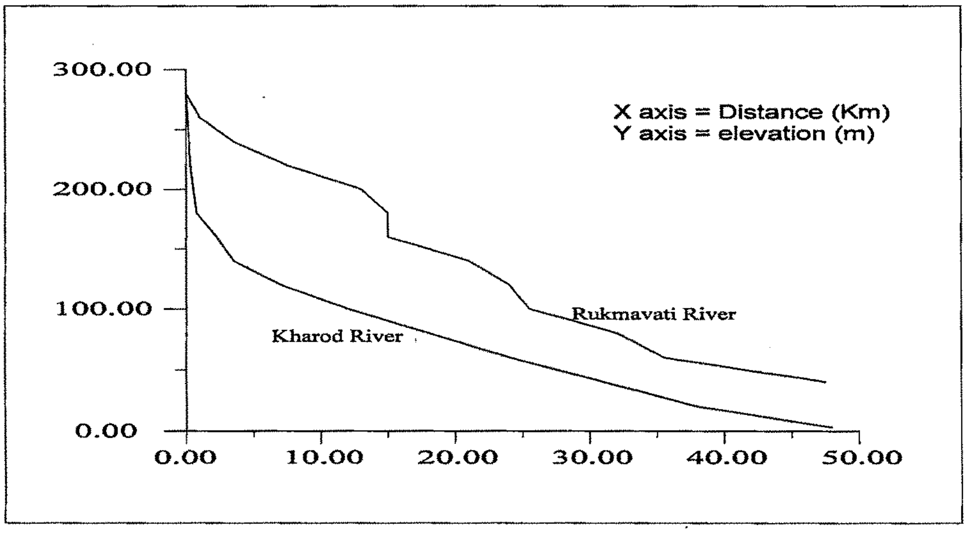


Figure-8: Long profile of River Rukhmavati and Kharod

the asymmetrical ravines dominated block moved up along the transverse faults. Preferential development of the ravines suggests strong tectonic control in limiting their distribution in distinctive fault bounded blocks (Ouchi, 1985). Abrupt physiographic breaks in coastal plains mark an active tectonics (Mc Pherson et al. 1987; Bull, 1968; Blair and Mc Pherson, 1994) along E-W and N-S directed transverse faults indicating the recurring tectonic activities along these lineaments.

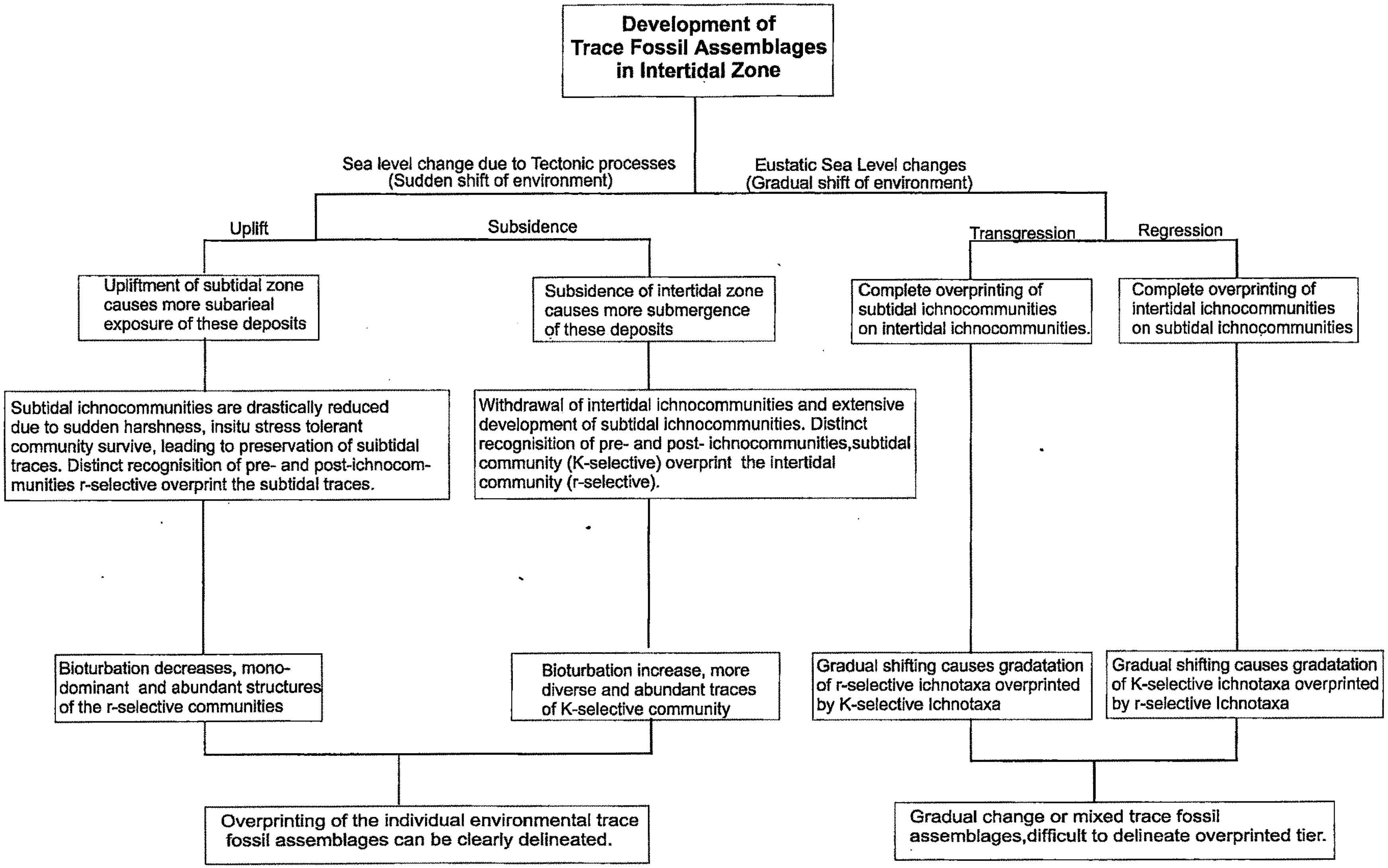
Study area is remarkably different in their morphology and structures, becomes nearly East-West and continues so, till the head of the gulf. Between 69^0 15'E to 69^0 30'E a prograding coast is being build by heavy sedimentation on account of high velocity tidal streams (Nair et al. 1982). All along this coast rivers drains into the gulf carrying small quantity of water inspite of having broad valleys (800-900 m) which consists of sand and gravel.

The upliftment along the coast was not consistence but pulsative (Biswas, 1971, 1974; Kar 1988, 1993; Patel et al 2001). The upliftment caused due to active fault systems, which borders the area and accumulates the stress subjecting Kachchh to episodic upliftment (Thakkar et al, 1999; Malik et al 2001; Sohoni et al 1999). According to Talwani (1989) the reactivation of the pre-existing zone of weakness is the result of the ambient stress field. This stress accumulation can be identified on the basis of the hypo-central alignment of the low level seismicity, along with major high magnitude seismic shock and with zone of fractures and faults (Median High; Katrol hill fault; Gulf of Kachch fault; Bharapur fault).

3.3 ICHNOLOGIC APPLICATIONS IN TECTONICS

Kachchh uplifted shorelines represented by raised beaches and paleo, partially dewatered raised mud flats are characterised by *Gastrocheonolites, Skolithos, Ophiomorpha, Thalassionides,* and *Polykladichnus* trace fossils and polychaetes calcite tubes of the intertidal/subtidal origin, exposed in the supratidal region. The simplified flowchart (Figure.9) shows the development of the different trace fossil assemblages and effect of sea-level rise or fall due to tectonic processes or eustatic. In eustatic sea level changes: Transgression/regression of the sea causes gradual shift in coastal biological/ ecological / ichnological zones. In transgressive sea the K-selected (Pianka, 1970) species try to adapt to the new sea level, filling the ecological vacuum, usually colonising and overprinting the traces of *r*-selected species (Pianka, 1970), while abandoned previously colonised substrates either in parts or whole (Pemberton and MacEachern, 1992; Strios et al, 2000). The *vice versa* would be for the regression of sea, where by the *r*-selected traces would be overprinted on the K-selected traces. To survive in gradually shifting environment, any resident organisms must have adapted to cope with the full range of physical and biotic conditions which prevail at a given locality (Pianka, 1970). More over the Stress-Tolerant Species (*Sensu strictos* Vermeij, 1970) of the intertidal zone would not be affected by any substantial changes in

Figure-9: Simplified flow chart-showing effect of sea level and tectonic changes on trace fossil assemblages.



Development of Trace Fossil Assemblages in Intertidal Zone
Sea level change due to Tectonic processes (Sudden shift of environment)
Eustatic Sea Level changes (Gradual shift of environment)
Uplift
Subsidence
Transgression
Regression
Upliftment of subtidal zone causes more subarieal exposure of these deposits
Subsidence of intertidal zone causes more submergence of these deposits
Complete overprinting of subtidal ichnocommunities on intertidal ichnocommunities.
Complete overprinting of intertidal ichnocommunities on subtidal ichnocommunities
Subtidal ichnocommunities are drastically reduced due to sudden harshness, insitu stress tolerant community survive, leading to preservation of suibtidal traces. Distinct recognisition of pre- and post-ichnocommunities r-selective overprint the subtidal traces.
Withdrawal of intertidal ichnocommunities and extensive development of subtidal ichnocommunities. Distinct recognisition of pre- and post- ichnocommunities,subtidal community (K-selective) overprint the intertidal community (r-selective).
Bioturbation decreases, mono-dominant and abundant structures of the r-selective communities
Bioturbation increase, more diverse and abundant traces of K-selective community
Gradual shifting causes gradatation of r-selective ichnotaxa overprinted by K-selective Ichnotaxa
Gradual shifting causes gradatation of K-selective ichnotaxa overprinted by r-selective Ichnotaxa
Overprinting of the individual environmental trace fossil assemblages can be clearly delineated.
Gradual change or mixed trace fossil assemblages,difficult to delineate overprinted tier.

the environment, they would soon adapt to the new environmental conditions. Depending on the amplitude and velocity of the sea level shift, the new trace fossil assemblages may be partly or totally printed over the older ones.

In case of tectonic shift (Figure-9), the gradation are sudden, without giving ample time for organisms to recolonise, thus, it may preserve distinct successive tiering of trace fossil assemblages. In case of seismic land uplift, the shifting of the environment-specific substrate or the ichnological zones are momentary processes, and the parts of the subtidal area crosses the Lower intertidal zone and Lower intertidal zone to upper intertidal/supratidal without being colonised by the intertidal/supratidal stress-tolerant community. Similar Holocene seismic coastal uplift case for the rocky coast have been exemplified by Strios et al (2000) for Aegean Sea, taking in to account of fossil vermetid microreef of polychaetes *Vermetus triqueter*.

Intertidal/subtidal soft ground deposit display two phases of upliftment on the Kachchh coastline, consisting of pre-omission suits of *Ophiomorpha* and Sabelleried polychaete calcitic tubes. These deposits are subjected to uplift, followed by dewatering of the sediments, previous community have perished leaving behind *insitu Ophiomorpha* and *Thallasinoides* burrows. The dewatering in the intertidal zone caused hardening of the sediment and invited *Glossifunguites* community like *Bernea truncata* in newly formed lower/middle intertidal zone. Then with later phase of uplift, they left behind dead colony of bivalve *Bernea truncata* and its boring structures-*Gastrocheonolites*. The final stage of the upliftment gave rise to bioturbated-raised beach and raised tidal mud flats. The evidences of trace fossil assemblages and soft sediment deformational structures suggest that the observed uplift were episodically and conspicuously seismic.