LATE QUATERNARY MORPHODYNAMIC EVOLUTION OF THE NORTHERN COAST OF GULF OF KACHCHH, GUJARAT, WESTERN INDIA

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By

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CERTIFICATE

This is to certify that the contents of the thesis entitled “Late Quaternary Morphodynamic evolution of the Northern coast of Gulf of Kachchh, Gujarat, Western India” comprises original research work of the candidate and have no time been submitted for any other degree or diploma from this or the other university/institute. The candidate has fulfilled the requirements regarding attendance contained in O.Ph.D. 3(i).

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Shashi Bhushan Shukla

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1
Introduction
About the study and study area

Coastal zone is one of the most dynamic physical environments in the nature and it is very important to study how its landforms are changing in time and space (Pethick, 2000). Different coastal geomorphic landforms are signatures of the active coastal processes in association with available sediment influx. Sediment dynamics in the macrotidal environment like the Gulf of Kachchh are very complex and their significance has been widely appreciated (Pelletier and McMullen, 1972; Reineck and Singh, 1980; Stride, 1982; Nair et al., 1982a & b; Chauhan and Vora, 1990). Offshore currents are responsible for the reworking and distribution of sediments flux along the coast. Hence, to understand the coastal geomorphic evolution one needs to appreciate the coastal sediments, their provenance, pathways and accommodation in sinks and sub-sinks. The study of morphodynamic evolution of a coastline accounts for evolution of coastline in relation to its offshore and onshore dynamics that also include sea level changes and tectonic activities (Carter and Woodroffe, 1994). The understanding of morphodynamic evolution is of vital importance in a better management and sustainable development of coastal zone (Prizomwala et al., 2010; Vethamony and Babu, 2010). More than 10% of the world population now resides along the coastline (Hinrichsen, 1998), and nearly 60% of investments are being made in the vicinity to coast (IUCN, 2007). The Kachchh coast is one of the most rapidly industrializing coastlines in western India (Swaminathan, 2005). Therefore, the present study has a prime purpose to prepare an intense scientific database that would lead to understand the natural dynamics read through the coastal landscape that has emerged out of the response provided by the sedimentary systems to these dynamics over a period since late Quaternary.

The present study documents various geomorphic assemblages along the northern coast of the Gulf of Kachchh and evaluates its evolution with regards to coastal dynamics, using various conventional techniques like high resolution geomorphic mapping, textural-compositional analysis for sediments and a modern technique like Ground Penetrating Radar (GPR) to depict the shallow subsurface sedimentary architecture as fingerprinting the microenvironments along the Kachchh coastline. The study has strong implications in appreciating the coastal response to sediment flux, various coastal events and coastline dynamics in space and time.

Objective

With the purpose stated earlier, the present study attempts to achieve the following objectives;

1. To understand the ongoing coastal geomorphic processes and their relationship with coastal dynamics around northern coast of the Gulf of Kachchh.
2. To understand the sediment characteristics of the Holocene sequences along the Kachchh coast.
3. To evaluate the sedimentological proxies for understanding the morphodynamic evolution of the study area.

Methodology

To achieve the aforesaid objectives, the following methodology was adopted.

1. Available published data on the stratigraphic, structural, Geomorphic, Sedimentological, Geophysical and seismotectonic aspects of the coastal region of Kachchh were critically studied and evaluated to understand the regional geological setting and possible influences of these on the geomorphic set up of the study area.
2. A large scale geomorphic mapping of the study area was carried out using remote sensing (Landsat and Google earth satellite images, Survey of India topographic sheets) and field data.
3. Primary surveys for knowing the subsurface sedimentary architecture were carried out using GPR.

4. Geomorphic domains were categorized based on gross depositional and/or erosional characteristics.
5. The exposed Quaternary sediments were studied with a view to understand the genetic aspects of the landforms and stratigraphic evolution. Coastal sediments were investigated in more detail.
6. The palaeo and present coastal geomorphic domains in the study area were sampled by using PVC pipe cores and by digging the trenches at selected sites.
7. The samples were analyzed for its sedimentological (textural and compositional) attributes using standard laboratory procedures.
8. The database was evaluated for understanding the morphodynamic evolution of the coastal landscape of Kachchh region.

STUDY AREA

Regional Setup

The Gulf of Kachchh is a structurally controlled indentation which is situated in the northern Arabian Sea lying between 22°15’ to 23°N and 69° to 70°15’E (Figure 1.1). The region is characterized by arid/semi-arid climate with an average annual rainfall of 50 cm. The Gulf of Kachchh is 140 km in length, and 70 km wide near the mouth and gets narrowed to about 3 km in intrinsic creeks at the head of the embayment. It is a macrotidal environment with tidal range of 3 m at the mouth to about 7 m at the head. The coastal areas of the Gulf of Kachchh are presently an active industrial hub.

There are about ten small and large ports such as Kandla, Mundra, Okha, Mandavi, Bedi, Sikka, Salaya and Tuna, along with many jetties, pipelines, water intakes and single point moorings associated with refineries. The Kachchh mainland, which bounds the northern side of Gulf of Kachchh, has several seasonal rivers flowing into the Gulf of Kachchh. These rivers mostly drain sedimentary rocks of Jurassic, Cretaceous and Tertiary age, and basalt of Late Cretaceous age; in coastal area they flow through unconsolidated Quaternary sediments. The major lithology is sandstone, shale, limestone and basalt. The Saurashtra peninsula in the south of the Gulf of Kachchh mostly consists of Tertiary shale and limestone along with Late Cretaceous basalt and laterite rocks outcropping in the coastline.

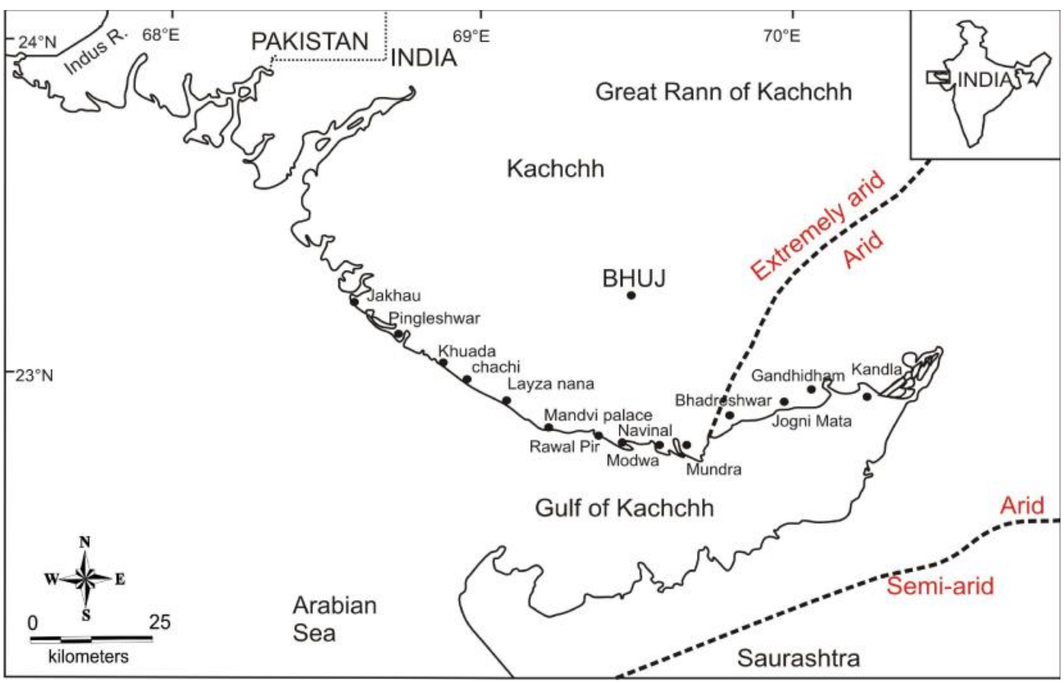


Figure 1.1: Map of the study area showing various locations referred to in the text and its general climate.

The present study has remained confined to the northern coast of the Gulf of Kachchh only that encompasses the track from Jakhau (23°13'8.51"N and 68°42'25.92"E) to Kandla (23° 6'45.40"N and 70° 6'2.16"E), running for about 200 km in length. The present geomorphic configuration of the Kachchh basin is the result of post-Mesozoic differential uplift along various intrabasinal faults which are also responsible for recurrent seismic activity in the region (Kar, 1993). Accordingly, the Kachchh coast exhibits distinct geomorphic zones viz., deltaic coast, irregular coast, straight coast, sandy cuspate and mudflats. The coastline of Kachchh comprises of Tertiary and Quaternary sequences which are mainly consisting of friable sandstone, sand and silty sand units along with tidal clay.

Communication

Kachchh has a reasonably good network of all weather roads. The Ahmedabad-Kandla national highway is the only national highway in the entire Kachchh district which connects it with other parts of the country. Amongst the state highways the important one are the Bhuj-Anjar-Gandhidham road, Bhuj-Mandvi road, and Bhuj-Desalpar-Roha-Naliya-Jakhau road (Figure 1.2). Mandvi situated in almost center of study area between Jakhau and Kandla, is well connected with all other taluka head quarters of the Kachchh.

In Kachchh district almost half of the villages are connected directly or indirectly by motorable roads with state highway. Bhuj-Lakhpat state highway, starting from Bhuj and terminates at the north-west corner of Kachchh near Lakhpat, is a good road to reach the north western corner of this coastline. The rail link is also available up to Bhuj via Gandhidham. Study area is having two major ports Kandla and Mundra along with some small ones like Mandvi, Jakhau, Randh, Modwa, Tuna, etc. The only functioning airport available for civilian air travels is the Bhuj airport.

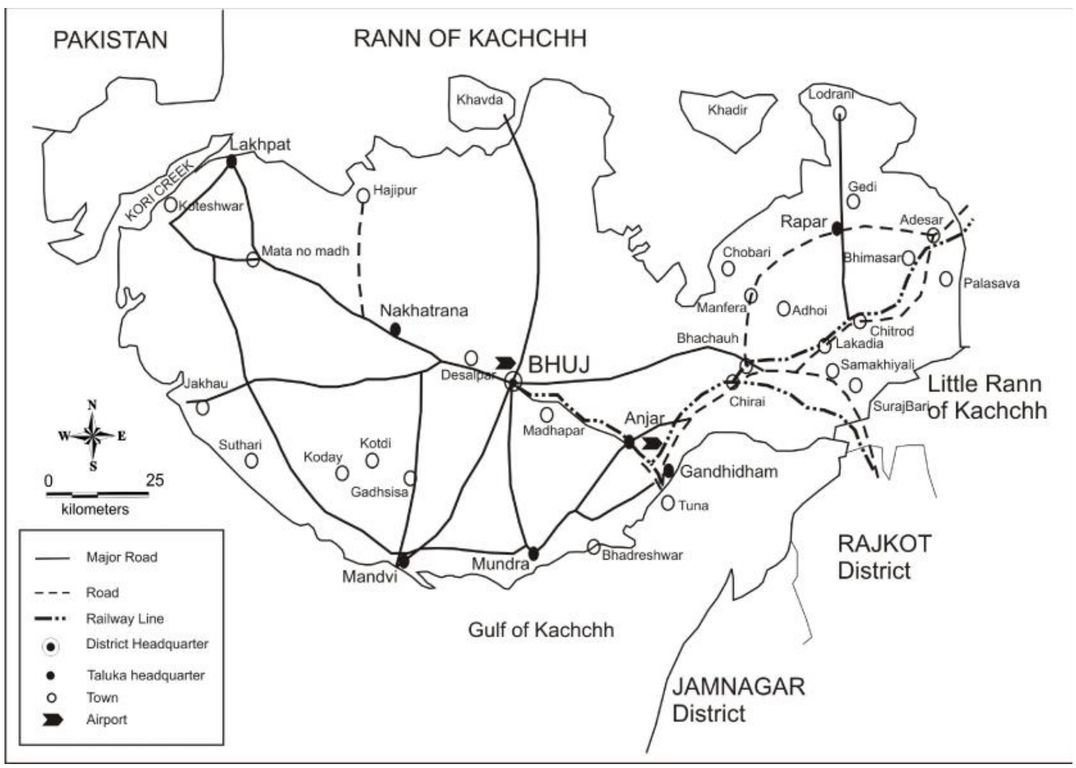


Figure 1.2: Communication map of the Kachchh district showing major road and rail network with main location.

Climate

The Kachchh region in general falls within the arid to hyper arid belt of western India (Figure 1.1). Average rainfall in the district is between 300 to 400 mm/year. On an average there are very less, approximately 15 rainy days during the entire year that has increased to ~25 days in recent years. The day temperatures particularly in summers are generally low in the coastal region than the interior. In summers the day temperatures go above 46^{o}C. January is the coldest month of the year when the mean daily maximum temperature is 26^{o}C and the mean daily minimum temperature is 11^{o}C. However, during the cold wave conditions due to the NW disturbances, temperature goes down below the minimum level. Humidity remains high throughout the year along the coast, generally exceeding 60% on an average.

Flora

Kachchh has practically no forest and very few trees. The Kachchh flora is mostly characterized by thorny and non-thorny shrubs and trees. The wild tree growth is almost entirely confined to thorny like Baval, Kher etc. Several varieties of Acacia occur. The coastline exhibit swamps vegetated with mangrove forest and grasses covering dunes and sand flats. The main varieties of flora found in the study area- Avicennia officinalis (Tavar Tarvariyan), Leptadenia spartium (Khip), Casuarina Equisetifolia (Saru), Halopyrum inucronatum (Dariyai Kansdo, Dariyai Kans), Melia azadirachta (Limbdo), Acacia Arabica (baval), Cassia auriculata (Aval), Sporobolus indicus (Velari charchar), Sueda maritime (Lano, Luno), Euphorbia tirucalli (Thor, Kharsani Thor, Dandalio Thor), Leucoena glauca (Laso baval, Vilayati baval) etc. The coastal plain is extensively used for agriculture where various crops (Jowar, Bajri, Wheat, Mag and Math) including those of fruit and vegetable are grown.

Fauna

The chief domestic animals found in the area are horses, camels, oxen, cow, buffaloes, sheep, goats and asses. Absence of forests means a general lack of wild animals. The wild animals are the Panthera pardus (Panther), Canis lupus (Indian wolf), Canis aureus (Jackal), Vulpes bengalensis (Fox), Sus scrofa (wild boar), Antelope cervicapra (Black buck), Equus hemionus pallas (Wild ass), and Lepus nigricollis (Indian hare) and various kinds of poisonous and non-poisonous snakes. The resident and migratory birds are commonly found in Kachchh. The migratory birds are found plentiful during winter season in the organic rich zone of the coastal flats bordering the Gulf of Kachchh and the vast saline expanse of the Little Rann of Kachchh.

Drainage

The drainage of Kachchh provides an interesting example of a combination of lithologic and tectonic controls along with the influence of sea level fluctuations during Quaternary Period. The central Highland forms the main watershed with numerous consequent streams draining the slopes with a radial pattern and pouring their water and sediment load into the Arabian Sea, the Gulf of Kachchh and the plains of Banni and the Rann in west, south and north respectively (Figure 1.3).

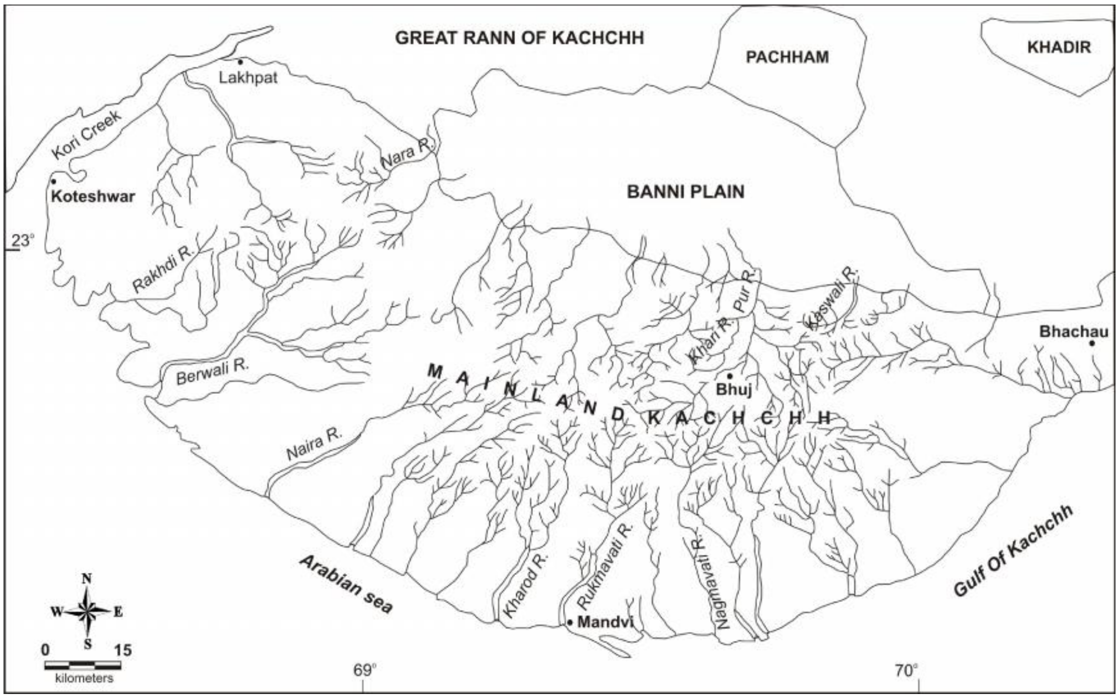


Figure 1.3: Regional drainage map of the Kachchh.

The southward flowing streams include Naira, Kankawati, Chok, Sai, Vengdi, Kharod, Rukmawati, Khari, Nagavanti, Phot, Bhuki, Mitti, Sakra and Larekh streams which empty their water into the Gulf of Kachchh and the Arabian Sea. The streams originating from the northern slopes of the central highland, join the streams originated from the Northern Hill Ranges and pour their water into the Chhari, Bhukhi, Tambo, Kaila, Pur and Kaswali streams which, in turn, debouch into the Great Rann of Kachchh through the Banni Plains. In general, the streams are ephemeral (seasonal) and carry water only during good monsoon. Many streams like Kankawati, Kaswali, Kharod, Rukmawati and Bhukhi etc. show very broad channels and vertical cliffy banks in their lower reaches.

Physiography and Geomorphology

The mainland Kachchh has a rocky terrain with two sub parallel E-W trending hill ranges separated by an intervening rocky plain. The Southern faces Katrol hill Range and the Northern Hill Range, mark the Katrol Hill Fault (KHF) and Kachchh Mainland Fault (KMF). The Northern Hill Range, boundary of Kachchh mainland is bordered by the Banni Plain and the Great Rann of Kachchh (Figure 1.4) in the north and by the high upland areas in the south. This hill range comprises a chain of domes of Jurassic and cretaceous rocks (Biswas and Deshpande, 1970). The various domes associated with the KHF are Ler dome, Gangeshwar dome, Shiv Paras dome, Khatrod dome and Chadwa dome (Thakkar et al., 1999). The central rocky plain occupies the intervening area between the Northern Hill Range and the Katrol Hill Range. The plain is characterized by a gentle slope towards north.

The island belt comprises four highlands viz. Pacham, Khadir, Bela and Chorar. These highlands are commonly described as "islands" as they stand out amidst the Ranns/plains which get submerged during the monsoon. These four islands occur in east-west line to the south of the Great Rann. Northern boundaries of all the islands are steeper, while the gradient is very low towards south. The Pachham Island consists of two east to west running hill ranges, Kala-dongar (black hills) Range and Gora-dongar (white hills) Range. Khadir Island is featured by a hill range along its northern margin which forms a prominent escarpment facing the Rann. The physical features of Bela Island are similar to those of Khadir Island. Along the northern

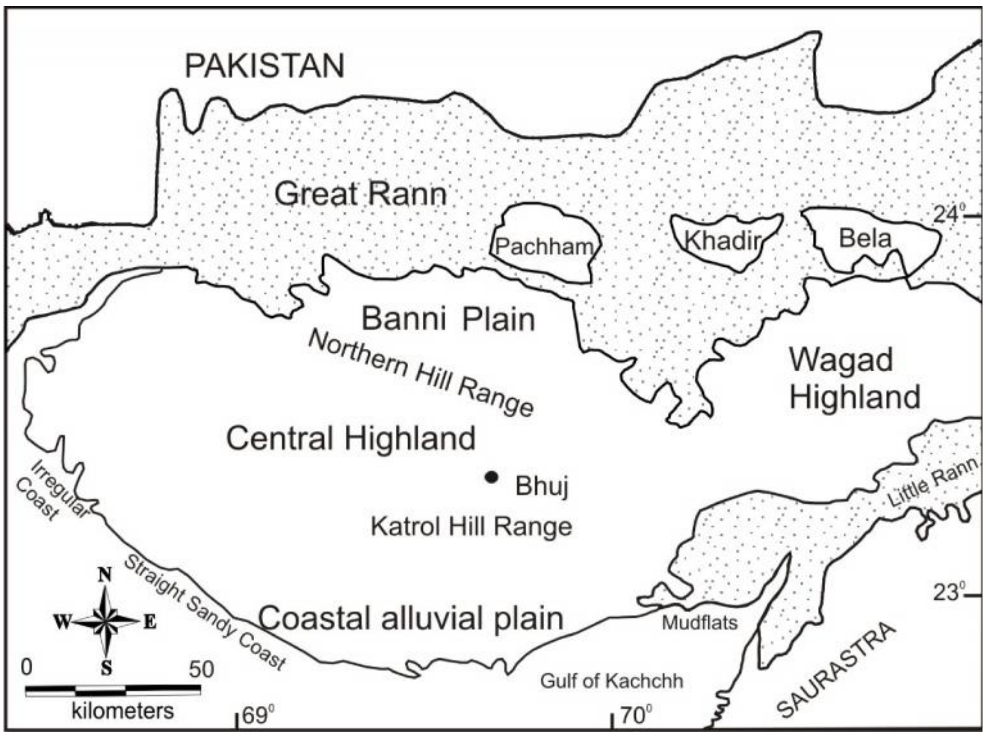


Figure 1.4: Map showing major geomorphic division of Kachchh.

margin occurs a high hill range with steep cliffs facing the Rann to the north. Chorar hills occur in the Banas Kantha district of Gujarat. The hills form a low ridge at the north-western fringe of Gujarat Plains close to the Little Rann.

A large upland region towards northeast of the Mainland Kachchh and south of the Khadir, Bela and Chorar islands is known as Wagad Highland. The Wagad Highland is the second largest hilly region in Kachchh. The central Wagad hill forms the main catchment area, from where the streams flow down in all directions draining the discharge to the surrounding plains. The southern range forms a subsidiary water shed from which the small streams and rivulets flow down to the central valley to the north and into the Lakadia plain to the south that occurs east of the Mainland Kachchh forming the shores of the Little Rann of Kachchh.

The Rann is a unique geomorphic feature which occupies eastern and northern parts and has a total area of 22,000 sq km. The Great Rann of Kachchh has been the site of the earthquake which produced surface rupture known as "Allah Bund" resulting in the upliftment of the northern part of the Rann (Macmurdo, 1823). The Rann is geomorphologically divisible into five units – (i) Bet Zone, (ii) Linear Trench Zone, (iii) Banni Plain, (iv) Great Barren Zone, and (v) the Little Rann of Kachchh (Roy and Merh, 1981; Merh and Patel, 1988). This vast wasteland is about 4m above the present high water line.

The Banni Plain is regarded as a raised mudflat between the Mainland Kachchh and the Great Rann. It occurs 3-10 m above the level of Great Rann. It is more or less flat and almost gradient less saline grassland covering an area about 3000 sq km. Three geomorphological sub units have been recognized – (i) high level mudflat, (ii) an undifferentiated sloping and low level mudflat, (iii) a residual saline depression.

A narrow belt of fluvial deposits fringing the pre-Quaternary rocks is present along the southern coast. The alluvial deposits are found to extend right up to the coast where coastal dunes, sandy beaches and tidal flats constitute a typical coastal geomorphic assemblage. Maurya et al. (2003a) have identified three geomorphic surfaces (S1, S2 and S3) from the late Quaternary fluvial and coastal records of southern Kachchh. Accordingly, the fluvial gravels and sand of Pleistocene age covered under the S1 surface are deeply incised by the S2 surface that shows deep gullies which suggests a post depositional phase of severe erosion during early Holocene. A third surface (S3 surface) is present within the various river valleys in the form of low 2-5 m deep fluvial valley fill terraces.

The Gulf of Kachchh, aligned approximately E-W, is 50 km wide at entrance with the width decreasing gently eastward along its length than it starts abruptly narrowing. The southern coast is fringed by numerous dead coral reefs, islands and extensive mud flats which dry at low tide. In contrast the northern coast is fringed by tidal flats only. A number of prominent shoals (Ranwara, Lushington, Gurur, Samiyani) are present in the Gulf of Kachchh. The gulf is relatively shallow basin and the maximum depth recorded is about 70 m. The topography is very irregular for about 75 km from the entrance to the central gulf; further east the depth decrease gradually towards the head and the bottom changes from rock, sandy clay to clayey silt. An elongate ENE-WSW trending depression with very steep slopes and very rough to rugged surface extending from the entrance to the Ranwara shoals.

GEOLOGICAL SET UP OF KACHCHH

General Geology

Geologically, the Kachchh is constituted by the rocks of Mesozoic and Cenozoic age (Figure 1.5).

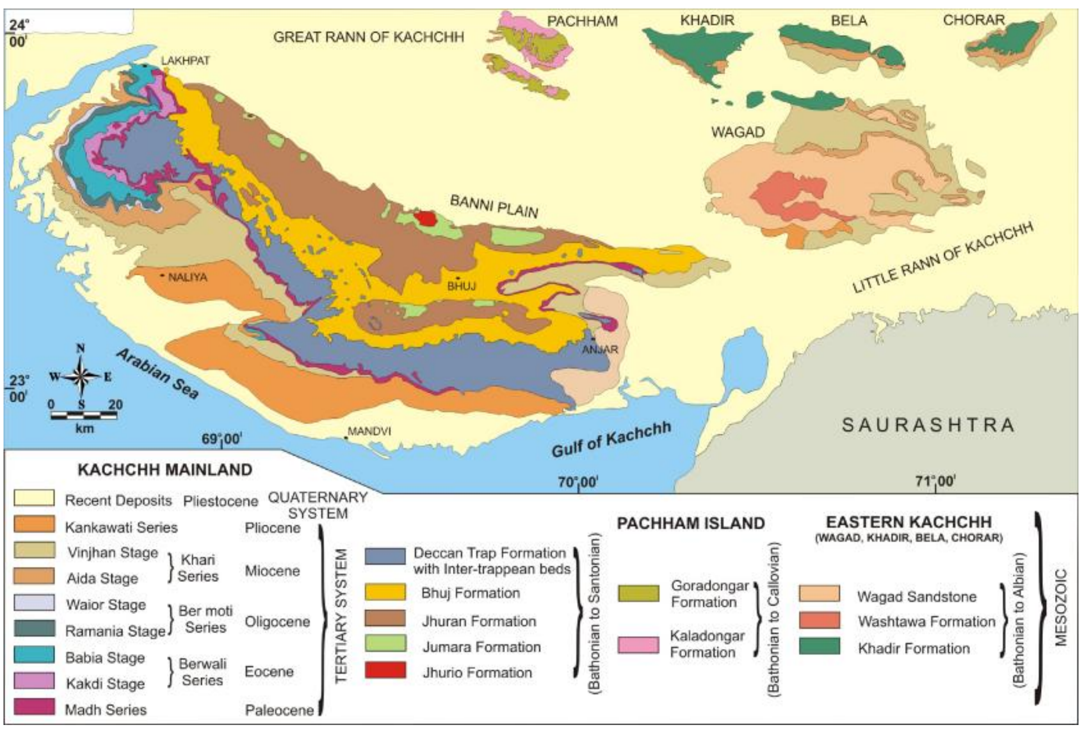


Figure 1.5: Geological map of Kachchh showing major stratigraphic units (After Biswas and Deshpande, 1970).

The Kachchh Mainland is having Jurassic rocks, mainly sandstone and shale with trappean basalt, whereas coastal areas are having Tertiary and Quaternary formations. The Great and Little Ranns contain Holocene sediments. The study area has exposures of Quaternary sediments overlying the Tertiary/Mesozoic basement. These Quaternary sediments were deposited into structural lows formed by the movement of dissected basement blocks in the Gulf of Kachchh half graben (Biswas, 1971). The coastal deposits comprise of a series of sandy ridge-runnel systems and offshore shoals, with wide intertidal mudflats containing oriented sand ridges (Chauhan and Almeida, 1993). The Holocene sediments of the study area consist of older partially dewatered mud and sand, which are overlain by the present day intertidal sediments.

Tectonic Framework

The structure, basin architecture and evolution of Kachchh region has been discussed in a series of publications by Biswas (1980, 1981, 1982 and 1987). The major faults like Kachchh mainland fault (KMF), Katrol hill fault (KHF), Island belt fault (IBF), Allahband fault, etc. have always been discussed by many while describing the tectonic framework of Kachchh basin (Figure 1.6). The basin is peri-cratonic embayment through a marginal graben between Nagar Parkar and Saurashtra uplifts, respectively to the north and south. To the east, the basin is limited by the Radhanpur arch. The regional slope of the basin is towards WSW and the depositional axis passes close to the Saurashtra uplift to the south. Basinal hinge zone

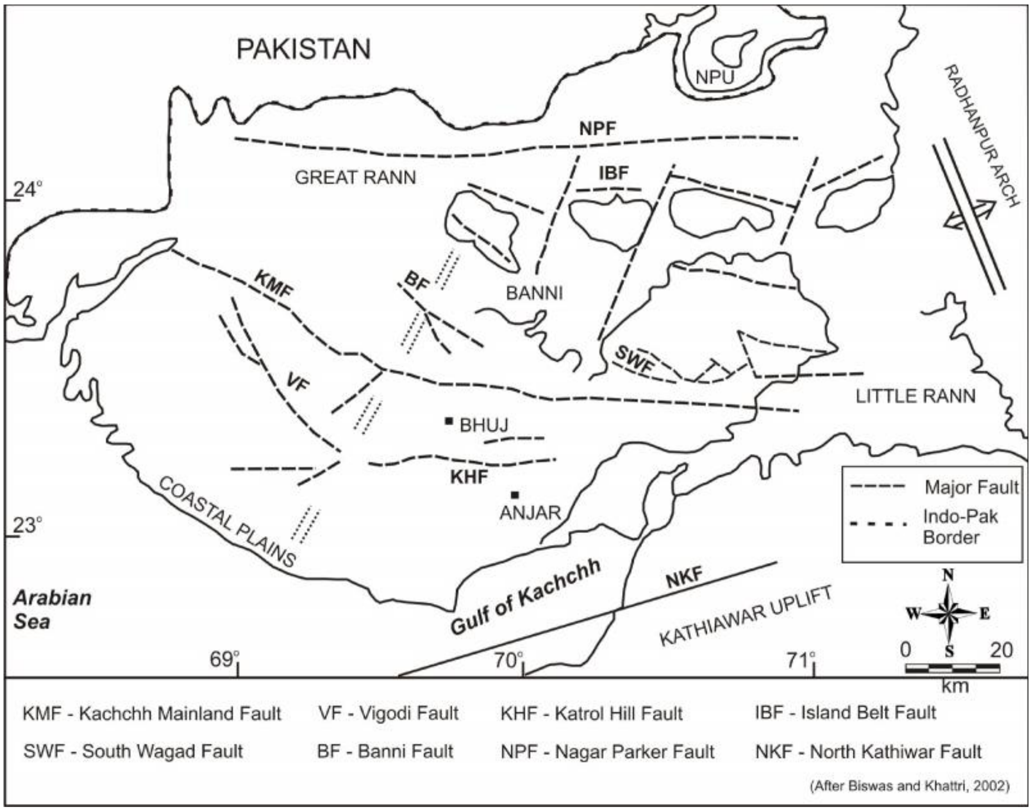


Figure 1.6: Tectonic map of Kachchh (After Biswas and Khattri 2002)

is marked by a first order basement high (Median high) across the middle of the embayment. This hinge zone is the extension of the Indus shelf hinge perpendicular to the depositional axis (Biswas, 1987). The basin is featured by residual basement ridge along primordial faults parallel to the major Precambrian trends (Biswas, 1982). These ridges were passive highs within the basin but later rejuvenated by reactivation of the faults. They are manifested in subparallel uplifts with narrow flexures along the master faults (Biswas, 1980). Mesozoic rocks are exposed mainly in these uplift areas surrounded by "residual depression" (Beloussov, 1962) which are occupied by vast mud and salt flats of the Great and the Little Ranns of Kachchh and the Banni Plains. The culmination along the marginal flexures formed domal structures which expose older Mesozoic strata.

Stratigraphic Framework

The Middle Jurassic to Lower Cretaceous rocks are exposed in the highlands, while the Upper Cretaceous sediments have been encountered only in the offshore wells in Kachchh continental shelf, about 35km from the coast. The early Middle Jurassic strata are exposed in the northern island chain, whereas a complete and thicker succession ranging from Middle Jurassic to Lower Cretaceous is exposed in the Kachchh Mainland which is the depocentral region. Strata of intermediate age are seen in Wagad highland. Excepting in the south where the Mesozoic rocks are covered by 1000 m thick Deccan Trap lava flows, these rocks are overlain by the Tertiary and Quaternary deposits.

Mesozoic Record

Wynne (1872) was the first to suggest a two-fold sub-division of the Mesozoic rocks of Kachchh based on general lithological characteristics after extensive mapping of the entire basin. Later Waagen (1875) divided the stratigraphy of the mainland in to four units and Rajnath (1932) into five units. Biswas (1971) proposed a new lithostratigraphic classification which is widely accepted (Table 1.1).

The lithostratigraphic sequence of the Mainland Kachchh is divided into four formations named as the Jhurio (Jhura), Jumara, Jhuran and Bhuj Formations in ascending order. The Bhuj Formation is disconformably overlain by the basaltic flows of the Deccan Trap Formation (Biswas and Raju 1973) on the south while the base of the Jhurio Formation is unexposed. In Pachchham island stratigraphic sequences divided in two formations namely, Goradongar and Kaladongar whereas remaining island belt (khadir, Bela) and wagad has been marked with Wagad, Wasthawa and Khadir formation.

Jhurio Formation

A thick sequence of limestone and shale with bands of 'golden-oolites' in the lower part of the sequence has been named as the Jhurio or Jhura Formation after the type section in Jhurio (Jhura) Hill in north-central Kachchh. The Formation is exposed only as small inliers in three hills which are large domal structure, along the northern margin of the Mainland-Habo, Jhurio and Jumara, from east to west. The maximum thickness of this formation is exposed in the Jhurio Hill.

Table 1.1: Mesozoic Lithostratigraphy of Kachchh (Biswas, 1971).

AGE	MAINLAND			PATCHAM			E. KACHCHH (KHADIR-BELA-WAGAD)		
	Formation	Member	Lithology	Formation	Member	Litho	Formation	Member	Lithology
NEOCOMIAN TO ALBIAN	BHUJ	Upper +260m	Cross-bedded sst, clay-stone.						
		Ukra +30m	Sst, Sh, Fossilifer						
		Ghuneri 325m	Sst- sh, Plant, fossils				WAGAD SST	Gamdu + 165 m	Felds-sst, sh, red iron-stone plant fossil
	JHURAN	Katesar 190m	Cross-bedded sst,fossils						
KIMMERI-DGIAN TO TITHO-NIAN		Upper 300m	Thin-bedded calc sst,					Kanthkot 200m	(Upper) Sst-sh
		Middle 160m	Shales						(Middle) X-sst
		Lower 120m	Shale / sst Fossils						(Lower) Silt-sh
OXFOR-DIAN	JUMARA	Dhosa Oolite 113m	Shales oolitic- lst bands				WASTHAWA	Bamanka Shales 160 m	Sh, fossils
CALLO-VIAN		Middle 75m	Sst - Lst, Golden Oolite	GORADONGAR	Modar Hill		KHADIR	Gadhada 189m	Sh and sst
		Lower 89m	Green shales		Raimalro			Hadibhadang 280m	(Upper) Lst and cherty
	JHURIO	Upper 70m	Bedded limestone		Gadaputa				(Middle) Sst
BATHO-NIAN		Middle 85m	Shales with Golden Oolite		Flagstone				(Lower) Shales Fossils
		Lower 139m	Lst-Sh, interbed--ded	KALA DONGAR	Kala Dongar Sand-stones			Cheriyabet 25m	Pegmatitic Granite-Cobble-Conglo. and arkose
					Kuar Bet				
								Precambrian	Granitic basement

The upper part of the Jhurio Formation is made up of thinly bedded white to cream colored limestones whereas, the middle part is composed of thick beds of grey, yellow shales alternating with thick beds of oolitic limestone. The maximum thickness estimated in type section is about 300 m. The base of this formation is not seen anywhere. It's boundary with overlying formation is conformable and well marked by the contrast of its white limestones and the green shale of the Jumara Formation. The environment of deposition is littoral to infra-littoral. The age of the Jhurio Formation ranges from Middle Bathonian (?) to Lower Callovian.

Jumara Formation

A thick argillaceous formation overlying the Jhurio Formation has been named after its type section in Jumara Hill near the Rann, north of Jumara Village. The Jumara Formation is exposed as inliers at the centres of the domal and anticlinal hills along the northern edge of the Mainland Kachchh and in Central Charwar Range as circular and elliptical outcrops. Lithologically, the Formation is characterized by monotonous olive-grey gypseous laminated shale with thin ferruginous bands, alternating with beds of limestone and occasional sandstone. The thickness of this formation is more or less uniform throughout the area varying between 250-300 m. Its upper boundary with Jhuran Formation is conformable excepting local disconformity observed at a few places where the Jhuran shales are seen resting over the eroded Dhosa Oolite Member of the Jumara Formation. From lithological aspect, the environment of deposition for Jumara formation can be envisaged below wave base in circa-littoral environment. The age of Jumara Formation is equivalent to 'Chari Series' and therefore, it ranges between Callovian to Oxfordian.

Jhuran Formation

It comprises a thick sequence of alternating beds of sandstone and shale. The Jhuran Formation is defined by Dhosa Oolite Member below and non-marine sandstone of Bhuj Formation above. The Formation is divided into four informal members - Lower, Middle (Rudramata Shale), Upper and Katesar Members. Lithologically, the Lower Member consists of alternating yellow and red sandstone and shale beds in almost equal proportion with thin bands of hard yellow, fossiliferous, pebbly, calcareous sandstone. The Middle Member predominantly comprises of monotonous succession of dark grey to black well laminated gypseous shale weathering in to olive-grey color. Thin bands of ferruginous sandstones, laminated micaceous siltstone and yellow ochreous mudstone are common in shale. The Upper Member is predominantly arenaceous and composed of red and yellow, massive current bedded sandstone with intercalations and alternations of shale, siltstone and calcareous sandstone bands in the middle. The Jhuran Formation is thickest in Jara-Mundhan area of NW part of the Mainland Kachchh where it is about 800-900 m thick but, thins down eastwards to 425 m. in the type-section after attaining the minimum 350 m in the central part of the Mainland. The upper limit of this formation is defined by the contact between marine and non-marine rocks. The environment of deposition shifted from sub-littoral to supra-littoral environment and finally into continental deposition of the overlying Bhuj Formation. Age of this formation is Kimmeridgian to Valanginian.

Bhuj Formation

A huge thickness of non-marine sandstone of uniform character constitutes the youngest formation of Mesozoic stratigraphy of Kachchh. Named after its type locality around Bhuj, the capital city of Kachchh, this formation is defined by the marine beds of the Jhuran Formation below and the igneous rocks pertaining to the Deccan Trap Formation above.

The rocks of Bhuj Formation are exposed extensively in the Mainland Kachchh occupying about 70% of total area of the Mesozoic outcrops. It crops out in two wide belt stretching from Bhachau on the east to Ghuneri on the west, occupying lowland between the hill ranges. Lithologically, the lower member is characterized by cyclic repetition of ferruginous or lateritic bands, shale and sandstone. The upper member consists of whitish to pale brown, massive, current-bedded coarse grained, well sorted sandstone with kaolinitic shale and ferruginous bands alternations at thick intervals. The Formation is bounded by the planes of disconformity. In the south, Deccan Trap flows rest on the eroded undulating surface of this formation. Sediments represent deltaic deposits with distal part (delta front) towards the west and the proximal part (fluvial) to east in the direction of the land. Age of the Bhuj Formation is lower Cretaceous (Valanginian) to Santonian.

Deccan Trap Formation

The Deccan Trap Formation is restricted only to the Kachchh Mainland bordering the Mesozoic extending from Lakhpat in the west to Anjar in the east. Lava flows are dominantly tholeiitic basalts that overlie the Jurassic sandstone, occupying the southern and southwestern slopes of the central highland. Six major flows have been reported at the eastern extremity where they show alterations of columnar and amygdaloidal basalts. Occasionally separated by inter-trappean shale units, flows are also traversed by a number of long narrow dykes that occur to the north, northwest and northeast of the lava flow occurrence. Most of the dykes occur along transverse faults extending N-S, NNE-SSW and NNW-SSE. An interesting aspect of the Deccan volcanism in Kachchh is the occurrence of alkali basalt and its derivatives as plugs, laccoliths and sills within the domal structures in the Mesozoic rocks. The inter-trappean beds were deposited in shallow basin and depression over trappean surface fed by simultaneously formed rivulets. An uppermost Cretaceous age is inferred for this inter-trappean bed. The laterites form a narrow elongate Paleocene belt, a few hundred meters wide and several hundred kilometers long sandwiched between the basalts of the Deccan Trap Formation and the Tertiary sediments.

Cenozoic Record

The geological record pertaining to the Cenozoic age is restricted to the northwest, west and south areas of Kachchh, mostly comprising its coastal region. It is important for its Eocene-Oligocene boundary and also for a thick Miocene-Pliocene sequence.

However, the Pleistocene record is relatively patchy, although an important unit Miliolite Formation is present. Table 1.2 presents the lithostratigraphy of the Tertiary succession in Kachchh.

Mata-no-madh Formation

Mata-no-madh Formation is named after Matanomadh village in western Kachchh around which the Formation is best developed and exposed. The type section is exposed in the Bhuj-Lakhpat road section, east of Matanomadh and in the Madhwali Nadi to the south of village. The lithological succession is extremely variable and consists of a variety of brightly colored rock-types showing different admixtures of clastics and volcanic material. Trap derivatives give rise to a wide range of rocks from laterite to clays in the lower part of the Formation. The common rock types are laterite, bauxite, lateritic trap-pebble-conglomerate, trap-wash, variegated bentonitic clay and yellow ferruginous clays, grey and white tuffaceous shale and red tuffaceous sandstone and occasional layers of lignite. The Formation directly overlie the Deccan Trap Formation and the contact is sharply defined by the laterites or trap-conglomerates above the green coloured basalt of the Deccan Trap Formation. The upper contact is conformable and marked by a lignite band in the type locality. Elsewhere, the contact is unconformable separating the overlying gypseous shale form the brightly colored clays. The Formation does not contain any diagnostic fauna but the type section is rich in flora. The age of this formation is estimated to be Paleocene and the environment of deposition mainly continental (Mathur, 1978).

Naredi Formation

The Naredi Formation is named after village Naredi. The type section is discontinuously exposed in the cliffs along Kakdi Nadi near Naredi and partly (i.e. upper parts only) along the Guvar streams to the NNW of Naredi. Three distinct members are recognized in the type locality. The lower Gypseous Shale Member is about 25 m thick and consists of grey, brown and olive green, splintery, glauconitic claystone and shale with occasional thin layers of gypsum, yellow limonite and also a few layers of calcareous concretions which occasionally contain fossil in its core. The middle Assilina Limestone Member is about 6 m thick and consist dirty white argillaceous limestone and yellowish, grey marl studded with Assilina. The upper Ferruginous Claystone Member is about 10 m thick and consists of grey, yellowish brown claystone with layers of gypsum and red ferruginous laminae. In the type locality, the Naredi Formation directly overlies the Deccan Trap Formation, but a little to the south of Naredi, it unconformably overlies the Mata-no-madh Formation. The middle part of the unit contains micro-fauna that has suggested lower Eocene age of the Naredi Formation. The environment of sedimentation of this formation varies from lagoonal to marine inner shelf, becoming non-marine towards the upper part.

Table 1.2: Tertiary Litho-stratigraphy of Kachchh (After Biswas, 1992).

Age	Formation	Members
Middle to Upper Miocene	Sandhan	
Lower Miocene (Burdigalian)	Chhasra	Siltstone
		Claystone
Lower Miocene (Late Aquitanian)	Khari Nadi	
Upper Oligocene	Maniyara Fort	Bermoti
Lower Oligocene		Coral Limestone Lumpy clay Basal member
Late Middle Eocene	Fulra Limestone	
Middle Eocene	Harudi	
Upper Paleocene to Lower Eocene	Naredi	Ferr. Claystone
		Assilina Limestone
		Gypseous Shale
Upper Paleocene	Matanomadh	
Cretaceous–Lower Paleocene	Deccan Trap	

Harudi Formation

This formation is named after a small village Harudi to the north-west of which the Harudi Formation is very well exposed in an impressive escarpment. The type section is continuously exposed over a short distance of 300 m along the escarpment at a locality about 2 km NW of Harudi on the Naliya-Narayan Sarovar Road. The Formation consists of green and greenish grey, splintery shale with yellow limonitic partings in the lower parts and calcareous claystone and siltstone with occasional layers of gypsum and carbonaceous matter in the upper part. Occasionally concretionary fossiliferous marl bands are seen in the lower part. Nummulite bed is a characteristic marker bed within the formation. The lower contact of the Formation is disconformable and fixed on the top of the laterite bed of the Naredi Formation. The upper contact is conformable and is placed at the base of the lowest massive foraminiferal limestone bed containing characteristic saddled to undulated Discocyclina. The environment of deposition of this formation varies from littoral to middle shelf condition in a slowly transgressive sea.

Fulra Limestone Formation

The Fulra Limestone Formation is named after the Fulra village. The type section is best exposed along the southern flank of Babia Hill, about 1.7 km SW of Fulra. The upper part is also well exposed in the nala to the south of Fulra. The entire Formation is made up of thickly bedded, creamy to dirty white and buff coloured foraminiferal limestone. The limestones are fossiliferous micrites and biomicrites. Large saddled to undulated Discocylina, large flat Nummulites and other larger foraminifera are abundant throughout the formation and they give a characteristic appearance to this formation. The Fulra Formation is also very well exposed in impressive scarps along Berwali Nadi where it is about 40 m thick. The lower contact is conformable and is fixed at the base of the massive foraminiferal limestone. The upper contact is para-conformable and well exposed in all stream section. It is locally disconformable showing cut and fills structure.

Maniyara Fort Formation

This formation is named after the Maniyara Fort. The type section is continuously exposed along a stream flowing between the Maniyara Fort and the Bermoti village from a locality 1.6 km NNE of Bermoti to a locality about 450 km SE of Bermoti. The Maniyara Fort Formation is divided into three Members viz., the Basal Member, Lumpy Clay Member, Coral Limestone Member and Bermoti Member in stratigraphically ascending order. The Basal Member consists of alternating beds of foraminiferal, glauconite, brownish to yellowish siltstone and calcareous, gypseous claystone studded with reticulate Nummulites, Pecten and other fossils. The Lumpy Clay Member consists of cement grey coloured to brownish calcareous lumpy claystone, occasionally containing thin limestone and marl beds. The Coral Limestone Member consists of dirty white nodular limestone which weather in characteristic bouldary pattern, alternating with calcareous claystone in lower part. The upper part comprises of this member is grey to dirty white massive limestone with abundant corals, frequently forming small bioherms. All the three members are very well exposed in the stream west of Ramania. The Bermoti Member is the upper most unit and best developed in the streams SE of Bermoti and also NNE of Waior. The lower part consists of rusty brown, friable glauconitic argillaceous sandstone.

The upper part is composed of thinly bedded, very hard, grey to yellowish foraminiferal limestone with interbed of silty marl full of Spiroclypcus.

The lower contact of the Maniyara Fort Formation is paraconformable. The upper contact is not well exposed in the type locality; it is noted to be conformable in other section. The Basal Member and Lower Clay Member are of Lower Oligocene; the Coral Limestone Member is of Middle Oligocene and the Bermoti Member is of Upper Oligocene age. The environment of deposition of this formation is mainly inner shelf to littoral and locally lagoonal.

Khari Nadi Formation

The Khari nadi formation is named after a small river Khari Nadi. The type section is exposed along cliffs on banks of Khari Nadi between its confluence with Sugandhi Nadi near Goyela. The lithology consists of laminated to very thin bedded red and yellow mottled to variegated siltstone and occasionally grey brown gypseous claystone. A bluish grey claystone bed occurs consistently near the base in every section. Cross-bedded, fine grained micaceous sandstone is present in the middle part, while a few thin fossilferous arenaceous limestone beds are present in the middle and upper part of the type section. The lower contact of this formation is conformable and is fixed on top of the Spiroclypeus limestone bed and at the base of the bluish grey claystone bed. The upper contact is also conformable and gradational.

The environment of deposition of this formation varies from tidal flat to littoral and shallow marine environment of a slowly transgressive sea.

Chhasra Formation

The Chhasra formation previously called Vinjhan Shale Formation is named after the Vinjhan village. The type section is continuously exposed along the Kankawati river between a locality north of Vinjhan and a locality 1 km south of Vinjhan. The formation consists of two distinct members. The type section is exposed along Khari Nadi from top of the Khari Nadi Formation to locality 1 km south of Chhasra village. The lithology consists of grey and khaki colored, laminated, gypseous shales and calystones with alternations of thin, hard, yellowish, highly fossiliferous, argillaceous limestone. Several Foraminifera Ostracoda, are found. The microfauna indicate the age of the member is probable of Late Aquitanian to Burdigalian age.

Siltstone Member is the upper member well exposed along the Kankawati river from a locality just east of Vinjhan to a locality 1 km south of Vinjhan. This member consists predominantly of alternating micaceous siltstones and laminated silty shales of monotonous khaki color. The upper part is reddish. A few thin fossiliferous marl beds are present. A post- Burdigalian (Langhian) age is suggested for this member. The lower contact of the formation is confirmable with the Khari Nadi Formation and distinguished between the overlying khaki claystone and underlying variegated siltstone. The environment of deposition of the sediments varies from shallow marine to littoral.

Sandhan Formation

This formation is named after the Sandhan village. The type section is exposed along the Kankawati River from Sandhan to 1 km south of Vinjhan. It is well developed in the coastal plain of southern Kachchh where good sections are seen in cliffy banks of major consequent streams. The lower part of the formation consists of well sorted, medium to coarse grained, massive, micaceous sandstone, clayey laminated siltstone and thin, yellow, fossiliferous marl bands. The middle part comprises conglomerate and grey coarse grained sandstone with lenses of conglomerate. The upper part is mainly hard, brown, calcareous grit overlain by pink and grey mottled silty sandstone with calcareous nodules. Probable Pliocene age is suggested for this formation. The sediment indicate littoral to supra-littoral environment of deposition.

Quaternary Sediments

There are two principal areas of extensive Quaternary sedimentation, one is the Rann areas and the other is the narrow alluvial plain bordering the coastline in southern Mainland Kachchh. The Rann, which constitute a very flat terrain with no surface exposures, are obviously the product of marine deposition. The second area is the narrow E–W trending plains of southern Mainland Kachchh which are mainly formed by fluvial processes. These are characterized by basal unit of gravels which are either crudely stratified or are showing planer cross stratification. The gravels are overlained by bands of sand and silt which at places are pedogenised at top and inturn overlain by silty sand. Some units of silt-sand exposed in the coastal river sections consists pedogenised calcretes and are dated to about 25 ky (Maurya et al. 2008). The Miliolite Formation of Middle to Late Pleistocene age is also present in various parts of Kachchh, which is a unique geological record in Gujarat better studied from and best developed in the Saurashtra (Bhatt, 2003). Alluvium, unconsolidated sand, Rann clays and mudflats of inner Gulf of Kachchh constitutes the Holocene record in the region.

Soils

Entisols have developed over traps and alluvium in parts of Kachchh. They are light grey, grayish brown and reddish brown in colour, and have formed under tropical semi arid climate marked by annual precipitation of 55 to 950 mm and mean temperatures of 25^{o} C to 26^{o} C. The depth of the soils ranges from a few cm to 1 m and the profiles show A-C horizons. Texturally, they are sandy clay, loam or clay-loam to clay. Structurally weak, mainly sub-angular, blocky and at places crumb like, these soils are calcareous and alkaline in nature. The Entisols of Gujarat taxonomically represent Ustorthents, Ustripsamments and Ustifluvents.

Inceptisols soils are found along the coastal plains. These have formed over basaltic and alluvial parents; occur on gentle to moderate and steep pediments, in sloping isolated plateaus, valley bottoms and moderately sloping interfluves. These are dark grey to light grey, reddish brown, yellowish-red and dark reddish brown in colour and are products of weathering under tropical semi-arid to humid climates with annual precipitation of 500 to 2000 mm and mean temperature of 26^{o} C. Inceptisols are generally calcareous in nature and vary indepth from 30 to 80 cm. Structurarally, these are sub-angular and blocky and have A-C horizon characteristics. Texturally, the soils are silty-loam to clay, and are neutral to alkaline in reaction. The coastal Inceptisols have sandy-clay-loam to clay texture. Ustochrepts, Helaguepts, and Haplaquepts are the main taxonomic soils of this order.

Ardisols have mainly developed over the Aeolian silts and dune sands. Distributed on residual hummocky dunes and ridges, pediment surfaces, mud flats and dissected flood plains of Kachchh. Aridisols develop under arid climate with mean annual rainfall below 450mm and mean annual temperature of 26^{o}C having acidic moisture regime. The soils are fairly deep, light grey to brown in colour, having no definite structure. Texurally, these are sandy to sandy-loam with silty clay-loam. A few of the soils are salty. Some have argillic and nitric horizons and when dry are not hard and massive; others have either a calcic or petrocalcic or cambic horizon or a duripan.

2

The Gulf of Kachchh

Physiography and dynamics

The study area, southern coast of the Kachchh, faces one of the most striking macro-tidal basins, the Gulf of Kachchh. The coastal landscape is controlled by the prevailing dynamics of this gulf and also bears signatures of its past nature. It is felt therefore necessary to introduce the physical nature of the Gulf of Kachchh for better appreciation of its coastal geomorphology and its systematic variation along the coast that makes a major content of the forthcoming chapters.

PHYSICAL SETUP

The asymmetrically rifted sub-basins of the Kachchh mainland comprises a series of east–west trending half grabens and have undergone cycles of subaqueous and submarine conditions (Biswas, 2005). The east–west trending Gulf of Kachchh forms southernmost part of the Kachchh mainland sedimentary basin. Its formation has been linked with counterclockwise rotation of the Indian Plate and a failed rift fracture in the Jurassic Period (Biswas, 1982). Detailed physiography of the gulf has been described by Wagle (1979), Rao (1988) and Chauhan and Vora (1990). Its sediments increase in thickness up to 4 km toward the south, underlain by pre-Quaternary sediments and basalts (Michael et al., 2009). About 170 km long and 75 km wide at its mouth, the Gulf of Kachchh covers an area of about 7300 km^2 and forms a volume of 220,000 million cubic meters. It is an east west oriented indentation in the coastline of India at the western extremity, however, the inner gulf is oriented NE-SW (Figure 2.1). Bordering the Gulf of Kachchh at its head is the Little Rann of Kachchh, a desiccated saline flat region. The Gulf of Kachchh presents a complex set up of a macro-tidal region, marked by existence of shoals, channels, inlets, creeks and islands (Kunte, 2003). The islands covered by mud and mangrove swamps are surrounded by coral reefs in the form of fringing reefs, platform reefs, patch reefs, and coral pinnacles (Figure 2.1).The water depths range from 10 to 55 m, the deeper areas (> 20 m) occurring along the axial part of the gulf along which E-W flowing high tidal currents prevail (Naval Hydrographic Office, 1976).

Within the Gulf of Kachchh, though water depths of 25 m exists in broad central portion upto a longitude 70°E, the actual fairway in the outer gulf is obstructed by the presence of several shoals. The high tidal influx covers the low-lying areas of about 1500 km^2 comprising a network of creeks and alluvial marshy tidal flats in the interior region. All along the coast, very few rivers drain into the gulf and they carry only a small quantity of freshwater, except during monsoon. They are broad-valleyed and the riverbeds are mostly composed of coarse sand and gravel. The gulf-bed is characterised by a rugged bathymetry with steep, 6-32 m high scarps

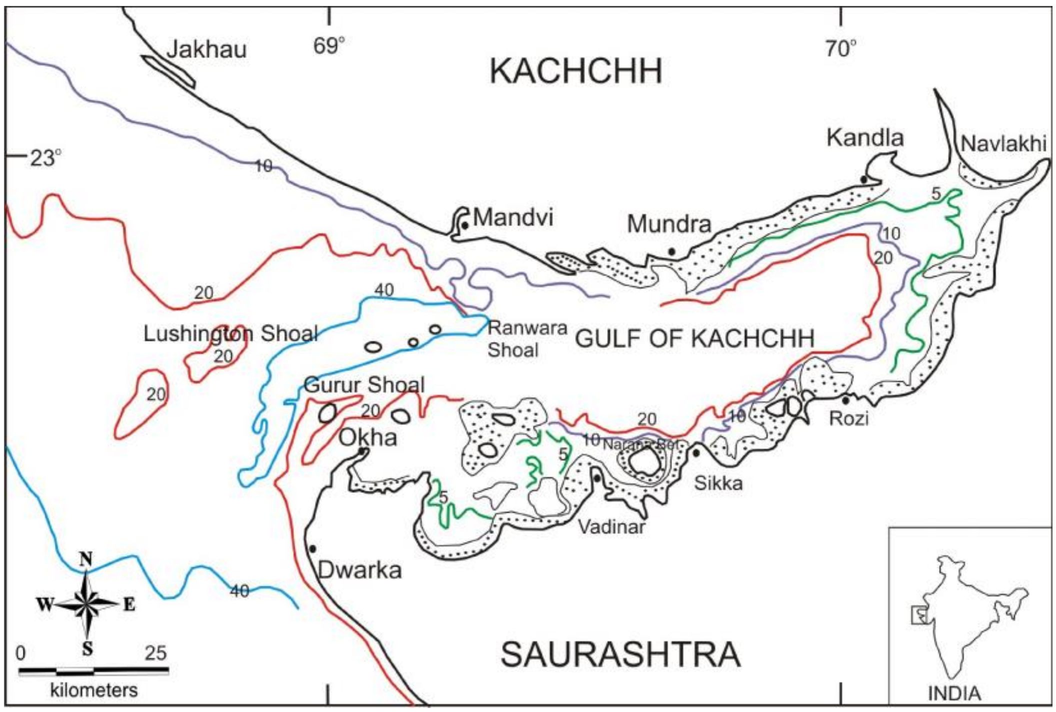


Figure 2.1: Physiography and bathymetry of the Gulf of Kachchh (After, Kunte et al. 2003). Because of the dynamic nature of mud deposition around coral island in southern part the contours are broken.

(Wagle, 1979). The topography of the outer gulf is more rugged as compared to the inner parts. The southern shore has numerous islands and inlets covered with mangroves and surrounded by coral reefs. The northern shore is predominantly sandy or muddy confronted by numerous shoals. The sediments transported into the Gulf of Kachchh along with those denuded from the shores and wind borne sands give rise to poly-model character to the sediment.

The large variation of air and water temperature and scanty rainfall, makes the Gulf of Kachchh a high saline water body due to less discharge and comparatively higher evaporation rate. In general, the maximum salinity ranges from 36.6 psu (practical salinity unit similar to parts per thousand or ppt) at mouth to 45.5 psu near the head of Gulf of Kachchh (Vethamony et al., 2007). The creek at the mouth of the gulf receives negligible freshwater inflow during the dry season since there is no major river. Hence, the evaporation exceeds precipitation leading to salinities higher than that of typical seawater (35-36 ppt). The higher salinities may also result due to the drainage of brine from saltpans since a number of salt pans exist within the Gulf of Kachchh coastal areas. Salinities upto 50 ppt (part per thousand) have been recorded in the Little Rann of Kachchh (Nair, 2002).

GULF DYNAMICS

Tides

Tides are oscillations of ocean waters due to the gravitational forces exerted by the Moon and the Sun upon the oceans. The rising tide is usually referred to as flood, whereas falling tide is called as ebb tide. Tidal currents are the horizontal water movements corresponding to the rise and fall (flood and ebb) of the tide. High tides are the highest when the Earth, Moon and Sun are all lined up, about every two weeks. Such tides are known as spring tides. When the Moon is perpendicular to the Earth - Sun line (also about every two weeks), high tides are the lowest, called neap tides. Tides move enormous amount of water four times a day, yet the topographic effect of tides on the coastal zone is small because of their relatively low speeds. In narrow bays and passages, tides move quickly forming so called tidal currents. Tidal currents are capable of erosion. In well-sheltered gulfs and estuaries tides lose their speed and deposit the fine material (clay, silt) that tidal waters carry. Thus bays slowly turn into mud flats, then to marshes. The gravitational force of the Moon, and to a lesser extent, the Sun, creates tides. These forces of attraction and the fact that the Sun, Moon and Earth are always in motion relative to each other, cause waters of the ocean basin to be set in motion. These tidal motions of water masses are a form of very long period wave motion resulting in a rise and fall of the water surface at a point. There are normally two tides per day, but some localities have only one per day. Tides constantly change the level at which waves attack the beach. The tidal currents and surges play an important role in the nearshore dynamical system (Kunte, 2003).

The Gulf of Kachchh is under pronounced tidal influence and therefore, it is categorized under a macro-tidal regime. Tides in the Gulf of Kachchh are mixed type and predominantly semi-diurnal with a large diurnal inequality. The time taken for a tidal wave to travel from the mouth to the head is approximately 3 to 3.5 hr (phase lag). Bathymetry, funnel shape of the Gulf of Kachchh, coastal configuration and orientation of the coast are probable reasons for the geometric effect contributing amplification of tide. Therefore, the tidal front enters to the gulf from the west and due to shallow inner regions and narrowing cross-section, the tidal amplitude increases considerably east of Vadinar. Thus for instance, the mean high water spring tide (MHWS) of 3.47 m at Okha increases to 5.38 m at Sikka and further to 7.21 m at Navlakhi, at the head the of Gulf.

Table 2.1: The tidal elevations (in meter) along the Gulf of Kachchh (After Nair, 2002) MHWS – mean high water spring, MHWN – mean high water neap, MLWN - mean low water neap, MLWS – mean low water spring, MSL – mean sea level.

Station	MHWS	MHWN	MLWS	MLWN	MSL
Okha	3.47	2.96	1.20	0.41	2.00
Vadinar	5.3	4.3	1.7	0.70	3.00
Sikka	5.38	4.35	1.74	0.71	3.04
Mundra	5.50	5.00	2.00	1.20	3.40
Rozi	5.87	5.40	1.89	1.00	3.60
Kandla	6.66	5.17	1.81	0.78	3.90
Navlakhi	7.21	6.16	2.14	0.78	4.20

Waves

Idealized waves of sinusoidal form have wavelength (length between successive crests), height (vertical difference between trough and crest), steepness (ratio of height to length), amplitude (half the wave height), period (length of time between successive waves passing a fixed point) and frequency (reciprocal of period). Water waves show cyclical variations in water level (displacement), from the trough to the crest. Displacement varies not only in space (one wavelength between successive crests) but also in time (one period between crests at one location). Steeper waves depart from the simple sinusoidal model, and more closely resemble a trochoidal wave form. Most sea-surface waves are wind-generated. The stronger is the wind, the larger is the wave, and so variable winds produce a range of wave sizes. A constant wind speed produces a fully developed sea, with waves of H1/3 (average height of 33% of the waves) characteristic of that wind. Wave climate at the head of the Gulf of Kachchh is dominated during SW monsoon period (June to September). High waves with comparatively shorter periods occur during the monsoon period and the sea appears to be calm in non-monsoon period except for the cyclonic events (Nayak et al., 1990). The Gulf of Kachchh is famous for its recent storm history; two significant storms are recorded in past 15 year, one during 5th to 9th June 1998, and another during May 16-22, 1999. The Gulf of Kachchh coast has experienced a tsunami surge in recent past that is recorded as the Makran tsunami which occurred on 28th November, 1945 (Pendse, 1948; Ramasamy et al., 2006; Heidarzadeh, 2008; Jaiswal et al., 2008; Shukla et al., 2010).

Currents

The primary driving force behind ocean currents is constant winds. Wind creates currents as it blows over the water surface, producing a stress on the surface water particles and starting the movement of the water particles in the direction in which the wind is blowing that give rise to a surface current. Thus, a surface current is created. When the surface current reaches a carrier, such as the coast, water tends to pile up against the land. Of all currents, those that flow near coasts have substantial effect on coastal landforms. The most important type of current in the coastal zone is a longshore current. Longshore current ("along the shore") is a current that flows in shallow water, parallel to the shoreline, generally downwind. Longshore currents transport sediments along the coasts, sometimes they are powerful enough to erode sea bottom. Surface currents in the Gulf of Kachchh are driven mainly by tides, except during a short spell, when surface currents are influenced by the monsoon winds (Table 2.2).

Table 2.2: wind speed and wind direction along the Kachchh coast during different periods (Vethamony and Babu, 2010).

Period	Wind speed (ms^{-1})	Wind Direction
North East Monsoon	3.5	NNE (337^o)
Pre Monsoon	4.5	WNW (292^o)
South West Monsoon	6.5	SSW (247^o)

As per the current understanding (Nair et al., 1982a & b; Guptha and Hashimi, 1985; Kunte et al., 2003; Deshmukh et al., 2005) a tidal barrier exists across the Gulf of Kachchh that prevents Indus load from reaching directly southward to the Arabian Sea and diverts that towards the Gulf of Kachchh (Figure 2.2). The longshore currents move eastward along the northern flank of Gulf of Kachchh till they reach to the head of the Gulf of Kachchh, and continue to flow along the southern flank to finally exit the mouth at Okha from where they are throwing the sediments at depths of >200m into the Arabian Sea. The presence of tidal barrier (Figure 2.2) has been attributed to the higher amount of Indus sediments off the mouth of Gulf of Kachchh and dominance of characteristic peninsular load off the Saurashtra coast (Nair et al., 1982).

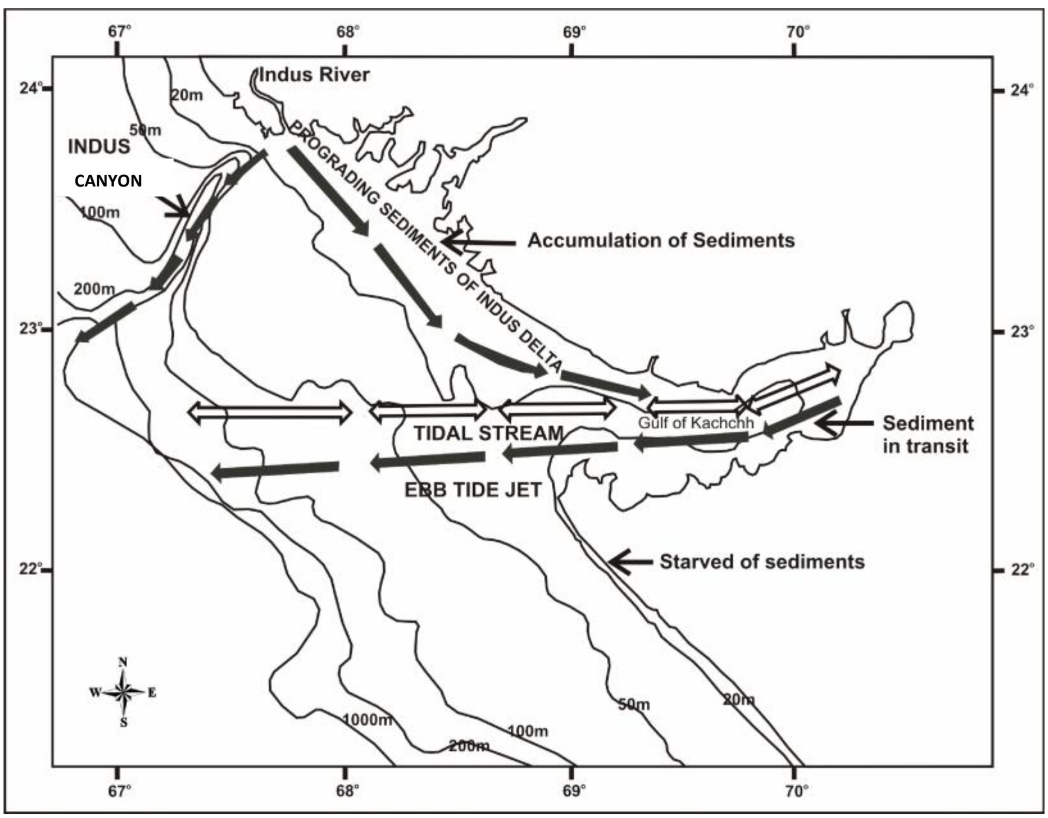


Figure 2.2: Inferred sediment transport direction (After Nair et al. 1982)

As suggested by Chauhan (1994) the dominant current directions influencing the sediment distribution in and off the mouth of Gulf of Kachchh are northwest, southeast and east-west. Whereas, Kunte et al. (2003) presented a new finding of previously unnoticed seasonally northward and northeastward moving currents along the Saurashtra coast during the months of December to March (Figure 2.3). Average current velocity reported by Chauhan and Vora (1990) at Kandla is 3.27kn (Knot is a unit of speed equal to one nautical mile or 1.852km per hour) and in Navlakhi is 3.88kn.

Runoff to the gulf

The residence/turnover time of the Gulf of Kachchh ranges from 8-51 days, decreasing upstream. The gulf is surrounded by arid to semi-arid landmass from where the river runoff is negligible. However, as it happens in typical dryland river systems, flash floods do occurs in the study area during which the river carries a sizable amount of water and also brings sediments eroding its channel as well as banks. The weak monsoonal rains and high rate of evaporation not only make the land area arid but also influence the seawater salinity to increase. Long-term mean rainfall on the surrounding area is 42 cm/y leading to a rainfall volume of 3087 Mm^3/y. Thus, the Gulf of Kachchh is an area of negative water balance.

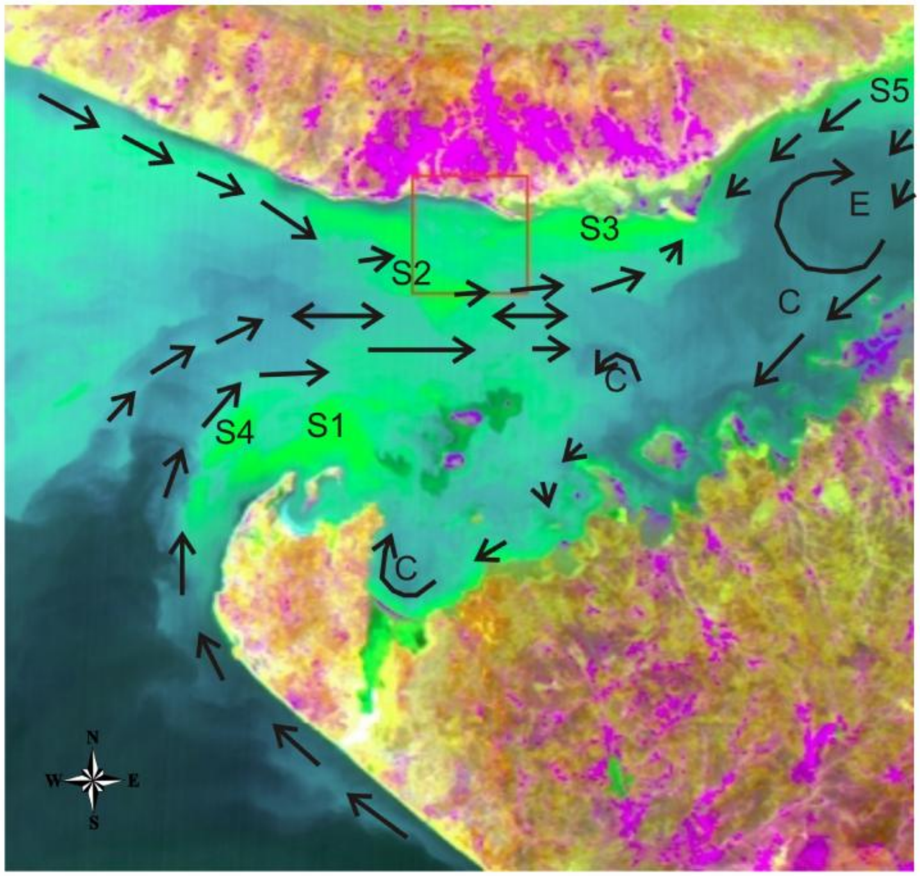


Figure 2.3: A False colour composite Image showing major offshore sand shoals and current dynamics (Kunte et al. 2003). S1 – Bobby shoal, S2 – Ranwara shoal, S3 – Navinal shoal, S4 – Gurur shoal, E – clockwise eddy structure, C – curly movement of sediment. Red box showing Turbidity is greater towards the coast than in the middle.

Since there are no major rivers discharging sediment directly in to the gulf, suspended sediments constitutes a major sediment influx from the gulf water to its coastal areas. Primary control on suspended sediment concentration (SSC) seems to be the availability of fine grained sediments on the sea floor as high SSC are observed along the northern coast and head of the gulf, where the sea floor has a mud cover (Vethamony and Babu, 2010). Kunte et al. (2003) have noticed higher SSC values near the headward area of the gulf (Table 2.3).

Table 2.3: Observed SSC range at various stations (After Kunte, 2003).

Station	**Observed SSC range (mgl^{-1})**	
	Surface	***Bottom***
Okha	11-17	11-12
Salaya	18-25	24-30
Vadinar	18-35	20-32
Sikka	15-23	17-24
Bedi	17-23	-
Mundra	189-294	-
Luni	25-33	-
Navlakhi	49-180	136-282
Kandla	59-255	205-282

3
Coastal Geomorphology
The Kachchh coast

Geomorphology is the science of studying the external landscape architecture of earth's crust, which stands as a testimony not only to the palaeo-morphotectonic and morphodynamic activities but, for the present day geological processes as well. The coast forms a transition zone between the land and a major water body or a space wherein terrestrial environment influences the marine and vice versa (Carter, 1988). The coast is classified either based on origin of the landforms (e.g. Emerging, Submerging, Outbuilding and Eroding coasts of Valentin, (1952) referred to in English by Holmes, 1978) or based on the form of the landscape (e.g. Deltas, Reefs, Mountain, Headland and bays, etc. of Inman and Nordstrom, 1971). Ahmad (1972) has classified the Kachchh coast as a 'submergent (estuarine) coast'. Kar (1993) divided the Kachchh coast in to five segments based on the style of landforms viz., deltaic coast, irregular coast, straightened coast, spits and cuspate foreland complex, and mudflat coast (Figure 3.1). As mentioned by Firth (2000), none of the classification of the coasts mentioned above is ideal, and to understand the true nature of a coast both, genetic as well as descriptive terms are required. Depending upon the need, especially for coastal management purpose different schemes of classification have been employed.

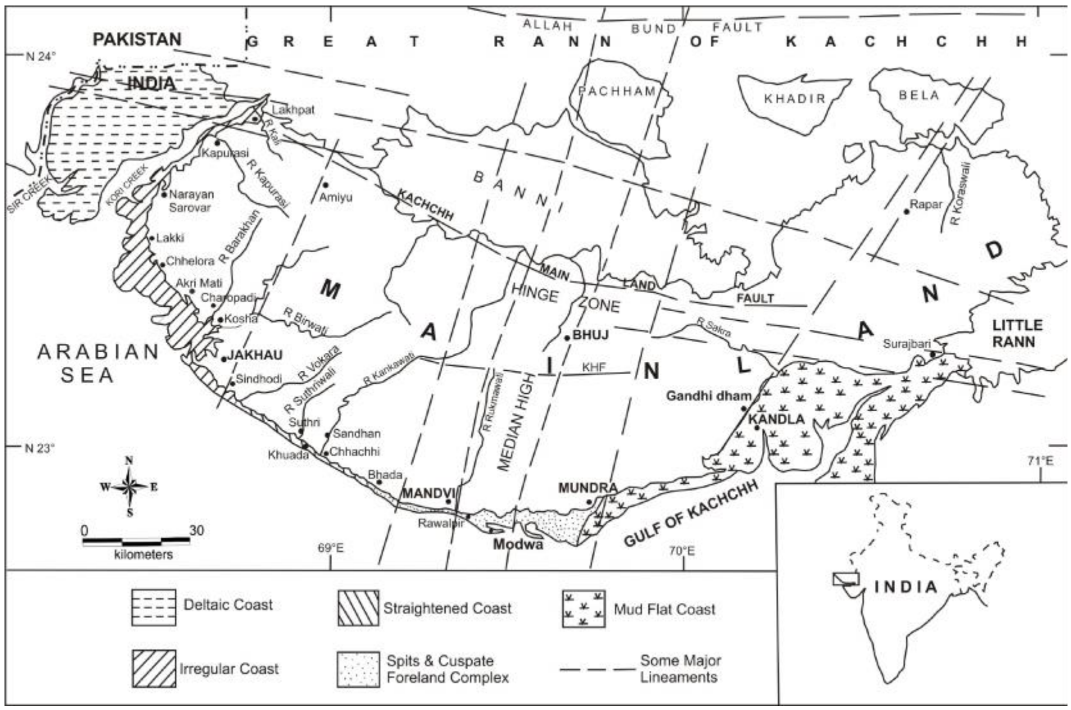


Figure 3.1: Regional geomorphic setup of the Kachchh coastline (After Kar, 1993).

One of such commonly adopted scheme in India is proposed by Nayak (2000; 2002) which has used the scale of mapping as base to group the geomorphic forms in to the Level-I, Level-II and Level-III categories with increasing scale. Accordingly, the Level-I features include vegetated and non-vegetated coastal areas, water bodies, shore land and other man made features whereas, the Level-II includes all major landforms in its descriptive sense like mangroves plantation, mudflats, sand, bays, lagoon, delta plain, back swamps, coastal dunes and ridges, etc. The Level-III specify the features at much higher scale like intertidal zone, high tide and low tide lines, spits, bar, chennier, tidal channel, dense and sparse vegetated areas, etc. For the present study author has largely used the descriptive terms which either depict the sediment nature or the style of geomorphic unit.

The coastal geomorphic system is a most sensitive system that always tries to be in equilibrium with its environment either by deposition of sediments or by erosion of the once formed landscape. Both, the depositional as well as erosional features thus provide an insight on the coastal response to eustatic and/or tectonic changes in the region (Carter and Woodroffe, 1994). The dynamic nature of coastline gets readily reflected in its geomorphic variants at higher temporal scale. However, appreciation of the control of lithology, structure, active systems that either input sediments or provide conveyer system for the same and also the accommodation space that provides sinks and sub-sinks to the sediments, comes from a better understanding of the present day geomorphic scenario at spatial scale. It is therefore necessary to identify, understand and document various geomorphic forms in the study area. This chapter deals with the description, mapping and field documentation of various coastal geomorphological assemblages along the southern and southwestern coast of Kachchh. The area comprises of an interesting assemblage of palaeo and neo coastal landforms which include spits, beaches, bars, creeks, beach ridges, swales, raised mudflats, saline flats, non-saline flats, stabilized and active dunes, chennier ridge/chennier plain, mangrove swamps, tidal channels, tidal flats, etc.

METHODOLOGY

The Survey of India topographic maps, other than field investigations, are very useful to depict the primary and basic information of geomorphic and tectonic elements of this terrain. These maps show a variety of landmarks and landscape information both, natural and man made. The 1:250,000 scale maps provide regional geomorphologic setting and other relevant information such as spot height, transportation network, important localities etc. of the area. The 1:50,000 scale maps are very useful in the identification and analysis of local ambiguities of the area. The primary database of the study area has been generated with the help of Survey of India topographic maps on 1:250,000 and 1:50,000 scales. The SRTM (Shuttle Radar Topography Mission) derived Digital Elevation Model (DEM) was studied at various scales with various views (orientations). The SRTM data for topographic information are acquired by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA) utilizing a radar system that flew onboard the Space Shuttle Endeavour in February 2000. SRTM derived DEM is available with WGS84 datum and EGM96 geoid model at Three arc-second (~270') for all the areas between 60º North and 56º South latitudes. SRTM is widely used for topographical, structural and coastal landform studies on regional scale (Simard et. al, 2008; Kumar et. al., 2010). Map-Info professional GIS (Geographic Information System) software was used to prepare first generation geomorphological maps based on the satellite data (Landsat and Google Earth), which were refined using more advanced graphic software like the CorelDraw version 13. GIS software is widely used for preparing coastal geomorphic map since it allows to see various type of datasets in a single window. Scanned toposheet and high resolution google earth images of the study area were georefferenced by using Map Info Professional version 10 and then various geomorphic maps were prepared for different segment of the study area. The various geomorphic units identified and mapped are defined as under.

Sandy Beach

Komar (1976) defined beach as the zone in which coastal sediments are affected by wave processes, but commonly the deposition of sediments along the shoreline are referred to as the beaches (Reineck and Singh, 1980). In the study area beaches are present for about a length of 110 kilometers in a linear form from Modwa to Jakhau in the western part of study area. Whereas, these have a very limited extent like a pocket beach in eastern most part of study area from Randh Bandar up to Kandla. In general, majority of beaches are curved in outline from Modwa to Layza and many of them are made up of a series of regularly spaced curved features between Modwa and Navinal area. Minor geomorphic units of any beach like runnel, ridge, trough, bar, etc. can be seen associated with the beaches of study area (Figure 3.2).

A marked landward ridge which forms the landward limit of wave swash is referred to as the berm. Berm is prominently visible near Raval Pir location. Also it has been observed all along the beaches between Modwa and Jakhau. In general, beach morphology of the study area is highly dynamic and changes with wave energy, sediments supply, longshore currents and substrate physiography. This gets manifested by change in the width of this zone, beach angle and patches of inliers of older rocks. Beaches of study area contain mostly sand to medium gravel size clasts those are mainly detrital. The beach deposits are also characterized by low angle planner and trough cross stratification along with the biogenic structures mainly related to the skolithoes and glossofungite ichnofacies. The surface structures like various types of ripples and rill marks also occur.

Figure 3.2: A beach of Dhrabudi near Mandvi showing intertidal zone with foreshore ridge and runnel system.

Beach Ridges

Sandy beach ridges mark the position of former shorelines, forming where sand have been stacked up by wave action along a prograding coast. Beach ridge is the most common and extensively used term in the coastal geomorphology with reference to its use as palaeo sea level indicator. Johnson (1919) introduced this term for the ridges constructed by waves along the successive shore position. Otvos (2000) has redefined the beach ridges as "stabilized, relict, intertidal and supratidal aeolian or wave built shore ridges that may consist either siliciclastic or calcareous clastic matter of wide range from fine sand to cobble and boulders". Such type of sandy ridges and swales are found on Modwa coast and are linked with progradation by Shukla et al. 2008 (Figure 3.3). Chenniers are low and long ridges of sand surrounded by low lying mudflats. Chenniers ridges and modified chennier plains are also available around Navinal to Mundra area.

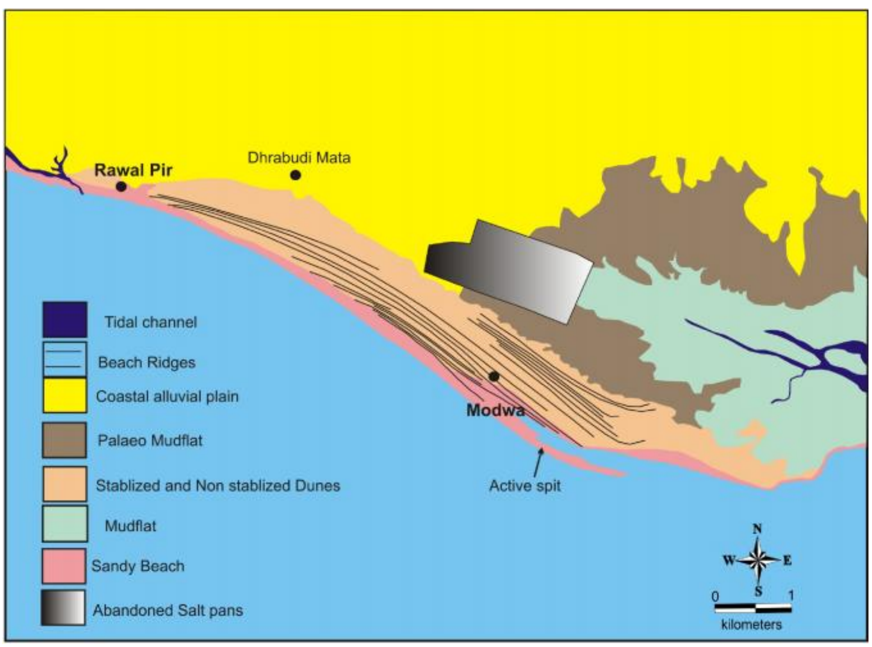


Figure 3.3: Geomorphic set up of Modwa and adjoining coastal areas.

Swales are a long, narrow, generally shallow, trough like elongated depression between two successive beach ridges, and are roughly aligned with the coastline. They form small valley (depressions) between two successive beach ridges. Generally the swales are filled up with the subtidal or supratidal sand. Swales are present along the coastline between Mandvi and Modwa area. A beach ridge that is no longer under the influence of sea wave due to a relative drop of sea level or progradation at the beach ridge base is called palaeo beach ridge. Paleobeach ridges are also identified in the Bhada-Mundra segments of study area .

Mudflat

Mudflats are developed where enough fine sediment are available and the wave action is not strong enough to disturb the sediments (Reineck and Singh, 1980).

Figure 3.4: Satellite Image of the Inner Gulf area showing conspicuous occurence of the mudflats.

Generally such a kind of condition favorable for their development is behind the barrier, lagoons and near estuaries. Coastal areas of the inner Gulf of Kachchh are very much suitable sites for the deposition of mudflats (Figure 3.4) because of the availability of sediments (mostly suspended very fine grained), low wave velocity and flat gradient.

The striking features of the mudflats are tidal channels developed within them which are branched towards the landward side. These channels are formed due to fluctuation in the tidal currents where the current velocity reaches up to 30-50 cm/sec small current ripples are also produced.

The mudflats which are not in connection with the active tidal processes and are flanking the active mudflats are termed as paleo mudflats. This unit is also remarkable in the study area.

Mangrove Swamp

Mangroves are trees and shrubs that grow in saline coastal habitats in the tropics and subtropics, mainly between latitudes 25° N and 25° S. The saline conditions tolerated by various species range from brackish water, through pure seawater to water of over twice the salinity of ocean seawater where the salt has become concentrated by evaporation. The areas covered by mangroves have muddy sediments with a very high amount of water saturation and are known as the mangrove swamps (Figure 3.5). The Gulf of Kachchh coast constitutes about 96% of total mangrove vegetation in the Gujarat state which stands just next to the sundarban.

Figure 3.5: Mangrove swamp near Jakhau.

Coastal dunes

Coastal dunes occupy a broad zone along the coast (Cooper, 1967) and abut against the backshore region of a beach. Sediments from the intertidal area get regularly and periodically exposed to the onshore winds to be reworked in the form of coastal dunes. These coastal dunes acquire various shapes depending upon the coastline configuration and the wind direction. Cooper (1967) distinguished two types of dune ridges in non-vegetated region viz.

(i) Transverse dunes – where wind blows constantly from same direction, these are normal to wind direction and migrate slowly, and

(ii) Oblique dunes – where the wind blows from two quarter at different times; they are stationary and do not migrate.

Figure 3.6: Photograph showing partially eroded coastal Dune near Suthari.

The coastal dune can attain a height of more than 20m as Kachchh coast near Suthari dune height has reached around 22m (Figure 3.6) and if conditions are favorable, can cover a large area to form extensive dune field. The cut faces of dunes exhibit high angle planner tabular and wedge type cross stratification, very large trough and also noticeable grain fall lamination on its lee side. The coastal dunes also show cross bedding with abundant curved erosional surfaces, if the dunes are developed on stable and especially prograding shores (Gripp, 1968).

Sand Flat

A sandy flat area which is in general devoid of vegetation is considered in this class (Figure 3.7). Sand flats are found in the back of coastal dune fields almost all along

Figure 3.7: Photograph showing barren saline sand flat near Modwa.

the study area. This forms a transition zone between the shore area and the coastal plain and gets inundated during monsoon time.

Tidal Creek

A tidal creek is the portion of a stream that is affected by ebb and flow of ocean tides. Thus this portion of the stream has variable salinity and electrical conductivity over the tidal cycle. No. of creeks are presents between Vandh and Kandla area. There is a network of creeks and marshy tidal flats in the interior part of the Gulf of Kachchh. The creek system consists of three main creeks namely Nakti, Kandla and Hansthal in the inner gulf region.

Coastal Alluvial Plain

An alluvial plain is relatively flat landform created by the deposition of sediment over a long period of time by one or more rivers coming from highland regions. A coastal plain is an area of flat, low-lying land adjacent to a seacoast and separated from the interior highland by a distinct topographic break.

The coastline of Gulf of Kachchh has been divided into four major segments on the basis of ongoing processes and landforms developed therein (Prizomwala et al. 2010);

1. The straight sandy segment between Jakhau and Mandvi.
2. Crescent sand ridges and mudflat segment between Mandvi and Mundra.
3. Wide mudflat dominated segment between Mundra and Vadinar.
4. Narrow mud/sand flats and rocky cliff segment between Vadinar and Okha.

The present study is confined on the northern coast of the Gulf of Kachchh that extends between Jakhau and Kandla. This part of the coastline of the Kachchh exhibits three distinct depositional energy domains that have unique geomorphological attributes. The northwestern part of coastline between Jakhau and Bhada is relatively straight. Then Bhada to Mundra is a mix coast having both sandy and muddy features in equal amount. Last segment has been marked between Mundra and Kandla as a tide dominated coast. All three segments are described systematically as follows.

JAKHAU - BHADA SEGMENT

This is the western most segment along the Kachchh coast that lies between the Jakhau and Bhada stretching for about 75 km length (Figure 3.8).

Figure 3.8: Landsat image of western Kachchh showing the straight sandy coast between Jakahu-Bhada.

The area exhibits straight coastal configuration along NW-SE direction. This segment is characterized by sandy beaches including ridge and runnels, berm ridge and berm plain, foreshore and backshore dunes, and occasitional presence of mudflats, saline sand flats and coastal alluvial plain. The area exhibits a variety of depositional and erosional geomorphic features at local scale like barrier beaches, lagoons, wave cut shore platform and inland saline sand flat. The river mouths in this segment take a sudden turn before debouching into the sea. This is caused by the accretion of the barrier bars which forms a typical Yazoo pattern at the mouth. Due to this reason barrier beach complex in the foreshore zone are backed by the coastal dune, Palaeo beache ridges, followed by low lying muddy lagoon fills and saline sandflats (Figure 3.9).

This segment has almost continuous occurrence of sandy beaches and backshore dunes, except at Naira river mouths. The beach ridges are 3-5m high with a steeper (~15^{o}) seaward slope. The presence of stabilized and active coastal dunes is marked all along the coast behind the beach ridges. The dune fields are not of a large width but, attain a considerable height at places; for example near Pingleshwar the dune crest reaches up to 6 to 8 m height above mean sea level. Overall the intertidal zone is steeper and narrow in this segment between Jakhau and Bhada. The segment also has some broad intertidal zone areas. Near Sindhodi Mota village intertidal zone becomes very broad around 2km. Paleomudflats and sandflats are also present here which forms a barren land of about 3.5 to 4km width. Vokaro river abut in this barren land. In this segment between the mudflat and the coastal alluvial plain the streams are generally arranged in a parallel pattern. However, due to the formation of barrier bars across their mouths, the streams are either blocked, forming a lagoon (e.g the

Kankawatl river to the south of Sandhan, Figure 3.9), or flow parallel to the barrier to find an opening into the sea (e.g. the Suthriwali river near Suthari). The entrenchment of many streams by about 2-3m in this zone suggests a gentle warping that led to the recession of the sea (Biswas, 1974) and formation of the parallel drainage pattern. Naira river is the major river of this segment. It flows in NE-SW direction along a fault called Naira river fault (NRF). Suthriwali and Bandhawali cheli, these two rivers also abut against a mudflat and are not in a contact with the Gulf due to the presence of 8m high beach ridges (Figure 3.9).

Rocks are available only between Suthri to Khuada coastline in this segment but those can be seen only during low tide. Here coastal alluvial plain is absent and paleo mudflat and sandflat become wider. Near Khuada sandy beach ridge and stabilized dunes make a significant height of around 16m. Kankawati river terminates against these barriers. A set of 2 or 3 shore parallel beach ridges with stabilized dune runs continuously up to Bhada, attaining height of about 23m near Dharmasala village. Chok, Sai and Vengdi are the other major streams of this segment. Chok and Sai river act as a tidal rivers during high tide in rainy season. Except rainy season, they remain disconnected from the gulf due to less surface runoff since Kachchh region falls under the arid climate zone. Several small streams are also present between Sai and Vengdi river, with NE-SW orientation. These streams are originating from saline sandflats and finish in the same sandflats. From the mouth of Sai river the beach ridge becomes wider around 400m between Dharmsala and Bhada.

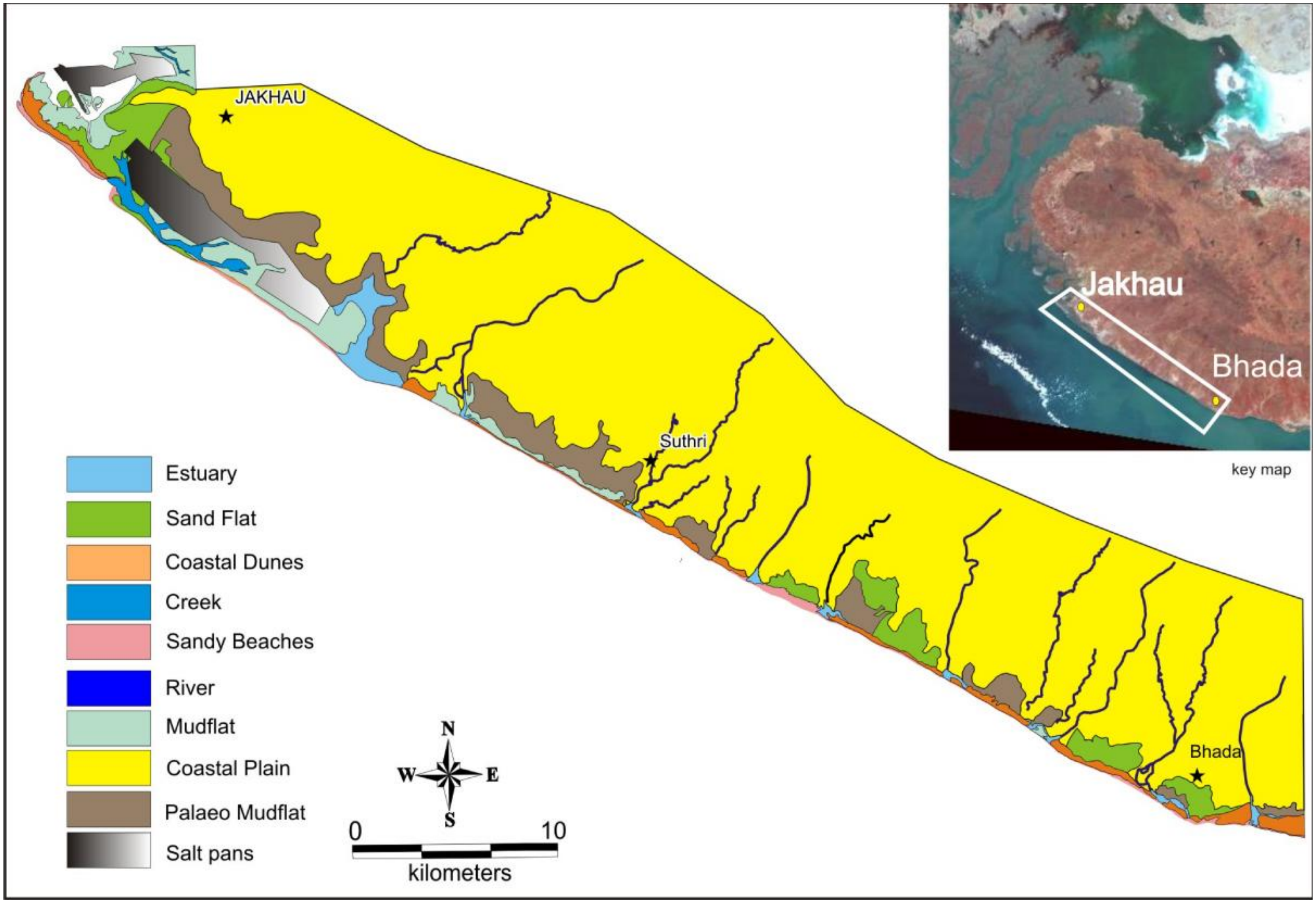


Figure 3.9: Map of Jakhau-Bhada segment showing various coastal geomorphic units.

This segment is mainly characterized by wave dominated land forms. Also the occurrences of tertiary rock right up to the coast. The surface of exposed Tertiary rocks is a peneplained erosional surface known as the early Quaternary planation surface (Biswas, 1974). The coast Khuada to Bhada is located over the N-S trending zone of a subsurface structural high termed as the Median high (Figure 3.1). Figure 3.10 depicts some field views showing characteristic features of this segment.

BHADA - MUNDRA SEGMENT

This coastal segment is about 40 km in length and has a presence of features like 20-50 m wide beaches, about 50-200 m wide coastal dunes and a number of coastal streams. The coastline is composed of minor cuspets along the seaward margin of the beach, beach cusps of 30 to 70 m average length along the berm outline and sand waves of 500-700 m length, which includes all the minor features between the berm with foredune and the low-tide level. Dolan et al. (1974) defined these features as hierarchical, produced by superposition of processes with different scales of motion. A noticeable increase in steepness of beach angle is observed at places like Chhachhi having beach angle around 18-20^{o}. This segment has a presence of most famous beach for tourism along Kachchh coast. Mandvi is a famous ancient port town for its small-shipping industry situated on the bank of River Rukmavati.

(a)

(b)

(c)

(d)

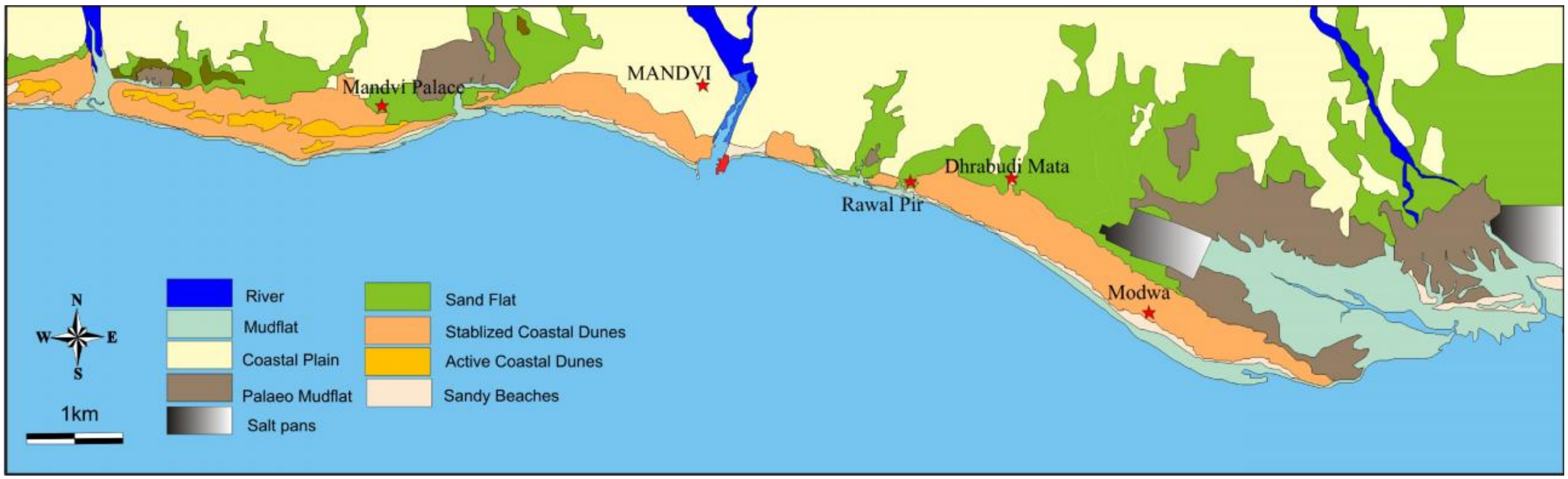
(e)

(f)

Figure 3.10: Field photographs from Jakhau-Bhada segment showing
(a) General landward view from pingleshwar dune ridge, showing barren saline sandflat, (b) 8^o to 10^o slope of the beach of Pingleshwar with active foredunes, (c) Oyster and barnacle shaded rocks exposed during low tide near Jakhau, (d) Degraded mangrove swamp near Jakhau, (e) river blockage and formation of lagoon due to beach ridges near sandhan, (f) stacking of dune over an older beach ridge on Sandhan coast.

Historical monument like Vijay Vilas palace is also situated on the coast of this segment. The coast of Mandvi contains widest dune complex (250-300m) in the study area, having stabilized as well as active dunes (Figure 3.11a). The Bhada– Mundra segment displays a distinctly different geomorphic setup compared with the previous Jakhau – Bhada segment. The main distinguishing characteristics of this coastal segment are wavy outline of the coastline, wide intertidal mudflat zone with extensive mangroves, sandy landforms like sand ridges, spits and bars, and a well-developed coastal alluvial plain (Figure 3.11 and 3.12). The usual landform sequence from the low tide region to the coastal alluvial plain are two to three sets of ridges and runnels, beaches with 5^o to 8° average slope, berm and berm plain, about 2 to 3 m high paleo-mudflats, 4 to 6 m high coastal dunes with 22°-24° landward slope and 10°-12° seaward slope, mudflats with tidal creeks, the saline sand flat and the coastal alluvial plain. The coastline shows well-developed beachridge complex near Modwa. The beaches display gentle seaward slope with a moderately broad zone of active foreshore dunes. The dunes are partially stabilized on the landward side. Numerous crab holes were noted with associated mounds of loose excavated sand, the hole to mound distance being 20 to 22 cm almost everywhere. These holes, perhaps, contribute to the erosion of the foreshore slope during high tides as water gushes through the holes at high pressure, it erodes more sand than elsewhere, and leads to collapsing of the burrows and then slope failure. A number of major rivers viz., Kharod, Rukmavati , Khari , Nagwanti, Phot and Bhukhi, enter to the sea along this segment. An active spit growth can be seen to the east of Modwa (Figure 3.11b). The coastline near Mandvi is also characterized by a well-developed ridge and runnel system. Overall, the segment shows active progradation and aggradation as the dominant process. However, the sediments become progressively finer toward the east as evidenced by the replacement of sandy beaches with muddy coast. The Kharod river is one of the major river of this segment. It flows mostly through pre-Quaternary rocks except in the vicinity of the coast where it flows through alluvial deposits for a few kilometres, forming a narrow estuarine mouth before meeting the sea. The coastal dune field is narrowing down toward the east. The paleomudflats comprise mostly organic rich clays with intervening layers of silt. The organic rich clays show internal laminations, whereas the sandy silts show trough cross-stratification at places. Sandy beaches with berm plain are found to be well developed east of Mandvi town and are presently undergoing erosion all along its length as can be seen in the form of cliffs developed in the backshore dunes (Figure 3.13). The 2–3m high cliff exposes mainly coarse sand and show horizontally stratified and cross-stratified layers. Further east, the coast shows an increasing extent of intertidal mudflats that become widest near Mundra (Figure 3.12).

The mangroves also show increasing abundance along this direction. The coastal zone near Mundra is characterised by a wide zone of mudflats containing scattered sand units like chenniers, sand ridges and beaches.



(a)

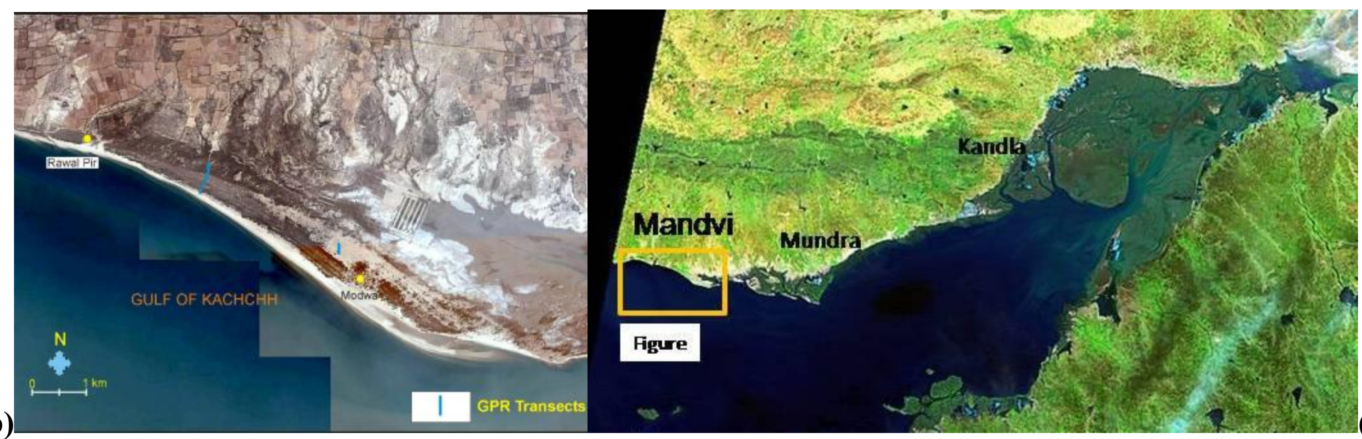
(b)  (c)

Figure 3.11: (a) Geomorphic map of area between Kanthada and Rawal Pir. (b) Google earth Image showing Modwa beach ridge complex. A number of beach ridges are seen due to linear confinement of the vegetation along swale. Active growth of the spit can also be seen at its southeastern end. (c) Key map for Mandvi segment.

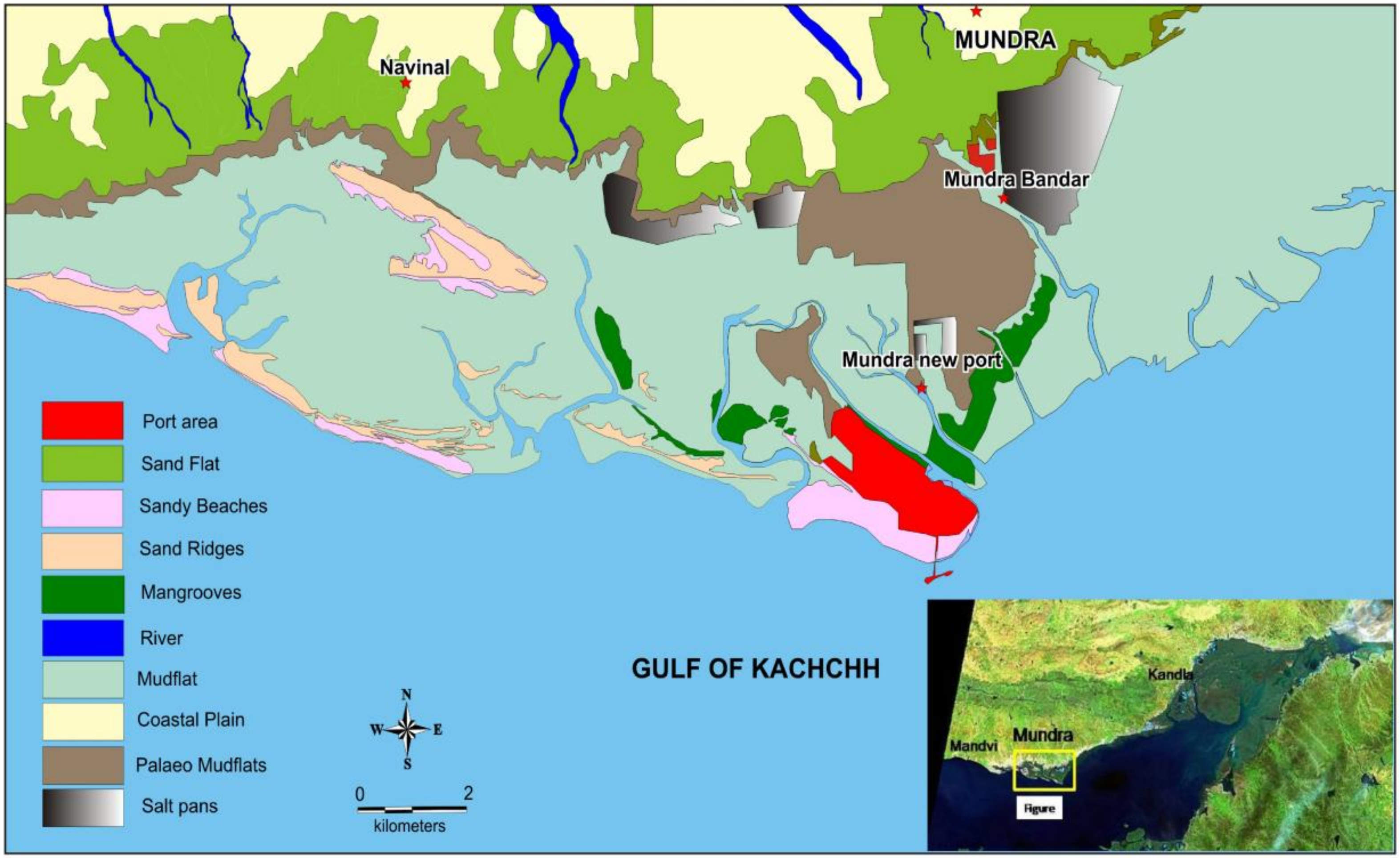


Figure 3.12: Geomorphic units of the coast around Navinal to Mundra.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 3.13: Photograph showing (a) wide berm plain with a gentle beach at Rawal pir, (b) Cliff along Modwa coast, (c) crab activity in intertidal zone, (d) parallel ripples in upper intertidal zone, (e) foredune and (f) swale flowing parallel to the coast at Mandvi.

The area around old Mundra port has extensive paleo mudflats and stumps of dead mangroves. The mangroves around this port are also undergoing rapid degradation. A new port has been constructed in the last decade, Adani Port, which is located about 3–4 km further south along the Navinal Creek. The total distance from this port to the oldest abandoned port is about 12 km, which points to high amount of siltation. The NW-SE oriented straight coastal outline of the Jakhau-Bhada segments takes an east ward turn of 23° in Bhada-Mundra coastal segment. As a result the waves, normal to the straight coast segment, impinge against the bent coastline at an angle 40^{o} to 50^{o}.

Wave action, along with a strong eastward longshore drift is responsible for the gradual development and subsequent decay of a number of spits and sandy ridges from the headland, while wave refraction at the tip of the spit produces complex recurvatures. It can also be obsereved in satellite images in the form of the truncated spits and hook remnants, with 3 to 7 m high sand ridges (chennier) and dunes over the mudflats (e.g. Dhoa Reserve Forest) which indicate a gradual shifting of the spit-building activity from ENE to WSW. The best example is the Rawal Pir-Modwa spit whose western end near Rawal Pir is at present under an erosional phase, whereas a new spit is gradually emerging at Modwa. The present fulcrum of the spit lies at Modwa. The alignment of the older spit remnants is intersected by that of the newer shore lines at an angle of about 45 ° or more. Ones It is quite likely that under the attack of the dominant waves the older spits are also being displaced landward. Their juxtaposition near Mundra could be a major reason for the cuspate foreland formation. Characteristically, all the major tidal creeks of the Mundra region take a southeastward bend to meet the sea (e.g. Baradl Mata creek and Kotdi creek).

MUNDRA - KANDLA SEGMENT

The Mundra–Kandla segment forms the easternmost part of the Kachchh coastline. Further east the coastline joins the northern margin of the Little Rann of Kachchh (Figure 3.14).

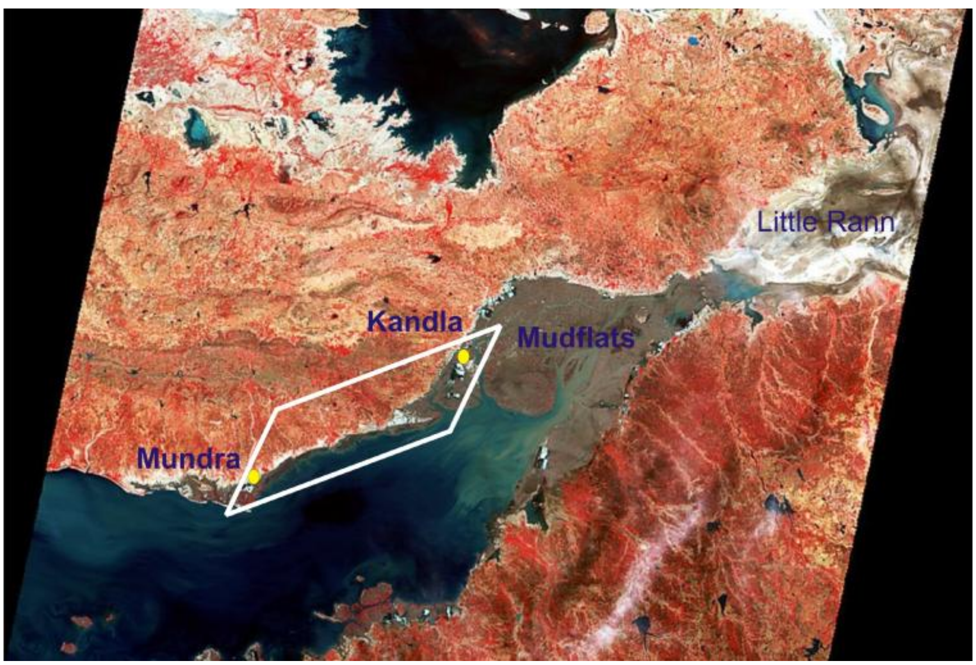


Figure 3.14: Landsat Image of eastern Kachchh showing Mundra-Kandla segment of study area, Wide mudflat zone and Rann surface are also clearly visible near Kandla.

This segment is about 55km in length with presence of geomorphic features like active mudflats, palaeo-mudflats, tidal creeks, narrow discontinuous sandy beaches, occasionally about 5 to 8 m high discontinuous and vegetated dunes of fine sand and silt, saline sandflat, ebb tide delta and small chennier ridges near river mouths along with the coastal alluvial plain (Figure 3.15).

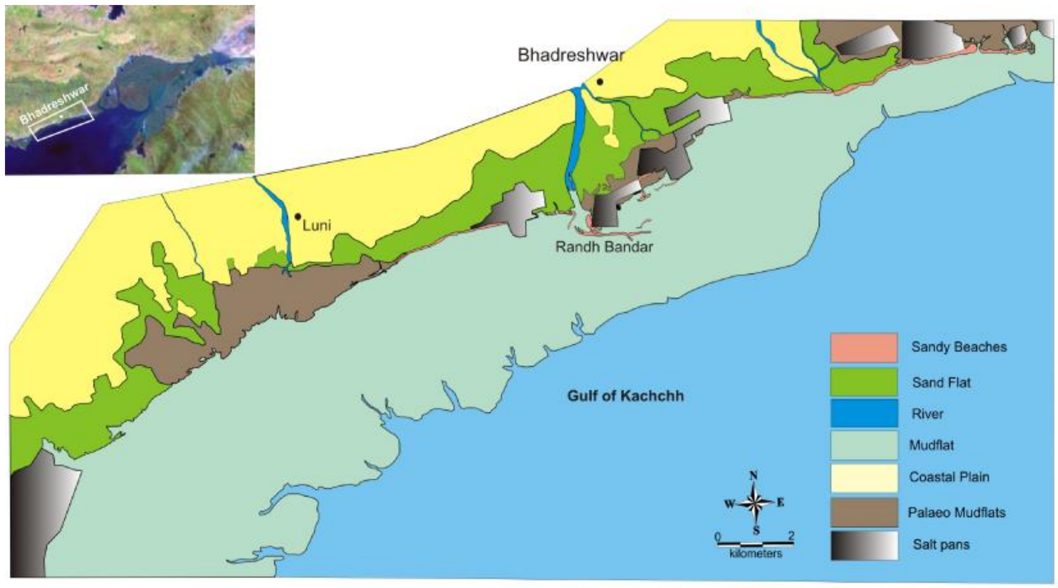


Figure 3.15: Geomorphic map of the Mundra-Bhadreshwar segment.

The wide mudflat coast starts from the east of Mundra and extends for more than 120 km up to the Little Rann and gradually widens eastward near Kandla and beyond (Figure 3.16). Its widest part is to the east of Kandla port where it fills a 40 km wide stretch of the gulf between the Kachchh mainland and the Saurashtra coast. Kandla is one of the biggest port having heavy shipping cargo business due to its direct connectivity of capital and central part of the country. This segment has a presence of geomorphic landforms like active mudflats, palaeo-mudflats and mangrove swamps (Figure 3.17). This coastal segment is characterised by the width of the Intertidal zone varies from 0.5 to 1.5 km. The offshore region is marked by several creeks. A number

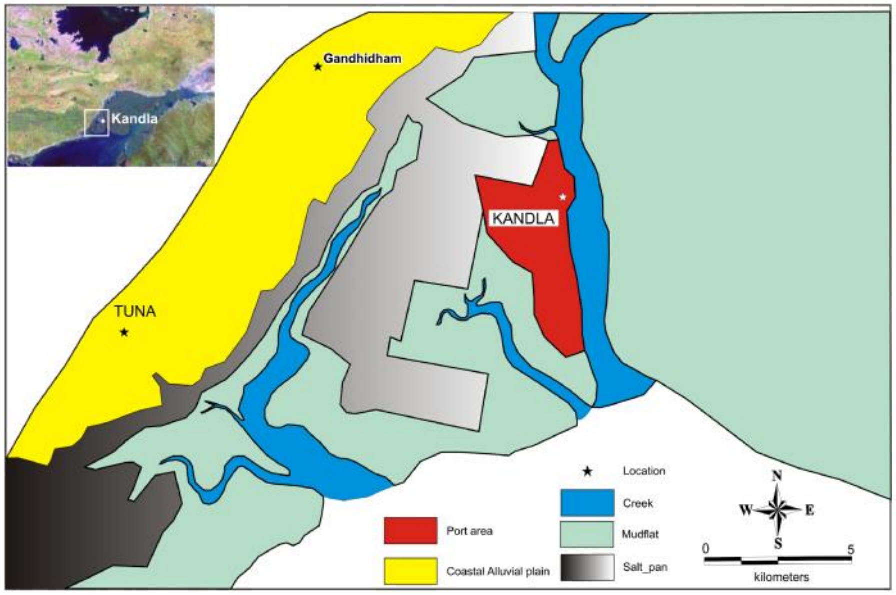


Figure 3.16: Geomorphic map between Tuna and Kandla area.

of tidal creeks flow through the intertidal mudflat area. Notable among these are the Hadkiya, the Chach, Hansthal and the Kandla. The sources of sediments are the Banas and the other minor streams which make their way through the Little Rann during the monsoon and the long-shore drift from Kori Creek eastward (Patel et al. 1988). A major feature of this coastal segment is the presence of a narrow zone of paleomudflats and alluvial plain all along the coastline. The alluvial plain along this coastal segment forms a part of the large alluvial tract separating the Mainland Kachchh and Wagad and is known as the Bhimasar–Lakadiya plain. The rivers joining the sea have short courses and disappear into the palaeomudflats (Figure 3.17).

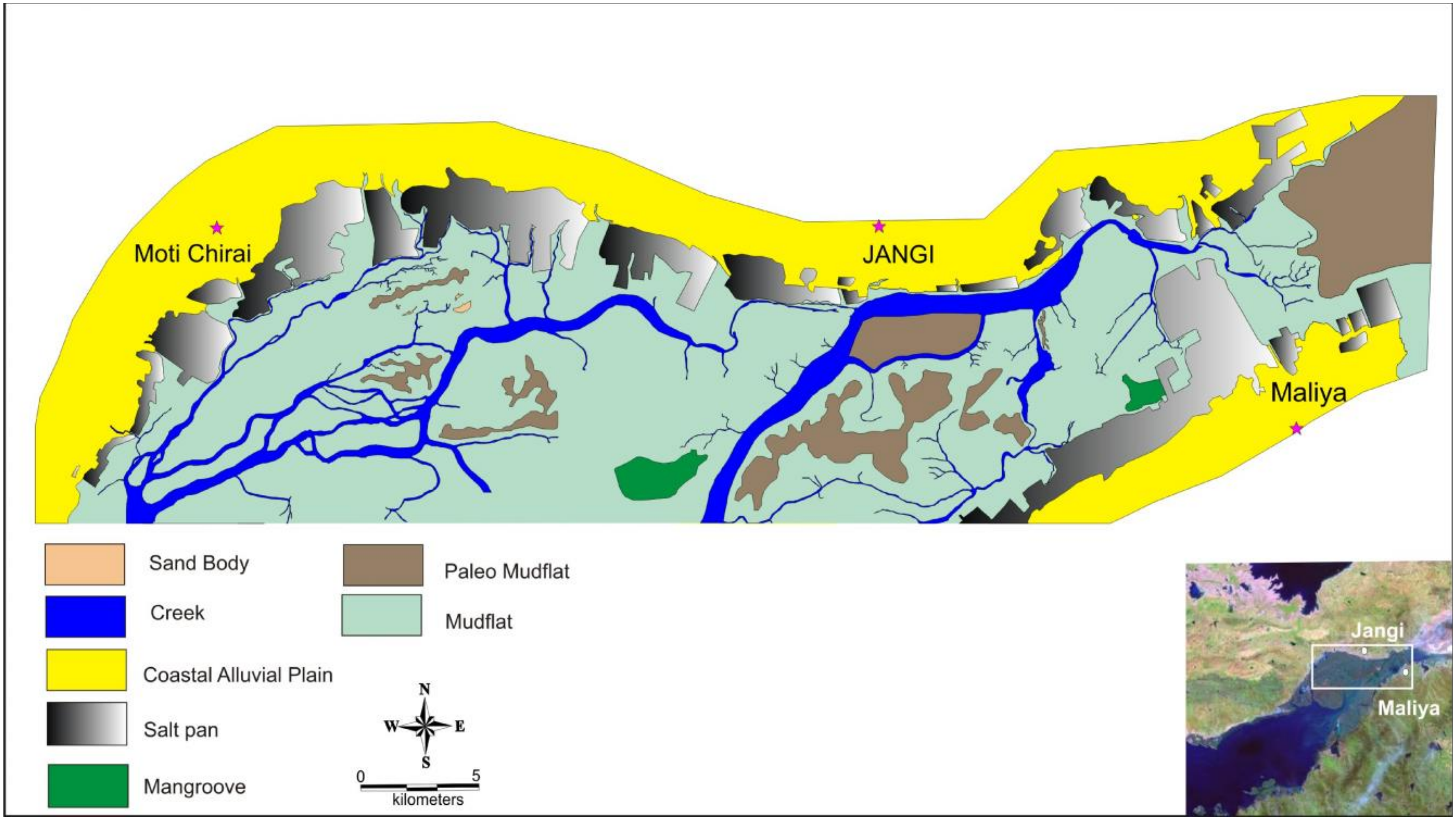


Figure 3.17: Geomorphic map of the headward of the Gulf of Kachchh.

The palaeomudflats gradually rise above the intertidal flats and merge into the alluvial plain further inland. Coastal dunes occur as small scattered patches along the coastline. The palaeomudflats dominantly comprise internally laminated tidal clays. A four-layered sediment succession is reported from the adjacent Little Rann of Kachchh (Gupta, 1975). The Little Rann is known to have been affected by a slow upheaval through the Quaternary that caused the gulf to recede (Biswas, 1974).

4

Ground Penetrating Radar (GPR)

Imaging shallow subsurface sand body architecture

A better understanding of geomorphic evolution of any part of terrain requires idea about the morpho-stratigraphy and possible sedimentary environments that gave rise to the landscape under study. Reconstruction of past sedimentary environment is possible using data describing sediment-body geometry, its internal architecture and the characteristics of sediments. Examination of the shallow subsurface sedimentary architecture can be attempted by digging a trench or hunting for a natural section. It is usually very difficult to encounter such exposed sections in an active coastal depositional system subjected to episodic erosion by storm events. Digging a trench is also costly and many times not permitted due to environmental impact. GroundPenetrating Radar (GPR) proves to be an important noninvasive tool in the studies of coastal landforms, especially the sand bodies. The correctly processed radar profiles have been successfully used to construct the radar stratigraphy in both, ancient and modern sand bodies (Jol and Smith, 1991; Gawthorpe et al., 1993). However, the use of GPR to map shallow subsurface sedimentary architecture is uncommon in India. Shukla et al., 2008 have presented such an example from the

Modwa area of Kachchh coast. The application of GPR in sedimentology requires systematic collection, processing and interpretation of the radar profile with awareness about distortions of reflection and the reception of discrete pulses of high frequency electromagnetic waves by the sediments in varied textural and moisture conditions. Using GPR profiles various bounding surfaces and radar facies could be identified that provided clues in understanding the coastal dynamics and responsive sedimentation along the northern coast of the Gulf of Kachchh.

GROUND PENETRATING RADAR

Principle and Product

Like all other geophysical methods that use electromagnetic (EM) waves the Ground Penetrating Radar (GPR) technique is also based on the propagation and reflection of EM waves which sense the changes in physical properties and composition of the subsurface material like grain size, moisture, dielectric permittivity and electrical conductivity (Davis and Annan, 1989; Daniels, 2000; Jol and Bristow, 2003). The radar waves, a type of electromagnetic waves typically in the 1 to 1000 MHz frequency range, spread out by transmitter antenna travel downward in the subsurface and get scattered back to the surface from the interface with the material having contrasting electromagnetic properties, and are detected by a receiving antenna (Figure 4.1). The application of GPR technique in understanding shallow subsurface requires knowledge about the velocity of radar waves in different geological material, that is controlled by electromagnetic properties of the medium which are primarily governed by water content, dissolved minerals and expansive clay, and heavy mineral content (Topp et al., 1980; Olhoeft, 1984; Davis and Annan, 1989; Beares and Haeni, 1991; Jol and Bristow, 2003).

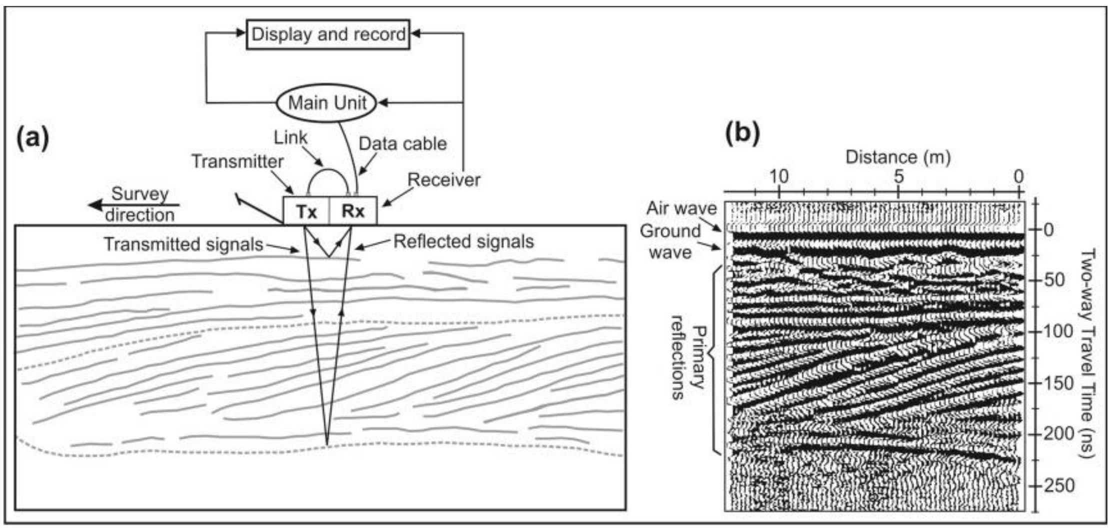


Figure 4.1: GPR data acquisition and the resulting radar profile in wiggle mode. (a) The GPR system components, manner of signal penetration and internal architecture of the subsurface reflectors. (b) GPR reflection profile in wiggle mode. Position of Ground waves, Air waves and primary reflections are indicated (after Neal, 2004).

A GPR profile is an array of traces made by continuously towing the monostatic antenna over the ground, or at discrete point along the surface using bistatic antenna. It is a time series record of radar waves transmission and receiving measured in nanoseconds. Scattering of radar waves occurs at the interface of media having different dielectric permittivity (Reppert et al., 2000). Basic understanding of the scattering pattern of the EM waves is an important criterion to interpret the GPR profiles. Daniels (2000) described four types of scattering; (i) specular scattering, (ii) refraction scattering, (iii) diffraction scattering and (iv) resonant scattering. The downward radiated EM waves when reflected back from the interface of different dielectric permittivity, the angle of incidence is equal to the angle of reflection which is known as specular scattering (Figure 4.2). It is common in bistatic GPR antenna arrangements, where the transmitter and receiver are the separate entities. The refraction scattering occurs in GPR data when some amount of radiated radar energy are re-emitted to the surface from the contrasting subsurface interfaces and the remaining energy propagate downward with different speed in the direction of diffraction (Figure 4.2). The angle of the diffraction depends on the contrast between the electrical properties of the propagation media and can be determined by Snell's law. Diffraction scattering is a common phenomenon in the GPR profiles. If the object has higher electromagnetic conductivity than the host medium, there is some bending of energy from a point and the waves are separated out in various directions (Figure 4.2). The nature of diffracted energy depends upon the shape of the object, wavelength of incident waves and the roughness of the interface boundaries (Daniels, 2000). The geological features like vertical fault planes, unconformity, lithological boundaries and abrupt facies changes generally diffract radar energy and seen in GPR data as semi-coherent energy pattern, and where the reflections play out in different directions from a point (Daniels, 2000). Resonant scattering of the signals occurs when a layer or object of higher electromagnetic conductivity is sandwiched between the layers having relatively low electromagnetic conductivity (Figure 4.2). This is very common in sedimentary terrains because of the occurrence of alternate layers of varying dielectric permittivity (Neal, 2004).

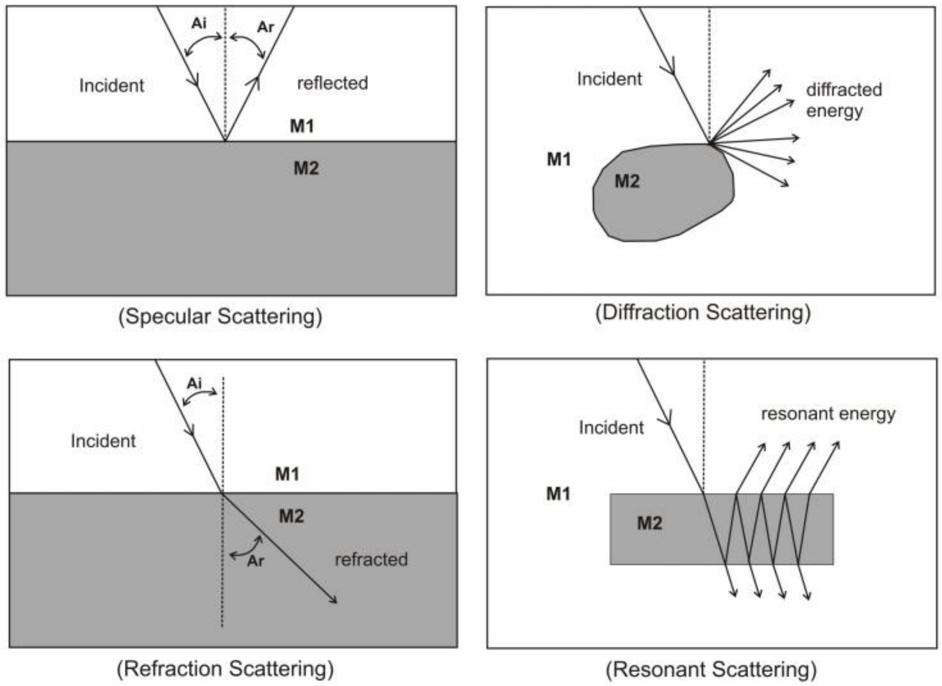


Figure 4.2: General scattering patterns for radar waves (a) specular reflection scattering (b) refraction scattering (c) diffraction scattering (d) resonant scattering (after Daniels, 2000).

GPR studies are non-destructive subsurface investigations which provide high resolution profiles of depths up to 50 m, depending upon the selection of radar wave frequency and degree of resolution. GPR is thus an important tool ideally suited for obtaining high resolution profiles of the 'blind zone' (~50 m depth), which otherwise is not possible by other geophysical methods. GPR gives a more direct/realistic high-resolution image of the subsurface than other methods.

The instrument used in the present study is Geophysical Survey Systems Inc., USA product SIR-20 model (Figure 4.3) which is compact and easy to handle compared to the logistic requirement of other geophysical survey instruments, hence can be easily transported and operated in far-off places.

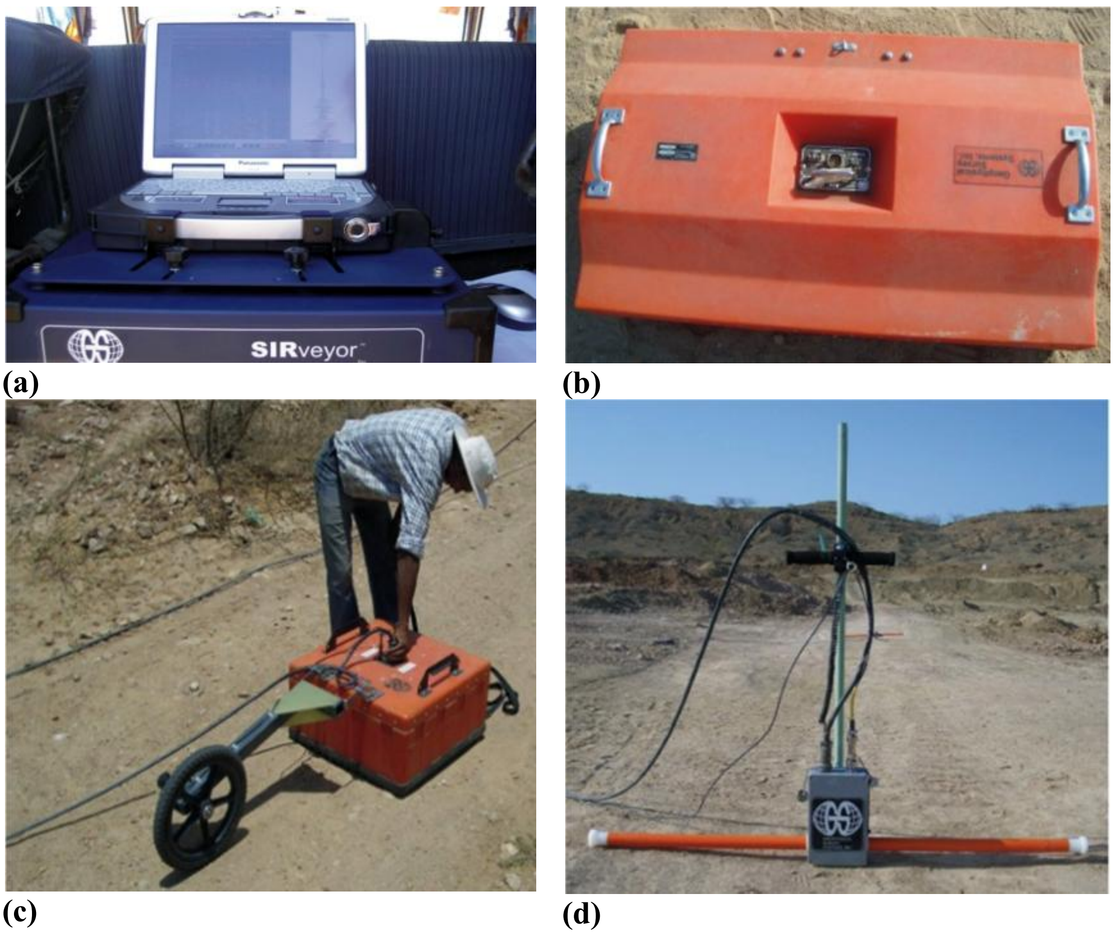


Figure 4.3: GSSI SIR-20 GPR with its different components. (a) Control unit mounted with toughbook system computer, (b) Shilded monostatic antenna of 100Mhz frequency, (c) shielded monostatic antenna of 200Mhz attached with survey wheel and (d) bistatic unshielded receiver antenna of 80Mhz frequency which can be changed by extending the length of horizontal rods.

GPR is now widely used to image the shallow subsurface and its applications in neotectonic, palaeoseismic and sedimentological studies have been demonstrated from different parts of the world. Jol and Smith (1991) and Van Overmeeren (1998) studied sedimentary features in various depositional environments using GPR. Radar facies and sequences have been recognized and linked directly to sedimentological characteristics seen in cores and trenches. GPR studies carried out by Bridge et al. (1998) revealed more in situ details particularly in delineating the lithofacies, geometry and orientation of large-scale inclined strata sets associated with channel bar migration and channel-filling. GPR surveys have been carried out on alluvial fan sediments mainly to characterize reflection patterns and to assess the potential of GPR in these deposits (Porsani et al., 2005). GPR studies have also been widely conducted in the field of archaeology and civil engineering. Depth of water table and sedimentary facies which correspond to bars and channels are also imaged by GPR. GPR studies have helped in identifying sand-blow features induced by historic earthquakes in shallow sedimentary deposits and to delineate the subsurface pattern and palaeoseismic facies in active areas (Maurya et al., 2006).

Data Acquisition

The GPR survey is possible in two different modes i.e. monostatic and bistatic. The shielded monostatic antenna is dragged along a survey line to record continuous cross-section of the subsurface (Figure 4.3c). The monostatic antenna contains a pre-fixed unmovable configuration of transmitter and receiver inside a shielded cover that can be attached with an odometer based survey wheel to measure the horizontal length of the survey line. In bistatic antenna configuration the transmitter and receiver are separate entities and the measurements are made by manually shifting the points along the surface (Figure 4.3d). The profiling with unshielded bistatic antennas are quite time consuming and gives low-resolution images of subsurface compared to monostatic antenna. However, the bistatic antenna can achieve greater depth by changing the center frequency (Jol and Bristow, 2003). The various modes of GPR data collection with bistatic antenna suggested by Huisman et al. (2003) and Neal (2004) are shown in Figure 4.4. The Common-Offset (COS) GPR profiling is commonly used for geological applications to map continuity of the features at depth. In this mode the transmitter and receiver antennas are gradually moved over the points with common-offset distance (Figure 4.4a). The Common Mid-point (CMP) method is generally used to analyze the subsurface velocity structure of the survey area (Huisman et al., 2003; Jol and Bristow, 2003). To measure the traces by CMP method, the transmitter and receiver antennas are manually shifted away from a mid point upto a maximum distance, where receiver records the signals in stacked form. In CMP profiling the transmitted EM waves repeatedly travel through same material but the offset distance between the antennas are changed (Figure 4.4b). The calculated velocity by this method is used to convert the nanosecond time window into the depth scale and advanced GPR data processing (Yilmaz, 2000; Huisman et al., 2003). In the Common Source method the transmitter is fixed and the receiver is gradually shifted opposite to source with common step size where the common receiver method allows shifting the position of transmitter away from the stable receiver antenna (Figure 4.4c and 4.4d).

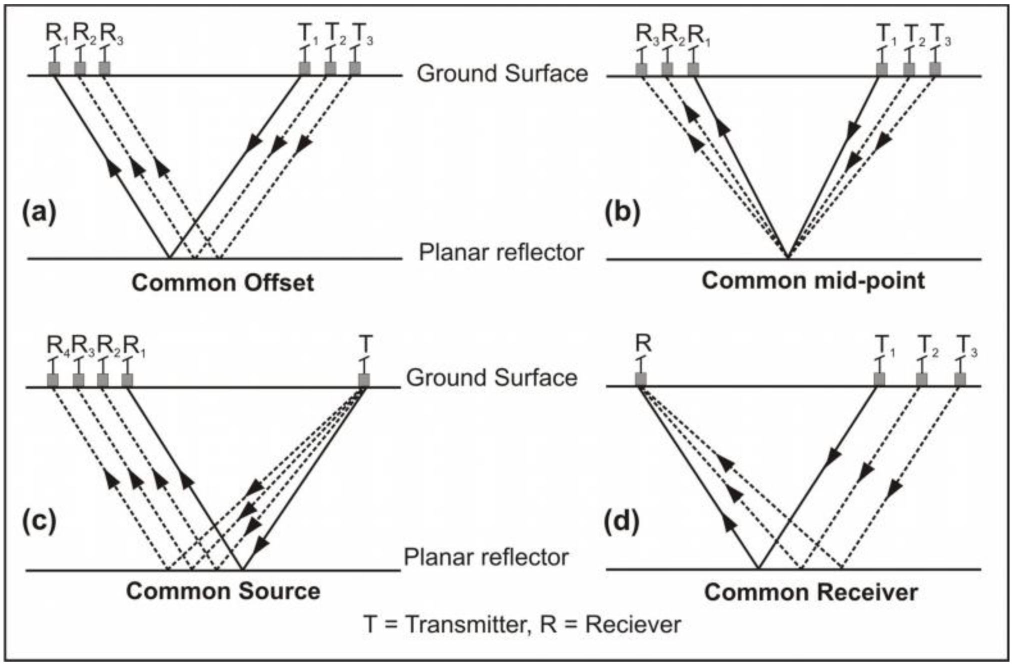


Figure 4.4: Modes of bistatic GPR survey (After Neal, 2004).
(a) Common Off-Set (COS) mode, (b) Common Mid-Point (CMP) mode,
(c) Common Source Mode and (d) Common Receiver Mode.

The Common Source and Common Receiver methods of GPR data collection are also known as Wide-Angle-Reflection-Refraction (WARR) technique and generally used to delineate the penetration speed (velocity) of the radar waves in a rugged terrain (Neal, 2004).

Data Processing

Understanding of geophysics is necessary for the processing and analysis of GPR data. The energy propagated in the ground by a transmitting antenna interacts with subsurface materials in many ways like attenuation, reflection, refraction and diffraction. The raw GPR data may not show the true subsurface image because of external noises produced by electronic bodies, geometrical inhomogeneity of the subsurface materials, concrete structures, metallic bodies, etc. To reduce the noises care should be taken during data collection (Jol and Bristow, 2003). Field maps of survey design are prepared to identify the cluttered signals in post survey data processing and interpretation. Software to process large amount of 2D and 3D GPR data allowing imaginable manipulations are available (e.g. RADAN for MS Windows, 2000). The general steps of GPR data processing are shown in Figure 4.5. A backup of raw data is taken before starting the processing. Header file parameters are edited using field notes like the data collection parameters, range of time window, scanning speed and relevant background information. Information pertaining to data profile is maintained in background file which includes survey direction, elevation details, survey grid layout and physical and electrical properties of the medium. The next is to apply the time-zero correction for shifting the traces along the time (ns) to correct the topographic effects followed by the Distance Normalization Operation to reduce the difference of antenna towing speed and accuracy of horizontal scale for GPR profile. Frequency spectrum is calculated and appropriate frequency filters are used to diminish the effects of unwanted signals from GPR profiles. Occurrence of multiple reflections called ringing is very common in GPR profiles caused by resonant scattering of radar signals received due to unfavorable subsurface conditions or instrumental errors. These cause misinterpretation of objects. Deconvolution 'DEWOW' function is therefore applied to eliminate the effect of ringing from GPR

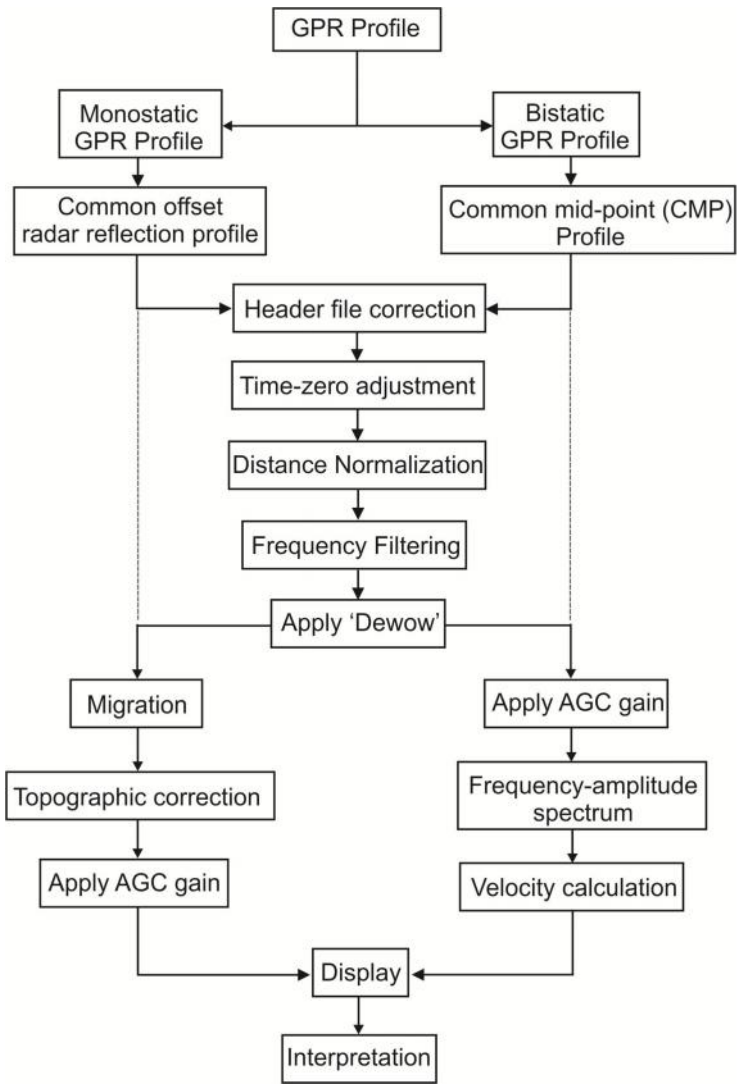


Figure 4.5: GPR data processing sequences for monostatic and bistatic antennas based on geophysical softwares developed by various commercial agencies. (Chamyal et al., 2007)

data (Todoeschuck et al., 1992). The migration function helps in rearranging the true position of steeply dipping reflections and hyperbolic diffractions (Young and Sun, 1998). The profiles raised over undulated terrain require topographic corrections to repositioning of traces at their original place. Surface normalization is necessary to determine the accurate depth of subsurface features. To correct the spherical dispersion and enhance the quality of radar signals, automatic gain control (AGC) function is used. AGC function computes the signal amplitude of individual trace over a time window (Annan, 1999).

Data Interpretation

The interpretation of GPR data is based on the characterization of specific signal patterns received from the subsurface discontinuities. Identification of origin of these reflections is important prior to GPR data processing and interpretation, whether they are the true reflections or clutters from external objects (Jol and Bristow, 2003). To interpret GPR profiles one must be aware of field conditions and survey strategies. The raw GPR data at times does not represent the real image of subsurface because of diffraction of radar energy from complex buried structures. These appear in GPR profile as a random or multiple reflections and such profiles require special processing steps (Annan, 1999; Daniels, 2000).

All the GPR profiles show two near horizontal continuous reflections with high velocity and low attenuation at the top, representing the position of direct air and ground waves (Figure 4.1). These reflections illustrate highest amplitude strength in GPR profile without any fluctuation. The first return is result of high velocity (near the speed of light ~0.3 m/ns) and low attenuation of radar energy in air which is marked as a direct air wave. Its arrival time is often used as a time zero marker for static correction. The next return is the direct ground waves, which travel directly from the transmitter to the receiver antenna through the top skin of the ground. The fluctuation in the ground waves along the time axis may reveal important information about the changes in dielectric permittivity of the upper surface layers (Bano et al., 2000; Kruk and Slob, 2004). The thickness variations in the reflected signals and changes in the dip of the reflections, intensity variations of reflected signals and their termination along the planes, displacement of reflections and reductions in amplitude strength, presence of diffraction hyperbolas and many other complementary reflection patterns that appear in radar profiles are to be evaluated critically. The presence of water strongly affects the radar returns, because the pores of unconsolidated sediments are filled with water and the dielectric constant will be greater than when they are filled with air (Ekes and Hickin, 2001; Sridhar and Patidar, 2005). It is an important criterion to demarcate the lithological boundaries and stratigraphic interfaces in the sediments having contrasting electromagnetic properties. Variation in the reflection patterns due to amount of water and clay contents are displayed by changing the strength of amplitude in GPR profiles (Carreon- Freyre et al., 2003).

GPR STUDIES ON KACHCHH COAST

Keeping in view the above discussed factors, the GPR surveys in the study area were planned and various profiles at selected areas were studied raising 2D GPR data from the sand bodies. The mud dominated geomorphic units attenuate the radar waves and so are not suitable for GPR surveys (Figure 4.6).

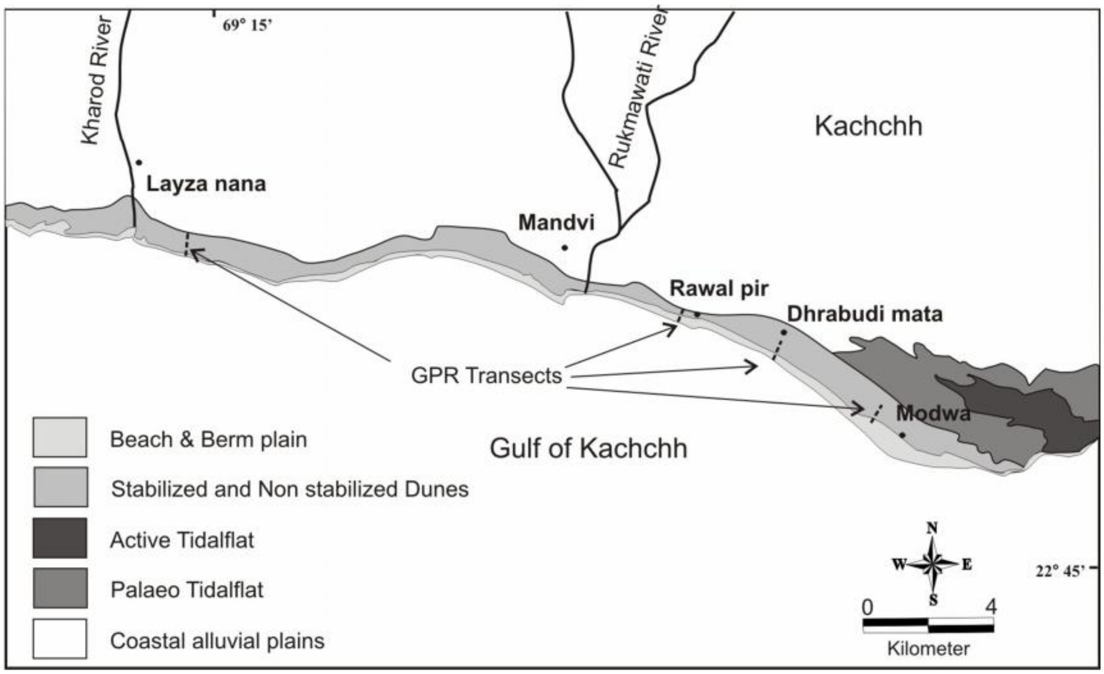


Figure 4.6: Map of parts of study area showing GPR location.

The GSSI, USA make SIR20 system which has been popularly used by many groups world over was used for the current study. This system has been successfully used in India with validation of the reflections through trenching (Sridhar and Patidar, 2005; Maurya et al., 2006). The survey was carried out using 200 Mhz center frequency shielded monostatic antenna attached with an odometer based survey wheel. The antenna was dragged continuously along the selected profile line (Figure 4.7) to acquire the GPR data. The positions of end points of these profiles were recorded using Geoexplorist 210 GPS.

Figure 4.7: Field photograph showing GPR survey on Layza coast

The profiles were collected in distance mode with 512 samples/scan and 16 Bits/sample resolution. The range of the time window defer from 100-160 ns. Some long profiles were raised along the profile line and some interesting transects were repeated and marked for the final data acquisition.The data were post-processed using the RADAN software in MS Windows environment. The profiles were analyzed for the style of reflections in light of the available literature and characteristic reflectors were identified as keys (Figure 4.8) to interpret the profiles in detail.

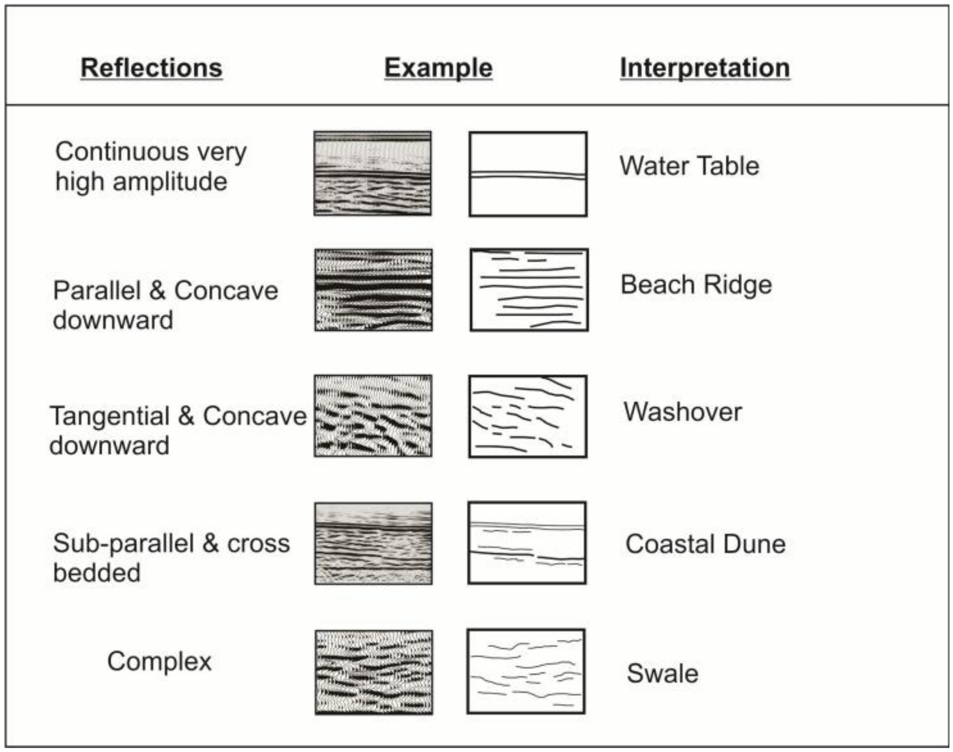


Figure 4.8: Major radar facies encountered from the various GPR profiles of study area (Shukla et al. 2008).

The raw GPR data contain interference from the external objects and subsurface discontinuities in the form of noise. These GPR signals were analyzed in the frequency spectrum and the band pass filters were used to remove the noise. The deconvolution and migration functions were applied to remove the effect of scattering of signals and to rearrange the dipping reflections at their true position (Annan 1999; Jol et al., 2002; Costas et al., 2006). The post processing also included the application of automatic gain control (AGC) function to make low-amplitude signals more visible. The GPR system noise can be readily identified due to its appearance at regular interval along the profile, having relatively consistent amplitude (Annan and

Daniels 1998). Gawthorpe et al. (1993), McMechan et al. (1997), Corbeanu et al. (2001) and Garrison et al. (2010) have demonstrated the GPR applications in sedimentological characterization of the sand bodies in ancient and modern geological records.

Site 1: GPR Survey on Dhrabudi coast

This profile was taken from south to north direction normal to the shoreline, starting from the bermline to backshore dune field. The 30m long profile was initiated from 22°48.306'N; 69°24.497'E and ended at 22°48.325'N; 69°24.503'E. The topmost uniform reflections represent air waves that are followed by very distinct high amplitude reflections visible as a thick black line are derived from the ground waves and are seen up to the depth of 0.8m (Figure 4.9). Another very prominent reflection can be seen at the depth of 3.5 to 4m (75 ns) in the form of two thick lines. This represents the ground water table (Costas et al., 2006). The water should be of brackish nature since the same will be found in a well located behind Dhrabudi temple near the GPR profile line. A distinct line at the depth of 8m can also be seen along the complete length of profile. Its uniform amplitude and depth suggest that it is a system noise. Although, attenuation of the radar signals becomes profound below this reflection, the continuation of the inclined reflectors can be still seen. As the dug well data in the nearby coastal plain indicate much deeper (more than 30 m) occurrence of the Pre-Quaternary substrate, the possibility of this continuous reflector being underlying coastal plain hard ground is ruled out. The profile (Figure 4.9c) clearly shows three radar surfaces that bound the radar facies characterized by its own style of reflections. Following the procedure suggested by Neal (2004), these surfaces have been designated as the bounding surfaces (S1bs, S2bs and S3bs) whereas, the facies as Rf1 to Rf4 with abbreviations representing its depositional environments (Figure 4.9b). The radar facies characterized by continuous sub-horizontal, parallel and very gently seaward dipping and concave downward with relatively higher landward dipping reflections are interpreted as the beach ridge (br) reflections (Psuty 1965; Collinson and Thompson 1989). Near the base of a beach ridge mainly horizontally laminated sand units are found separated by an erosional surface from the substrate. The concave downward units follow this towards the land which may be interpreted as the swash or washover facies (wo). The cross bed sets and cosets have been successfully recognized within the GPR by Corbeanu et al (2001). The washover facies are reflected by discontinuous, relatively more inclined landward dipping (7^{o}–12^{o}), low amplitude reflectors with tangential-oblique configuration (Shukla et al., 2008). During exceptional high tides aided by storms, more sediment can be eroded from the subtidal and intertidal areas and deposited further landward in the form of washover fans (Schwartz 1982; Neal et al 2003; Reineck and Singh 1980). The small scale reflectors containing radar facies which dip in different directions and at different angles with occasional discontinuous bounding surfaces are described earlier as eolian deposits (Schenk et al., 1993; Van Heteren et al., 1998; and Costas et al., 2006). Here it is considered as coastal dune (cd) facies as it occurs at a higher elevation towards land.

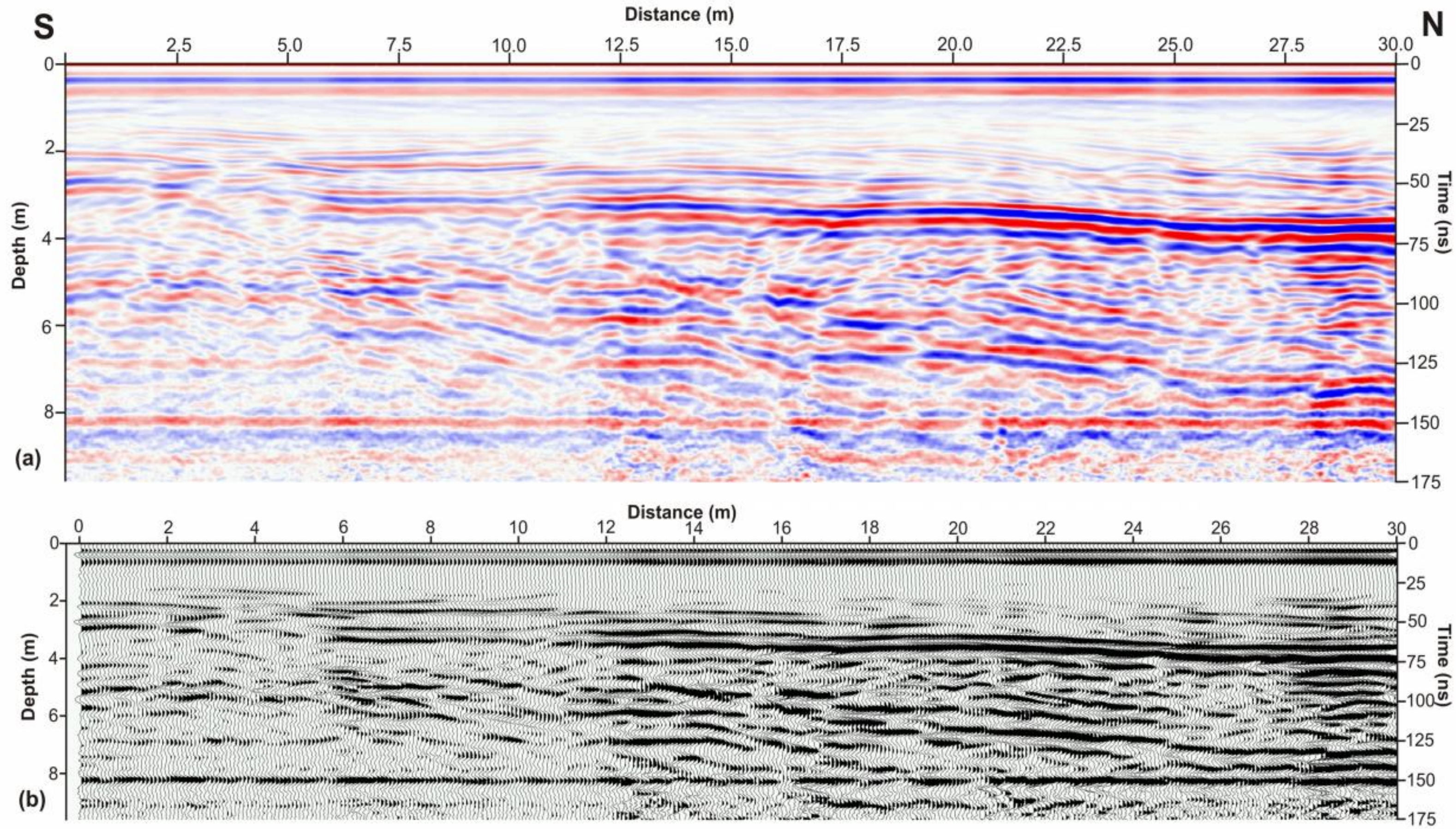


Figure 4.9: GPR profiles of Dhrabudi coast. (a) 200 MHz GPR Profile from the Dhrabudi temple coast shown in scan mode. (b) 200 MHz GPR Profile from the Dhrabudi temple coast shown in wiggle mode.

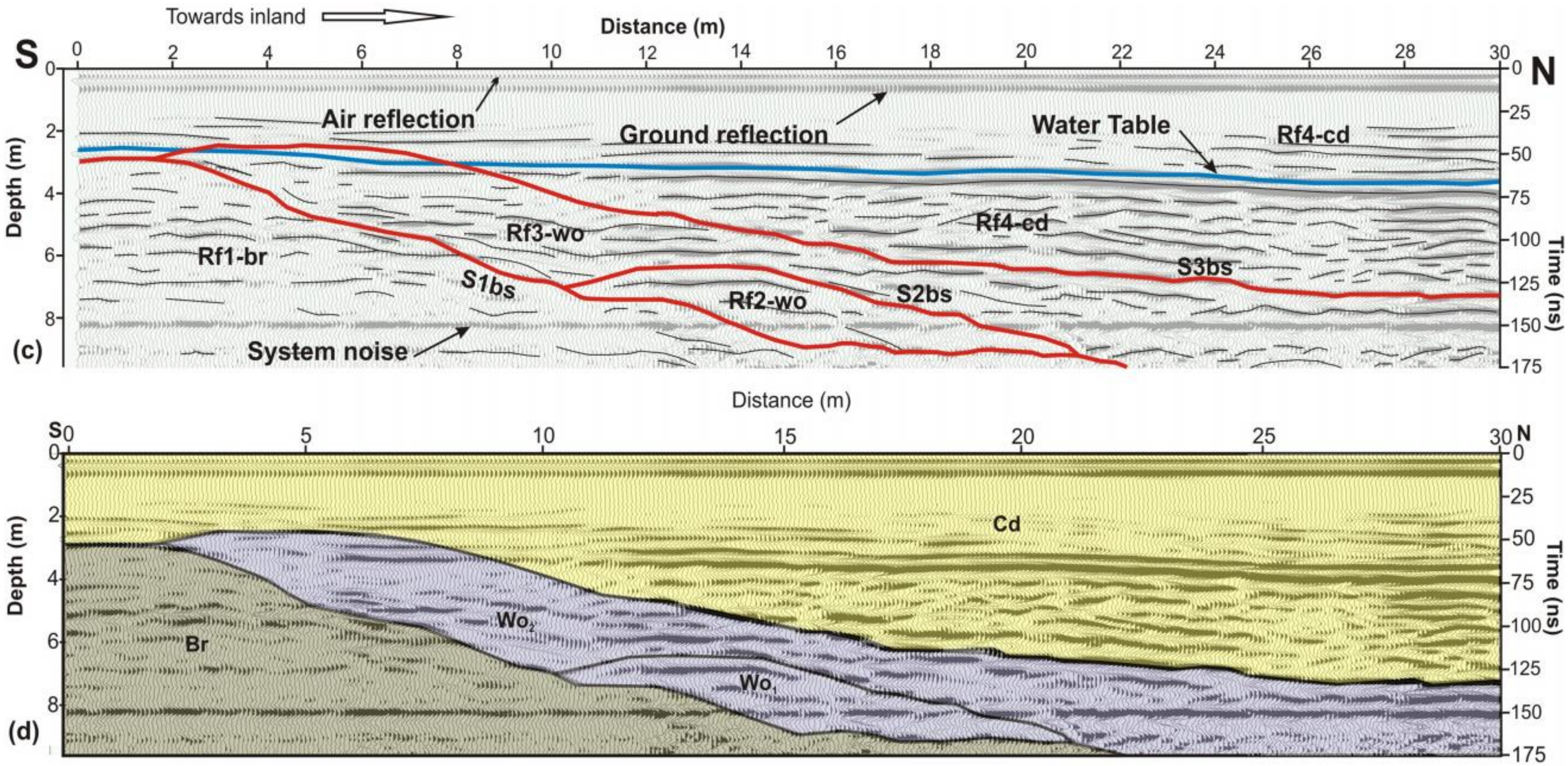


Figure 4.9: (c) Various reflections, radar surfaces S1bs to S3bs (bs - bounding surface) and radar facies Rf1 to Rf4 as interpreted from the GPR profile of the Dhrabudi coast in wiggle mode. br: Beach ridge, wo: Wash over, cd: Coastal dune
(d) Interpreted 200 Mhz GPR profile of the Dhrabudi coast in wiggle mode showing 3 major zones marked due to different reflections suggesting various micro environments of deposition.

Site 2: GPR Survey near Modwa village

GPR profile was taken on eastern side of the Modwa beach ridge complex near Modwa village beside the road between 22^{o}47.630 N, 69^{o}26.070 E and 22^{o}47.604 N, 69^{o}26.077 E, using shielded monostatic 200Mhz antenna. First reflection which is occurring at 0.1m to 0.2 m depth is air reflections. The ground reflection occurs at 0.8 m depth. 46 m long profile has 3 distinguish zones. Zone 1 contains parallel to sub parallel reflections. Zone 2 shows dipping reflection having 5^{o} to 15^{o} landward dips at 12.5 to 20 m distance from the start point in the profile. These dipping reflections are showing parallel to sub parallel dips at 20 m to 30 m and just after this it again shows 5^{o} to 15^{o} dips but, this time dipping reflections occur seaward (Figure 4.10). These reflections indicate the presence of palaeo swales which separate two different ridges. Indicators of paleoswales can also be seen in satellite images where distinct lines of preferred vegetation growth run due to the available moisture (Shukla et al. 2008).

Site 3: GPR Survey on Rawal Pir coast

Rawal pir, is a famous location east of Mandvi. This profile was taken from south (22^{o}48’46’’N and 69^{o}23’26’’E) to north (22^{o}48’47’’N and 69^{o}23’26.66’’E direction on a wide berm plain near Rawal Pir village . The length of profile is 40 m and it shows four major radar facies with several bounding surfaces (Figure 4.10b).

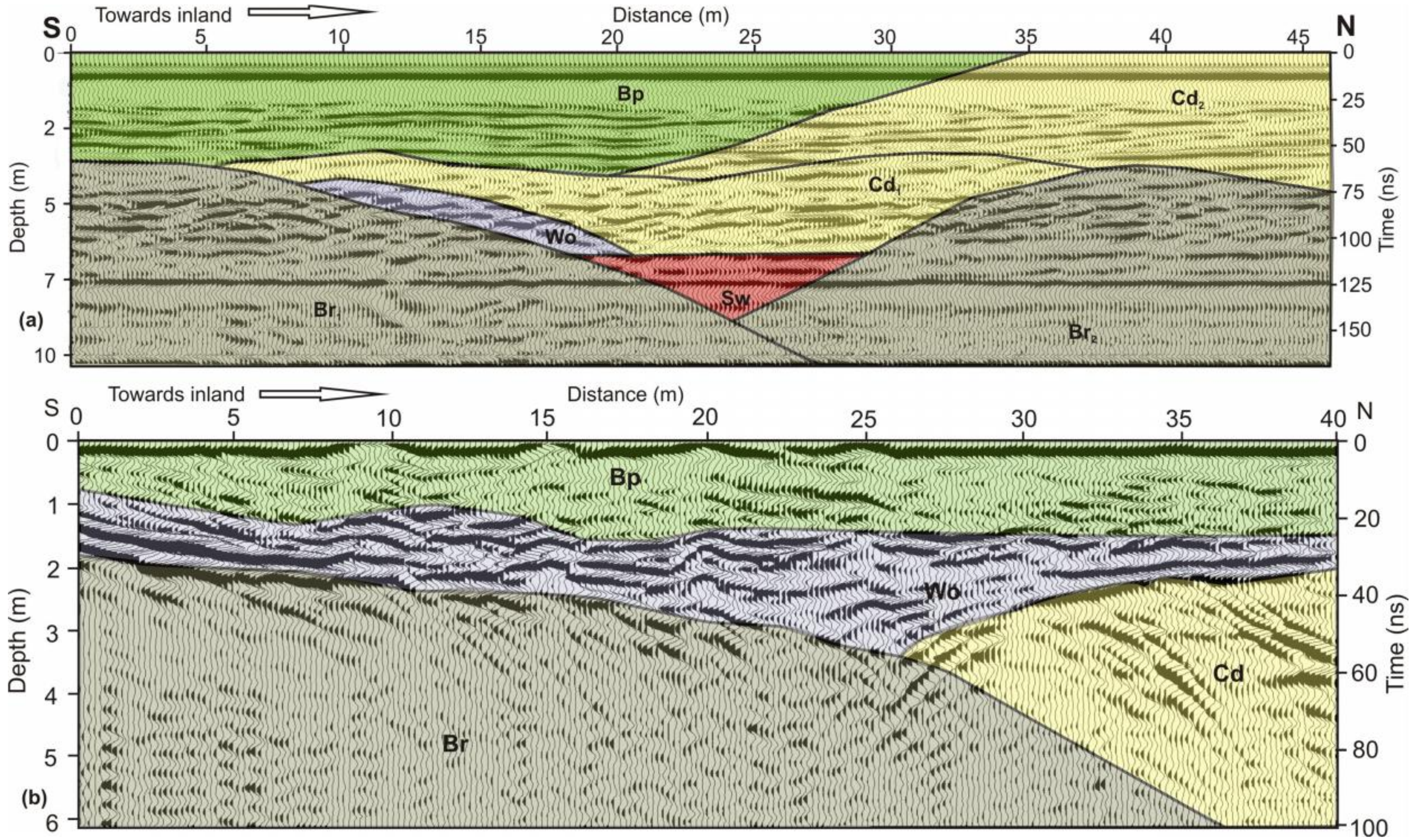


Figure 4.10: (a) Interpreted 200Mhz GPR profile of the Modwa site showing four different radar facies, marked on the basis of different reflection pattern.
(b) Interpreted 200Mhz GPR profile of the Rawal Pir coast. (Br: Beach ridge, Wo: wash over, Cd: coastal dune, Bp: berm plain)

The top 1 m of the profile comprises moderately continuous sub-parallel low amplitude reflections which are interpreted as berm plain (Bp) facies. Berm plain is a commonly occurring, flat topographic surface above the berm line extending till foreshore dunes. It gets sediment supply from subtidal and intertidal regions on account of high tidal surges and hence the sediments are usually coarse grained in nature (0.5 - 1.2 phi) compared to intertidal (1.5 - 2 phi) to dune (2 - 2.5 phi) microenvironments (Prizomwala et al., 2010, in press). On the seaward side from the depth of 2 m an ancient beach ridge (Br) unit is present which extends landwards atleast up to 35 m. It is bounded with coastal dune (Cd) facies with an onlap relationship. Above the beach ridge facies and coastal dune facies is a washover (Wo) unit indicated by landward dipping wavy reflections. It shows erosional contact with both, the beach ridge facies and the coastal dune facies.

Site 4: GPR Survey on Layza coast

This profile was collected along south (22^{o}50’13.31’’N and 69^{o}13’4.12’’E) to north (22^{o}50’18.70’’N and 69^{o}13’6.66’’E) direction starting from berm line to backshore dune field for 180m in length near Layza Nana village. This is the longest profile that runs for about 200m length. The interpreted profile (Figure 4.11) shows several bounding surfaces which demarcate different radar facies characterized by distinct reflection pattern. The radar facies at depth of 2 m on the seaward side of the profile are interpreted as beach ridge (Br) facies. They are characterized by sub horizontal, near continuous, gently seaward dipping and concave downward landward dipping reflectors. The gently seaward dipping reflections is an indicative of accretion by beach processes (i.e. wave activity), whereas the landward dipping concave downward reflections are indicative of sediments deposited during high tide surge and/or eolian transport, which is common process in coastal environments. Overlying the beach ridge facies, the discontinuous, more landward dipping reflections with tangential oblique configuration is interpreted as a washover (Wo) facies. Washover facies is bounded by erosional contact with adjoining beach ridge (Br) facies. Small scale concave downward reflectors dipping in different directions with discontinuous bounding surfaces often present in a stacked manner in the profile is interpreted as coastal dune facies (Cd). In all a total of five different coastal dune units have been identified in the profile which are separated by erosional surfaces and are abbreviated as Cd_1 to Cd_5. Above Cd_3 and Cd_5 between 57 m to 103 m for top 2-3 m there is a sand sheet (Ss) unit characterized by sharp bounding surface and low amplitude sub-parallel reflections. This must have been deposited on account of eolian activity, but is different from coastal dune facies on the basis of reflection pattern. Separating the Cd_2 and Cd_4 is a unit from 122 m to 155 m with thickness of 2 m is a swale (Sw) facies, which is characterized by continuous horizontal reflections present with convex downward bounding surface between two successive coastal dune units.

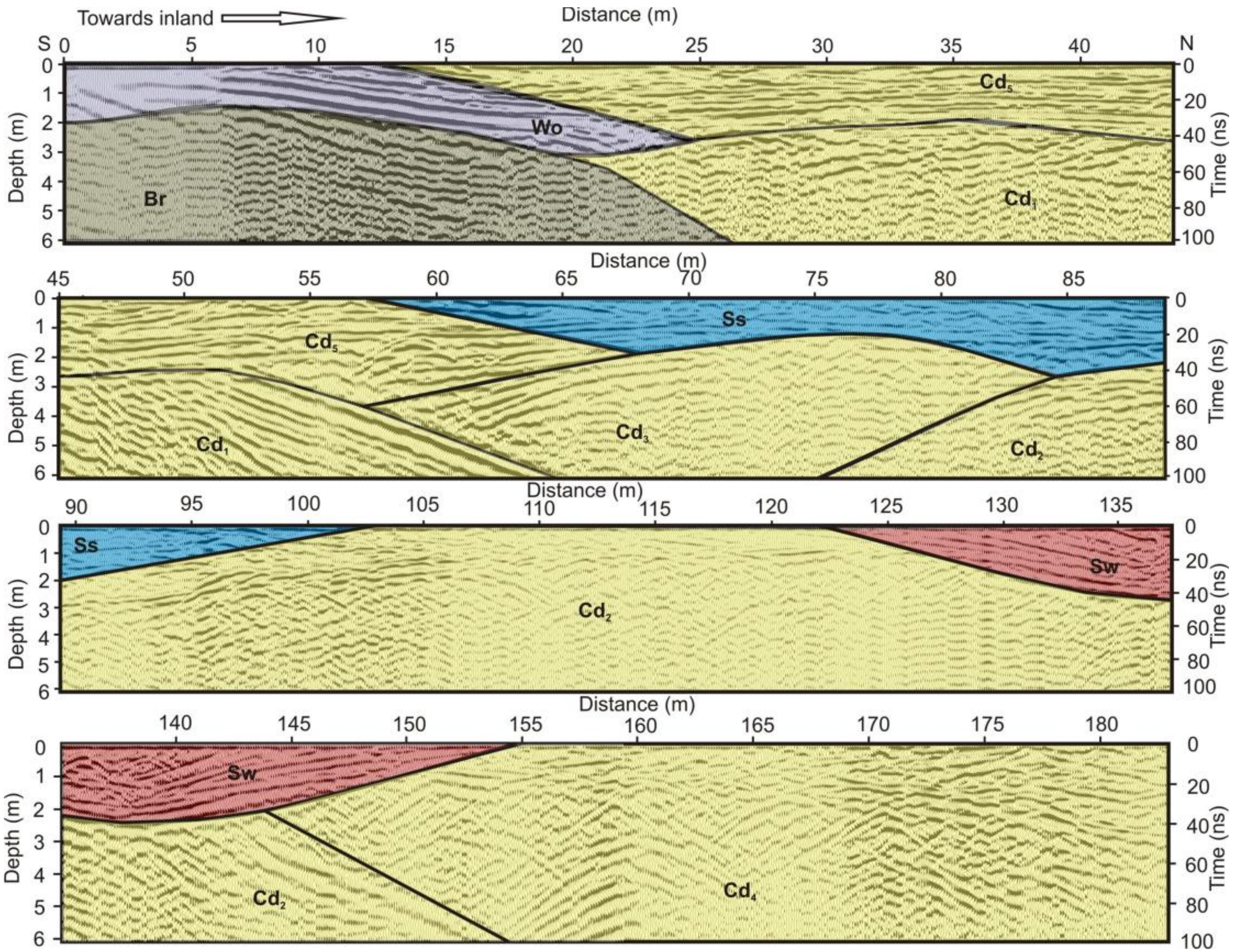


Figure 4.11: Interpreted 200Mhz GPR profile of the Layza coast; 0 to 45m, 45 to 90m, 90 to 140m, 140 to 185m. (Br: beach ridge, Wo: wash over, Cd: coastal dune, Ss: sand sheet, Sw: swale)

The study has documented various microenvironments present within shallow subsurface (6 - 10 m) along the sand dominated coastline of Kachchh, western India. Six different radar facies and several bounding surfaces were identified on the basis of reflection pattern and sediment body geometry. These include;

1. beach ridge (Br) facies with sub horizontal, near continuous, gently seaward dipping and concave downward landward dipping reflectors,
2. washover (Wo) facies with discontinuous, more landward dipping reflections with tangential oblique configuration,
3. coastal dune (Cd) facies with small scale concave downward reflectors dipping in different directions with discontinuous bounding surfaces,
4. swale (Sw) facies with continuous horizontal or complex reflections present with convex downward bounding surfaces between two successive coastal dune / beach ridge units,
5. berm plain (Bp) facies with moderately continuous sub-parallel low amplitude reflections and
6. sand-sheet (Ss) facies with sharp bounding surface and low amplitude sub-parallel reflections.

The presence of a beach ridge facies at a depth of 2 m in all the profiles is an indication of a prominent beach ridge dune complex existing below the present day coastal configuration. Beach ridges are defined as relict, semi-parallel, multiple, wave and wind-built landforms that originated in the intertidal or supratidal zones; the outermost and still active wave-built ridge is termed as berm ridge (Otvos, 2000). The beach ridge facies in the present study is characterized by sub horizontal, parallel, gently seaward dipping and concave downward landward dipping reflections. The gently seaward dipping reflections are indicative of accretion by beach processes (i.e. wave activity), whereas the landward dipping concave downward reflections are indicative of sediments deposited during high tide surge and/or eolian transport, which is a common process in coastal environments (Collinson and Thompson, 1989; Bennett et al., 2009). The GPR profile and surface expression of amalgamated beach ridges outlined by linear swales have confirmed the progradation history of Modwa spit as suggested previously (Maurya et al., 2008). The studies on the textural and mineralogical characteristics of southwest Kachchh coast have also deduced that the sediment supply to this Modwa spit is primarily from fluvial systems of Kachchh which debouch west of study area (i.e. Naira, Kankawati, Kharod and Rukmawati rivers) and their sediments are redistributed by the longshore currents and monsoonal winds (Prizomwala et al., 2010).

The presence of washover units exhibiting discontinuous, more landward dipping reflections with tangential oblique configuration has been reported from all the profiles. They are mostly linked with sediments being eroded from subtidal / intertidal regions and deposited more landwards on account of high tide aided with storms and/or high energy events like storms, tsunamis, etc. (Reineck and Singh, 1980; Neal et al., 2003). There have been a number of studies on washover deposits in recent times, as they serve as geological records of past high energy events along a coast and can be used to reconstruct their cyclicity (Neal et al., 2003; Switzer et al., 2006; Wang and Horwitz, 2007; Bennett et al., 2009; Garrison et al., 2010). Their conspicuous presence in all the profiles is an indication that the Kachchh coast has remained prone to high energy events since recent past.

The Kachchh coast is situated in arid region with an average wind speed of 15 $km.hr^{-1}$ and hence eolian activity is a continuous process. Coastal dunes normally exhibit a cross bedded internal architecture (Reineck and Singh, 1980), which is very evidenced by coastal dune facies A number of studies have also documented the internal architecture and processes acting in dune fields in a coastal configuration employing the GPR technique (Bristow et al., 2000; Havholm et al., 2004; Bristow and Pucillo, 2006). The stacked nature of the dune facies (Cd_1, Cd_2. Cd_5), which have been observed in Figure 4.11 is an indication that conditions similar to the present day existed in recent past.

The understanding of morphodynamic evolution of a coastline is based upon knowledge of evolutionary history of different landform assemblages in recent past. In the present study as outlined by the GPR profiles, on the seaward side the stacked nature of berm plain facies and coastal dune facies overlying the beach ridge facies point out towards transgressive coastal landform assemblage. Similar studies on beach ridge systems from other parts of the world have showcased its significance in better understanding the past sea level stands and temporal evolution of the coastal configuration (Costas et al., 2006; Bennett et al., 2009; Clemmensen and Nielsen, 2010).

5

Sedimentology

Sediments texture and composition

The sediments received by a sink manifest the geological history since their derivation from the pre-existing rocks in the provenance to their transportation in various energy mediums and post depositional modifications under the influence of the physicochemical environment of the sink itself (Allen, 2008). Thus, the sedimentological studies, especially for the sediment texture and composition, shed light on its journey through the space and time which inturn explains the geological dynamics involved in shaping the landscape from which this sediments are drawn. Sediment transport processes are quite complex in the shore zones of macrotidal regimes like the Gulf of Kachchh due to its high tidal range (Alexander et al., 1991; Kuehl et al., 1996; Hequette et al., 2008; Webster and Ford, 2010). In such cases the coastal zone receives sediments from both, offshore and onshore regions which get mixed differently in different parts under the influence of local constrains like shore line configuration, fresh water inflow, local gradient, wind speed and direction, etc. Present chapter deals with the methodology and results of texture and composition studies of coastal surface and shallow subsurface sediment samples drawn from various micro-environments that provide transport avenues and sub sinks to these sediments before their ultimate deposition.

SAMPLING

The Kachchh coastline is characterized by dunes, beach ridges, berm plain and beaches in its western part between Jakhau and Mandvi and by monotonous wide mudflats in the eastern side. Surface samples were collected from all these microenvironments by taking 3 cm thickness below 1 cm surface skin. Apart from the surface samples, shallow subsurface sampling was also employed at selected sites (Figure 5.1). For the purpose about 1 m deep pits were dug and sampled at 2 to 5 cm intervals depending upon the physical variations observed. Additional half a meter depth was sampled by inserting 75 mm diameter PVC pipes (Figure 5.2b).

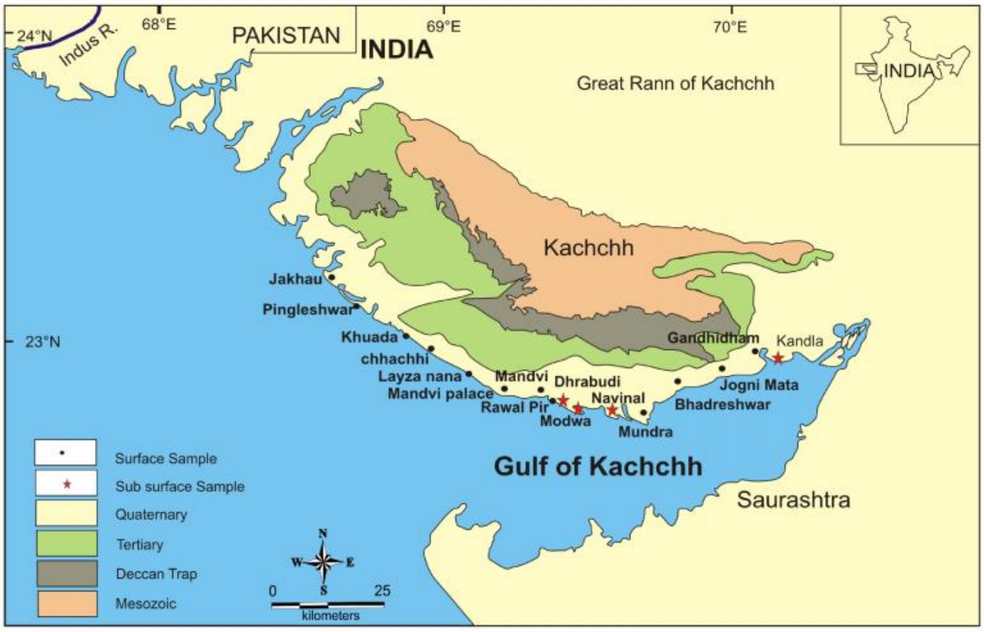


Figure 5.1: Map showing various sample location from study area.

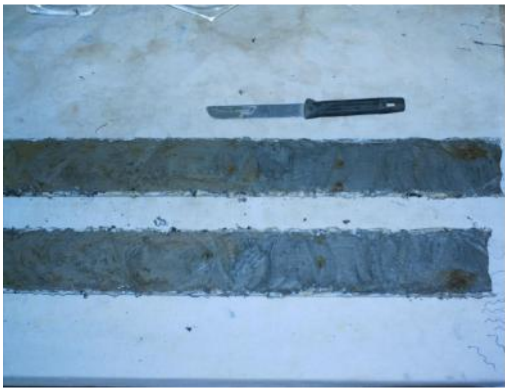
(a)

(b)

(c)

(d)

(e)



(f)

Figure 5.2: Photograph showing (a) 1m pit in palaeomudflat unit, (b) >1m sample collection through PVC pipe in same pit, (c) sampling from intertidal through PVC pipe, (d) sampling pit on sandy unit, (e) cutting of PVC pipe in lab and (f) Splitting and slicing of core.

In mudflat intertidal areas the pipes were inserted from the surface as digging was not possible. This has reduced the sampling depth. The pipe cores were brought to the laboratory and were splitted and sliced at 2 cm interval. The samples thus obtained were preserved in food grade plastic bags for grain size and mineralogy analyses.

GRAIN SIZE ANALYSIS

Two distinct types of sediments viz., (i) sandy and (ii) muddy, constitute various geomorphic units in the study area. Standard procedures for the grain size analysis of these classes of sediments are different. The sediments having more than 50% of particles having >63 micron size were analyzed using mechanical sieving method whereas, those with dominant composition of particles finer than 63 microns were subjected to the pipette analysis (Folk, 1974).

Mechanical sieving

About 50 gm of sample was subjected to the mechanical sieving after homogenisation of the sample collected from field. For this purpose 'coning and quartering' method was used. A standard ASTM sieve set ranging from 10 ASTM (>2mm) to 230 ASTM (<0.063mm) was used. The sieves were arranged on mechanical sieve shaker in decreasing sieve size from top to bottom with a pan at the base. The analysis was done with half phi size interval to study the grain size variations at a moderate resolution. After keeping the homogenised sample in the top most sieve, the sieve shaker was turned on for 20 minutes and then the weight retained in each sieve was measured using digital weighing machine with two decimal accuracy. Different statistical parameters like Mean, Median, Standard Deviation, Skewness, and Kurtosis were calculated following Folk (1974).

As described before, the western coast of the study area consists of geomorphic units which are in general sand built. These include coastal dunes, berm plain, berm and intertidal micro-environments. Therefore, these sediments were analysed using mechanical sieving technique and the statistical parameter like mean, median, standard deviation, skewness and kurtosis are listed in Table 5.1.

Table 5.1: Grain size parameters of sediments from different micro-environments of the sandy units from western part of the study area.

Micro environment	Location	Mean	Standard Deviation	Skewness	Kurtosis
Dune	Pingleshwar	0.79	0.6	0.2	1.06
	Khuada	1.86	0.55	0.14	0.94
	Chhachhi	0.97	0.8	0.31	1.03
	Layza nana	2.44	0.46	-0.08	1.38
	Mandvi	1.96	0.58	-0.07	0.91
	Rawal Pir	1.35	0.83	0.1	0.81
Berm Plain	Pingleshwar	0.73	0.76	0.05	1.16
	Khuada	1.84	0.56	0.13	0.95
	Chhachhi	0.51	0.64	0.05	1.47
	Layza nana	1.51	0.95	-0.04	0.71
	Mandvi	1.14	1.19	0.33	0.92
	Rawal Pir	1.14	0.8	0.26	0.89
Berm	Pingleshwar	0.75	0.66	0.18	1.16
	Khuada	1.84	0.56	0.13	0.95
	Chhachhi	1.37	0.67	0.0	1.07
	Layza nana	2.54	0.32	0.11	1.22
	Mandvi	1.9	0.61	0.0	0.93
	Rawal Pir	0.62	1.04	0.22	1.11
Intertidal	Pingleshwar	0.9	0.68	-0.05	0.98
	Khuada	1.04	0.57	0.04	0.91
	Chhachhi	1.01	0.71	-0.15	1.0
	Layza nana	1.93	0.76	-0.25	1.11
	Mandvi	2.01	0.81	-0.44	1.26
	Rawal Pir	1.69	0.91	-0.27	0.66

The findings show that the intertidal and dune micro-environments have a finer grain size in comparison with the berm and berm plain, and the berm plain has the coarsest size fraction amongst all. The mean grain-size range between 0.5 and 2.5 phi. Fining of grains size can be seen eastward, from mean value of 0.5 to 1 phi at Pingleshwar which is situated at the western end, it remain 1 to 2 phi value at the Raval Pir near Mandvi that defines eastern end of the sandy segment. The intertidal area is the most active microenvironment in the coastal configuration for sediment transport and sediment supply. The accretion of sediments in the berm plain is mostly caused by spring high tides or storms that deposit large amount of sediments in the supratidal regions, whereas the dunes get their sediment supply due to aeolian action that does winnowing of the exposed sediments in the intertidal, berm, and berm plain areas making it coarser.

A pit was also dug for 2m depth in a berm plain to see composition of shallow subsurface sandy segment on Dhrabudi coast (Figure 5.2d). The depth profile indicates in general fining upward nature and the surface profile reflects the coarsening along high water line. Following (Table 5.2) are the results of grainsize analysis of samples drawn from this pit.

Table 5.2: Textural variation along depth profile of Dhrabudi sand pit.

Depth	Mean	Standard deviation	Skewness	Kurtosis
0-5	1.27	0.83	0.21	0.82
5-10	1.28	0.83	0.20	0.77
10-15	1.17	0.91	0.36	0.79
15-20	0.97	0.78	0.32	1.07
20-25	0.72	0.96	0.44	0.84
25-30	0.62	0.89	0.40	0.85

30-35	0.72	0.92	0.40	0.84
35-40	1.15	0.71	0.20	1.03
40-45	0.66	0.89	0.39	0.85
45-50	0.98	1.05	0.18	0.82
50-55	0.37	1.35	0.40	0.74
55-60	0.65	1.09	0.22	0.96
60-65	0.52	1.19	0.37	0.83
65-70	0.78	0.86	0.24	1.17
70-75	1.07	1.14	-0.13	0.69
75-80	0.56	0.54	0.27	1.26
80-85	0.57	0.62	0.33	1.41
85-90	0.25	0.69	0.36	1.56
90-95	0.59	1.19	0.38	0.77
95-100	0.73	1.11	0.21	0.88
100-105	0.58	1.27	0.31	0.65
105-110	0.65	1.11	0.43	0.69
110-115	0.63	1.13	0.35	0.75
115-120	-0.25	0.78	0.17	1.27
120-125	0.21	1.14	0.35	1.36
125-130	0.72	1.11	0.34	0.71
130-135	0.07	1.16	0.60	1.44
135-140	-0.09	1.04	0.44	1.52
140-145	0.01	1.00	0.36	1.46
145-150	-0.03	1.08	0.43	1.45
150-155	0.69	1.17	0.44	0.76
155-160	1.03	1.27	-0.07	0.64
160-165	0.30	1.55	0.33	0.57
165-170	-0.02	1.23	0.35	1.92
170-175	-0.45	0.69	0.35	2.03
175-180	-0.44	1.06	0.30	1.72
180-185	-0.76	0.95	0.27	2.21
185-190	0.37	0.99	-0.01	1.81

At Dhrabudi station additional 24 surface samples were collected at 5m interval along a shore normal profile that started from low water line towards the backshore dunes. Table 5.3 presents the grain size parameters calculated for these samples. These data are further discussed in the next chapter to understand sedimentation processes in the study area.

Table 5.3: Textural variation along surface beach profile of Dhrabudi coast.

S. No.	Distance	Mean	Standard Deviation	Skewness	Kurtosis
1	0-5	1.12	0.78	0.28	1.01
2	5-10	1.16	0.80	0.26	0.92
3	10-15	1.26	0.65	0.47	0.89
4	15-20	1.07	0.88	0.33	0.86
5	20-25	1.10	0.79	0.23	0.96
6	25-30	1.32	0.89	0.27	0.91
7	30-35	1.23	0.85	0.21	0.81
8	35-40	1.35	0.71	0.15	0.84
9	40-45	1.26	0.73	0.14	0.90
10	45-50	1.08	0.90	0.21	0.95
11	50-55	0.85	1.00	0.28	0.92
12	55-60	0.80	0.96	0.19	1.11
13	60-65	1.09	1.03	4.16	0.75
14	65-70	0.68	1.19	0.41	0.91
15	70-75	0.52	1.33	0.42	0.74
16	75-80	-0.48	1.13	6.09	1.56
17	80-85	1.09	1.61	-0.53	0.64
18	85-90	0.15	1.55	-6.06	1.14
19	90-95	0.35	1.45	0.23	1.20
20	95-100	0.61	1.46	0.29	0.68
21	100-105	1.77	1.19	-0.54	1.49
22	105-110	2.31	0.73	-0.28	2.06

Pipette Analysis

Inexpensive size analysis of sediment containing significant fines is most satisfactorily achieved by the use of the pipette method (Krumbein and Pettijohn, 1938; Galehouse, 1971; Folk, 1974). This technique relies on the fact that in a dilute suspension, particles settle through a column of water at velocities which are dependent upon their size. If a material behaves according to Stokes' Law then, by repeatedly sampling at a fixed depth below the surface progressively finer and finer sediments are present at the sampling depth. Temporal variations of solid concentrations at that level indicate the relative abundance of particles whose diameters may be calculated.

The sample was initially sun dried for few days till it gets completely dry. The dried sample was weighed to about 10 gm of weight and taken in a 1 litre borosil glass beaker which was filled up with distilled water and kept undisturbed for 24 hours. After the settling of sample at bottom, the beaker was emptied to half of its volume carefully, without disturbing the sample which is settled at bottom. Same procedure was followed another day by filling up the beaker by distilled water and keeping it for again next 24hrs. Next day the water was drained as much as possible, by taking care that sample is still remaining in beaker. About 5ml of 30%W/V H_2O_2 (Hydrogen peroxide) was added to the sample for removal of organic matter and again the beaker was kept undisturbed for about 24hrs. Clay has cohesive properties and hence it forms aggregates when saturated, therefore 10 ml of known concentration (44gm/100ml) sodium hexa-meta-phosphate solution was added as a dispersant. After adding the dispersant the sample was again kept for 24 hrs. The concentration of dispersant solution should be known to obtain the weight correction factor to finally estimate the clay %.

Next day the sample was passed through 230 ASTM sieve and collected in a cylinder of 1 litre capacity. The sample retained in the sieve was dried and weighed to estimate the sand fraction whereas, sample collected in the cylinder represents silt and clay fraction. The cylinder was then filled up with distilled water till 1 litre mark and agitated vigorously till the entire amount of sample comes in suspension. Using a pipette 10 ml of volume of solution was withdrawn from the top 10 cm depth of cylinder and taken in a dry (pre-weighed) petridish. It was kept for drying in electric oven for 24 hrs at 50°C. As the viscosity of medium is temperature dependent and settling velocity is viscosity dependent, temperature at which the pipette analysis is done decides the time of the withdrawal of clay solution by pipette after its homogenisation in the cylinder. Folk (1974) has suggested specific time of the withdrawal for different temperature values of experiment (Table 5.4).

Table 5.4: Suggested temperature and pipetting time for clay separation (After Folk, 1974)

Temperature	Time interval
For 28 degree C	1H:42M:45S
For 29 degree C	1H:40M:13S
For 30 degree C	1H:37M:42S
For 31 degree C	1H:35M:15S
For 32 degree C	1H:33M:51S

The present study was carried out as per this guideline. The calculation of clay fraction percentage was done using the following equation.

Clay % = (A - B) x KD

Where,

A = weight in grams of dried pipette fraction
B = weight correction for dispersing agent
K = 1000/(volume contained in pipette)
D = 100/(initial oven dry weight of sample)

Now subtracting the weight percentages of sand and clay fraction from 100 would give the silt percentage in the sample.

The surface samples collected from various locations in the mudflat areas of Kachchh coast were analysed for sand, silt and clay proportions using the above described pipette technique. Table 5.5 enlist these values.

Table 5.5: Sand, silt and clay percentage in the surface sediments from intertidal.

Sample Station	Sand	Silt	Clay
Jakhau	15	72	13
Pingleshwar	99	0.4	0.6
Khuada	99	0.2	0.8
Chachi	98	0.6	1.4
Layza nana	98.4	0.4	1.2
Mandvi Palace	97	1.2	1.8
Mandvi	94.6	1.3	4.1
Rawal Pir	97.9	0.9	1.2
Navinal	7.1	61.46	31.44
Mundra	14.31	60.88	24.88
Bhadreshwar	61.11	33.93	4.95
Jogni Mata	1.97	62.23	35.79
Gandhidham	24.92	58.76	16.32
Kandla	11.49	63.78	24.73

Three shallow cores of about 1 to 1.5 m were raised from the intertidal zone of Modwa, Navinal and Kandla areas. Table 5.6 contains the results of pipette analysis of samples sliced at 5 cm interval from these shallow cores. The dataset pertaining to the textural analysis of sandy and muddy geomorphic units are discussed at length in the next chapter.

Table 5.6: Variation in sand, silt and clay percentage in the shallow subsurface samples from mudflat area.

S. No.	Sample no	Depth	Sand	Silt	Clay
Modwa					
1	M-1	0-5	4.3	71.46	24.24
2	M-2	5-10	2	55.6	42.4
3	M-3	10-15	1.9	52.37	45.73
4	M-4	15-20	2.4	39.5	58.1
5	M-5	20-25	3.4	34.34	62.26
6	M-6	25-30	3.7	42.9	53.4
7	M-7	30-35	4.7	52	43.3
8	M-8	35-40	3.9	52.6	43.5

9	M-9	40-45	5.1	46.9	48
10	M-10	45-50	6.2	63.1	30.7
11	M-11	50-55	5.7	59.6	34.7
12	M-12	55-60	7.1	54.9	38
13	M-13	60-65	8	58.7	33.3
14	M-14	65-70	7	55.7	37.3
15	M-15	70-75	8.4	56.9	34.7
16	M-16	75-80	5.7	61	33.3
17	M-17	80-85	9.2	61.5	29.3
18	M-18	85-90	6.2	61.1	32.7
19	M-19	90-95	9.5	53.2	37.3
20	M-20	95-100	8.5	63.5	28
21	M-21	100-105	1.9	52.1	46
22	M-22	105-110	2.3	56.4	41.3
23	M-23	110-115	1.2	36.8	62
24	M-24	115-120	1.8	82.2	16
25	M-25	120-125	1.6	60.4	38
26	M-26	125-130	1.7	55	43.3
27	M-27	130-135	2.1	61.2	36.7
28	M-28	135-140	1.8	54.9	43.3
29	M-29	140-145	0.9	51.1	48
30	M-30	145-150	0.8	38.5	60.7
31	M-31	150-155	3.3	92.6	4.1
32	N-1	0-5	2.5	64.7	32.8
Navinal					
33	N-2	5-10	2.1	67.78	30.12
34	N-3	10-15	2.2	53.8	44
35	N-4	15-20	2.5	53.02	44.48
36	N-5	20-25	5.6	70.92	23.48
37	N-6	25-30	6.2	65.4	28.4
38	N-7	30-35	19.4	52.56	28.04
39	N-8	35-40	2.9	58.06	39.04
40	N-9	40-45	2.8	56.2	41
41	N-10	45-50	13.8	54.2	32
42	N-11	50-55	1.1	80.3	18.6
43	N-12	55-60	7.1	61.46	31.44
Kandla					
44	K-1	0-5	2.9	51.9	37.3
45	K-2	5-10	1.8	54.7	35.5
46	K-3	10-15	3.6	49.4	38.8
47	K-4	15-20	1.9	49.2	40.6

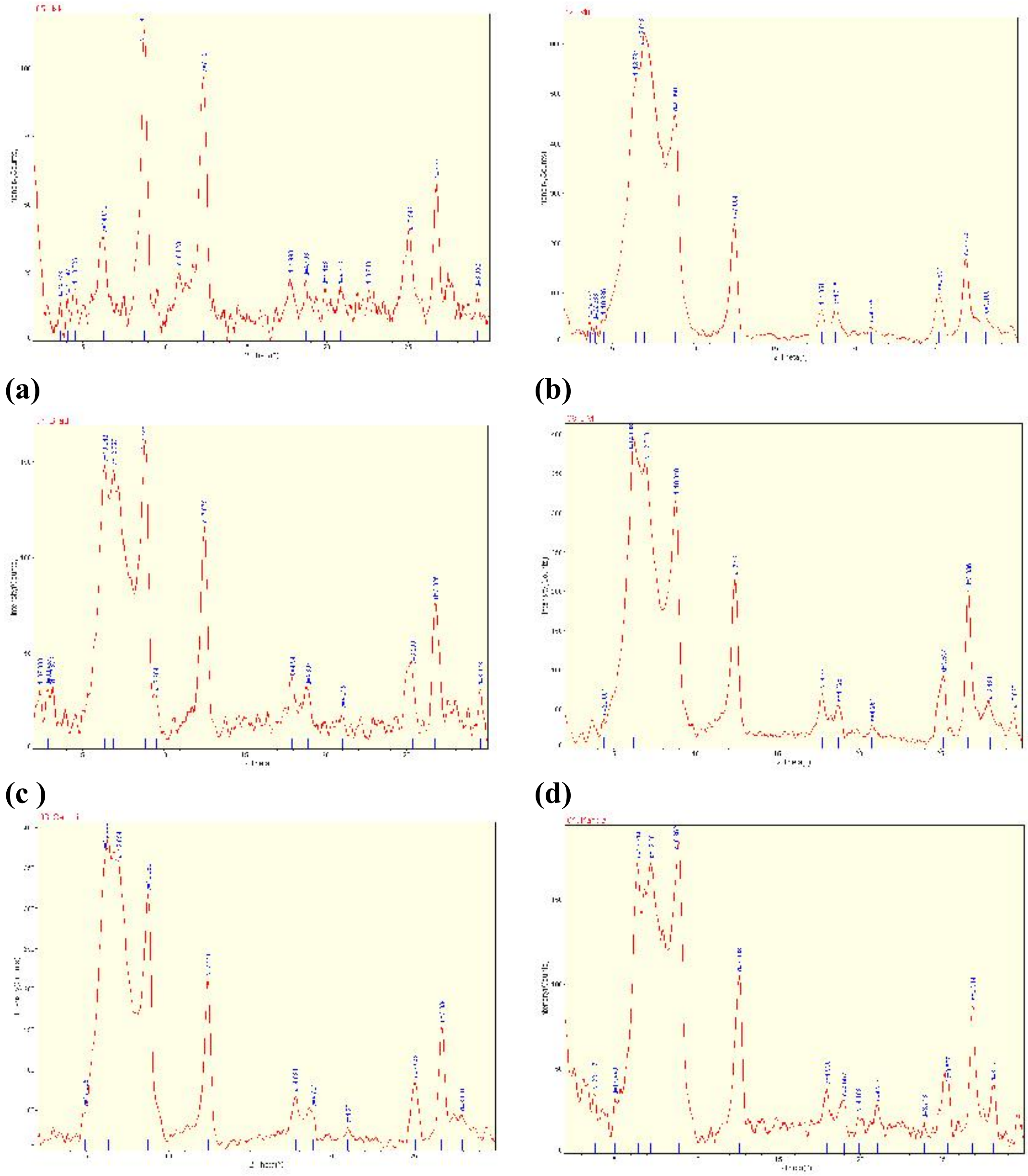
48	K-5	20-25	1.1	49.5	40.7
49	K-6	25-30	2.1	46.1	43.9
50	K-7	30-35	1.7	46.3	42.6
51	K-8	35-40	11.7	50.7	37.6
52	K-9	40-45	11.1	53.5	44.8
53	K-10	45-50	10	49.7	48.2
54	K-11	50-55	9.8	57.9	41
55	K-12	55-60	10.2	57.3	40.8
56	K-13	60-65	11.8	52.2	44.2
57	K-14	65-70	9.8	55.4	42.8
58	K-15	70-75	10.8	59.4	37.7

CLAY MINERALOGY

The clay samples were extracted from the settling cylinder of pipette analysis along with the pipetting for grain size analysis. The aliquot was concentrated by centrifuging the sample. The glass slides were kept at an inclination of 1-2 degree and few drops of concentrated clay aliquot were slowly released with the help of a dropper. The aliquot slowly spread over the slide making a thin uniform layer over it. The slides were allowed to get dry by normal evaporation. Each sample was prepared in triplets.

The X-Ray Diffraction analysis of thus prepared oriented clay slides was done using Rigaku's Ultima-II automatic XRD machine at ONGC Ltd, western Onshore, Vadodara. Few samples were analysed at the Wadia Institute of Himalayan Geology, Dehradun. The XRD was run between 2° to 45° 2θ goniometer angle at step size of 0.005 (relative speed). The identification was carried out following basal peak reflections (Biscaye, 1965; Petschick et al., 1996). Specimens were exposed to glycolation treatment using ethylene glycol for 12 hrs. XRD test after glycolation was used for the confirmation of swelling clays like smectites (e.g. montmorillonite, nontronite, and beidellite), some mixed-layer clays, and vermiculite. Ethylene glycol was poured to 1 cm depth in the desiccator. Oriented clay slides were placed on the shelf of desiccator. Desiccator was placed in oven at 60 to 70°C for overnight. Samples were used for X-ray diffractometry as soon as they were removed from the desiccator. Also some selective samples were heated at 550°C and run for same setting to confirm the presence of kaolinite and chlorite (after heating at 550°C kaolinite converts to metakaolinite which is amorphous and hence, doesn't show any diffraction pattern). Heating at various temperatures is commonly used to help identify clay minerals by revealing changes in crystal structure spacing or loss of the structure. Depending on the temperature and the mineral species, these treatments can collapse the structure by dehydration. Furnace was preheated to 550°C and the slides were placed in the furnace. Furnace was switched off precisely after half an hour. Samples were removed from the furnace and taken for XRD analysis after they gained the room temperature. These heated samples were scanned from 24° to 26° 2θ value at 0.5° 2θ min^{-1} speed to differentiate kaolinite and chlorite peaks (Biscaye 1965).

The d-spacing and 2θ values from XRD plots have indicated presence of clay minerals like smectite, illite and kaolinite/chlorite (Figure 5.3). The presence of montmorillonite belonging to the smectite group was confirmed by XRD analysis after its treatment with ethylene glycol, as after glycolation the peak intensity has increased and is shifted towards lesser 2θ angle. The next peak is that of illite characterized by a more intense peak at 10 Å (at 8° 2θ) and a less intense peak at 5.03 Å 002 (at 18° 2θ) and 3.35 Å (at 26° 2θ). Illite shows almost reverse trend compared to the montmorillonite. Illite is essentially a group name for non-expanding, clay-sized, dioctahedral micaceous minerals. It is structurally similar to muscovite, as that its basic unit is a layer composed of two inward pointing silica tetragonal sheets with a central octahedral sheet. Illite clay is a weathering product of alkaline rocks. However, the hinterland of Kachchh does not constitute major exposure of any alkaline rock, and therefore there are negligible chances of this mineral getting derived from the Kachchh provenance. Third major clay mineral present is kaolinite which is confirmed by heating the sample at 500° C for ½ hour. Two distinct peaks of 7.18 Å (at 12.5° 2θ) and of 3.58 Å, (at 12.5° 2θ) could be seen in untreated samples. The peak of kaolinite gets destroyed after heating at 550°C. Relative abundances of the clay minerals were calculated from the ratios of intensities (areas) of peaks from minerals of the untreated sample. In principle the peak intensity is associated with the number density of each emitting species in the plume and this, in turn is associated with the concentration of specific elements in the ablated material. This principle has been used to calculate relative abundance of montmorillonite, kaolinite and illite in the samples from various ranges (Table 5.7). Five samples collected from 0 to 25cm depth (at 5cm interval) of the pit at Modwa were also analysed for its clay mineralogy (Table 5.8). Interestingly the peak of montmorillonite could not be seen in these samples. Instead a prominent peak of quartz has been obtained which must be representing the clay size quartz present in the sediments. This dataset was compared with the clay mineralogy data of subsurface samples from other stations along the Gulf of Kachchh coast to discuss about sediment dispersal system of the gulf by Prizomwala et al. (2010).



(a) **(b)** **(c)** **(d)** **(e)** **(f)**

Figure 5.3: Sample XRD plots of the clay slides from study area. (a) Jakhau, (b) Mundra (c) Bhadreshwar, (d) Jogni Mata (e) Gandhidham, (f) Kandla

Table 5.7: Relative abundance of various clay minerals in the surface sediments from mudflats of Kachchh coast.

Sample Station	Illite	Chlorite	Montmorillonite	Kaolinite
Jakhau	46.2	20.6	7.7	25.5
Mundra	41.8	18.7	26.5	13
Bhadreshwar	44.8	18.7	26.5	13
Jognimata	32.6	11	48.2	8.2
Gandhidham	34.7	18.8	42	4.5
Kandla	44.2	20.4	30.4	5

Table 5.8: Relative percentage of illite, chlorite, kaolinite and quartz in the Modwa shallow subsurface sample.

Sample number	Illite	Chlorite	Kaolinite	Quartz
M-1	40.17	39.03	0	20.76
M-2	33.04	48.78	0	18.15
M-3	42.75	40.45	0	16.8
M-4	37.98	27.82	10.99	22.7
M-5	34.77	38.85	9.28	10.12

HEAVY MINERAL ANALYSIS

Minerals having density more than 2.89gm.cm^{-3} are known as the heavy minerals. Such minerals are good tracers of the sediment provenance as they weather very slowly. Some of the heavy minerals like zircon, staurolite, sillimanite, kyanite are characteristic metamorphic minerals whereas like diopside, magnetite, olivine etc. are characteristically derived from the basic igneous rocks. The relative abundance of heavies can be used to understand the sediment pathways. Heavy mineral analysis of the sediments from the study area was performed on bulk samples collected from the intertidal micro-environment. These are mostly fine and medium grained sands. Heavy mineral separation was done from the bulk samples following standard conventional technique of density separation using the bromophorm that has a density value 2.89gm.cm^{-3} at 20^{o}C. The heavy minerals were separated by pouring 10 gm of sample in a standard 250 ml separatory funnel filled with the bromophorm. The settled grains were allowed to flow through a funnel lined with filter paper, by opening the stop cock. The grains collected on filter paper were dried and mounted on glass slide to examine them under petrological microscope. Tourmaline was identified due to its look as rounded grains or elongate crystal segments, its pleochroic, its colors ranging from pale brown to dark brown or nearly opaque. The staurolite shows characteristic pleochroic colors ranging from pale reddish brown to dark brown, and commonly contains many inclusions of magnetite. In general the staurolite grains are well rounded. Two types of zircon occur in the Kachchh coast, one being colorless and the other brownish. The colorless zircon occurs in small euhedral, only slightly abraded crystals, and also in well rounded grains. Muscovite and biotite are characterized by a platy flake shape and almost the same density.

Heavy mineral analysis of the surface sediment samples has suggested the presence of minerals like tourmaline, staurolite, zircon, sillimanite, biotite, muscovite and diopside. Table 5.9 shows the recorded relative concentration of heavy minerals in the sediment samples from various stations.

Table 5.9: Distribution of heavy minerals (in %) in intertidal micro-environment along the southwest Kachchh coast.

Location	**Tourmaline**	**Staurolite**	**Zircon**	**Sillimanite**	**Biotite**	**Muscovite**	**Diopside**	**Opaques**
Pingleshwar	12	10	4	2	19	14	0	39
Khuada	12	8	5	1	17	10	0	48
Chhachhi	3	3	1	0	15	8	10	60
Layza nana	3	2	1	1	14	9	16	54
Mandvipalace	2	1	0	0	15	9	18	55
Rawal Pir	2	0	0	0	12	7	21	58

6

Morphodynamic Evolution

Sediment response to dynamics

The latest chapter of the earth's history, the Quaternary Period that covers a time span of about last 2.6 million years (earlier 1.8My; Singhvi and Kale, 2008) has gained importance amongst the earth scientists due to its dramatic episodes and their relevance to the existence of human race. Rapid changes in the earth's temperature and resultant fluctuations in the sea level during this period remained a subject matter of investigation world over. Obviously the coastal areas are of utmost importance to appreciate such environmental changes due to its potential of recording it in the form of oscillations in the land-sea interface. The evolution of coastal landscape is out of a net response of the land to various erosional and depositional processes that tries to maintain equilibrium between sediment flux, energy domains and accommodation space; in the case of a coast relative sea level and local tectonics define such morphodynamic evolution (Carter and Woodroffe, 1994). To differentiate local tectonic effect from the climate driven change in the sea level one needs a reference curve known as the glacio-eustatic sea level curve. One widely referred sea level curve based on oxygen isotope studies of undisturbed marine sediments (foraminiferal tests) that could be translated to changes in the ocean water volume, is that of the Shackleton (1987; Figure 6.1). Accordingly, there occur at least five events of relatively higher sea level since ~350 kyr. These are termed as the Marine Isotope Stages (MIS) or Oxygen Isotope Stages indicated with odd numbers viz., MIS 1, MIS 3, MIS 5, MIS 7 and MIS 9. The stages indicated by even numbers represent intervening lower sea levels. Out of these, MIS 5 and MIS 1 had remained higher than the present sea level, while the MIS 2 represents latest significant lowering of sea level by about 110 m referred to as the Last Glacial Maxima (LGM). The global rise in the sea level, which accompanied the melting of great ice sheets of the last glacial episode, started ca. 14.5 kyr BP and continued with minor oscillations till the present sea level was reached. Mainly, there exists three views on the sea-level changes during the last 10 kyr viz., (i) the sea level underwent relatively large and repeated fluctuation from 1.5 m below to 3 m above the present level (Fairbridge, 1961); (ii) the sea-level has been lower than the present but, has maintained a continuous rising trend with an ever decreasing amplitude, before reaching its present level (Shepard, 1964), and (iii) the sea-level rose above the present level at about 5 kyr BP and oscillated between 2 m above and the present level (Baker and Haworth, 2000). However, for the Holocene (<11.5 kyr) time there is no general agreement for a global sea level curve (Pirazzoli, 1991). Therefore, region specific sea level curves should be referred to and such popularly accepted curves for Indian coast are presented by Kale and Rajaguru (1985) and Hashimi et al. (1995) which are presented in Figure 6.2. with some additional data points from Saurashtra, an adjacent region to the study area.

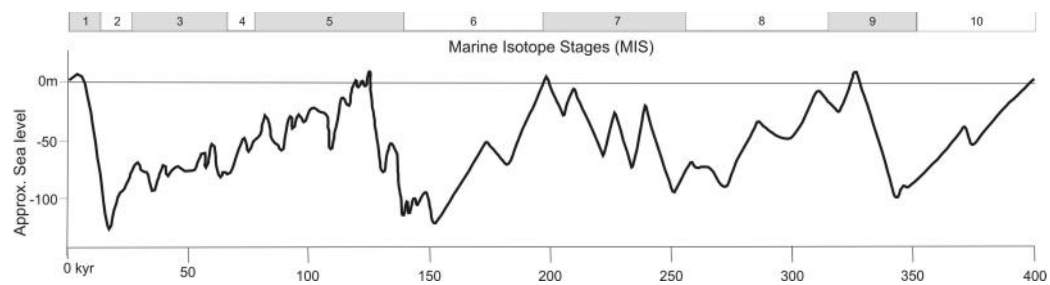


Figure 6.1: Global sea level curve and marine isotope stages after Shackleton (1987).

The studies of Quaternary geological records in coastal areas of the Gujarat State have mainly remained focused on the carbonate deposits occurring all along the Saurashtra coast, famous among earth-scientists as the 'miliolitic limestone' or the 'Miliolite Formation' for its direct relevance to the Quaternary sea level changes and climatic fluctuations (Gupta and Amin, 1974; Brückner et al., 1987; Patel 1991; Juyal et al., 1995; Bhatt and Patel, 1998; Mathur and Pandey, 2002; Mathur, 2005; Bhatt and Bhonde, 2006).

In comparison, the Quaternary sediments from Kachchh have gained lesser attention. Although, the miliolitic limestone have been dated to range from 37 to 140 kyr from Kachchh using Uranium disequilibrium technique (Baskaran et al., 1989; Chakraborty et al., 1993). The miliolitic limestones of Kachchh are in general aeolian deposition on the hill slopes and fluvial reworking in the valleys; a conspicuous absence of coastal miliolitic limestone is noticeable (Patel and Allahabadi, 1988; Bhatt, 2003).

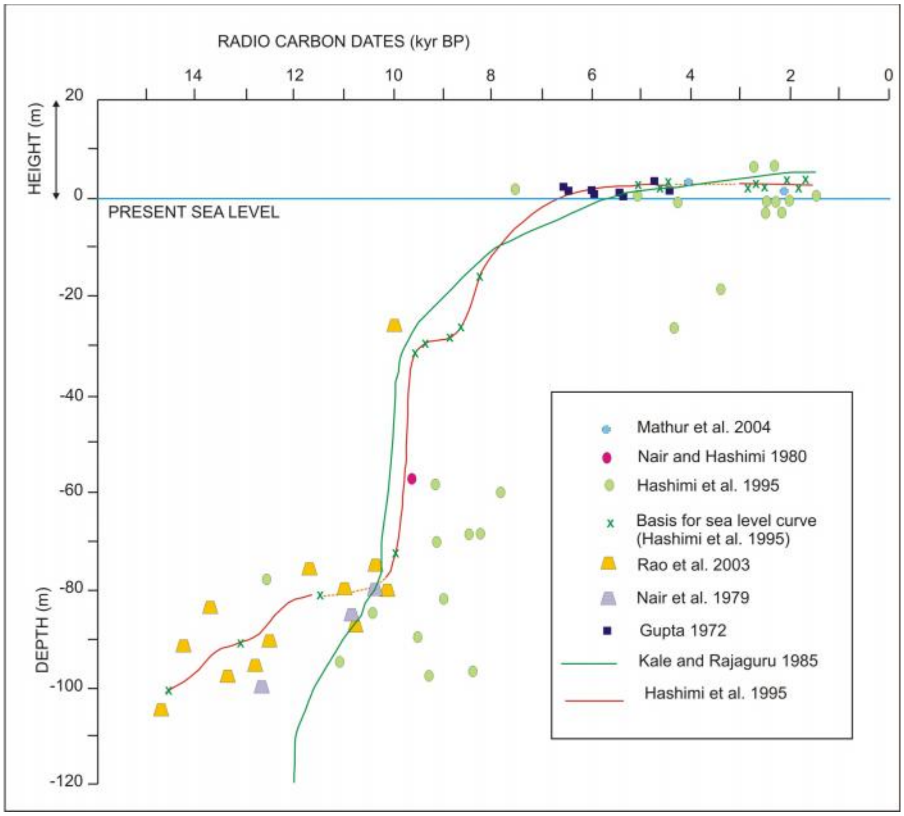


Figure 6.2: Holocene sea level curve for western Indian continental margin with added data points from recent studies (After Kale and Rajaguru, 1985; Hashimi et al, 1995).

Recently Maurya et al. (2003a & b) presented a detail account of coastal Quaternary sediments with some radiocarbon ages of calcretes formed due to the pedogensis in fluvial sediments of Rukmavati, Naira and Nagwanti rivers of the coastal alluvial plain of south Kachchh. The fluvial sequence of the coastal plain of Kachchh consists planar cross-bedded gravels, sandy gravels, cross-stratified sand and silt with a red to brown coloured palaeosol from where the pedogenic calcretes have been dated (18.9 to 24.3 kyr BP) to suggest pre-LGM fluvial activities and weakening of the same (as indicated by pedogenesis) close to the LGM (Maurya et al., 2003). However, the coastal geomorphology of the Kachchh especially the ancient mudflats and raised beaches have been discussed by previous workers with tentative chronology linking them to about 6 to 2 kyr sea levels but, relating their disposition to the tectonic uplift (Kar, 1993; Maurya et al., 2008; Patel and Desai, 2009). The review of available studies on geomorphology of the Kachchh coast suggests the followings.

1. Based on geomorphology the Kachchh coast is divisible in to distinct segments like deltaic coast, irregular coast, straight coast, spit and cuspate coast, and mudflat coast.
2. The western part of the coastline characterize drowned coast while towards east it appears as emergent coast with a presence of palaeo mudflats.
3. The Median High passing through Mandvi-Mundra area has controlled the two distinct domains on either side having sandy straight coast on its west and mudflat coast on its east.
4. The occurrence of abandoned cliffs amongst the tidal flats, moderate cliffs in the tertiary rocks, abandoned river mouths due to the mouth bar formation, fringing of mudflats by palaeo mudflats, etc. have been considered to be a manifestation of tectonic uplift in recent time.

The present author is of the opinion that all these features can also be explained in relation with the coastal sedimentary processes and the Holocene sea level history of the region. Particularly the occurrence of similar landforms at same elevation along the coast of Saurashtra and South Gujarat, and also some part of Maharashtra raises a question against such a simplistic interpretation (Merh, 1987; Patel, 1991; Mathur, 2004). The study discussed in the previous chapters is summarized in the following text to appreciate these. The dependable geochronology *albeit* can constrain the evolution history and can also identify the tectonic episodes more precisely. This part could not be attempted in the present study.

Coastal Landscape

Coastal areas are known to respond the sea level changes and sediment fluxes by the formation of unique landforms that include single to multiple terraces and lateral geomorphologic variations (Ramirez-Herrera and Urrutia-Fucugauchi, 1999). To see the reflection of neotectonics and sea level changes in various geomorphic landforms, coastal geomorphic study was attempted and discussed in detail in chapter 3. The Gulf of Kachchh is a macrotidal environment and its coast is characterized by sand composed geomorphic landforms like beaches and backshore dunes in its western or mouth areas that stretch between Jakhau and Bhada facing the wave dominant coast of the Arabian Sea whereas, wide mudflats occur in the eastern tide dominating part or head ward areas of the Gulf of Kachchh. The geomorphic assemblage indicates that the Bhada-Mundra segment of the study area acts as a transition zone between the sand rich coast in its west and the mud rich coast towards its east due to a mix wave and tide dominating nature of the coast. The amalgamated beach-ridge complex at Modwa is prograding along its eastern end. In continuation of its extent and orientation some distinct sand ridges can be seen surrounded by the active mudflats in this segment. These ridges are not receiving sand anymore, as the eastward progradation of the Modwa beach-ridge entraps the sediments transported by littoral drift. This has cut off the sand supply to these sand ridges. Some narrow chennier ridges however receive sand near low water line as the tidal waves carrying fine sand from the offshore shoals breaks here. Such abandoned sand ridges therefore indicate a change in sediment dynamics but, not necessary a tectonic uplift. The coast between Mundra and Kandla shows the presence of extensive mudflats which are about 1.5–2 km in width. The mudflats are silt and clay dominated landform that gradually becomes clay rich eastwards. The mudflats receive suspended sediments at slow but steady pace, which are not eroded after deposition due to their cohesive nature and currents of lower energy. Thus, they define a prominent ‘sink’ for the suspended sediments in the Gulf of Kachchh. Surface suspended sediment concentration in this head ward region of the Gulf of Kachchh reaches up to $443 mgl^{-1}$ (Ramaswamy et al. 2007). Thus, the Kachchh coast has three distinct energy domains from west to east that characteristically provide sub sinks to selected size fraction of sediments under transportation. This also partially sort out the sediments from two end provenance viz, Indus River and Kachchh hinterland. The sand dominating straight coast running between Pingleshwer and Layza has a narrow coastal zone that accommodates the sand size sediments derived from the Kachchh hinterland brought to the coast by the rivers like Nayra, Kharod, Rukmavati and debouched against a strong littoral drift.

Obviously the beaches, bermplain, foreshore and backshore dunes are repository of these sediments. Whereas, the suspended sediments manages to travel further to form the mudflats with decreasing effect of the tidal currents. On a gross look, similar conditions have prevailed on the Kachchh coast since Middle Holocene. Therefore, in the present study much emphasis has been given to understand the sediments and their dispersal system that finally shape out the coastal landscape.

GPR Studies

Recent advances in geophysical exploration techniques have made it possible to understand the shallow subsurface sedimentary architecture, especially in the sand bodies (Jol et al., 2002; Neal, 2004; Switzer et al., 2006; Lindhorst et al., 2008; Shukla et al., 2008; Bennett et al., 2009; Garrison et al., 2010). GPR studies were attempted in the study area and details are discussed in chapter 4.

GPR studies in Bhada-Mundra segment demonstrate recognition of various sedimentary reflectors that can be suitably interpreted as bounding surfaces and facies, manifesting a gross sedimentary architecture of the body. The study indicates major radar surfaces that delineate depositional facies, reflecting the dynamic nature of this beach ridge system. These bounding surfaces and radar facies delineate beach ridge (br), washover (wo), coastal dune (cd) and swale (sw) depositional facies. Similar facies have been identified by adopting the principles of radar stratigraphy in the coastal areas of England (Neal and Roberts 2001; Neal et al., 2002; 2003). The

GPR data and the surface expression of the amalgamated beach ridges, outlined by vegetated linear swales, confirm the progradation history of the Modwa beach.

The GPR profiles from the coastline of Kachchh show a presence of prominent beach ridge system at 2 – 3 m depth in the segment between Layza Nana and Modwa, which probably could be imprints of low stand of sea just before the Middle Holocene. Also the conspicuous presence of washover deposits from all the profiles point towards the high energy events (storm?) coeval to a transgressive phase whereas, the more inland presence of stabilized coastal dunes could be related to higher sea stands. After the LGM, the Gulf of Kachchh started getting inundated by ~15 kyr as inferred on basis of radiocarbon dates of dolomite crust and corals from the offshore (Rao et al., 2003). The global and regional sea level history of western India (Fairbank, 1989; Kale and Rajaguru, 1985; Hashimi et al., 1995) shows lower sea level then present in the Early Holocene. The beach ridge facies documented in present study would have acted as an active berm ridge / foreshore dune along the coastal configuration just before Middle Holocene high stand (Figure 6.3a). The sea level kept on rising and about 6 kyr BP it reached its peak with a high stand of 2 – 4 m above present day mean sea level (Hashimi et al., 1995; Rao et al., 1996; 2003). Owing to this high stand coastal dune building activity took place, which can be presently seen in the form of wide stabilized coastal dune field. Such stabilised dunes linked with higher sea level during this period are also reported from the Gujarat plains, Nal Sarovar-Bhal area and coastal Saurashtra (Patel, 1991; Prasad et al. 1997; Chamyal et al., 2003; Juyal et al., 2003). The period also witnessed seasonal high energy events along the Kachchh coastline, which have been documented in present study in the form of washover deposits and formation of swales in between successive foreshore dune ridges (Figure 6.3b). It is believed that after reaching the peak at 4 kyr BP the relative sea level started to recede and since 2 kyr BP the present day coastal setup had been established (Figure 6.3c). Tectonic uplift along the coastal segment have been cited as reason for sea level to fall rather than glacio-eustacy, owing to active tectonic setup of Kachchh . However, in absence of stratigraphically or geomorphologically constrained ages the present author refrain from concluding tectonic uplift in this study.

Sediment Texture and Composition

To examine the nature of sediments constituting various geomorphic units on the Kachchh coast, grain size and mineralogical analyses were done following standard laboratory procedure and the results of the same are presented in chapter 5.

The statistical parameters like skewness, kurtosis, standard deviation and mean of the sand dominated coarser than 63micron sediments from different sub environments were calculated and standard deviation values were plotted against the skewness values on standard discriminatory plots of Friedman (1967), which suggested that most of the samples correspond to riverine environment and very few to marine environment (Figure 6.4). This is supplementary to the inference that this segment acts as 'sub-sink' for coarse sediments which are mostly derived from hinterland rivers.

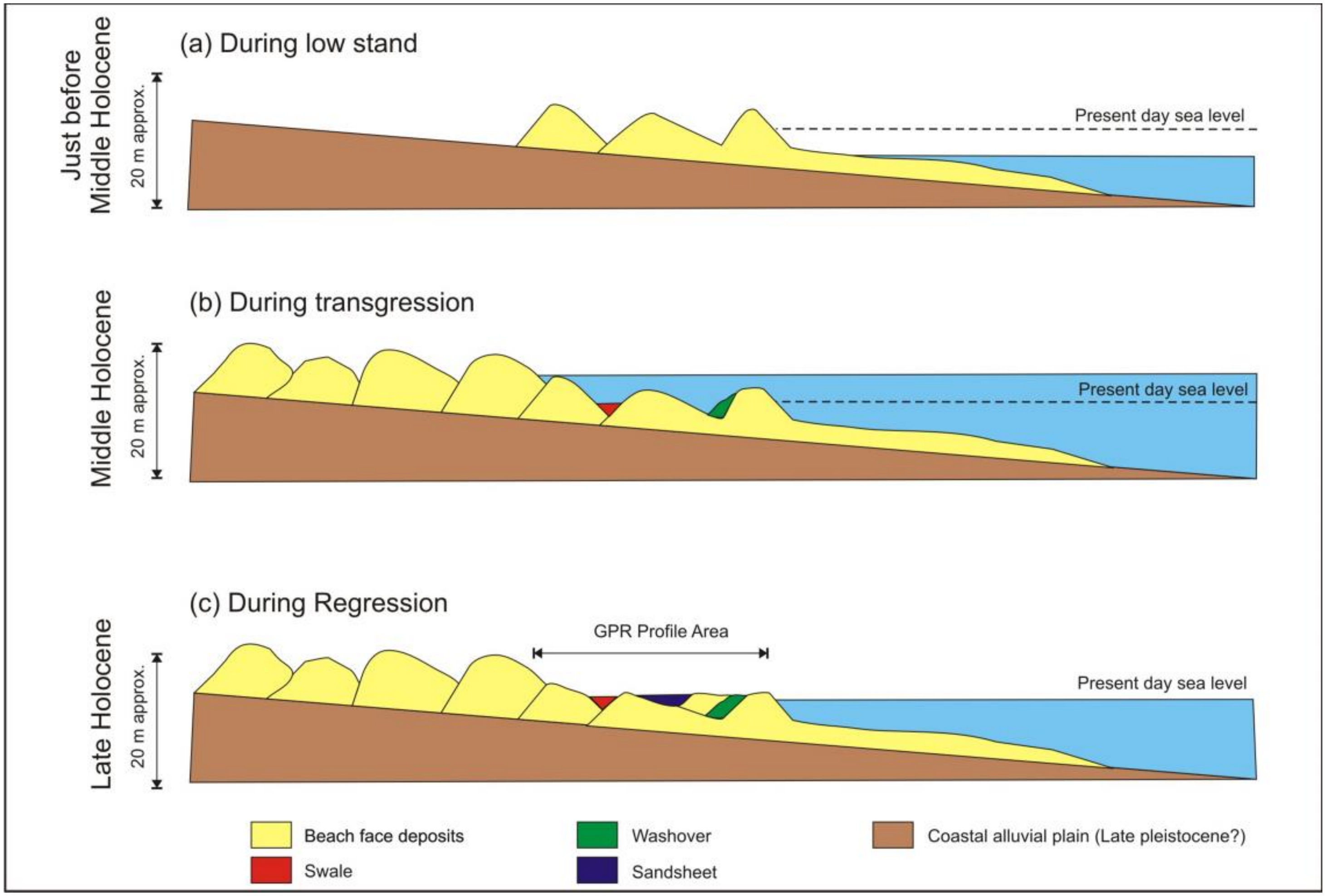


Figure 6.3: A schematic model of relative change in sea level and response of the sandy segment as inferred from GPR studies.

Geomorphologically, this stretch of coast consists of two major zones: the straight and sandy segment between Pingleshwar and Layza Nana and the transition zone from Layza Nana to Rawal Pir (Prizomwala et al., 2010). The result of the granulometric analysis shows the fining in sediments and the increase in standard deviation from the west toward the east (Figure 6.5).

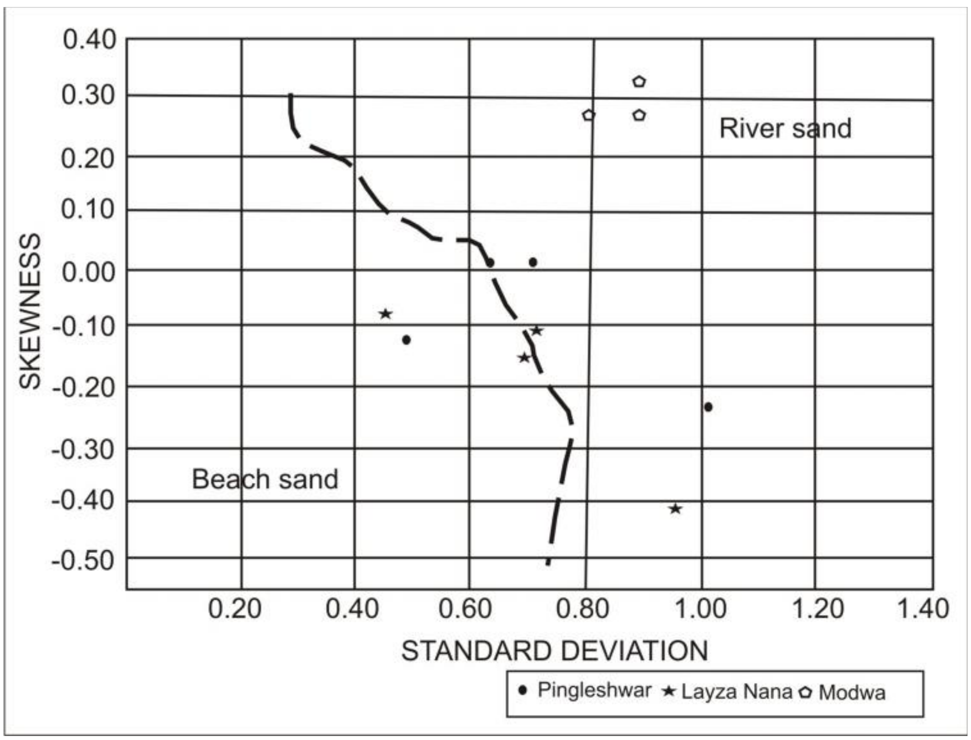
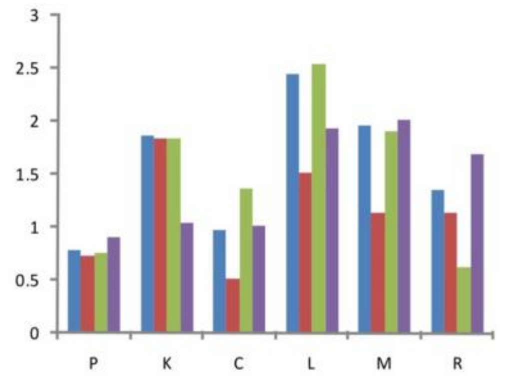


Figure 6.4: Discriminatory plot (Friedman, 1967) of sand samples from Kachchh coast indicating its derivation from river environment and a very less effect of marine transportation.

The Kurtosis values decrease from the west to the east, indicating increased bimodality in grain-size distribution, which is due to the mixing of varied sediment sizes transported in the longshore currents and supplied by the coastal rivers

(Kankawati, Kharod, Rukmawati, etc.). The increased negative skewness of the intertidal microenvironment is indicative of strong wave actions leading to fine sediments being washed away. The granulometric characteristics of the dune, berm plain, berm, and intertidal microenvironments are indicative of nearshore mixing and subordinate sorting of sediments supplied from two distinct sources viz., the distal Indus River mouth and the proximal Kachchh mainland.

Hitherto, it was thought that the River Indus was the only major source of sediment in the region because it is the region's only perennial river, and the Kachchh falls within arid/ hyperarid climatic regime (Chauhan, 1994; Chauhan et al., 2006; Ramaswamy et al., 2007). The Kachchh mainland has numerous coastal seasonal rivers, and the arid climate characterizes the coastal fluvial systems with no/sparse vegetation on its channel banks. Typically, such dryland rivers are highly susceptible to the erosive effects of flash floods because of limited resistance from the sandy bank material and the sparse vegetation (Tooth, 2000). Some previous studies have found that dryland rivers are likely to transport large quantities of sediments during flood events, both as suspended load and as a bed load (Reid and Frostick, 1997). Hence, the absence of any perennial river in the Kachchh mainland doesn't prevent it from being a source of sediment supply within the Gulf of Kachchh.



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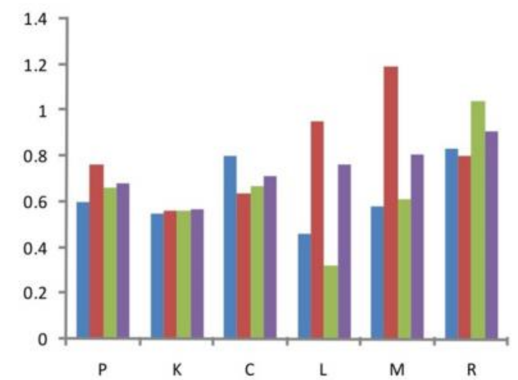

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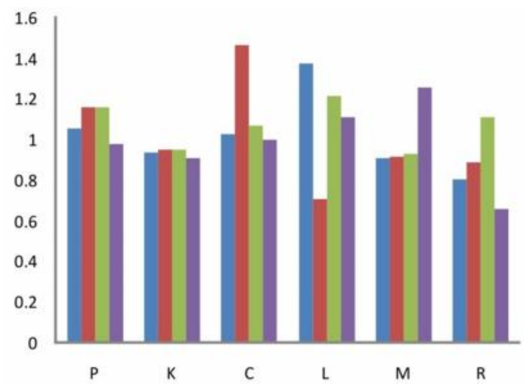

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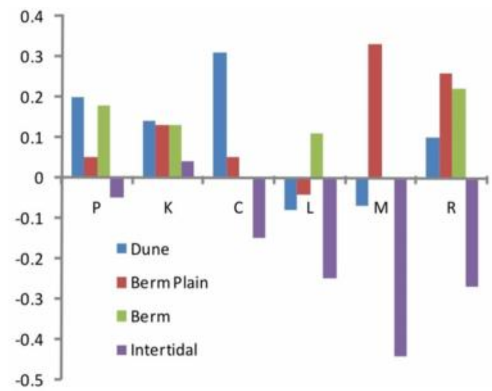

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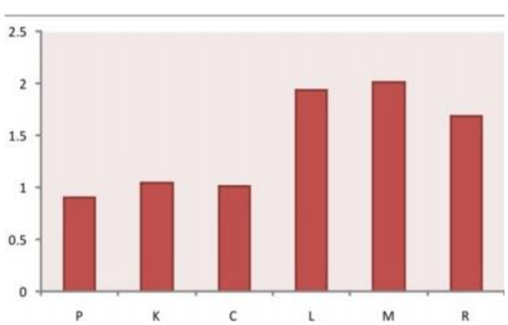

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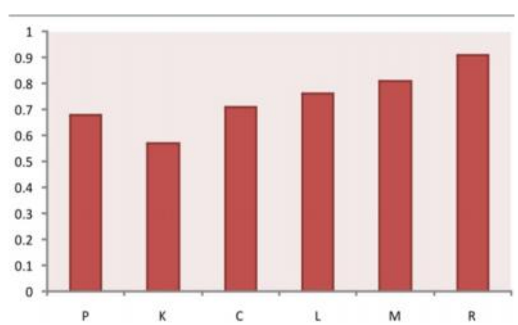
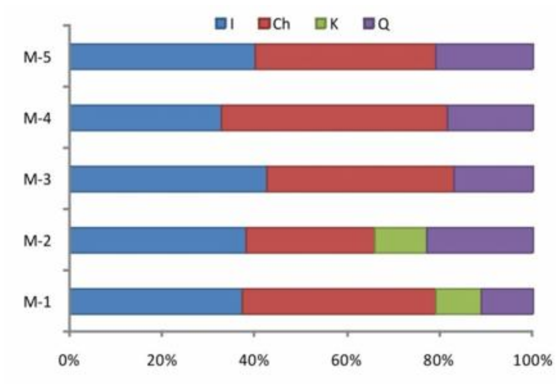


(f)

Figure 6.5: Relationship between different statistical parameters derived from the granulometric analysis of the sediments from sandy segment of the Kachchh coast (P: Pingleshwer, K: Khuada, C: Chhachhi, L: Layza, M: Mandvi, R: Raval Pir).
(a) Mean, (b) Standard Deviation, (c) Kurtosis, and (d) Skewness values from different station; (e) variation in Mean and (f) variation in Standard Deviation from west to east.

The distinction between sandy outer coast and muddy inner coast can also be linked with the presence of a barrier across the Gulf of Kachchh between Mundra and Vadinar that controls the tidal currents and movement of sediments within the Gulf of Kachchh (Vethamony et al., 2005). The compositional studies of the fine grained fraction using XRD analysis have revealed dominance of illite and chlorite, and lesser amounts of kaolinite and montmorillonite. The sediments delivered from Himalayan rivers like Indus and Ganga-Brahmaputra are rich in illite and chlorite, while sediments derived from peninsular Indian source are rich in kaolinite (Goldberg and Griffin, 1970; Kolla et al., 1976; Naidu et al., 1985; Chauhan, 2006). This major difference in physical and mineralogical characteristics of these sediments makes it possible to distinguish the provenance of the offshore sediments in the Gulf of Kachchh (Ramaswamy and Nair, 1989; Ramaswamy et al., 1997; Chauhan et al., 2006). The rivers from Saurashtra and Kachchh which debouch into the Gulf of Kachchh drain from Deccan Trap Formation basalts, but due to their lower discharge the amount of montmorillonite is negligible. The dominance of illite and chlorite also indicate that the Indus river is a major source for the clay minerals in the Gulf of Kachchh. The presence of montmorillonite in the samples from the southern coast of the Gulf at Jodiya and Pindara (Figure 6.6) (Prizomwala et al., 2010) is due to the filtering of most of the Indus borne clay sediments in the sediment sink in headward area and nearness of weathered basalt source to these stations.



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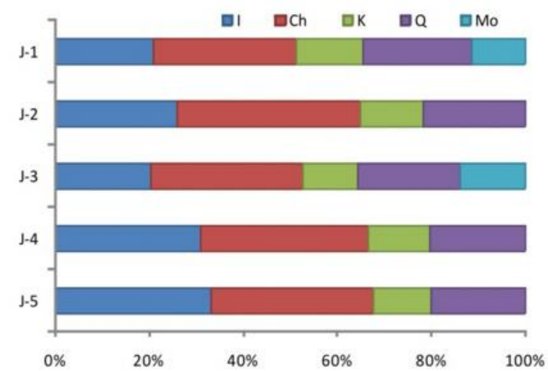

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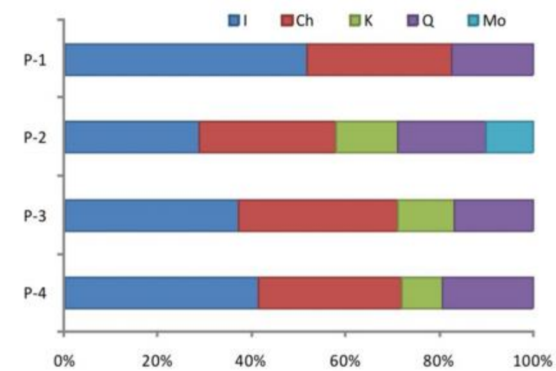
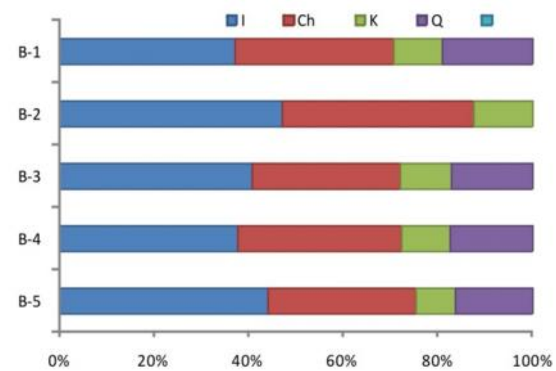


(c)



(d)

Figure 6.6: Relative abundance of clay minerals in mudflats sediments along the Gulf of Kachchh coast at (a) Modwa, (b) Jodiya, (c) Pindara and (d) Bedi (I-Illite, Ch-Chlorite, K-Kaolinite, Q-Quartz and Mo-Montmorillonite).

The coast between Mundra and Kandla is acting as a sink for suspended sediments. A north-south zone between Mundra and Vadinar in the Gulf of Kachchh has suspended sediment free zones habitat to the corals in the offshore. The occurrence of carbonate sediments, which are mostly molluscan shell fragments, coralline debris and foraminiferal tests, show that the northern and eastern part of the Gulf of Kachchh provide pathways for the Indus borne fine sediments and locally derived coarse sediments with sub-sinks for coarse and fine sediments that are deposited into beach ridges and mudflats. The head area of the Gulf of Kachchh forms a large sink for most of the suspended sediments and thus, the southwestern coast receives mainly locally derived detritals from the hinterland that mix with offshore derived carbonate sands.

Sedimentary processes, such as weathering, physical abrasion, and hydrodynamic sorting during transport, storage, and diagenesis may obscure the sediment provenance signature (Morton and Hallsworth, 1994). The heavy-mineral assemblages have still long been regarded as strong indicators of sediment source (Garzanti et al., 2005; Garzanti and Ando, 2007). Garzanti et al. (2005) have documented the heavy-mineral signatures of the Indus River sands in a study of the sediment provenance of areas of the Himalayas and the palaeo drainage changes recorded by clastic wedges deposited in the Himalayan foreland basin and the Arabian Sea. River Indus traverses through granitic, gneissic, and various grades of metamorphic terrain and is rich in tourmaline, zircon, staurolite, sillimanite, biotite, and muscovite (Mallik et al., 1976; Chauhan, 1994; Garzanti et al., 2005). Because the Kachchh mainland is devoid of any metamorphic or granitic source, the presence of these minerals in considerable amounts along the coast can be attributed to the longshore currents, which redistribute these minerals along the entire coast. The heavy-mineral analysis strongly distinguishes the sediment provenance of different sources along the coastline by contrasting and characteristic lithologies in their catchments. Based on mineralogy, there are three distinct sediment provenance assemblages:

- tourmaline–zircon–biotite–muscovite mineral assemblage, indicating a granitic–gneissic source;
- staurolite–sillimanite assemblage, indicating medium- to high-grade metamorphic source; and
- diopside–magnetite assemblage, indicating a Deccan Trap basalt source.

The granitic–gneissic and medium to high-grade metamorphic source can be linked to the Indus River catchment because, it is known to carry these sediments and also to the absence of such parent rocks in the Kachchh hinterland. Because Deccan Trap basalt is present in the Kachchh mainland, its derivatives can be considered to be solely of hinterland/Kachchh mainland origin. Figure 6.7 shows relative percentage of these three distinct assemblages at different locations along the coast.

It clearly shows how the River Indus source sediments are dominant in heavy-mineral assemblages at Pingleshwar, and thereafter the Kachchh mainland (i.e., Deccan Trap Formation) source dominates in the sand fraction of the sediments. The enrichment in heavy minerals from Chhachhi eastward indicates that the Kachchh mainland is a rich source of heavy minerals, which seems to have been governed by the Deccan Trap basalts in its hinterland. The lower concentration and the less distinctive mineralogical trends in heavy mineral distribution at Khuada can be explained by the geological setup of the Naira River basin just west of Khuada. Naira flows through Tertiary and Quaternary sediments and covers a lesser extent through

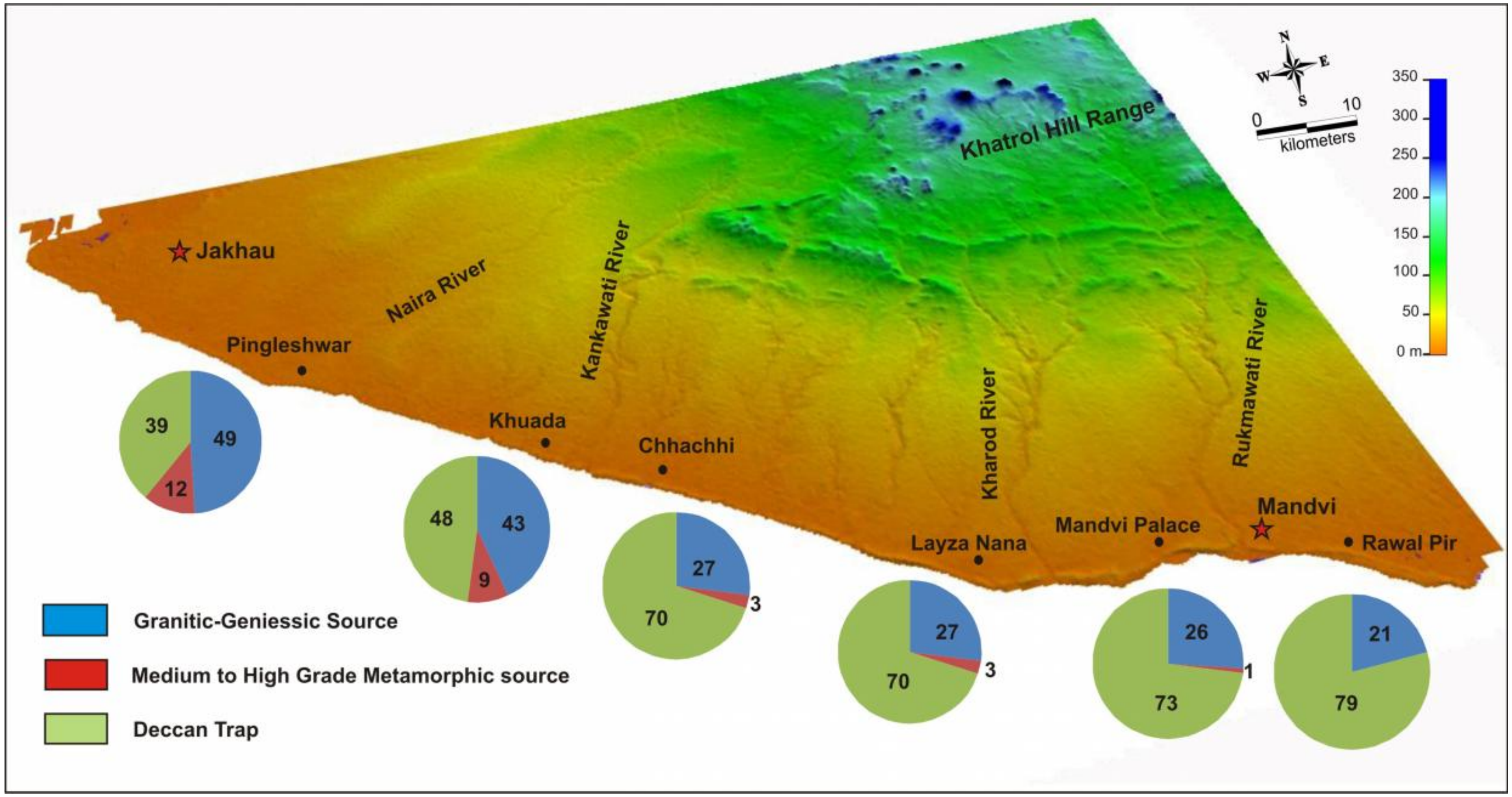


Figure 6.7: Heavy mineral analysis of intertidal sediments along the coast showing relative abundance of different end members.

the Deccan Trap rocks, which is again seen in less concentration in the Deccan Trap–derived sediments at Khuada.

Dominance of Indus-born sediments at Pingleshwar is due to the direction of the currents in the region, which are toward the east (Nair et al., 1982a) and Pingleshwar is situated west of the Naira River mouth.

Microscopic studies confirmed the presence of muscovite and biotite as dominant mica minerals in >63micron sediment fraction. The Cretaceous, Tertiary and Quaternary formations of Kachchh have major lithology like basalt, sandstone, shale and limestone whereas, Saurashtra has Late Cretaceous basalt and lateritic rocks with a cover of Tertiary shale and limestone. These are devoid of mica which is a major product of metamorphic terrain. River Indus travels through a varied lithology including high-medium grade metamorphic, igneous and sedimentary rocks of Himalaya and debouches about 50 x 10^6 tons of sediments annually into the Arabian Sea (Chauhan, 1994; Garzanti et al., 2005). Part of these sediments travels under the influence of long-shore currents to enter the mouth of Gulf of Kachchh and moves eastwards. River Indus is known to have a significant amount of mica in its sediment load (Mallik, 1976; Garzanti et al., 2005; Chauhan et al., 2006). The mica minerals being flaky in nature are capable of being transported for longer distances in suspension due to their shape. It is estimated that >63micron size of mica grain has similar transit mechanism as of silt size quartz being transported by suspension making them hydraulically equivalent (Doyle et al., 1983). Figure 6.8 depicts

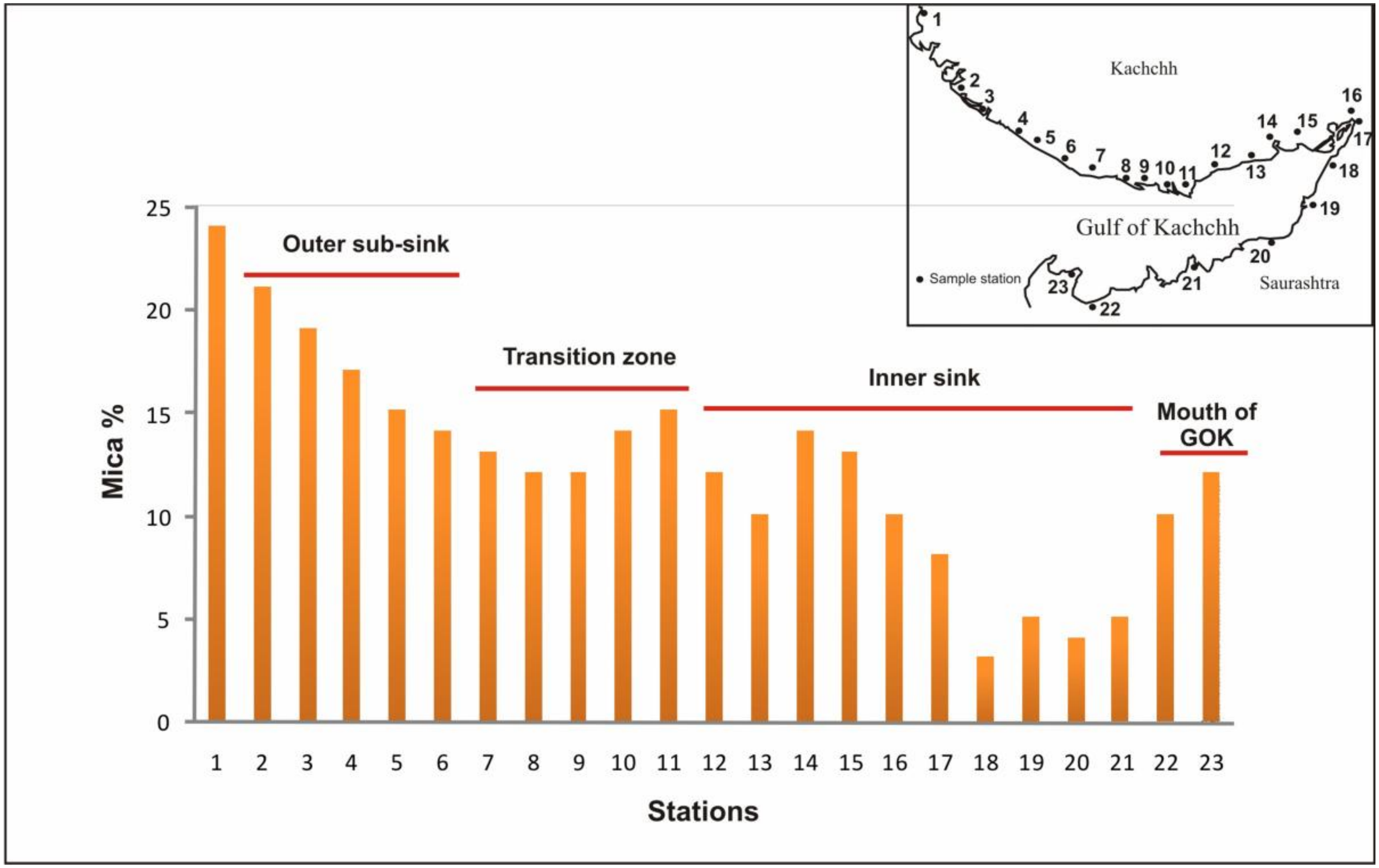


Figure 6.8: Variation in the concentration of mica grains in the surface sediments of various parts of the Gulf of Kachchh (locations of stations are shown in the inset figure). (1) Koteshwar, (2) Jakhau, (3) Pingleshwar, (4) Khuada, (5) Chhachhi, (6) Layza Nana, (7) Mandvi Palace, (8) Rawal Pir, (9) Modwa, (10) Navinal, (11) Mundra, (12) Bhadreshwar, (13) Jogni mata, (14) Gandhidham, (15) Kandla (16) Surajbari A, (17) Surajbari B, (18) Navlakhi, (19) Jodiya, (20) Bedi, (21) Vadinar, (22) Pindara and (23) Okha.

variation in the concentration of mica along different parts of the Gulf of Kachchh coast viz., outer subsink, transition zone, inner sink and the gulf mouth.

The straight coastal segment between Jakhau and Bhada is consisting of sandy landforms like beaches and dunes, and exhibits higher concentrations of mica minerals (Figure 6.8). Koteshwar is the most proximal station to mouth of River Indus and is situated near Kori creek. It has highest concentration of mica (24%). This higher concentration of mica minerals is linked with its proximity to the River Indus mouth. The lithoclasts concentration varies from 2-8%. This is due to the coastal rivers which debouch their load with increasing lithoclast proportion mostly derived from basalt and sandstone country. The sediments of this segment have provenance signatures from Kachchh mainland in the form of increase in lithoclast percentage and from the River Indus as mica minerals.

The coast between Bhada and Mundra hosts both, sandy landforms like wide beaches and dunes as well as muddy landforms like mudflats. The >63micron fraction from the mudflats exhibits a comparatively higher concentration of mica minerals (14-15%) than that of the sandy landforms (12-13%). The concentration of lithoclasts is low to about 2-4%. Studies on mudflats worldwide have shown that mudflats act as major receptors of suspension load (Allison et al., 1996; Kuehl et al., 1996) and are potentially good archives to palaeo-environmental changes. Due to longer residence time of sediments in mudflats the relative concentration of mica minerals in mudflats is more than sandy landforms.

The inner most part of the Gulf of Kachchh is predominantly composed of monotonous mud bearing landforms i.e. mudflats. The mica mineral concentration is varying along the northern and southern coast of Gulf of Kachchh. Higher concentration of mica minerals is seen in mudflats of the Gulf of Kachchh coast i.e. Mundra (15%), Bhadreshwar (12%), Jognimata (10%), Gandhidham (14%) and Kandla (13%). These stations being distal ones compared to the stations of previous segments should continue a decreasing trend of mica concentration. However, a slight increase in mica concentration is seen at stations 10 and 11 that supplement the fact that mudflats act as 'sub-sinks' for the sediments being transported as suspension load in a sediment transit system. The southern coast having wide mudflats shows lesser concentrations of mica minerals with increased lithoclast and carbonate proportion as seen at stations 18 to 20 (Navlakhi, Jodiya, Bedi and Vadinar). The reason for this drop could be an increase in locally available sediments from the Saurashtra being transported by the rivers like Machchhu, Aji, Rangmati, Ghi, etc. These largely basalt derived sands suppress the relative proportion of mica in the >63micron sediment fraction in the mudflats.

As per the current understanding (Nair et al., 1982; Guptha and Hashimi, 1985; Kunte et al., 2003; Deshmukh et al., 2005) a tidal barrier exists across the Gulf of Kachchh that prevents Indus load from reaching directly southward to the Arabian Sea and diverts that towards the Gulf of Kachchh. The longshore currents move eastward along the northern flank of Gulf of Kachchh till they reach to the head of the Gulf of Kachchh, and continues to flow along the southern flank to finally exit the mouth at Okha from where they are throwing the sediments at depths of >200m into the Arabian Sea. A small portion of it is transported southward along the Saurashtra coast. This inferred sediment transport model was proposed on basis of mica and clay mineral distribution in and off the mouth of Gulf of Kachchh that has shown reduction in amount of mica and lack of variation in amount of clay minerals south of the tidal barrier. The presence of tidal barrier has been attributed to the higher amount of Indus sediments off the mouth of Gulf of Kachchh and dominance of characteristic peninsular load off the Saurashtra coast (Nair et al., 1982a & b). However, this variation can also be explained on simple basis of 'vicinity and proximity of sources' off the Gulf of Kachchh mouth and Saurashtra. Note the trend of mica distribution all along the coast of Gulf of Kachchh (Figure 6.8). If the presence of tidal barrier which effectively reduces the movement of mica across the gulf mouth, the amount of mica should subsequently reduce all along the coast and it should become negligible at the southern mouth of Gulf of Kachchh. However, an anomalous increase at southern mouth of the gulf has been noticed in our study (i.e. stations 22-Pindara and 23-Okha). This implies that there exists a very complex movement of currents in and off the mouth of Gulf of Kachchh, which are seasonally dynamic as supported by study of suspended sediment transport using OCM satellite imagery by Kunte et al. (2003). During summer the dominant currents in and adjacent to the gulf are southward, southeastward and east-west which controls the movement of Indus sediments and makes them to enter the mouth of Gulf of Kachchh and travel all along the northern flank, up till they reach the head of the gulf and then travel along the southern flank to finally exit the mouth. During winter months dominant current direction along the northern coast of Gulf of Kachchh remains southeastward and eastward whereas, currents move northward along the Saurashtra coast and partly enter in to the mouth of the gulf.

On account of this, the increase of mica at southern mouth of the gulf can be explained by two ways;

(1) The tidal barrier is ineffective in restricting the movement of mica across gulf mouth, due to transit mechanism of mica minerals being in suspension.

(2) The southern flank of mouth of gulf receives mica from the seasonally northward and northeastward currents.

As stated earlier, fine to very fine mica grains behave hydraulically identical to silt size quartz (Doyle et al. 1983). Therefore, an anomalous increase of mica mineral concentration in >63micron sediment fraction from 5% at Vadinar to 10-12% at Pindara and Okha points more likely towards direct transport of mica from north as River Indus is well known rich fluvial source of it (Mallik, 1976; Garzanti et al. 2005; Chauhan et al. 2006). In absence of this possibility the increase in mica mineral concentration would not be of considerable amount, due to the lack of mica minerals in the country rocks of northern Saurashtra and near shore currents of the Arabian Sea in this part of the region. The second possible mechanism requires enough proportion of mica in the Arabian Sea near to Okha. Moreover, if it is true then seasonal variation in the concentration of mica should be there which is not yet noticed.

In general, the present study has demonstrated the sediment dispersal system along the Gulf of Kachchh coast that receives the sediments from distal source, like Indus River and proximal source like Kachchh hinterland which gets mixed in the coastal environments and subjected to relative sorting under the influence of the strong tidal currents. Further reworking of these sediments transfers the sediments from intertidal areas to the foreshore and backshore zones to give rise to the berm plain, foreshore and backshore dunes and also thin sand sheets with varying width of the coastal zone. As the whole coastal sedimentary package rest on the fluvial sediments constituting the coastal alluvial plain that has stabilized by ~20 kyr (Maurya et al., 2003b), the sequence under study should be linked with the relatively higher sea level during the middle Holocene that shows now a low stand. The stratigraphic relationship between the various coastal sequences, younging towards the shore (an onlap sequence) further supports this inference. However, chronology of the geomorphologically or stratigraphically constrained samples is highly warranted to identify any anomaly directing towards the neotectonic uplift of the area. Only available geochronology on the Gulf of Kachchh coast suggests 11040-10430 and 10150-9530 cal yr BP age of the mudflats at 1.3 and 2.0 m depth near Navlakhi, below this depth the substrate of Deccan Trap basalt was encountered (Rajshekhar et al., 2004). The present arguments like lateral discontinuation of raised beaches, occurrence of rocky shore platforms, closure of river mouths by mouth bars, siltation of tidal channels, incision of coastal rivers and the presence of palaeo mudflats considered as a manifestation of neotectonic uplift (Kar, 1993; Maurya et al., 2008) can also be explained by lateral sedimentary facies variation due to coastal processes and sea level change. For example, the present disposition of sandy and muddy landforms along the Kachchh coast clearly suggests their formation due to change in the energy condition and shoreline configuration from the west to the east. Similarly, in the arid and hyper-arid area like Kachchh the rivers are seasonal and their runoff can not flush out the sediments deposited by strong long shore currents in its mouth area and thus form typical yazoo pattern. The upwarping of the coast is therefore not necessary. The incision of fluvial sequences that are older than ~20 kyr could be linked with the sea level drop during LGM. However, this does not rule out the neotectonic activities in Kachchh; only objection is to its appreciation from the coastal landscape. It is therefore, necessary to identify the changes in the coastal sediment fluxes during the Holocene with its dependable chronology to decipher the real neotectonic effects in the coastal area. This can be attempted from the mudflat areas as they represent an archive with negligible erosive effects. The absence of coastal deposits related to the MIS 5, which are otherwise very distinct in the adjacent coastal areas of Saurashtra further needs to be explained while building the Quaternary history of the Gulf of Kachchh.

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List of Publications

Full Length Papers:

1. Prizomwala, S. P., **Shukla S. B.**, Basavaiah, N. and Bhatt, N. (in Press): Provenance Discrimination Studies on Sediments of the SW Kachchh Coast, Western India: Insights from Heavy Mineral and Mineral Magnetic Analysis. Journal of Coastal Research, West Palm Beach, Florida

2. Prizomwala, S. P., **Shukla, S. B.** and Bhatt, N. (2012): Distribution of Indus born mica along Gulf of Kachchh coast: Implication in understanding current dynamics. Journal Geological Society of India, Vol. 79, June 2012, pp. 557-562.

3. **Shukla, S. B**., Prizomwala, S. P., Ukey, V., Bhatt, N. and Chamyal, L. S. (2010): Coastal geomorphology and tsunami hazard scenario along the Kachchh coast, western India. Indian Journal of Geo-Marine Sciences, Vol. 39(4), December 2010, pp. 549-556.

4. Prizomwala, S. P., **Shukla, S. B.** and Bhatt, N. (2010): Geomorphic assemblage of the Gulf of Kachchh coast, Western India: Implication in understanding the pathways of coastal sediments. Zeitschrift fur Geomorphologie, V. 54(1), pp. 31-46, Stuttgart, March 2010.

5. **Shukla, S. B.**, Patidar, A. K., and Bhatt, N. (2008): Application of GPR in study of shallow subsurface sedimentary architecture of Modwa spit, Gulf of Kachchh. Journal of Earth System & Science, 117, No. 1, February 2008, pp. 33-40.

Abstracts:

1. **S. B. Shukla**, Siddharth Prizomwala, Nilesh Bhatt, Vikas Chowksey, Deepak M. Maurya (2011): Ground Penetrating Radar (GPR) studies along the SW Kachchh coast, Western India: Implications in reconstructing high energy event history. XVIII INQUA Congress, 21-27 July 2011 held at Bern, Switzerland.

2. **S. B. Shukla** and Nilesh Bhatt (2010): Ground Penetrating Radar Survey along South Western Kachchh coast: Implications in understanding coastal progradation. Gujarat Science Congress, 6 March 2010 held at Gujarat University, Ahmedabad.

3. Nilesh Bhatt, Prizomwala S.P. and **S.B. Shukla** (2009): Textural and mineralogical characteristics of sediments of Gulf of Kachchh coast, Western India: Implications in understanding provenance and sediment pathways" National Conference, 25-26 Feb. 2009 held at Lucknow University.

4. Nilesh Bhatt, **S.B. Shukla** and Siddharth P. (2008): Sediment characteristics of the tidal flats of Gulf of Kachchh coast, western India : Implications in understanding the coastal dynamics. National Seminar by Indian Association of Sedimentologists, 26-28 Dec. 2008 held at The M S University of Baroda.

5. **S. B. Shukla** and Nilesh Bhatt (2008): Role of coastal dynamics in the geomorphic evolution of coastline between Mandavi and Mundra, Gulf of Kachchh, Western India" International Conference, 22-25 January 2008 held at Physical Research Laboratory, Ahmadabad.