Chapter 1

Introduction

1.1. Background

The Quaternary sediments of Gujarat, in western India, preserve a record of a complex interplay of eustatic, climatic and tectonic changes (Prasad *et al.,* 1998). Among these Quaternary sediments, occur the carbonate deposits of Saurashtra which are found in the southern and south-western coastal tracts of Saurashtra and also extend inland from the present sea coast. These carbonate deposits were first reported by Carter (1849) and introduced in the geological literature as 'Miliolites' or 'miliolitic limestone'. Fedden (1884) described these deposits in detail from Saurashtra with a mention of two distinct types, one coarse grained coast fringing rocks and another fine grained oolitic freestone. The Miliolite deposits of Saurashtra are similar to aeolianites elsewhere (Brooke, 2001). The term aeolianite was first coined by Sayles (1931) in Bermuda and in a strict sedimentological sense, describes any sediment deposited by the wind and subsequently lithified. However, the definition of the term by Fairbridge and Johnson (1978) reflects the widely accepted use of the term to define dune calcarenite. Based on optically stimulated luminescence (OSL) dating, Sharma *et al.* (2017) have attributed the coastal Miliolites exposed along the Saurashtra coastline to an age range of >156 ka to 45 ka, with the ages becoming progressively younger on moving from east to west along the Saurashtra coast.

Aeolian deposits of ages similar to those found in Saurashtra have also been reported from the Thar Desert in NW India (Glennie and Singhvi, 2002; Glennie *et al.,* 2002; Singhvi and Kar, 2004) and from Southern Arabia (Glennie and Singhvi, 2002; Glennie *et al.,* 2002). Interestingly, the Late Quaternary to present aeolian deposition in Saurashtra, Thar and Southern Arabia is controlled by the SW monsoon wind system which affects the entire belt corresponding to Sahara–Sahel, the Arabian Peninsula, north-western India and northern China (Zhongwei and Petit-Maire, 1994; Glennie *et al.*, 2002; Khadkikar, 2004; Singhvi *et al.*, 2012). The episodic glacial and interglacial phases during the past 200 ka largely affected the intensity of the SW monsoon wind system, which in turn, had its effect on the aeolian activities, processes and sedimentary records in the coastal and inland settings (Glennie and Singhvi, 2002; Glennie *et al.*, 2002; Singhvi and Kar, 2004). A comparison between the dune building episodes in Saurashtra on one hand and the Thar and Southern Arabia on the other, reveals that, while the major dune building phases in the former occurred during glacial epochs, in the latter they did not because of weakened SW monsoon winds (Glennie and Singhvi, 2002; Singhvi and Kar, 2004). The major dune building activities in the Thar

Desert, far inland Saurashtra and Southern Arabia rather correspond to the times of transition from glacial to interglacial epochs when the monsoon used to regain its strength (Glennie *et al.*, 2002; Singhvi and Kar, 2004; Singhvi *et al.*, 2012). Thus, the Late Quaternary coastal dune building events in Saurashtra are in 'correlative conformity' to the non-dune building episodes in Thar, inland settings of the Saurashtra, and Southern Arabia, and hence represent an important archive of Late Quaternary aeolian processes and climatic changes.

The Quaternary carbonate deposits of Saurashtra have received a wide spectrum of views regarding their depositional setting. Dominance of marine forms over land shells, seaward dipping oblique laminations, presence of ichno-fossils and other relevant sedimentary structures, led a group of workers (Shrivastava, 1968; Lele, 1973, 1975; Govindan *et al.*, 1975; Marathe *et al.*, 1977) to opine for marine origin for the carbonate deposits. These workers attributed the inland occurrences to high sea level stand of about 200 m from the present day. Lele (1975) on the basis of the field evidences further pointed out that the formation of Saurashtra carbonates was not a continuous process, but, an interrupted phenomenon. Another school of thought (Biswas, 1971; Sperling and Goudie, 1975) believed in an aeolian (coastal deposits) to fluvio-aeolian (inland occurrences) origin based on evidences like presence of rolled tests, lack of larger marine tests and abrupt reversals in dip directions of cross-beds. They further stated that marine origin cannot account for the sporadic carbonate occurrences in inland locations away from the coast. Baskaran (1985) ruled out the chances of high sea level stand during the Quaternary on the basis of global sea level records. He further questioned the long range transportation of foraminiferal tests inland by wind action on the basis of lack of systematic decrease in abundance of tests inland from the coast, no differential loss in foramiferal ornamentation and on the basis of settling velocity calculations. Merh (1980) held the view that investigations made by the earlier workers were on a local scale which led to over-generalized depositional models and gave rise to marine vs. aeolian controversy.

The age determination of the Saurashtra carbonate deposits was attempted using various methods like ^{14}C, $^{230}Th/^{234}U$, $^{234}U/^{238}U$ and Electron Spin Resonance (ESR) (Somayajulu *et al.*, 1985; Baskaran *et al.*, 1989; Bruckner, 1989; Gupta, 1991). Baskaran *et al.* (1989) suggested three age groups for the Miliolites of Saurashtra, viz., M-I (50–70 ka), M-II (75–115 ka) and M-III (140–210 ka). Age estimates were also informed by Paleolithic stone tools found intermingled with the carbonates in Saurashtra (Marathe and Rajaguru, 1977; Pappu and Marathe, 1977; Marathe, 1981; Rajaguru *et al.*, 2009).

Patel and Bhatt (1995) on the basis of examination of coastal cliffs reported several breaks in the process of carbonate deposition and attributed them to changes in depositional settings in terms of sediment supply and process dynamics. Bhatt (2003) reviewed the style of deposition, petrography, mineralogy, chronology, geoarchaeology and mode of origin of these deposits and

suggested two textural varieties, viz., (i) biogenic carbonate deposits with a distinct relation to intertidal to supratidal regimes along with backshore dunes linked to coastal environments and (ii) inland obstacle dunes linked to aeolian environments. He suggested that this scheme needs re-evaluation using sedimentology and geochronology to better understand the land–sea interactions in Saurashtra.

Khadkikar and Basavaiah (2004) identified three varieties of epikarst (Type 1–3) and five types of *terra rossa* (Type 1–5), besides cross-stratified Miliolites from Gopnath and adjoining areas in southern Saurashtra. They also identified phreatophytic rhizoliths, freshwater gastropods and fossilized bones from *terra rossa* horizons of Gopnath. Khadkikar (2004) attributed the formation of *terra rossa* like soils to periods of increased rainfall leading to weathering, while prolonged periods of reduced rainfall but strong winds favoured the formation of parabolic dunes which deposited the aeolianites. Khadkikar (2005) attributed the lamination types in Gopnath as grainfall deposits with absence of grain avalanching on account of high atmospheric humidity in coastal regions or possibly due to the action of salt sprays and partial cementation. He reported convex-up bedding geometries (dips in the range of 25º to 35º with NNE azimuth) from the Gopnath Miliolites and termed them as hump cross-bedding. This bedding geometry was related to sediment migration along an advancing parabolic dune nose or in some cases to an advancing lobe related to trough blow outs. Costa (2015) attributed the association of carbonate aeolianites and *terra rossa* to dune and interdune wetlands rather than a cyclical glacial–interglacial sequence. Costa (2015) also reported diverse Late Pleistocene fossil assemblage comprising numerous shells of snail *Zootecus insularis*, terrestrial tortoise, soft-shelled aquatic turtle, dog-like carnivores, equids, rhinoceros and bovines.

Recently, based on OSL dating, Sharma *et al.* (2017) have attributed the coastal Miliolites in Saurashtra to an age range from >156 ka to ~45 ka with the units becoming younger in age on moving from east to west along the Saurashtra coast.

The Miliolites along the southern Saurashtra coast of India exhibit land–sea interaction in the form of cliffs, marine terraces, wave-cut platforms and marine notches (Pant and Juyal, 1993; Bhatt and Bhonde, 2006). As far as geomorphological contributions are concerned, Pant and Juyal (1993) highlighted the different indicators of land and sea level changes, viz., marine terraces, staircase platforms, tidal notches (and raised notches) and drainage patterns from Jafrabad–Diu area. They defined three types of notches, viz., tidal notches, ripple notches and distorted notches. They attributed the tectonogenic features such as steep vertical cliff faces, distorted morphology of wave-cut notches and staircase platforms to fracture lineaments which are in keeping with the general structural set up of the coast. From a succession of raised terraces and wave-cut notches, Pant and Juyal (1993) established the Late Quaternary sea level changes in the region and attributed

the last interglacial high sea stand [Marine Isotopic Stage (MIS) 5] at ~7 m above mean sea level (MSL). They also envisaged a relative sea level change of 3 m during the Holocene and attributed the same to the sudden emergence of the landmass. Bhatt and Bhonde (2006) studied the coastal cliffs along Babarkot–Jafrabad and Diu (and adjacent areas) coastlines and generated certain cliff profiles which showed the presence of active and raised notches and raised shore platforms. They estimated an uplift of the coastal cliffs in the order of 2 m over 3 ka. Bhonde and Bhatt (2009) reported joints from Miliolite deposits of coastal Saurashtra (Dwarka, Diu–Babarkot and Veraval–Jafrabad areas) and analyzed their orientation. According to them NE–SW orientation of the joints is the most prominent which can be related to the maximum horizontal compressive direction suggested for the Indian sub-continent. However, joints with NNE–SSW, N–S, NW–SE and E–W were also recorded. Based on available geochronological data and morphostratigraphy of the coastal units, neo-tectonic episode younger than at least 125 ky was suggested for Saurashtra. Banerji *et al.* (2015) investigated two tidal notches (active notch and overlying raised notch) preserved near Vankwara (Diu) and suggested a tectonic uplift of the area by ~1 m during the mid-Holocene and an effective sea level high of ~2 m above the MSL. Kazmer *et al.* (2016) reported an uplift of 0.5 m in the last millennium from the coastline of Diu based on the study of a dysfunctional fish tank hewn in Miliolite. Prizomwala (2018) presented geological and geomorphic evidences of neo-tectonics from the region between Somnath and Jafrabad in southern Saurashtra. A geospatial dataset was used to highlight the neo-tectonically active nature of the region which was supported by field evidences and drainage network anomalies. The morphometric parameters like longitudinal river profile, drainage basin asymmetry, hypsometric integral and the presence of knick zone, ravines, coastal marine notches and offset channels/ridges suggested neo-tectonic activeness of the southern Saurashtra region. Besides, available literatures suggest that workers in different parts of the world also have variously contributed to the advancement of knowledge in the field of aeolianite geomorphology. Kaye (1959) described the formation of erosional and weathering features from the coastal aeolianite of Puerto Rico. Some authors (e.g., Coetzee, 1975; Kindler and Hearty, 1997) described weathering features (solution pipes) associated with karstification of coastal aeolianites. Miller and Mason (1994) provide an account of the contemporary erosional surface features of beach rock and aeolianite in the littoral zone of sub-tropical Kwazulu-Natal, South Africa. From Kwazulu-Natal (South Africa), Cooper and Green (2016) have described the intertidal and supratidal platforms formed in aeolianites, pothole dimensions and disintegration of platforms as well as studied the sub-merged aeolianites using multibeam bathymetric and high-resolution seismic reflection techniques.

Thus, from sedimentological point of view, a major part of the scientific efforts have so far been expended on understanding the Miliolite deposits of southern Saurashtra from the point of

view of their mode of origin, styles of deposition, petrography, mineralogy and geochronology. However, little efforts have so far been made to understand these deposits from the viewpoint of a repository of the Late Quaternary aeolian depositional processes and system that prevailed in southern Saurashtra. As far as the geomorphological studies are concerned, a large part of the efforts so far has been expended on establishing the tectono-eustatic changes along the southern Saurashtra coastline and understanding the neo-tectonic activities. Although worldwide extensive efforts have been put in understanding the aeolianites in terms of their environments and conditions of deposition, subsequent diagenesis, chronology and eustatic and climatic controls, comparatively little attention has been paid in understanding the contemporary geomorphology of the aeolianites in terms of their geomorphic responses when exposed to modern day coastal processes (Cooper and Green, 2016).

In light of the above discussion, the present study carried out on the coast fringing Quaternary carbonate deposits of southern Saurashtra, attempts have been made to bring about a detailed sedimentological analysis of these deposits to bridge the gap in understanding of the underlying depositional processes vis-à-vis with a geomorphological study to understand the present and past land–sea interactions.

1.2. Study area and Accessibility

The carbonate deposits along the southern Saurashtra coast were studied in three sectors, viz., Gopnath (Lat: 21º11’59.18” N, Long: 72º06’39.34” E), Babarkot (Lat: 20°52’19.88’’ N, Long: 71°24’27.61’’ E) and Diu Island (Between Lat: 20°44’39’’ and 20°42’00’’ N and Long: 70°52’26’’ and 71°00’24’’ E) covering a stretch of nearly 155 km from east to west along the coastline **(Figure 1.1)**. Gopnath and Babarkot are situated in Talaja Taluka of Bhavnagar district and Amreli district of Gujarat, respectively. Diu Island is situated at the southern tip of Saurashtra peninsula (western India), facing the Arabian Sea and is connected to the adjacent landmass of Saurashtra in the north by intertidal mudflats. While Gopnath occurs in close proximity to the Gulf of Khambhat, Babarkot and Diu face the open sea. From east to west along the coastline, the spring tidal range is ~7 m in Gopnath, ~2 m in Babarkot and ~2 m in Diu (Kazmer, *et al.*, 2015; Mahapatra and Ramakrishnan, 2015). The significant wave height in the three sectors ranges from 2 m to 3 m (Mahapatra and Ramakrishnan, 2015).

Gopnath is situated at a distance of 263 km from Vadodara (Gujarat) and can be reached via a combination route of GJSH–6, NH–51 and GJSH–31. Babarkot is situated at a distance of 350 km from Vadodara and can be reached via a combination route of GJSH–6 and NH–51. Diu is situated at a distance of 389 km from Vadodara and can be reached via GJSH–6, NH–64 and combination route of NH–64 and Kodinar–Amreli Highway.

1.3. Physiography, Climate and Vegetation

Gopnath is a small fishing village situated in the coastal tracts of the Talaja Taluka of Bhavnagar district. The area can be classified into two categories, viz., (a) cultivated land: irrigated fields, gardens etc. and (b) uncultivated land: hilly areas, grass preserves, waste lands, saline marshy land, salt pans and mud salinity affected areas. The topography of the region on the whole is undulating except the river basin. In the uplands, Deccan Trap ridges stand out prominently intervened by narrow ridges and the sea areas are covered with mixed forests. The elevation of the region varies from 60 m to 501 m above the mean sea level. The slope of the region is towards east and it is drained by the Shetrunji River and its tributaries. Soils of the coastal areas are clayey to sandy loam which is formed due to weathering of trap rock and wind-blown sands. 'Black-brown cotton soil' is the most predominant type of soil and covers major parts of Ghogha, Talaja and Rajula talukas where the trap rocks are and are not suitable for agricultural purpose. Vegetation includes Babul, Kikar, Safed Khair, Gum acacia, Neem, Ingudi (desert date), Jatropha, Jajoba (*Simmondsia chinensis*), Ber (*Ziziphus jujuba*) and Karira (*Capparis decidua*). Coastal mudflats are characterized by mangrove *Avicennia marina.* The plantation crops especially Coconut, Guava and Pomegranate are some of the well-known crops grown in this region. Besides, Groundnut, Jowar and Bajra are grown in Kharif season and Wheat in Rabi season. The climate is tropical type with general dryness, except in the coastal areas. The normal rainfall in the district is 598.4 mm [Indian Meterological Department (IMD) data] and 90% of the total annual rainfall is received during the monsoon season with average of 31 rainy days in a year. The maximum and minimum summer and winter temperatures are 44°C and 36°C and 23°C and 10°C, respectively.

Amreli district is mostly plain, except for a few isolated small hill ranges. Geomorphologically, the district can be divided into two major units, viz., (a) those formed by Quaternary/Tertiary formation (includes alluvial plains, salt flats, valley fills, coastal plains, coastal ridges, coastal depressions and piedmont zones) and (b) those formed by Deccan Trap (includes pediments, dissected hilly terrains, moderately dissected pediplains and denundation hills). The soils of Amreli district may be classified into four main categories, viz., (a) medium black soils, (b) coastal alluvial soils, (c) rocky soils and (d) alkaline soils. The drainage in the district is controlled by the topography and the lineaments. The major river draining the district is the Shetrunji River in the eastern part. While the northern part of the district is mainly drained by two small ephemeral streams, the southern part of the district, south of the Shetrunji River basin, is drained by small ephemeral streams which debouch into the Arabian Sea. The climate, in general, is of sub-tropical type. The mean maximum daily temperature ranges from 28°C to 40°C and the mean minimum daily temperature ranges from 11°C to 26°C. While April and May are the hottest months, the winters are generally pleasant with minimum temperatures around 12°C. The relative humidity

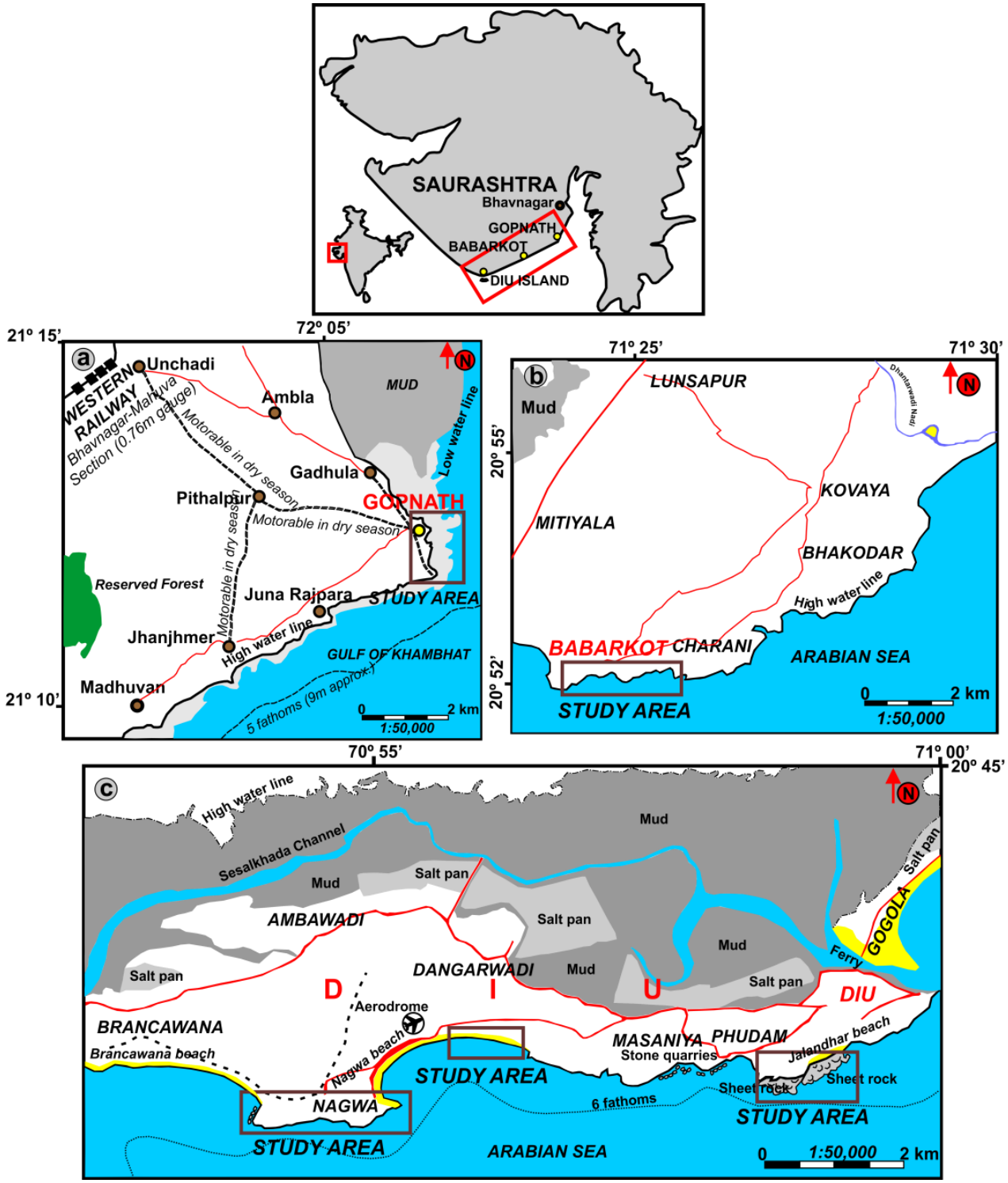

Figure 1.1. Study area. The present study was carried out along the southern coast of Saurashtra, India. Cliff forming Miliolites were studied for their sedimentological and geomorphological attributes in three sectors, viz., (a) Gopnath, (b) Babarkot and (c) Diu Island covering a stretch of nearly 155 km from east to west along the Saurashtra coast.

ranges from 81% during the monsoon season to 40% during the winter season. The mean wind speed ranges from 188 km/d during winter to more than 500 km/d during summer and monsoon. The area receives an average annual rainfall of 609 mm (IMD data). The agricultural lands yield Kharif and Rabi crops as well as fruits and vegetables. There are no important forest resources in the district. The main forest product is grass with other minor products as timber, firewood, bidi leaves and khakhara leaves.

Diu has a plain topography and the hillocks attain a maximum height of 30 m above the sea level. Several pocket beaches are developed along the coastline. The Chasi River to the north separates Diu from Junagadh and Amreli district of Gujarat, and, the remaining three sides are surrounded by the Arabian Sea. The soil in Diu is neutral to mildly alkaline and is characterized by light brown sandy loam soil. Diu being an island enjoys a maritime climate with constant sea breezes affecting its temperature. The weather remains dry, though, pleasant throughout the year. During summers, the temperature in Diu varies between a maximum of 36°C and a minimum of 20°C. However, during winters, the temperatures come down to a maximum of 26°C, while, the minimum temperature remains about 20°C. The monsoon season lasts from the month of June to September. The maximum rainfall during the monsoons is about 706 mm (IMD data). Trees like *Casurina, Procofis, Acasias, Fuliflora, Tortolis, Equisitifolia* and Hokka constitute the vegetation in the island of Diu. Palm groves and Coconut plantations are found scattered all over the place.

1.4. Geological setting

1.4.1. Regional geology

The Saurashtra peninsula (Between Lat: 20°30’ and 22°30’ N and Long: 69°00’ and 72°30’ E) is bounded by the Gujarat plains in the East and NE, by the Gulf of Kachchh and the Little Rann on the north, and on the SE by the Gulf of Khambhat. The Arabian Sea borders the entire southern seaboard. The Central part of the region forms an elevated table land from where most of the rivers rise and flow radially. The terrain generally slopes gently towards the peninsular margin to merge into the coastal plains and the great alluvial tract stretches to NE and east **(Figure 1.2)**. The sedimentary rocks along the coast form almost a low flat country. A characteristic feature is the occurrence of parallel running low and straight hill ranges which have formed due to intrusion of several radial basic dyke systems during Deccan volcanism. The region has experienced a distinct geological history that led this peninsula to evolve quite differently from the neighbouring regions of Kachchh and mainland Gujarat.

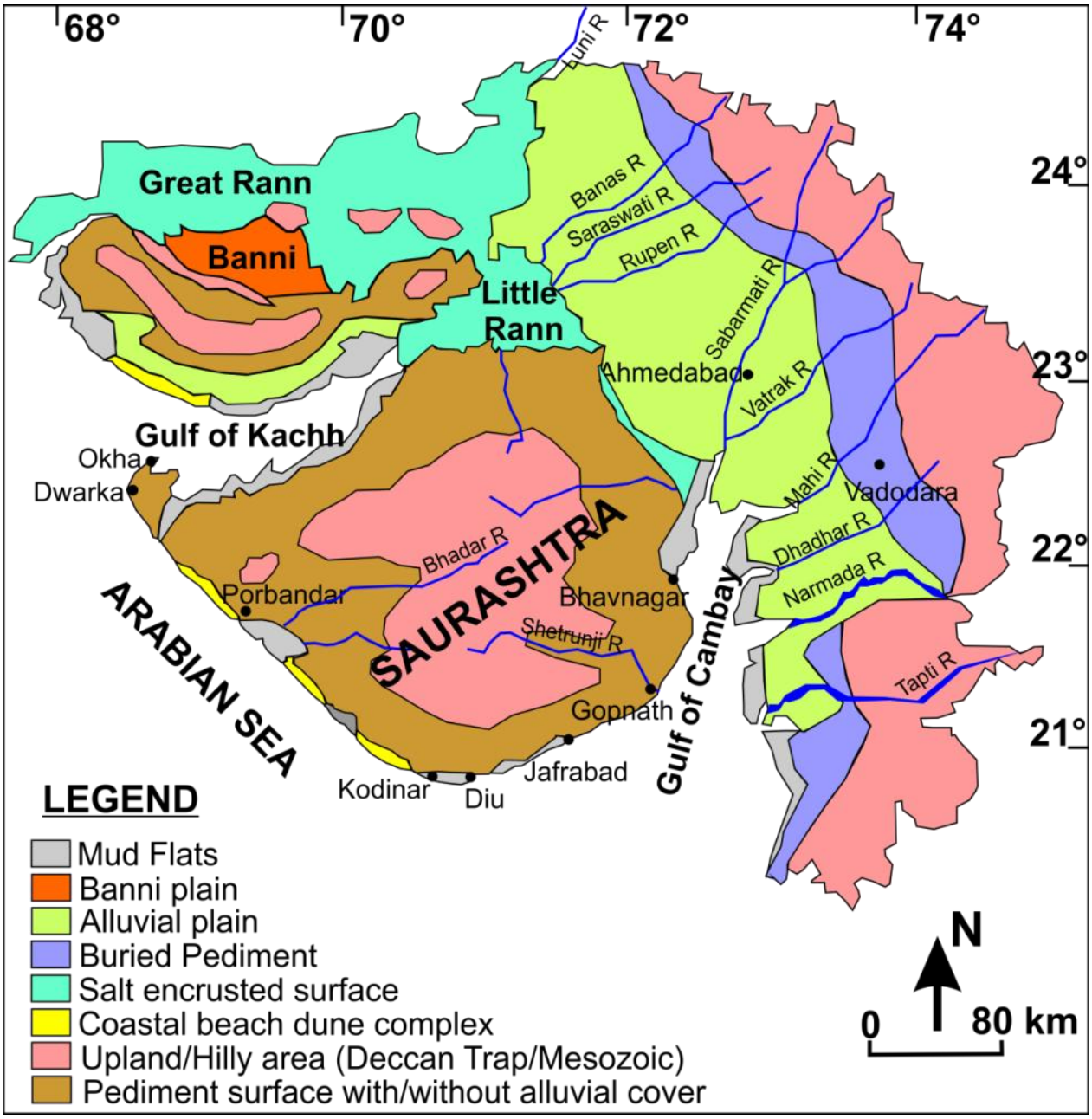

Figure 1.2. Map showing the major geomorphologic subdivisions of Gujarat. The Saurashtra peninsula is bounded by the Gujarat plains in the East and NE, by the Gulf of Kutch and the Little Rann on the north, and on the SE by the Gulf of Cambay. The Arabian Sea borders the entire southern seaboard. The Central part of the region forms an elevated table land from where most of the rivers rise and flow radially. The terrain generally slopes gently towards the peninsular margin to merge into the coastal plains and the great alluvial tract stretches to NE and east *(Modified after Chamyal et al., 2003)*.

1.4.2. Tectonic setup

Saurashtra massif is a horst (Biswas, 1982) bounded by the Kachchh rift in the North and the Cambay rift in the East. Extension of the Narmada rift and the West Coast Fault are accounted for the straight nature of the western and the southern coastline of the Saurashtra **(Figure 1.3)**.

Interactive movements of the Indian Plate during the Cretaceous, after breakup from the Gondwanaland, are the major factors responsible for the tectonic set up of Saurashtra (Biswas, 1982). A prominent feature observed off the Dwarka coast is the occurrence of the Saurashtra Arch that trends in NE–SW direction and separates the Saurashtra offshore basin from the Kachchh rift. Almost perpendicular to this, a major fault zone trending NNW–SSE off the Porbandar coast defines the Saurashtra platform and separates it from the deeper zone due West (Zutshi *et al.*, 1989). Four major structural trends have been identified from the lineament study of Saurashtra, viz., NE–SW, ENE–WSW to E–W, NW–SE and NNE–SSW to N–S trend. The gravity trends in Saurashtra indicated highs of 40 mGal to 60 mGal near Junagadh, Barda and Alech hills (Mishra *et al.*, 2001). The gravity anomaly is circular at Junagadh representing the volcanic plug, whereas, at Barda and Alech gravity anomalies are circular but together they form an E–W trend indicating fracture zone occupied by these volcanic plugs. Prominent low gravity of about -40 mGal has been observed over the Jasdan plateau that is attributed to the isostatic compensation or to some deep seated source, probably the upper mantle.

1.4.3. Stratigraphic setup

Saurashtra region contains a geological record ranging from the Mesozoic to the Cenozoic era **(Table 1.1)**. The lithostratigraphic sequence begins with the Dhrangadhra Formation followed upward by the Wadhwan Formation, the Deccan Trap Formation, the Gaj Formation, the Dwarka Formation, the Miliolite and the Chaya Formations and finally the Recent Deposits **(Figure 1.4)**.

Dhrangadhra Formation

The rocks belonging to this formation were first described by Fedden (1884) and Oldham (1893). Shrivastava (1963) assigned them a formal litho-stratigraphic status as the Dhrangadhra Formation. The rocks constituting the Dhrangadhra Formation are feldspathic sandstone (dominant), argillaceous sandstone, sandy shale and clay with occasional coal bands. The thickness of this formation has been estimated up to 550 m based on a borehole drilled near Dhandhuka where it lies over granite basement. Physical continuity of Wagad and Bhuj sandstone with the Dhrangadhra Formation has been envisaged by Biswas (1987). An occurrence of carbonized plant fossils in the Dhrangadhra Formation suggests their formation in coastal swamp environment; the Formation being considered to be of typical deltaic type environment (Karami, 1990). This Formation is also correlated with Himmatnagar Sandstone of north Gujarat which is thought to be Lower Cretaceous in age. The Dhrangadhra Formation has been assigned an age of Upper Jurassic (Tithomnan) to Lower Cretaceous (Neocomian and possibly extending up to Albian). Fedden (1884) correlated plant bearing beds of this formation with the Umia Beds of Kachchh.

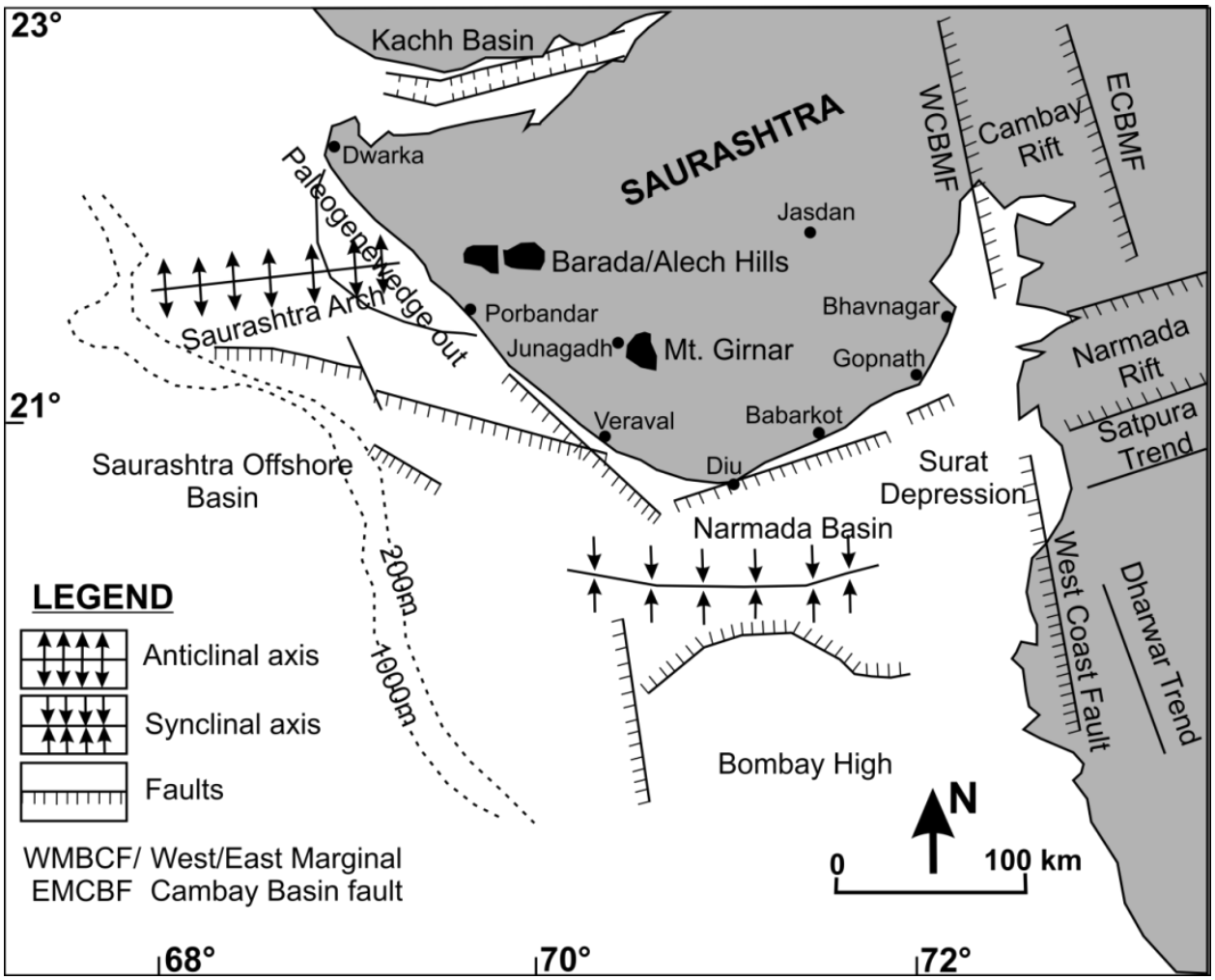

Figure 1.3. Tectonic framework of the Saurashtra peninsula. Saurashtra massif is bounded by Kachchh rift in the North and Cambay rift in the East. Extension of the Narmada rift and the West Coast Fault are accounted for straight nature of the western and southern coastline of Saurashtra. Four major structural trends have been identified from the lineament study of Saurashtra, viz., NE–SW, ENE–WSW to E–W, NW–SE and NNE–SSW to N–S trend *(Modified after Chauhan et al., 1993).*

Wadhwan Formation

The Wadhwan Formation conformably lies over the Dhrangadhra Formation with mostly gradational contact. This is best exposed in the Bhogavo River section near Surendranagar. Fedden (1884) was first to map this Formation and named this formation after its best exposure near Wadhwan village. Shrivastava (1963) identified several gastropods, pelecypods, bryozoans, echinoderms and microfossils (*Cytheretta* and *Quinquelocullina* and some *Rotalids*) to suggest a shallow marine origin for the Wadhwan Formation. The deltaic environment of the Dhrangadhra Formation became shallow marine when the sediments of the Wadhwan Formation were deposited (Merh, 1995). Chiplonkar and Borkar (1971) subdivided the Wadhwan Formation into three members, viz., the Surendranagar Sandstone Member, the Navania Limestone Member and the

Table 1.1. Generalized stratigraphy of Saurashtra region (after Merh, 1995)

Age	Formation	Depositional Environment
Holocene	Recent Deposits	Coastal dunes, tidal flats, beaches, alluvium etc.
----------Unconformity----------		
Lower Pleistocene to Upper Pleistocene	Chaya Formation Miliolite Formation	Littoral, coastal dune and aeolian
----------Unconformity----------		
Lower Miocene	Dwarka Formation/Piram beds	Littoral to shallow continental shelf/fluvio-littoral
----------Unconformity----------		
	Gaj Formation	Upper part continental shelf
----------Unconformity----------		
Paleocene	Laterite	Sub aerial weathering under tropical and subtropical conditions
Upper Cretaceous to Lower Eocene	Deccan Trap Formation	Extensive volcanic activities giving rise to basaltic lava flows and intrusive bodies
----------Unconformity----------		
Upper Jurassic to Lower Cretaceous	Wadhwan Formation Dhrangadhra Formation	Inner shelf marine environment Coastal swamp and deltaic deposits
----------Basement rocks not exposed----------		

Badhuka Limestone Member in ascending order. On the basis of faunal assemblage they correlated this with the Nimar Sandstone, the Nodular Limestone and the Coralline Limestone, respectively, of the Bagh Beds of Lower Narmada Valley. However, Biswas (1987) has explained them by correlating with the Bhuj Sandstone.

Deccan Trap Formation

A major part of Saurashtra peninsula is occupied by the magmatic rocks of the Deccan Trap Formation. These rocks occur as an elevated table land with an uneven topography. The bulk of the formation is made up of succession of lava flows dominantly of tholeiitic basalt. Common rock type encountered is fine to medium grained greyish black basalt with its variations and amygdaloidal basalt forming marker flows. Based on the Deep Seismic Survey (DSS) profiles, Kaila *et al.* (1981) estimated the thickness of the Deccan Trap Formation in the west of Junagadh to be ranging from 900 m to 1300 m, whereas, in the east, the thickness was found as low as 350 m. Within the Daccan Trap country, several igneous complexes occur as a result of magmatic differentiation. The Girnar, Barda, Alech, Osham and Chimardi hills are some of such examples that standout from the basalt

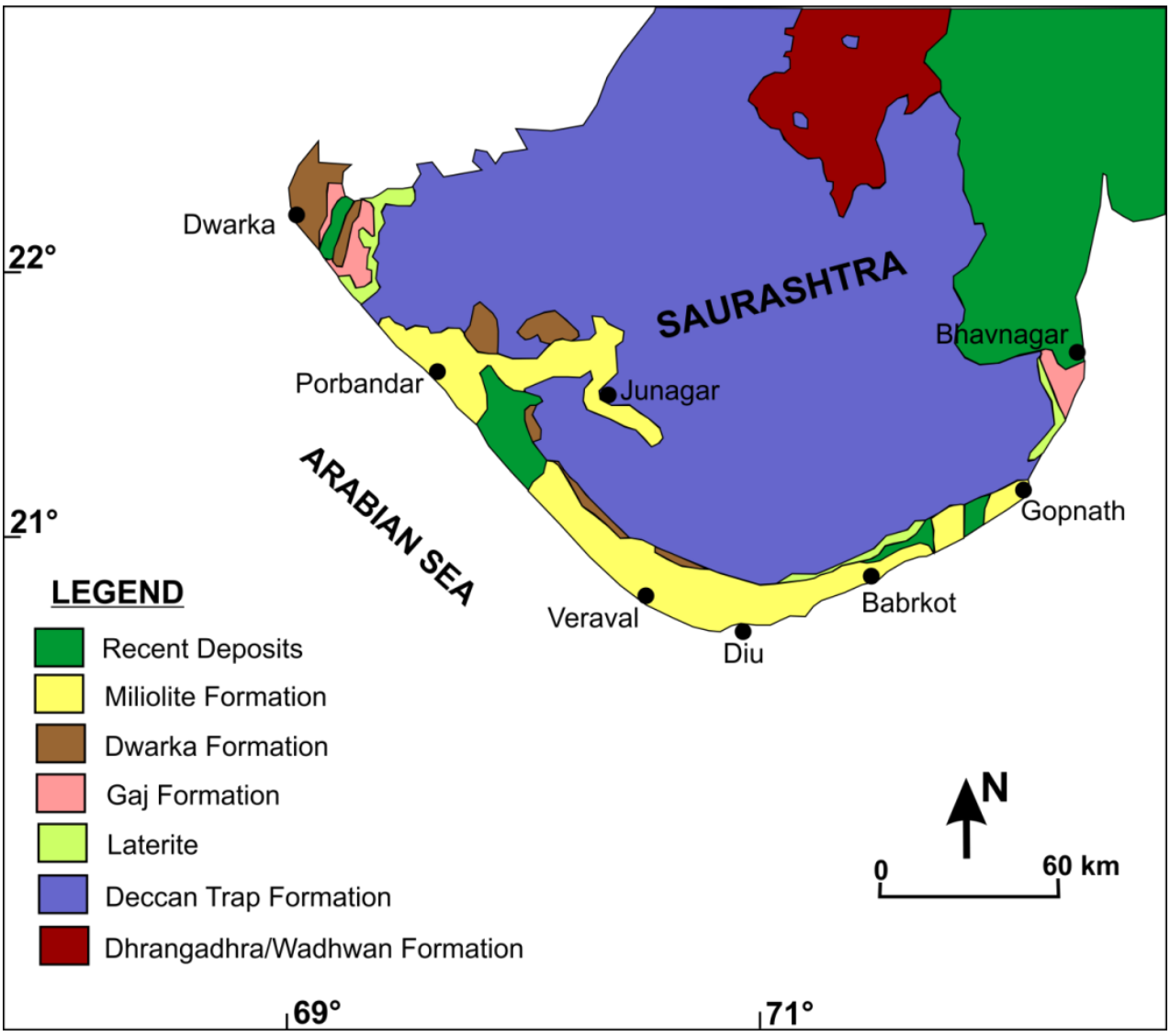

Figure 1.4. Geological map of the Saurashtra peninsula. Map showing the distribution of the different lithostratigraphic units across the Saurashtra peninsula. Mesozoic sediments (Dhrangadhra and Wadhwan Formations) are exposed in a small area in the north-eastern corner of the peninsula. A major part of the peninsula is covered by the Deccan traps. Paleogene and Neogene sediments (Gaj and Dwarka Formations) occur only in pockets, while the Quaternary sediments (Miliolite and Chaya Formations) cover the southern and western coastal tracts of Saurashtra *(Modified after Merh, 1995).*

plateau. Numerous dykes of basalt, dolerite and lamproite conspicuously occur in three major directions, viz., ENE–WSW, E–W and NE–SW. They range in width from 2 m to 5 m, but run for several kilometers. These are structurally controlled and follow major fracture and lineament trends. Many of the NE–SW trending dykes are now recognised as the fault controlled tilted flows manifesting the extension of the Narmada rift zone (Mishra *et al.*, 2001). At places, inter-trappean beds occur within the Deccan Trap Formation of Saurashtra and are observed near Bamanbore and Ninama, wherein, nearly 35 m thick basaltic flow succession contains massive, poorly bedded

chalky limestone with basal conglomerate. Based on the fossil remains, the age of these inter-trappean beds has been estimated to be Paleocene to Lower Eocene (Merh, 1995).

Laterites

Laterites form almost a continuous zone between the Deccan Trap Formation and the Gaj Formation and occur as discontinuous patches forming colorful ridges. The laterites extend right from Jamnagar in the north up to Bhavnagar in the south. Laterite shows a good development in the area about 40 km to 45 km west of the Khambhalia around the villages of Mewasa, Bhatia and Ran. Here, ferruginous duricrusts have been mostly eroded exposing bauxite horizon. Some sections clearly show the derivation of laterite from the underlying basalt. In contrast to this, laterite exposures along the coastal plain of the Junagadh and Amreli districts are fragmentary and highly ferruginous showing poor development of the profile. Laterite again shows a good development in the Bhavnagar area where it extends for almost 50 km and forms about 1 km to 5 km wide zone.

Gaj Formation

Sediments belonging to the Gaj Formation are best exposed in 30 m to 40 m high cliffs on the western flank of the Okha Rann. They are mostly argillaceous and partly calcareous comprising of yellow and grey colored clays, variegated clays with gypsum bands and calcareous silt and sandstone along with thin bands of yellow brown colored limestones. The Gaj Formation has been divided into two members, viz., the Ashapura Clay Member and the Ranjitpur Limestone Member (Bhatt, 2000).

The Ashapura Clay Member is dominantly composed of laminated clays with bands of grey maroon and yellow color. Topmost unit of the Member is made-up of yellow marl and siltstone which is dolomitic in nature. The Ashapura Clay Member is characterised by thin fossiliferous bands at different levels, wherein, most of shell materials have been dissolved out and only their moulds and casts are visible. In the eastern part of the Okha Rann, typical earthy yellow colored clay conformably lies over laterites with a bouldery conglomerate horizon at the base which becomes gravelly after a meter thickness towards top. This forms an unconformable contact between the Gaj Formation and the Laterites.

The Ranjitpur Limestone Member is not a dominant unit like the previous one and is having sporadic exposures. It attains the status of the Member due to its distinct calcareous nature within otherwise argillaceous Gaj Formation. The unit comprises typical yellow to brown colored, very compact, fossiliferous limestone with numerous borings and contains recrystallised shells of *Acila*, *Arca*, *Pecten* and *Ostrea*. Lower Miocene age has been suggested for the Member on the basis of *Pectunculus pecene*, *Pecten* sp., *Pecten bouei*, *Pecten faveri* and *Ostrea multicostata* and that of the larger foramimfera belonging to the *Miogypsinidae* family (Kachhara *et al.*, 1998).

Dwarka Formation

The Dwarka Formation has got a disconformable contact with the below lying Gaj Formation and comprises highly recrystallised limestone and sandy clay sequences. The Dwarka Formation is chiefly composed of two distinct fossiliferous sequences along with clastic dominated non-fossiliferous sequence in between. This Formation has been divided into three members, viz., the Poshitra Limestone Member, the Shankhodar Sand–Clay Member and the Kalyanpur Limestone Member (Bhatt, 2000).

The Poshitra Member consists of coralline and fossiliferous limestone which have been recrystallised. At places, the brown colored recrystallised limestone of this member exhibits trough cross beddings and ripple marks. The Member attains a maximum thickness of about 2 m in the subsurface.

The type section for the Shankhodar Sand–Clay Member is at Bet Dwarka, where, the coastal cliffs expose grey and yellow clays with occasional bands of brown colored sandy clays and grey white colored consolidated clays. The sequence also exhibits sedimentary structures like low angle cross-bedding, ripple drift laminations and ripple marks. The top of this member is marked by 0.5 m to 1 m thick conglomerate horizon. The total thickness of this unit ranges from 50 m to 60 m.

The Kalyanpur Limestone Member is characterized by pinkish to brown colored, highly recrystallised, fossiliferous limestone that has a sharp contact with below lying non-calcareous clastic dominated sequences. The rocks show planar and tough cross beddings. This member characterizes topmost part of the Dwarka Formation and occurs at many places in western Saurashtra. As the Member has a distinct unconformable contact with the general sand–clay sequences of the other part of the Dwarka Formation, a possibility of its being younger and different litho-unit cannot be ruled out (Bhatt, 2000).

Miliolite Formation

The Quaternary carbonate deposits designated as the Miliolite Formation are spread all along the southern and south-western coastline of Saurashtra. The Formation is composed of medium to fine grained, well sorted, rounded to sub-rounded allochems like forammiferal tests, peloids, molluscan shell fragments, corals, coralline algae, bryozoans, echinoderms, etc., chiefly cemented by the low magnesium non-ferron sparry calcite cement (Bhatt and Patel, 1996). The Milolite Formation shows varied thickness depending upon the pre-Miliolite topography (Patel, 1991). In the coastal areas, the Formation attains a thickness of about 25 m, whereas, in the inland areas it ranges from 2 m to 25 m. The details on this Formation have been reviewed by Merh (1980) and Bhatt (2003). This Formation has been divided into two members, viz., the Dhobalia Talav Member consisting of alternating pelletoid limestone and micrite, and, the Adityana Member

consisting of white colored pelletoid limestone 'calcarenite' (Grabau, 1904). Based on geochronology and palaeontological criteria the age range of the Miliolite Formation has been decided as early Middle Pleistocene to Late Pleistocene. It is understood based on their radiometric age data (Baskaran *et al.*, 1989) that the Miliolites are deposited in three different episodes, viz., M-I (50 ka–70 ka), M-II (75 ka–150 ka) and M-III (140 ka–210 ka).

Chaya Formation

Mathur and Mehra (1975) separated out the coarse grained bioclastic limestone deposits occurring in association with the Miliolite limestone in the coastal areas of the western Saurashtra as a formal litho-stratigraphic unit to define the Chaya Formation. The Formation consists of buff colored coarse grained gently seaward dipping rocks containing mega fossils that can be termed as the 'calcirudite' (Grabau, 1904). The rocks have been described in the literature as coast fringing rocks (Fedden, 1884) and ancient beach rocks (Patel, 1991). The significance of these bioclastic shore deposits in the study of Late Quaternary sea level changes in the region has been discussed by Bhatt and Patel (1998). The Chaya Formation is divisible into two members, viz., the Okha Shell Limestone Member which comprises white colored shell rich limestone and conglomerate of approximately 10 m thickness and the Aramda Reef Member made up of coralline limestone and found well exposed near village Aramda and attains a thickness of approximately 4 m (Bhatt, 2000). Recently Pandey *et al.* (2007) have added the Calearenite Member in this Formation and named it as Porbandar Calearenite Member. Rocks belonging to the Chaya Formation are encountered along the coastal belt at an elevation range of 4 m to 10 m. The Formation has been assigned Middle to Late Pleistocene age (Bhatt, 2003).

Holocene Deposits

The Holocene record of Saurashtra has not yet been investigated with much detail. It is characterized by stabilized coastal dunes, raised mudflats, shell beds, dead coral reefs, etc., that can be prominently used to re-construct the Holocene history of the region. Apart from these, the present day fluvial deposits, pediment debris, beach and tidal clay deposits etc. are considered under the Holocene deposits. De (1989) has classified the Holocene deposits from the southern Saurashtra into the Katpar Formation and the Mahuva Formation. The ancient pedogenised tidal flats and clays have been designated as the Katpar Formation of Middle Holocene age, whereas, alluvium, coastal beach, dune and tidal clays of the Late Holocene age are named as the Mahuva Formation.

1.4.4. Geology of the study area

The present study pertains to the Quaternary sequences exposed along the coastal tracts of southern Saurashtra, and hence, outcrops of the same have been recorded with more details **(Figure 1.5)**. As stated earlier, the Quaternary sequences consist of the Miliolite and the Chaya Formations

which are textural varieties of bioclastic (shell) limestones. The deposits of Miliolite Formation occur in the form of costal cliffs, shore platforms, coastal dune ridges and obstacle dunes. They contain allochems and lithoclasts cemented togerther by sparite cements. These can be termed as 'calcarenite' (Grabau, 1904) and stratigrphically can be classified as the Adityana Member of the Miliolite Formation. The deposits of Chaya Formation are mainly exposed as cliffs and benches. These are rich in large bioclasts like bivalves, gastropods, corals and algae and are termed as 'calcirudite' (Grabau, 1904). The Chaya Formation also bears fragments of older Miliolite units. The moderate to deep quarry sections and natural cuttings indicate more than one episode of Miliolite deposition with minor periods of quiescence.

1.5. Scope and objective of the present work

A survey through the available literatures (as discussed in section 1.1.) reveals that the Miliolites of Saurashtra are an important repository of Late Quaternary climate driven aeolian processes, eustatic and neo-tectonic changes as well as anthropogenic and faunal activities. The Miliolite deposits in the study area register younging of ages of the exposed sections on moving from east to west along the southern Saurashtra coast from Gopnath (>156 ka) to Diu (~45 ka) **(Figure 1.5)**. Thus, the exposed Miliolite sequences present a chance of understanding the aeolian depositional system and processes from the oldest to the youngest event spanning over a time window of ~100 ky. However, from sedimentological point of view, a survey through the earlier works reveals that a gap still exists in understanding the Saurashtra Miliolites from the viewpoint of aeolian depositional components, dune building processes and controls on sedimentation. Thus, a detailed sedimentological analysis is indispensable for unravelling and understanding the coastal dune building processes and controls that would augment the study of similar deposits in the Afro–Asian monsoonal belt in particular and the coastal belts in other parts of the world in general. While aeolian deposits of Proterozoic age from the Indian mainland have been studied in detail (Chakraborty, 1991; Bose *et al.*, 1999; Biswas, 2005; Basu *et al.*, 2014), the present study brings a new approach, hitherto unattempted, of looking into the aeolian deposits of Quaternary age occurring along the coastal tracts of peninsular India.

As far as the geomorphological studies on the Miliolites of southern Saurashtra are concerned, a large part of the effort so far has been expended on establishing the tectono-eustatic changes along the southern Saurashtra coast and understanding the neo-tectonic activities. Miliolite cliffs along the southern Saurashtra coast have been studied for their notches (and raised notches) and associated platforms (and raised platforms), but somehow lack detailed study with the objective of understanding their interaction with the modern day coastal processes. Rather, more emphasis has been laid on finding evidences for establishing tectono-eustatic changes in the area. Literature

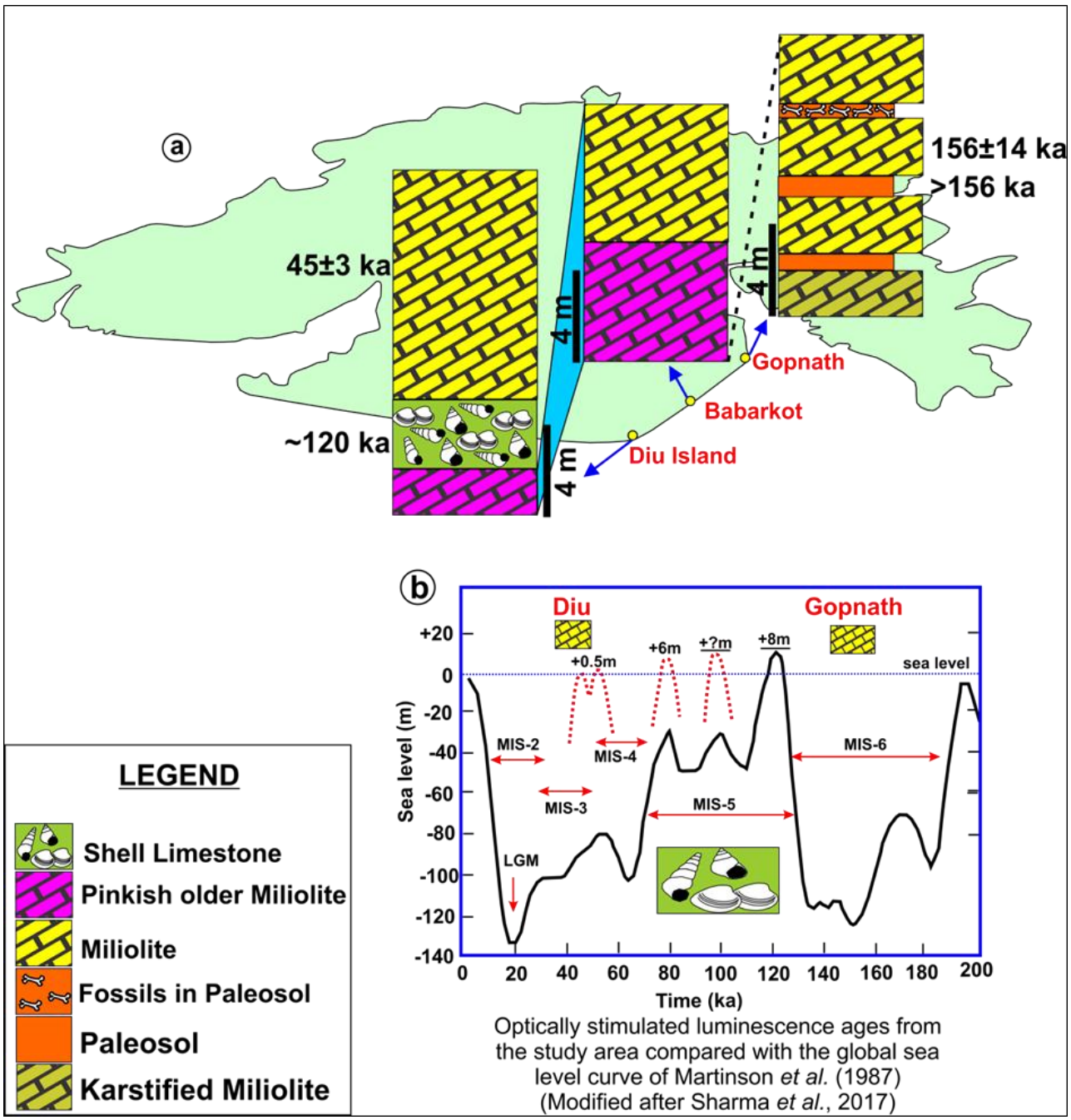

Figure 1.5. Distribution of different litho-units exposed along the coastal tracts in the study area. (a) The present study pertains to the Quaternary sequences exposed along the coastal tracts of southern Saurashtra. The distribution of the different litho-units exposed along the coastal tracts in the study area, available OSL ages and stratigraphic correlation are presented here. **(b)** A comparison of the available OSL ages with the global sea level curve of Martinson *et al.* (1987) brings out the relationship between the depositional phases and sea level oscillations *(Modified after Sharma et al., 2017).*

review further reveals that as far as the studies on coastal aeolianites in different parts of the world are concerned, they have mostly been focused on specific geomorphic issues and lack behind in representing the plethora of geomorphological expressions that are exhibited by aeolianites upon

interaction with the coastal processes. The present study carried out on the coast fringing Quaternary aeolianite deposits of southern Saurashtra tries to bring out the different facets of the geomorphology of coastal aeolianites in order to capture the geomorphic response of the aeolianites to the coastal processes of the present and the past, especially, considering their global distribution, geomorphological significance and the influence they can cast upon the coastal anthropogenic activities.

Thus, the objectives of the present study are:

- Understanding the aeolian depositional processes, depositional environment, dune morphology and morphodynamics
- Understanding the geomorphic response of the costal cliffs and platforms to the coastal processes

1.6. Methodology

For sedimentological studies, the aeolian litho-units were classified into sedimentary 'facies' based on lithology, internal structure and bed geometry. Each facies was further sub-divided into 'sub-facies' based primarily on the variations in internal structure of the parent facies. This approach was adopted to identify and document the minor variations in sedimentary structures within the parent facies so that the subtle variations in the inherent depositional processes and mechanisms could be analysed. Facies classification was then followed by detailed description and analysis of each facies. Miliolite succession was laterally mapped in a horizontal by vertical 1 m X 1 m grid and the data was compiled as a series of two-dimensional panels. Each panel records the sedimentary structures, stratification types, latero-vertical extent of facies, spatial arrangement of sets of strata and bounding surfaces and dip-azimuth readings from the cross-bedded units and bounding surfaces. Based on the occurrence of different facies, their geometry, lateral extent and bounding surfaces facies associations were established to identify the different phases of aeolian sedimentation. Finally, the results of facies analysis and aeolian architectural inputs were integrated into a conceptual stratigraphic and depositional model for the aeolian succession in the study area.

Geomorphological studies entailed the documentation of the lithology, internal structure, weathering conditions, vegetation cover, biological activities as well as wave and tide action on the coastal cliffs and shore platforms through field notes, sketches and photographs. However, more emphasis was laid on the study of the coastal cliffs. The study areas were visited during fair weather winter months for about four years (2015–2018). Measurements were made using a compass and a measuring tape. Cliff profiling was done using a handheld laser distance meter (Kazmer and Taborosi, 2012b) Leica Disto D510 (measuring accuracy of ±1mm) and the cliff profiles were generated by plotting the spatial relationships between the measured points using *Microsoft Excel*.

Scaled photographs of the notches were used to measure their geometric parameters (D_R, D_H, H_R, H_F, Eo) with an error percentage of ±5%. Locations of field observation were recorded by a GPS unit. The tide tables were obtained from *https://www.tide-forecast.com* during the field visits.