Summary

The Quaternary sediments of Gujarat, in western India, preserve a record of a complex interplay of eustatic, climatic and tectonic changes. 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 have been introduced in the geological literature as 'Miliolites' or 'miliolitic limestone'. The Miliolites belong to an age range of >156 ka to 45 ka and are similar to aeolianites elsewhere. The coastal aeolianites of southern Saurashtra gradually become younger in age while moving from east to west along the coastline. Aeolian deposits of ages similar to those found in Saurashtra have also been reported from the Thar Desert in NW India and from Southern Arabia. 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. 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. Considering the significance of Saurashtra Miliolites as a Late Quaternary sedimentary archive, 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. However, a gap still exists in understanding these deposits from the viewpoint of aeolian depositional components, dune building processes and controls on sedimentation. Another aspect of the coast fringing Miliolites is the land–sea interaction exhibited in the form of cliffs, marine terraces, wave-cut platforms and marine notches. This opens up a vast area of research pertaining to the understanding of the contemporary geomorphology of the aeolianites in terms of their geomorphic responses to modern day coastal processes, especially, when considered in terms of their global distribution and hence the influence they can cast upon the coastal anthropogenic 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. In 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.

The carbonate deposits along the southern Saurashtra coast were studied in three sectors, viz., Gopnath [optically stimulated luminescence (OSL) age: >156 ka], Babarkot and Diu Island (OSL age: ~45 ka), moving from east to west along the coastline. The Miliolite units along the southern Saurashtra coast are internally characterized by three basic lamination types, viz., grainflow, grainfall and wind ripple laminae accounting for *ca* 80%, 10% and 10% of the sedimentary succession, respectively. The grainflow strata are attributed to have been formed by avalanching on dune slip faces in the form of sand flow when deposition in zones of flow separation caused the slope angle to reach the initial angle of yield. The presence of grainfall lamination indicates that there must have been a zone of flow separation leeward of the dune crests, where, previously saltating grains fall on to the surface because of the change in energy conditions around the lee face. Wind ripple laminae are interpreted to belong to sub-critical climbing translatent strata and on microscopic examination are characterized by inverse grading. Wind ripples occur on interdune flats, on the stoss sides of dunes and on lee slopes that are inclined less steeply than the angle of repose.

Four types of aeolian bounding surfaces are recognized, viz., the surfaces which form in response to the migration of primary bedforms within an erg system (Type-I); the surfaces which form in response to the migration of secondary bedforms over large-scale primary bedforms (Type-II) and are bounded by Type-I surfaces; the reactivation surfaces (Type-III) that indicate changes in the character of the winds and are bounded by Type-II surfaces; and, the surfaces of unconformity (Type-IV) representing cessation of dunal activities.

The aeolianite succession in the study area has been classified into seven major facies and eleven sub-facies based on lithology, internal structure and bed geometry. The major facies are: plane laminated facies; cross-stratified facies; tabular sets of low angle cross-laminae; karst facies; paleosol facies; pinkish buff colored Miliolite facies; and, shell limestone facies. The plane laminated facies and the tabular sets of low angle cross-laminae are interpreted to be composed of subcritical climbing translatent strata formed due to migration and climbing of wind ripples under conditions of net sedimentation and have been deposited in interdune areas or as sand sheets. The cross-stratified facies are deposits of migrating dunes with abundant slip faces. Karst facies are attributed to karstification through dissolution processes, while, paleosol horizons indicate lengthy episodes of landscape stability. Thus, both karst and paleosol facies represent cessation of dunal activies. Pinkish buff colored Miliolite facies is characterized by strong diagenetic cementation and at places, even possible recrystallization and indicate a temporal break in aeolian sedimentation in the region which allowed for extensive diagenetic alteration of the pre-existing Miliolites. Shell limestone facies represent the bioclastic shore deposits formed during the last interglacial high sea stand.

The different dune–interdune sequences were deposited under dominantly dry aeolian conditions, wherein, the water table and its capillary fringe were at a depth below the depositional surface such that they had no effect on the substrate. In terms of regional water table, this suggests that the palaeo-coastline was further seaward of its present position and the dune–interdune sequences were deposited further inland. The presence of paleosol horizons in the older Miliolite record of Gopnath indicates occasional climatic amelioration from drier to wetter climatic conditions. However, the absence of such paleosol horizons in the comparatively younger Miliolite sequences of Babarkot and Diu indicates that the wetter climatic phases gradually became redundant and dominantly arid conditions of deposition prevailed over the area.

The high percentage of grainflow strata indicate migrating dunes with well-developed avalanche slip faces. The unimodal foreset dip distribution indicates that the majority of the dune slip faces were oriented perpendicular to the wind. The thick and laterally extensive cross-stratified Miliolite units of Gopnath, Babarkot and Diu are attributed to deposition by large transverse dune types. The general dominance of grainflow strata links the depositing aeolian dunes, at least qualitatively, to large crescentic dunes, which with the exception of the isolated barchans, are best able to amass thick accumulations of cross-stratified sandstone by virtue of their downwind migration accompanied by climbing.

The aeolian depositional pattern varied quite vividly from the oldest (Gopnath) to the youngest (Diu) aeolianite record preserved over a time window of ~100 ka. These variations were in terms of depositional climate, aeolian architecture and wind regime.

Eustasy and climate both went ‘hand in hand’ in depositing the Late Quaternary aeolianite succession in southern Saurashtra and exerted their controls on the sedimentation pattern. Eustatic lowstands favoured dune building by enhancing the sediment budget and lowering of moisture content of formative south-west monsoon winds leading to drier climatic conditions. On the other hand, eustatic highstands curtailed sediment supply, and, accompanied by increased precipitation from enhanced moisture contents of the south-west monsoon winds, led to dune field stabilization. Eustatic changes affected the atmospheric pressure variations which in turn controlled the nature of the wind regime (chaotic or non-chaotic) during the deposition of the Miliolites which is evidenced from the variations of the mean wind flow directions and in some cases proliferation of Type-II surfaces. The dominantly dry and extensive dune building events in southern Saurashtra during the Late Quaternary indicate that during eustatic lowstands the formative south-west monsoon wind system did not lose its strength in terms of its capability for aeolian entrainment; however, the moisture content of these winds was significantly lowered during eustatic lowstands which could only be regained during eustatic highstands leading to dune field stabilization.

The Miliolites form spectacular cliffs all along the southern Saurashtra coastline. The Miliolite cliffs of southern Saurashtra are non-plunging and have well-defined extensive shore platforms at their base which are horizontal to sub-horizontal in nature. The cliff profiles generated indicate that the cliff faces are either nearly vertical or dipping (and possessing a gentle convexity) towards the sea at an angle of ~20º to ~35º. The cliff profiles, with the exception of those in Gopnath, exhibit the presence of active and raised marine notches, raised platforms and occasional surf notches. The intact rock strength of the Miliolites occurs in the range of 12.5 MPa to 100 MPa. The cliffs are characterized by N–S to ENE–WSW trending vertical joints which are moderate to very open, large to very large, widely spaced and possess an aperture in the range of 0.5 cm to 2 cm. The inner surfaces of the joints are smooth, irregular and possess large undulations. The joints are mostly clean in nature. The shore platforms in Babarkot and Diu are highly rugged, possess an abraded topography and comprise numerous tidal pools of varying sizes (up to 70 cm wide). The platform in Gopnath, however, is less rugged and since it lies in the gulf area, a major part of it remains covered with clay and silt brought in by tidal action which is left over the platform. The shore platform is observed to be transected by a number of vertical N–S to ENE–WSW trending joints**.**

The active marine notches are exposed to the open sea and are either isolated or laterally continuous in nature. These notches were studied for their geometric variations and different geometric parameters (Eo, D, H, D_F, D_R, H_F and H_R) were measured. The active marine notches in the study area are asymmetric ($H_R/ H_F > 1$) in nature and occur in two morphological types, viz., notches with extended roof and short, steep floor ($D_R > D_F$) (Type-A) and notches with short roof and extended floor ($D_R < D_F$) (Type-B) with Type-A notches being dominant in occurrence. A comparison between the Type-A notches of Babarkot and Diu reveals that the roofs in Type-A notches of Babarkot are more extensive compared to those in Diu. However, as far as the Type-B asymmetrical notches are concerned, there is not much variation in the geometric parameters as measured in Babarkot and Diu. For the same rock type and similar wave and tide regime, the slope of the cliff face determines the depths of the roof and floor of a notch. If the cliff is steeper than 90°, notches with long roof and short, steep floor ($D_R> D_F$) are generated. On the other hand if the cliff is gentler than 90°, notches with short roof and extended floor ($D_R< D_F$) are generated. In case of both Type-A and Type-B notches, the Babarkot notches are deeper (higher depth values, D) compared to those in Diu. The higher depth values of the notches in Babarkot indicate that the marine erosional processes are stronger and more active at the cliff bases in Babarkot area. Since Babarkot and Diu, both face the open sea and belong to the same seasonal belt, the difference in the intensity of wave and tide activities is attributed to the coastal slope which is steeper in Babarkot compared to that in Diu (as supported by the coastal slope map of Saurashtra), thus, allowing the waves and tidal currents to retain their energy while moving shoreward and have a greater impact over the cliff bases. In general, the retreat point is observed at a greater elevation (Eo) in notches in Babarkot compared to those in Diu. Since the rock type is the same and the tidal ranges are similar in Babarkot and Diu, the wave regime plays the major role in controlling the variations in notch elevations. The lower coastal slope of the Diu area retards the incoming waves and tidal currents moving shoreward and reduces their impact over the cliff bases.

An attempt was made to identify the different bioeroding and bioconstructional agents active along the Miliolite coasts of southern Saurashtra. Bioerosional and bioconstructional processes were studied in details in Diu and Babarkot, however the rates of bioerosion could not be measured. Bioerosion over the coast is brought about by microorganisms such as algae and lichens as well as macrobioeroders such as limpets, littorinids, chitons and bivalves. Bioconstruction in the form of barnacle colonies is observed on the intertidal platforms as well as the upper intertidal portions of the Miliolite cliffs.

Erosion of the shore platform is brought about by bioeroders as well as by the force created on the walls of the joints present in the shore platform by breaking waves and tidal currents entering into them. Intersection of joint sets already enlarged by wave and tide action leads to breaking away of huge portions of the shore platform. Mechanical abrasion of the platform by tidal currents leads to the development of numerous tidal pools of varying sizes rendering the platform with a rugged topography.

Miliolite cliff erosion is brought about by mechanical erosion by waves and tides, biological agents and sub-aerial processes. The sub-aerial erosion is brought about by dislodgement of huge chunks of parent rock due to dissolution processes along the vertical joint systems present in the cliffs as well as by the lateral amalgamation of the dissolution channels formed by action of meteoric water over the exposed cliff surface. Although the biological rates of erosion could not be measured but field visits clearly suggested that marine and sub-aerial processes of erosion have an upper hand over biological erosion in causing the retreat of the Miliolite cliffs. The Miliolite cliff system along the coastal tracts of southern Saurashtra belong to the ‘active’ stage where the bedrock is exposed by continuous retreat of cliff system under the influence of both marine and sub-aerial processes of erosion.

For cliffs made up of the same inherent material, their profiles depend on the relative role of marine (M) vs. sub-aerial (SA) erosional processes. With increasing role of sub-aerial over marine erosional processes, the cliff profile gradually changes from vertical (M>>SA) → sloping (M>SA) → convex-up (M=SA) → concave-up (M<SA). The analysis of cliff profiles in the study area indicates that where ever marine erosion is dominant over sub-aerial erosion, Miliolite cliffs have

vertical faces; however, where the rate of marine erosion equals that of sub-aerial erosion, the slope of the cliff face is much reduced and a gentle convexity is developed. The degree of exposure to the marine processes appears to be determined by the orientation of the coastline with respect to the incoming waves and tidal currents, hindrance at the base of the cliffs in the form of talus deposits and protective action provided by the bioconstruction rims at the platform margins. As observed in the field, the extent to which solution channels can develop within the Miliolites and the presence or absence of joints and joint spacing influence the rate of sub-aerial erosion.

In keeping with the observations made by the earlier workers, occurrence of raised platforms and three instances of raised notches along the Babarkot–Diu coastline were observed in the present study. One instance of raised platform and raised notch occur at an elevation of ~3 m (Notch-2) above the low water line (LWL) in Babarkot and Diu, while, the other two instances of raised notches occur at elevations of ~6 m (Notch 3) and ~12 m (Notch 4) above the LWL in Babarkot, respectively. While Notch 4 has been attributed to last interglacial high sea stand (~120 ka), Notch 2 has been attributed to mid-Holocene (~3 ka) high sea. The occurrence of raised notches and platforms points towards the tectonically active nature of the southern Saurashtra coast. The morphodynamic events that took place along the southern Saurashtra coastline in a time window of ~120 ka to ~3 ka were classified into stages by earlier workers. These stages, however, have been modified in the light of the present study. The landmass emerged in three stages (Stage: I–III) followed by periods of landform stability leading to the formation of the notches which today appear at different elevations. While Stage-I witnessed an upthrow of ~7 m, Stage-II witnessed an upthrow of ~3 m. Stage-III accounts for a very recent event (mid-Holocene) of landmass upheaval and has registered an upthrow of ~1 m which is in accordance with earlier studies. However, it is worth mentioning that sea level did fluctuate during the formation of the terraces and the notches, but, in the absence of available ages from the raised notches and terraces it is quite difficult to assign them to a particular sea level stand and thus to precisely decouple the relative role of tectonics and sea level fluctuations.