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SEDIMENTOLOGY OF THE QUATERNARY CARBONATE DEPOSITS OF SOUTHERN SAURASHTRA: DEPOSITIONAL PROCESSES

Vis-à-vis

COASTAL GEOMORPHOLOGY

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1. Introduction

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 carbonate 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 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 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, northwestern 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.

However, from sedimentological point of view, a large part of the efforts made so far for understanding the Saurashtra Miliolites has been expended in establishing their marine or aeolian origin, which in fact, was summarised by Mehr (1980) as an outcome of investigations made by the earlier workers on a local scale which led to over-generalized depositional models and gave rise to marine vs. aeolian controversy. When considered in terms of the significance of the Saurashtra carbonates for unravelling and understanding the Late Quaternary dune building processes and controls in the Afro-Asian monsoonal belt as well as the coastal belts in other parts of the world, a survey through the earlier works reveals that 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 (Kale, 2014). This opens up a vast area of research pertaining to understanding 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 (Cooper and Green, 2016).

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.

2. Objectives

- To identify, describe and interpret the different aeolian facies
- To gain an understanding of the aeolian architecture and facies succession
- To gain an understanding of the aeolian depositional processes, depositional environment, dune morphology and morphodynamics

- To identify the autogenic and/or allogenic controls on aeolian sedimentation and accumulation
- To establish a model for the stratigraphic evolution of the Miliolite deposits in the study area.
- To examine the costal cliffs and platforms in terms of their geomorphic expressions in response to the coastal processes
- To determine the processes of coastal cliff and platform erosion
- To understand the spatial and temporal variations in geomorphic response to the coastal processes

3. Study Area

The aeolianite cliffs along the southern Saurashtra coast were studied in three sectors viz. Gopnath (Lat: 21º 11’ N, Long: 72º 6’ E), Babarkot (Lat: 21°41’37.07’’ N, Long: 71°20’31.73’’ E) and Diu Island (north latitudes 20°44’39’’ and 20°42’00’’ and east longitudes 70°52’26’’ and 71°00’24’’) covering a stretch of nearly 155 kms from east to west along the coastline (Fig. 1.1). Gopnath and Babarkot are situated in Bhavnagar and Amreli districts of Gujarat respectively. Diu Island is a Union Territory and 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 north by intertidal mudflats. From east to west along the coastline the spring tidal range is ~ 7m at Gopnath, ~2m at Babarkot and ~ 2m at Diu (Kazmer, et al., 2015; Mahapatra and Ramakrishnan, 2015). While Gopnath occurs in close proximity to the Gulf of Khambat, Babarkot and Diu face the open sea. The significant wave height varies between 2-3m (Mahapatra and Ramakrishnan, 2015).

4. 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 serie sof 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

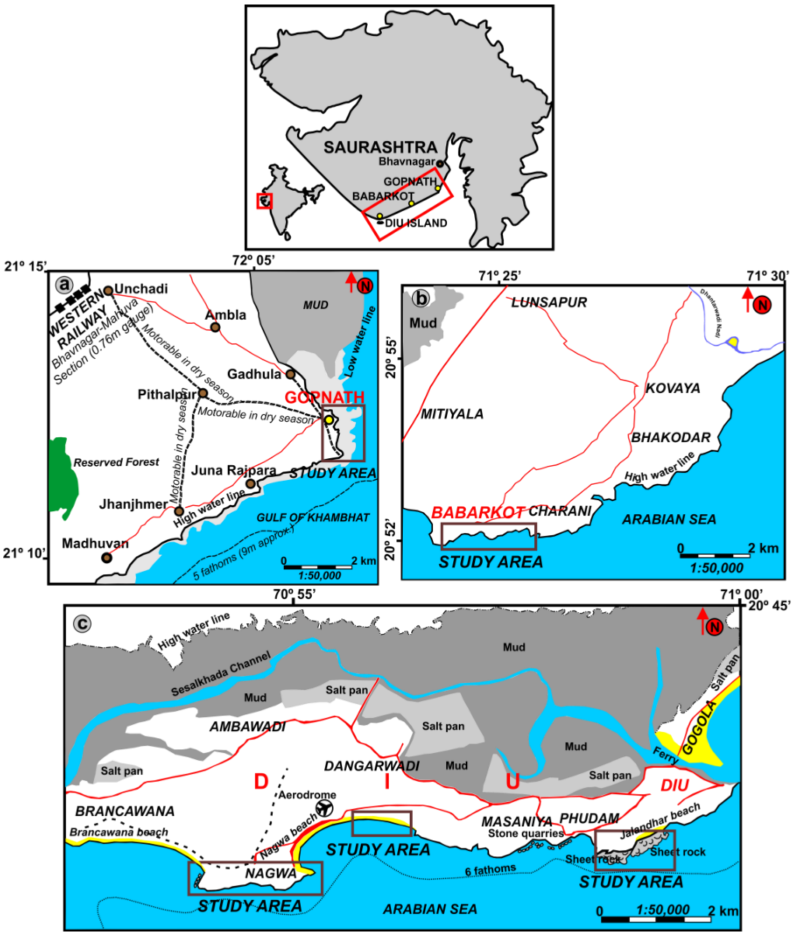

Figure 1.1. Study area. The present study was carried out along the southern coast of Saurashtra, India. Cliff forming Miliolites were studied for their sedimentological and geomorphological attributes in three sectors, viz., (a) Gopnath, (b) Babarkot and (c) Diu Island covering a stretch of nearly 155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

bounding surfaces facies associations were established to identify the different phases of aeolian sedimentation. Finally the results of facies analysis and aeolian architectural inputs, as obtained from lateral mapping, 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 and groundwater activities as well as wave and tide action on the coastal cliffs and shore platforms through field notes, sketches and photographs. Measurements were made using a compass and measuring tape.Cliff profiling was done using a handheld laser distance meter (Kazmer and Taborosi, 2012) 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*. Locations of field observation were recorded by a GPS unit. The tide table was provided by https://www.tide-forecast.com during the field visits.

5. Sedimentological Analysis

5.1. Aeolian Stratification Types

Three different aeolian stratification types were distinguished viz. grainflow lamination, grainfall lamination and wind ripple lamination comprising ca. 80%, 10% and 10% of the aeolianite deposits respectively. The grainflow strata is formed by avalanching on dune slipfaces in the form of sand flow and grainfall strata indicate the presence of a zone of flow separation leeward of the dune crests (Hunter, 1977). Wind ripple lamination belongs to sub-critical climbing translatent strata of Hunter (1977) and indicates deposition on inter-dune flats or on the stoss sides of dunes and on lee slopes that are inclined less steeply than the angle of repose.

5.2. Aeolian Bounding Surfaces

At least four types of bounding surfaces (Type-I-IV) are recognized in the study area and compared to those described by Brookfield (1977) and Kocurek (1988). The type-I surfaces are compared to first-order surfaces of Brookfield (1977) which form in response to the migration of primary bedforms within an erg system, interdune migration surfaces of Mountney and Howell (2000) and sand-drift surfaces of Scherer and Lavina (2005). Type-II surfaces are compared to second-order surfaces of Brookfield (1977) which form in response to the migration of secondary bedforms over large scale primary bedform and also to superimposition surfaces of Mountney and Howell (2000). Type-III surface is unconformity surface and is compared with super bounding surface (Kocurek, 1988) that form as a result of complete or partial termination of ergs or dune fields (Mountney and Howell, 2000). Type-IV surfaces are compared to the third order surfaces of Brookfield (1977) which are reactivation surfaces indicative of changes in character of the wind, either its velocity or direction, to which the cross-bedded units could not fully respond.

5.3 Aeolian Facies

Based on lithology, internal structure and bed geometry litho-units were classified into 'facies' and further sub-divided into 'sub-facies' based primarily on the variations in internal structure of the parent facies. The facies (and subfacies) identified are viz. (i) Plane laminated facies (Thin- and Thick-Plane Laminated), (ii) Cross-stratified facies (Thinly- and Thickly Cross-stratified), (iii) Tabular sets of low angle cross-laminae, (iv) Karst facies, (v) Paleosol facies (Subfacies-a, b, c and d), (vi) Shell limestone facies and (vii) Pinkish buff colored Miliolite facies. A brief description and interpretation of the aeolian facies is furnished in Table-1.

6. Coastal Geomorphology

6.1. Miliolite Cliffs

6.1.1. General characteristics

The Miliolites form spectacular cliffs all along the coastline of southern Saurashtra and vary in height from 3-15m.The Miliolite cliffs of southern Saurashtra are non-plunging (Sunamura, 1992) with well-defined, extensive, horizontal to sub-horizontal shore platforms at their base, and thus, attest to Type-B platform of Sunamura (1992). The Miliolites, in general, are moderately hard to hard (intact rock strength: 12.5-100 MPa) as observed by mechanical breaking from hammer blows using 1 Kg geological hammer (Hack and Huisman, 2002). The cliff sections are characterized by vertical NS to ENE-WSW trending joints (Figure). These joints are moderately to very open, large to very large, widely spaced and have an aperture of 0.5-2cm. The inner surfaces of the joints are smooth, irregular and possess large undulations. The joints are mostly clean in nature. Solution channels formed due to dissolution processes caused by meteoric water infiltration abound the top exposed surfaces of the cliffs and give it a honey-comb appearance.

6.1.2. Cliff Profiles

The Gopnath cliff profile has a typical ‘L’ shape and varies in height from 8–15 m. In general, the cliff profile can be subdivided, from bottom towards the top of the cliff, in to three distinct morphological sections viz. a sloping base, the steep cliff face and an angular crest. The base of the Gopnath cliff section (up to 5 m elevation) slopes seaward at an angle of ~25° and gives way to a steep (~90°) cliff face. The top 0.2 m of the cliff is rather angular in nature and stands out distinctly. The Gopnath cliff section is devoid of marine notches; however isolated, shallow sea caves are observed at the base of the cliff section.

The Miliolite cliffs in Babarkot are inadvertently characterized by sharp, angular, concave bases and angular cliff faces. The cliffs vary in height from 6–15 m. A close examination of the cliff profiles indicate the presence of active marine notches, surf notches, raised platform and raised marine notches. The cliff face occurs in two morphological variations: (i) nearly vertical and (ii) dipping towards the sea at an angle of ~20°–35°. Some of these dipping cliff faces have a gently concave upward shape.

The Miliolite cliffs in Diu Island are inadvertently characterized by sharp, angular, concave bases and angular cliff faces. The cliffs vary in height from 3–8 m.The cliff face dips towards the sea at an angle of ~20°. A close examination of these cliff profiles indicate the presence of active marine notches, raised platform and raised marine notches.

6.2. Marine notches

Field observations in Babarkot and Diu suggest the presence of tidal notches and occasional surf notches. The tidal notches are exposed to the open sea and are either isolated or laterally continuous in nature. The roofs and the floors of the notches are found to be highly irregular and pitted. While the roof of the tidal notches is colonized by littorinids and limpets, the floor is colonized by barnacles, limpets and algae. The present day tidal notches in Babarkot and Diu were studied in details for their geometric variations. The notch parameters were measured following Pirazzoli (1986) and Sisma-Ventura et al. (2017) and are provided in Table-2. As indicated by the tabulated notch parameters, the asymmetry ratio (H_R/H_F) is much greater than 1, indicative of the asymmetrical nature of the tidal notches. However a comparison between the D_R and D_F values for the different notches indicate that there are two principal types of asymmetrical notches viz. (A) notches with extended roof and short, steep floor ($D_R > D_F$)and(B) notches with short roof and extended floor ($D_R < D_F$). However, the type-A notches are the dominant variety in both Babarkot and Diu. Further, it is observed that the type-A asymmetrical notches differ among themselves in terms of the extension of their roofs (D_R and H_R values). A comparison between the type-A notches of Babarkot and Diu reveal that the roofs in type-A notches of Babarkot are more extensive compared to those in Diu Island. 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. In case of both type-A and type-B notches, the Babarkot notches are deeper (higher depth values, D) compared to those in Diu. In general, the retreat point is observed at a greater elevation (Eo) in notches in Babarkot compared to those in Diu. In general, the retreat point (Eo) is observed at a greater elevation in notches in Babarkot compared to those in Diu Island. The shape ratio (D/H) for the notches does not show any linear relationship between the notch parameters viz. the depth of the retreat point (D) and the height of the cliff (H). The D/H ratio of type-A and type-B notches of Babarkot and Diu Island varies between 0.18–0.78.

6.3. Miliolite platforms

The Miliolite cliffs along the coastal tracts of Saurashtra overlook the shore platform which occurs as a laterally extensive geomorphologic unit and exhibits horizontal to sub-horizontal dips. The shore platforms in Gopnath, Babarkot and Diu are rocky in nature with the exception that the shore platform in Diu is interspersed by pocket beaches. The shore platform is composed of Miliolites, however in Diu, shell limestone belonging to the Chaya Formation of Late Pleistocene age (Mathur and Mehra, 1975), also forms an important lithological component of the shore platforms. The platforms in Babarkot and Diu island 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 a major part of it remains covered with clay and silt brought in by the tidal action. The shore platform is inhabited by littorinids, limpets, chitons, barnacles, lichens and filamentous algae and is transected by a number of vertical NS to ENE-WSW trending joints.

6.4. Bioerosion and Bioconstruction

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. Algae accommodate the upper intertidal zone at the cliff base. The buff colored Miliolites in the upper intertidal zone are progressively corroded due to microbial activity imparting a dark-colored pitted appearance. Lichens (Figure) occur in the supratidal zone and bioerode the rock surface by etching tiny shallow holes while excreting oxalic and other acids at the rock surface (Adamo and Violante, 2000; Chen et al., 2000). Limpets (Patella vulgata)possess radula with silica-containing teeth used to scrape algae off and from within rock substrate (Kazmer et al., 2015) and thus cause mechanical wear and tear of the substrate.Littorinid snails inhabit rocky shorelines and specialize in scraping biofilms and turf algae off exposed surfaces. They are also capable of scratching the rock with their radulas and consuming endolithic organisms as well (Kazmer et al., 2015). Chitons are inhabitants of the intertidal zone and produce homing scars-larger pits that accommodate an individual animal’s body size and represent its long term residence (Kazmer and Taborosi, 2012) (Figure). Chitons are armed with a radula of extremely hard magnetite-capped teeth that allow them to easily remove layers of substrate while grazing on biofilms (Rasmussen and Frankenberg, 1990). Lithophaga borings of circular to dumbbell shape are observed on the present day notch roof and supratidal portions of the Miliolite cliffs (Figure) as well as in the pebbles and cobbles littered over the shore platform (Figure). Bioconstruction in the form of barnacle colonies (genus Balanus) is observed on the intertidal platforms as well as the upper intertidal portions of the Miliolite cliffs. The barnacle colonies act as bioprotecting agents by forming a cover over the exposed bedrock and minimizing its exposure to bioeroding organisms (Lace and Mylorie, 2013). However according to Kleemann (2001) and Pappalardo et al. (2017) the barnacles can also simultaneously act as bioeroders, likely causing corrosion of the rock surface by fostering dissolution of the sandstone carbonate matrix.

6.5. Coastal erosional processes

6.5.1. Erosion of the cliffs

Erosion of the Miliolite cliffs is brought about by marine, biological and sub-aerial processes of erosion. The presence of active notches and occasional sea caves at the base of the Miliolite cliffs suggest towards the active role of the marine processes of erosion. As discussed earlier, erosion of the Miliolite cliffs by biological agents is brought about by the actions of microorganisms such as algae and lichens as well as macrobioeroders such as limpets and littorinids. Sub-aerial erosive processes bring about large scale mass wasting of the Miliolite cliffs. The mass wastage of the Miliolite cliffs is brought into effect by two different sub-aerial erosional mechanisms. The first mechanism involves the widening of the already existing vertical joints through dissolution processes actuated by the passage of meteoric water along them and followed by subsequent detachment and toppling of a large block of rock. The second mechanism involves the development of vertical solution channels through meteoric water action over the exposed upper surface of the Miliolite cliffs which gradually get deepened and widened by progressive dissolution resulting from through flow of meteoric water. In due course of time, these channels happen to encounter one or more bedding planes allowing the meteoric water to spread along the same and cause large scale erosion through dissolution processes. At the same time, the vertical solution channels while widening laterally do coalesce with one another creating localized gaps or discontinuities within the parent rock body. At a certain point of time, lateral undermining of the substrate by flow of water along the bedding plane(s) and the gradual vertical detachment from the parent rock due to gaps generated within it by lateral coalescing of the solution channels lead to dislodgement of a huge block of Miliolite.

6.5.2. Erosion of the platforms

The erosion of the platforms is brought about by bioeroders as well as by the action of breaking waves and tidal currents. The role of bioeroders has already been discussed in section 6.4. As evidenced from field visits, the erosion of the platforms by tides and waves is actuated by mechanical abrasion as well as by the impact force of the breaking waves. Mechanical abrasion of the platform leads to the development of numerous tidal pools of varying sizes rendering the platform with a rugged topography. Large portions of the shore platform also get eroded away due to the breaking waves and tidal currents entering into the joint systems present in the platform. The water entering with force inside the joints tend to widen them by putting pressure on the joint walls. The joints also get widened by dissolution of the parent rock material by water action. During these processes, whenever sets of joints intersect, large blocks of Miliolites are dislodged, eroded and washed away into the open sea leading to large scale mass wasting of the platforms.

7. Discussion

7.1. Aeolian Depositional Processes

7.1.1. Type of aeolian system

The absence of wet or damp features, such as adhesion ripples, burrows, bioturbation, animal tracks and trails, desiccation cracks, etc. (Kocurek and Dott, 1981; Kocurek and Havholm, 1993; Mountney and Thompson, 2002; Scherer and Lavina, 2005) indicate that 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 surfacesuch that they had no effect on the substrate.

7.1.2. Dune morphology and morphodynamics

The unimodal foreset dip distribution indicatesthat the majority of the dune slip faces were oriented perpendicular to the wind (Clemmensen andAbrahamsen, 1983). The thick and laterally extensive cross-stratified Miliolite units of Gopnath, Babarkot and Diu are attributed to deposition by large transverse dune types. The apparent lack of inverse graded toeset strata and dominance of grainflow strata might suggest that the transverse dunes had well-developed slip faces and were affected only by weak and variable lee-eddy winds (Clemmensen and Abrahamsen, 1983; Kerr and Dott, 1988).

7.1.3. Aeolian architecture, growth and destruction of dunes

The coastal cliff section of Gopnath is characterized by the occurrence of weathered aeolianite (Type-IIa karst) at the base which is overlain by a vertically stacked association of cross-stratified, plane-stratified and palaeosol facies. Thus, the upper surface of the basal weathered aeolianite is a surface of unconformity named here as T3S-1and is compared with the super bounding surface of Kocurek (1988). Based on the occurrence of different facies, their geometry, lateral extentand bounding surfaces, at least three different episodes of dune building are identified. The different episodes of dune building belong to two different facies associations (facies associations A and B) bearing eustatic and climatic implications. Facies association A comprises isolated lensoidal thickly (Facies 2b) to thinly cross-stratified facies, thick (Facies 1b) to thin (Facies 1a) plane-stratifiedfacies and palaeosol facies (Facies 5a to5c). Lateral facies mapping reveals that the lensoidal cross-stratified units occur either as isolated bodies or in places climb over one another and are separated by stretches of plane stratified facies. This suggests localized dune building over a vast stretch of sheet sand. Therefore during this phase of aeolian sedimentation, dune building activities were only occasional, occurring whenever there was intensification of wind energy or increase in sand availability (Trewin, 1993; Veiega et al., 2002; Biswas, 2005). The lensoidal cross-stratified units show a maximum thickness of 0.6 to 2.0 m and extend laterally for 10 to 56 m. The height of depositing aeolian dunes is calculated using the formula (Rubin and Hunter, 1982) and occurs in the range of 0.63 to 2.63 m. Facies association B overlies the stacked palaeosol horizons belonging to Facies 5b and 5c. This facies association comprises verticallys tacked thinly cross-stratified facies (Facies 2a) with an intervening palaeosol horizon belonging to Facies 5d. The height of the depositing dunes is estimated (Rubin and Hunter, 1982) to be 3.4 m. The laterally extensive dune units represent renewed aeolian activities.

Aeolian sedimentation pattern happened to be comparatively different during the times of deposition of the relatively younger Miliolite succession of Babarkot in terms of the depositional climate, mean wind flow direction and the wind regime. In the first instance, the absence of paleosol horizons within the Miliolite succession in Babarkot indicates that the wetter climatic phases gradually became redundant and dominantly arid conditions of deposition prevailed over the area which continued even during the deposition of the still younger Miliolite succession in Diu area. Secondly, although, the regularized aeolian system (indicated by Facies association B) that was established during the deposition of Gopnath Miliolites continued into the times of aeolian sedimentation in Babarkot area resulting into deposition of laterally extensive, thick, cross-stratified aeolianite units; however, compared to the wind directions (dominantly NNE) that existed during the times of deposition of Gopnath aeolianites, the mean wind flow direction during the times of deposition of the relatively younger Babarkot aeolianites varied widely from NE to SE and to SSW indicative of frequent changes in wind direction which in some cases were completely reverse from the general trend. Thirdly, the height of the depositing dunes is estimated (Rubin and Hunter, 1982) to be 0.2–2.7 m (maximum thickness of 0.4–2.06 m and lateral extension for 2.5–60 m) which is comparatively smaller than those responsible for depositing the older Gopnath aeolianites. Fourthly, the younger aeolianite succession of Babarkot, as compared to the underlying older succession of Gopnath is characterized by proliferation of Type-II surfaces indicative of frequent dune superimposition suggesting more chaotic wind regime as also indicated by wide range of mean wind flow direction.

The cross-stratified Miliolite succession (Facies 2) in Diu area rests over the shell limestone facies (Facies 6) separated by thin plane laminated Miliolite facies (Facies 1a). The Shell limestone facies is underlain by older Miliolites and the contact between the two is clearly discernible at places and defines a surface of unconformity (T3S-5) which is attributed to MIS-5 high sea strand (Gupta and Amin, 1974; Bruckner et al., 1987; Juyal et al., 1995; Mathur and Pandey, 2002; Mathur, 2005; Bhonde, 2004). As compared to the cross-stratified units of Babarkot, those in Diu show lesser superimposition of successive dune forms and lesser variation in the mean wind flow direction (NE to ESE) indicating deposition under more stable wind conditions compared to those which deposited the underlying older Miliolite sequences. The height of the depositing dunes is estimated (Rubin and Hunter, 1982) to be in the order of 2.5 m.

7.1.4. Controls on sedimentation

Alternating periods of accumulation and erosion within ergs can occur as a result of changes related to eustasy, tectonics and/or climate (Kocurek, 1988). As far as the aeolian succession in south Saurashtra is concerned, based on the facies occurrences and their architectural pattern, eustasy and climate appear to have played a pivotal role in sedimentary accumulation. Eustasy regulates the availability of sediments for aeolian entrainment (Bauer et al., 2009) and as far as the Saurashtra aeolianites are concerned, eustasy also regulates the strength of the formative winds belonging to the south-west monsoon wind system which in turn controls the periods of wetness and dryness (Glennieet al., 2002; Khadkikar, 2004), and consequently the periods of fluvial and aeolian activities, respectively (Juyal et al., 2006). However, it is worth mentioning that dune building events in south Saurashtra indicate that, during eustatic lowstands, the south-west monsoon wind system did not lose its strength in terms of its capability for aeolian entrainment. The deposition of south Saurashtra aeolianites under dominantly dry conditions indicates that the moisture content of these winds was significantly lowered during eustatic lowstands.

7.2. Geomorphological analysis of the cliff and notch profiles

7.2.1. Cliff profiles and relative role of erosional processes

The cliff profiles in the study area have been analysed using the methods enumerated by Emery and Kuhn (1982). According to them, for cliffs made up of the same inherent material, their profiles depend on the relative role of marine vs. sub-aerial erosional processes. With increasing role of sub-aerial over marine erosional processes, the cliff profile gradually changes from vertical → sloping → convex-up → concave-up. However, where ever resistant rocks occur at the top or at the base of the cliffs, the tops and bases of such profiles become angular in nature. The cliff profiles as observed in the study area are characterized by either vertical or sloping cliff faces and inadvertently with angular tops. The cliffs with vertical faces, are thus, attributed to have formed under intensive marine erosional activities, while those with sloping faces were formed where the intensity of marine erosional processes were at par with those of the sub-aerial erosional processes. Since the underlying parent material is the same for the coastal cliffs, the relative importance of marine and sub-aerial processes acting over these cliffs is attributed to the orientation of the coastline with respect to the incoming waves and tidal currents as well as to the protective role of bioconstruction rims over the platforms (Antonioli et al., 2015; Sisma-Ventura et al., 2017). The orientation of the coastline determines the angle of incidence of the incoming waves and tidal currents, which in turn, controls the strength of the component force reaching the cliff base and eroding the same. Bioconstruction rims, on the other hand, act as an obstruction to the incoming waves and tides and dissipate the wave and tide energy that could reach to the cliff bases.

7.2.2. Notch geometry and geomorphological inferences

The geomorphological analysis of the notch profiles is presented under the following heads:

(i) Asymmetrical notch geometry: According to Pirazzoli (1986), the asymmetrical geometry is formed in notches when the cliff is not vertical. Under such circumstances, 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.

(ii) Notch depth (D) values: The Babarkot notches are characterized by higher notch depths (D) compared to those in Diu. Since the parent rock material is more or less of the same composition, 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. The higher intensity of marine erosional processes might be attributed to stronger wave and tide activities as well as a higher tidal range than the average. 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 in Babarkot and Diu might be attributed to the nature of the platform which might be short and steeper compared to that in Diu, thus allowing the waves and tidal currents to retain their energy while moving shoreward and have a greater impact over the cliff bases.

(iii) Notch elevation (Eo): The notches in Babarkot are characterized by greater elevation of the retreat points (Eo) compared to those in Diu island. This is attributed to a higher tidal range than that in the Diu Island.

(iv) Shape ratio (D/H): The shape ratio (D/H) for the notches does not show any linear relationship between the depth of the retreat point (D) and the height of the cliff (H). However, emaciation of wave and tide action over the cliffs due to the protection provided by abrasive platform with bio-constructions at their rims (Antonioli et al., 2015; Sisma-Ventura et al., 2017) might result into lowering of the D/H values.

7.3. Tectono-eustatic changes

The available geochronological data obtained on coral reefs and oyster from the Saurashtra coast indicate the existence of two major high sea strands corresponding to the last interglacial (MIS-5; 6-8 m of high sea) and mid-Holocene (Gupta and Amin 1974; Bruckner et al., 1987; Juyal et al., 1995; Mathur and Pandey, 2002; Mathur, 2005). These chronometric data compared with coastal geomorphic features of sea level changes suggest that the last interglacial (MIS-5) high sea strand had eroded the pre-existing Miliolite limestone sequences and deposited the bioclast rich beach ridges and associated dunes including the favoured growth of coral reefs in suitable coastal segments (Bhonde, 2004). The depositional units corresponding to MIS-5 high sea level are found in the adjacent areas occurring above the older recrystallised Miliolite limestone unit with an erosional contact (Juyal et al., 1995; Bhonde, 2004). This attests to the occurrence of unconformity surface T3S5 in Diu area as well as the occurrence of residual clasts of older Miliolite sequence within shell limestone facies (Facies 6) exposed on the platforms alongthe Diu coast. Since, the coastal Miliolites in Diu occur above the shell limestone facies (Facies 7) deposited during MIS-5 high sea and possess an age younger than those in Babarkot (Sharma et al., 2017), it is evident that the Miliolite sequences of Babarkot pre-dated the MIS-5 high sea strand.

The present study indicates the occurrence of two sets of raised platform and notches. One set of raised platform and notches occur at 3 m above LWL in Babarkot and Diu, while the other raised notches occur at an elevation of 6 m above the LWL as observed in Babarkot. Since the Miliolites in Babarkot pre-dated the MIS-5 high sea strand, the marine notch at an elevation of 6 m from the datum was supposedly formed during that time. The lower notches and platforms at an elevation of 3m from the reference datum occur above the present day notches. Using the 14C ages of Cerithium and Turbo from Porbandar and Mithapur areas, Mathur et al. (2004) invoked a 2 to 3 m higher mid-Holocene sea that had a falling trend since. The ages of oyster reefs occurring in Rupen river bed, north of Diu also indicate a 2 m higher sea at 2.5 and 3.3 ka (Juyal et al., 1995). The oyster bed occurring at 1 m AMSL near Khada Bandar has yielded a 3.47 ± 0.11 ka 14C ages. This suggests the Holocene high sea level of about 2 m in Saurashtra which correlates well with the global sea level of this time. Thus, the occurrence of notches and platforms at an elevation of 3 m above the reference datum and occurring over the present day notches suggest their formation during the mid-Holocene and subsequent tectonic upliftment in the order of 1 m within duration of nearly 3 ka.

8. Conclusions

(i) The Miliolite units along the south Saurashtra coast are internally characterized by three basic lamination types: grainflow, grainfall and wind ripple laminae accounting for ca 80%, 10% and 10% of the sedimentary succession, respectively.

(ii) At least four types of bounding surfaces (Type-I to IV) are recognized which have been compared to those described by Brookfield (1977) and Kocurek (1988).

(iii) The Miliolite sequences were deposited under dominantly dry aeolian conditions. The presence of paleosol horizons in the oldest Miliolite sequences in Gopnath indicates occasional climatic amelioration from drier to wetter phase. Absence of paleosol horizons corresponding to the unconformity surfaces (T3S) in the younger Miliolite sequences in Babarkot and Diu as compared to those in Gopnath indicates that the wetter climatic phases gradually became redundant and dominantly arid conditions of deposition prevailed over the area during the deposition of younger Miliolite sequences.

(iv) The Miliolite sequences were deposited by transverse dune systems. The high percentage of grainflow strata indicate migrating dunes with well-developed avalanche slip faces.

(v) The wide variation in mean wind flow direction and frequent presence of Type-II surfaces in the Miliolite succession at Babarkot indicate towards aeolian sedimentation under chaotic wind conditions as compared to the underlying older Miliolite sequence at Gopnath. The chaotic wind conditions during the sedimentation of Babrkot aeolianites are attributed to variations in atmospheric pressures over the region due to eustatic changes pre-dating MIS-5 high sea strand. However, the wind regime, as indicated by the aeolian architecture, got regularized during the deposition of the Miliolite sequences in Diu, post MIS-5 high sea strand.

(vi) Eustasy and climate both went 'hand in hand' in depositing the Late Quaternary aeolianite succession in south Saurashtra. 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.

(vii) The dominantly dry dune building events in south Saurashtra 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.

(viii) The cliff-platform relationship of the coast fringing Miliolite rocks attests them to Type-B platform of Sunamura (1982) wherein the platform is nearly horizontal and terminates abruptly with a cliff.

(ix) The analysis of the cliff profiles indicates that rate of marine erosion either dominates or equals the rate of sub-aerial erosion of the Miliolite cliffs. The relative importance of marine and sub-aerial erosional processes depends on the orientation of the coastline with respect to the incoming waves and tidal currents as well as the protective action provided by the bioconstruction rims at the platform margins.

(x) The present day tidal notches notches are asymmetrical and belong to two types viz. (A) notches with extended roof and short, steep floor and (B) notches with short roof and extended floor. However the type-A notches are the dominant modern day tidal notches.

(xi) The variations in the geometric parameters of the present day tidal notches are controlled by the intensity of the incoming waves and tides, the tidal range in an area and the protection at the base of the cliffs.

(xii) Bioerosion over the Miliolite cliffs and platforms 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.

(xiii) Miliolite cliff erosion is brought about by mechanical erosion by waves and tides, biological agents, wetting-drying cycles, salt weathering 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.

(xiv) 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.

(xv) The presence of raised notches indicates that the Babarkot-Diu area experienced a tectonic upliftment in the order of 1 m within the last 3000 years.

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