Chapter 4

Discussions

4.1. Introduction

The previous chapters dealt with a detailed sedimentological analysis of the Miliolite deposits in the study area in terms of aeolian stratification types, bounding surfaces, aeolian facies and facies analysis. This was followed by the geomorphological studies which highlighted the spatial variations in the geomorphic expressions along the southern Saurashtra coast in terms of variations in the geometry of the cliffs and notches as well as entailed a study of the marine, sub-aerial and biological processes of Miliolite cliff and platform erosion. Thus, the present study encompasses the domain spanning from the deposition of Miliolites as aeolian dune systems to their geomorphic expressions as a result of land–sea interaction post deposition and subsequent lithification. Based on the detailed sedimentological analysis of the Miliolites of southern Saurashtra, the present chapter tries to capture the essence of aeolian depositional processes in terms of depositional system, dune morphology and morphodynamics, aeolian architecture, wind regime, stratigraphic evolution and controls on sedimentation. From geomorphological point of view, the present chapter tries to probe into the causative reasons behind the spatial variations in the Miliolite cliff and notch geometries along the southern Saurashtra coast in terms of the variations in the nature of land–sea interactions. Further, in keeping with the observations made by the earlier workers, the present chapter, using the geomorphic signatures of past land–sea interactions, tries to highlight the tectono-eustatic changes that took place along the southern Saurashtra coast during the Pleistocene-Holocene period.

4.2. Aeolian depositional processes

4.2.1. 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 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 (Plater and Kirby, 2011) of its present position and the dune–interdune sequences were deposited further inland. Occasional deformed or contorted strata (as in Facies 2a) may be attributed to slumping on the dune lee face as a result of sand wetting by dew or rain or by

cementation (Scherer and Lavina, 2005). Presence of animal burrows restricted to a single unit belonging to Facies 2a in Babarkot also indicates towards occasional precipitation resulting into enhanced faunal activities. The dune–interdune and paleosol sequence as observed in the Gopnath cliff system suggests episodic switching between drier and 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.

4.2.2. Dune morphology and morphodynamics

The unimodal foreset dip distribution indicates that the majority of the dune slip faces were oriented perpendicular to the wind (Clemmensen and Abrahamsen, 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 toe set 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). The general dominance of grainflow strata links the depositing aeolian dunes, at least qualitatively, to large crescentic dunes (Kerr and Dott, 1988) 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 (Brookfield, 1977; Rubin and Hunter, 1982). Paucity of third order surfaces (Brookfield, 1977; Kerr and Dott, 1988) indicates infrequent lee slope erosion and reactivation (Kerr and Dott, 1988).

The existing understanding that the aeolianites in Gopnath and the adjoining areas have been deposited by a parabolic dune system (Khadkikar, 2005) does not hold true in the present study. In the case of parabolic dunes, vegetation and/or moisture is/are regarded as the primary agent(s) for stabilizing the dune arms (McKee, 1966; Halsey *et al.*, 1990). If the Gopnath aeolianites are deposited by parabolic dunes, then role of vegetation and/or moisture should be reflected in the rock record by relevant sedimentary structures within the dune units (such as calcareous root tubules and associated scour surfaces, presence of organic debris, adhesion laminae, etc.; Halsey *et al.*, 1990). However, no such sedimentary features have been recognized. Moreover convex-up bedding as seen along the depositional dip can also be generated by migration of transverse bedforms (Rubin, 1987). Regarding the aeolian stratification types, Khadkikar (2005) has attributed the lamination types in Gopnath and the adjoining areas as grainfall deposits; however, field observations suggest the dominance of grainflow strata. Khadkikar (2005) inferred the lamination types in Gopnath to be grainfall deposits because it was assumed that grain avalanching would not take place on account of high atmospheric humidity in coastal regions or possibly due to the action of salt sprays and partial

cementation. However, if deposition of carbonate aeolianites in Gopnath and the adjoining areas is considered to be during regression (Khadkikar, 2004), then the actual position of the palaeo-coastline during the same has never been addressed. Hence, how far the action of salt sprays, which is generally restricted very close (*ca* 200 m) to the seashore (Hossain and Easa, 2011), and cementation could be responsible for arresting avalanching is quite debatable. As far as atmospheric humidity is concerned, Ravi *et al.* (2004) suggested that the threshold friction velocity (u*) decreases with an increase in absolute humidity because higher air humidity is associated with relatively moister surface soils, hence with lower (absolute) values of metric potential (ψ_m) and weaker inter-particle forces. Thus, high atmospheric humidity does not appear to hinder grain entrainment by wind energy. Interestingly, dune fields in the south-western part of Morocco (Western Sahara) are characterized by the occurrence of barchans (indicative of active slip faces) even when located in an area with relatively high air humidity (above 80% on average) and relatively high annual rainfall, even exceeding 250 mm in some areas (Zmudzka *et al.*, 2014).

4.2.3. Aeolian architecture, growth and destruction of dunes

The oldest record of Miliolites from 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 paleosol facies **(Figures 4.1 to 4.5)**. The basal weathered aeolianite is exposed only in pockets and probably belongs to an earlier existing dune system which appears to lie buried under the modern-day coastal sand cover. The nearly pedogenized nature of the basal weathered aeolianite suggests a prolonged exposure to the atmosphere, hydrosphere and biosphere together with larger throughflow of meteoric water (Khadkikar and Basavaiah, 2004). Thus the upper surface of the basal weathered aeolianite is a surface of unconformity (Type-IV surface) named here as T4S-1 and is compared with the super bounding surface of Kocurek (1988). Based on the occurrence of different facies, their geometry, lateral extent and 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 lensoidal thickly (Facies 2b) to thinly (Facies 2a) cross-stratified facies, thick (Facies 1b) to thin (Facies 1a) plane-stratified facies and paleosol facies (Facies 5a to 5c). 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;

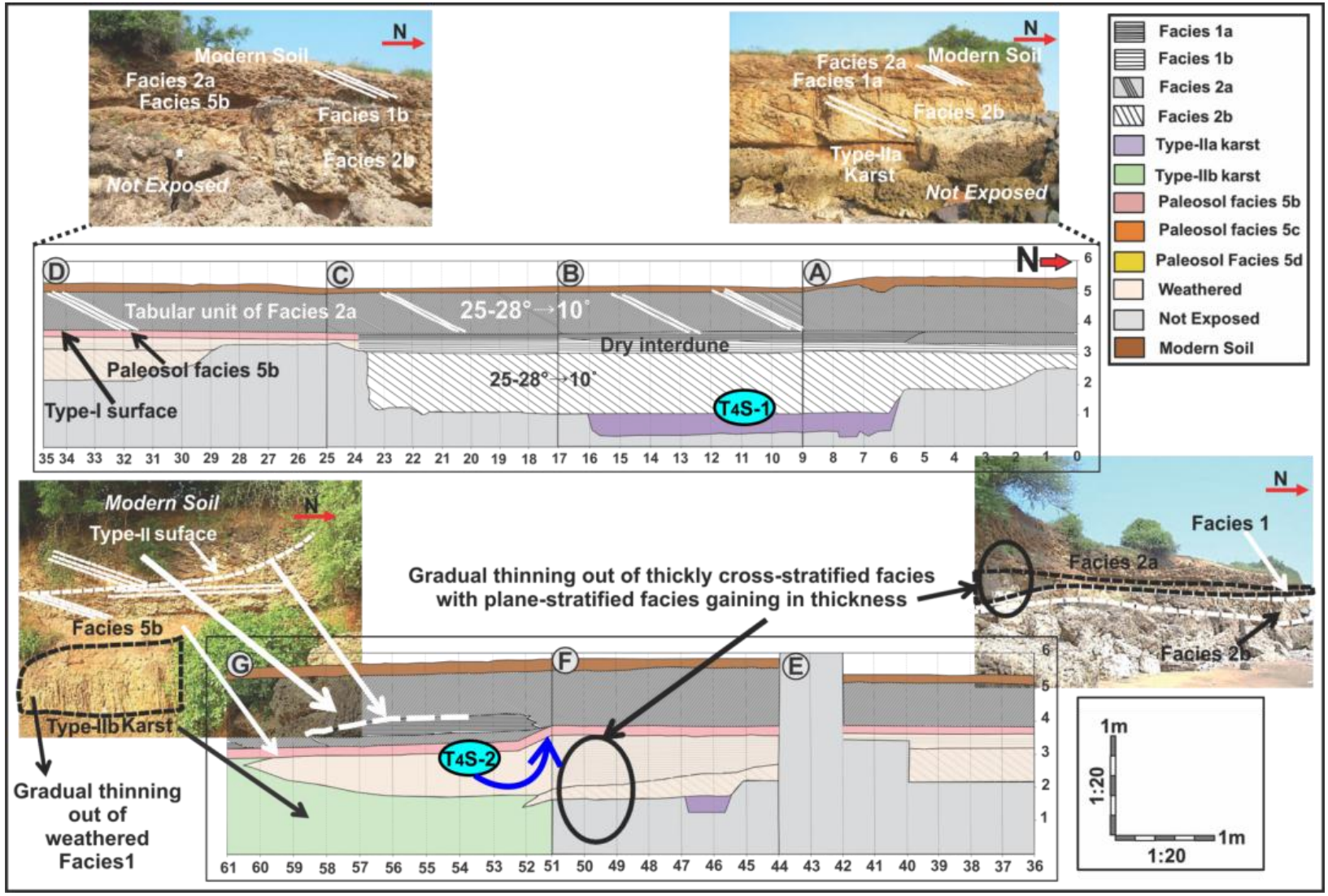

Figure 4.1. Lateral facies mapping. Panel diagram depicting facies occurrences, their geometry, lateral extent and bounding surfaces in a north–south cliff section at Gopnath. Detailed lateral mapping of the Miliolite succession at Gopnath was carried out to identify and standardize the different aeolian stratification types, bounding surfaces and facies which were then compared with the Miliolite sections in Babarkot and Diu. Legend and scale remains the same for the successive panel diagrams.

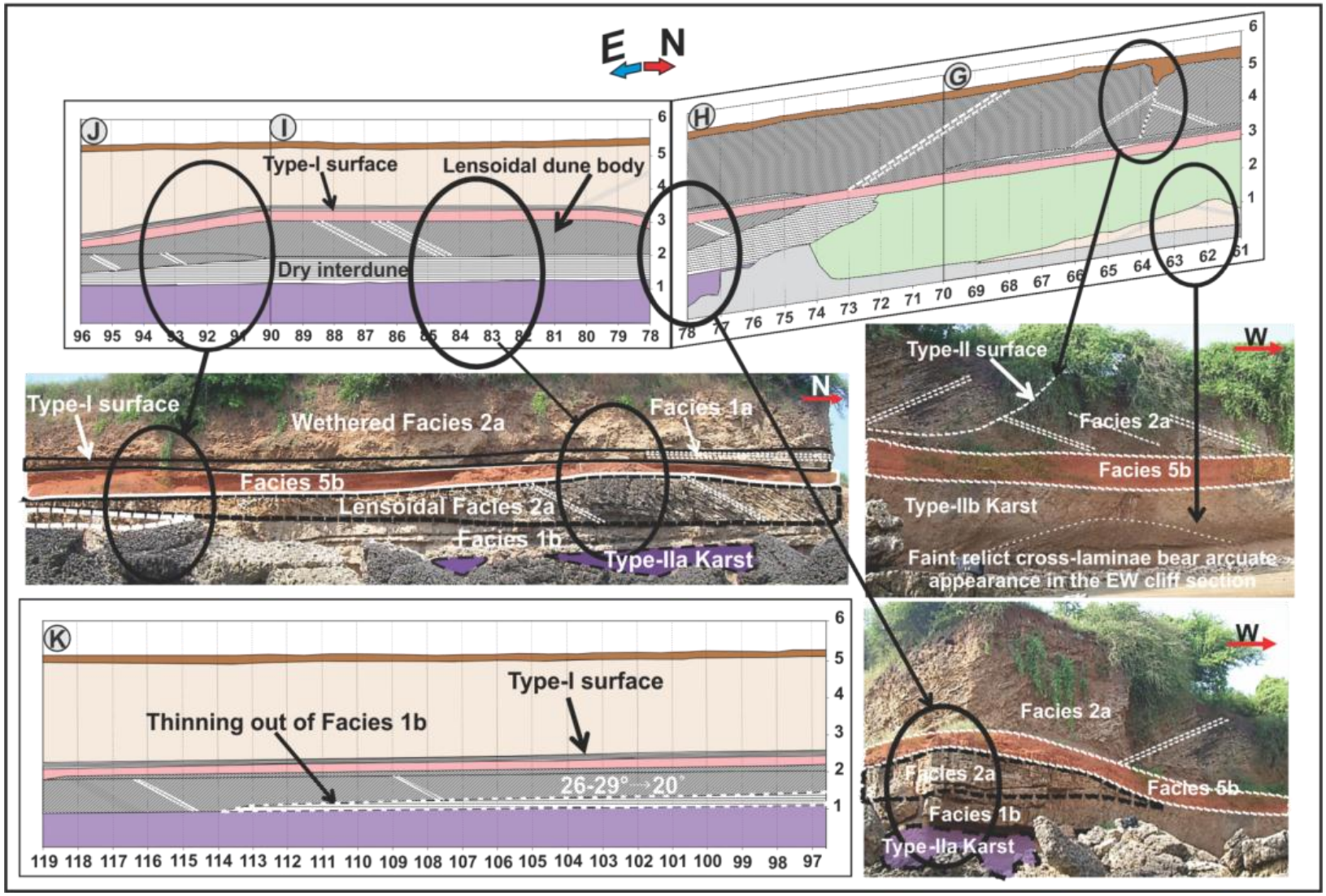

Figure 4.2. Lateral facies mapping. Continued lateral mapping along east–west (G) and (H) and north–south (I) to (K) cliff sections. Convexup bedding is observed in the lower portion of the east–west panel (G). While moving from the base towards the top of the cliff section, facies association of lensoidal dune bodies and interdune facies gives way to laterally extensive tabular cross-stratified units.

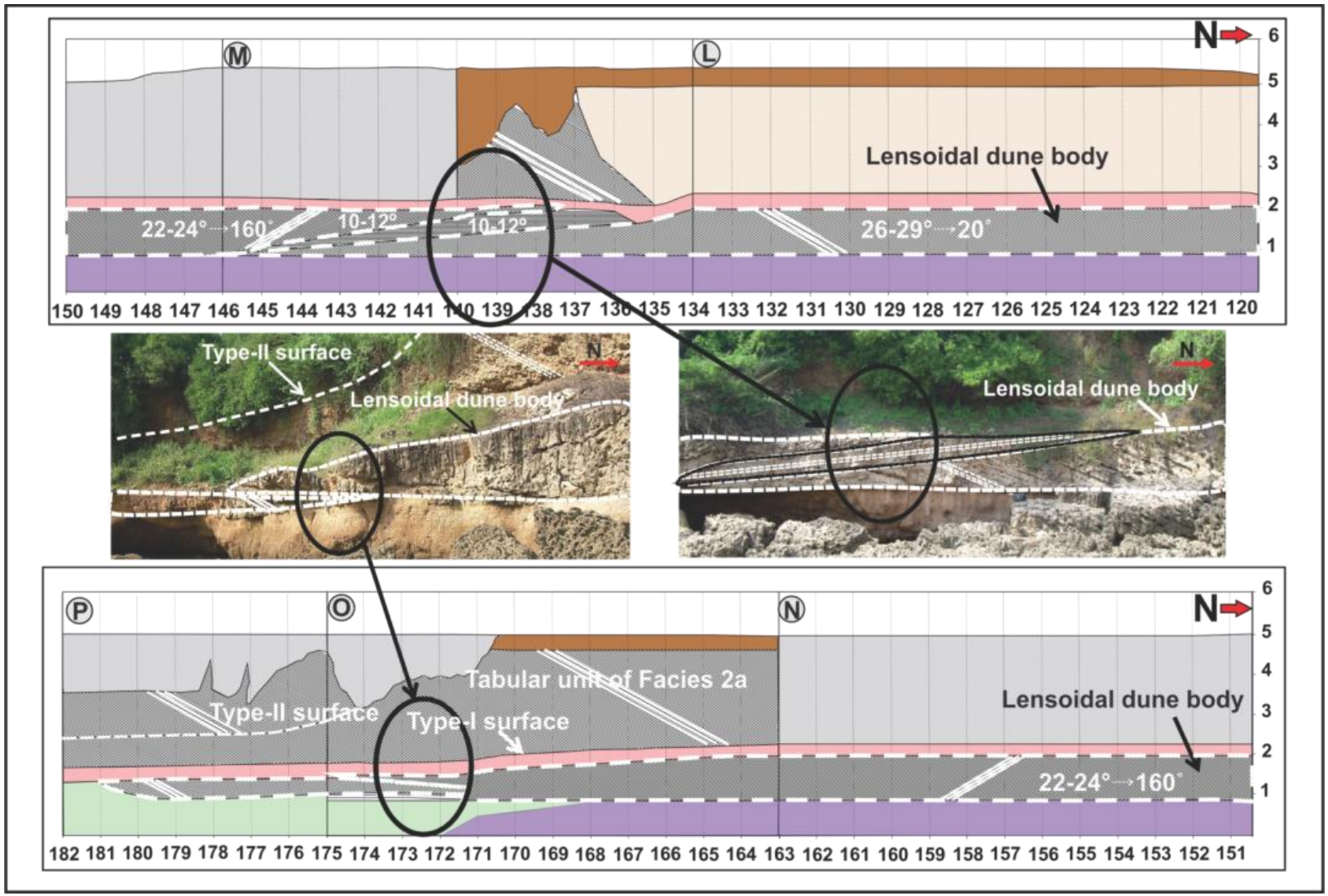

Figure 4.3. Lateral facies mapping. Continued lateral mapping along the north–south cliff section (L) to (P) shows superimposition of lensoidal dune units with varying foreset dip azimuths indicative of variations in palaeowind directions. (L) to (P) also depict the architectural elements of the overlying laterally extensive tabular cross-stratified unit.

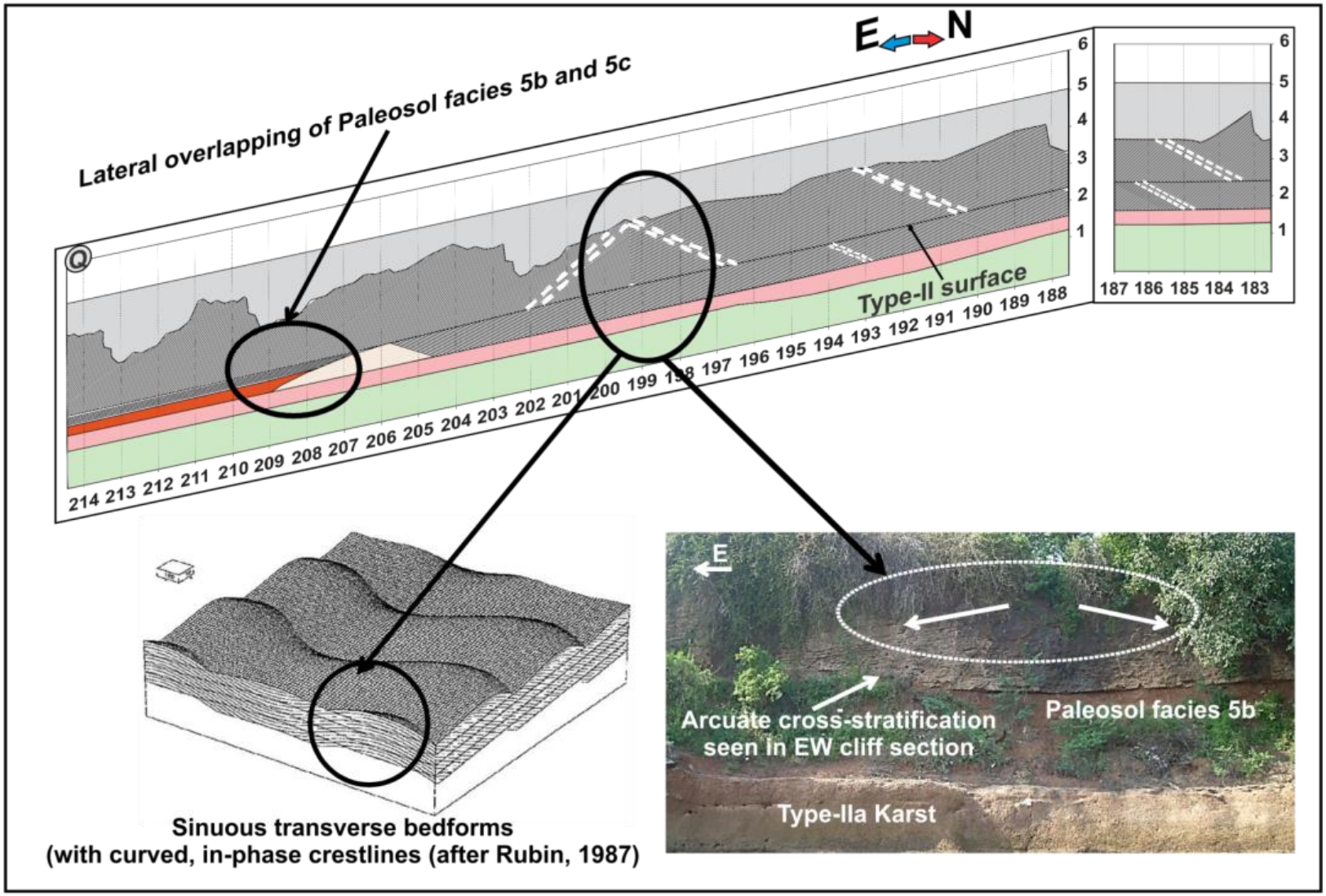

Figure 4.4. Lateral facies mapping. Continuation of lateral mapping along north–south (P) and east–west (Q) cliff sections. Lateral overlapping of paleosol Facies 5b and 5c is observed in (Q). Convex up bedding as seen in section perpendicular to dominant transport direction indicates deposition by transverse dunes with sinuous crestlines (Rubin, 1987).

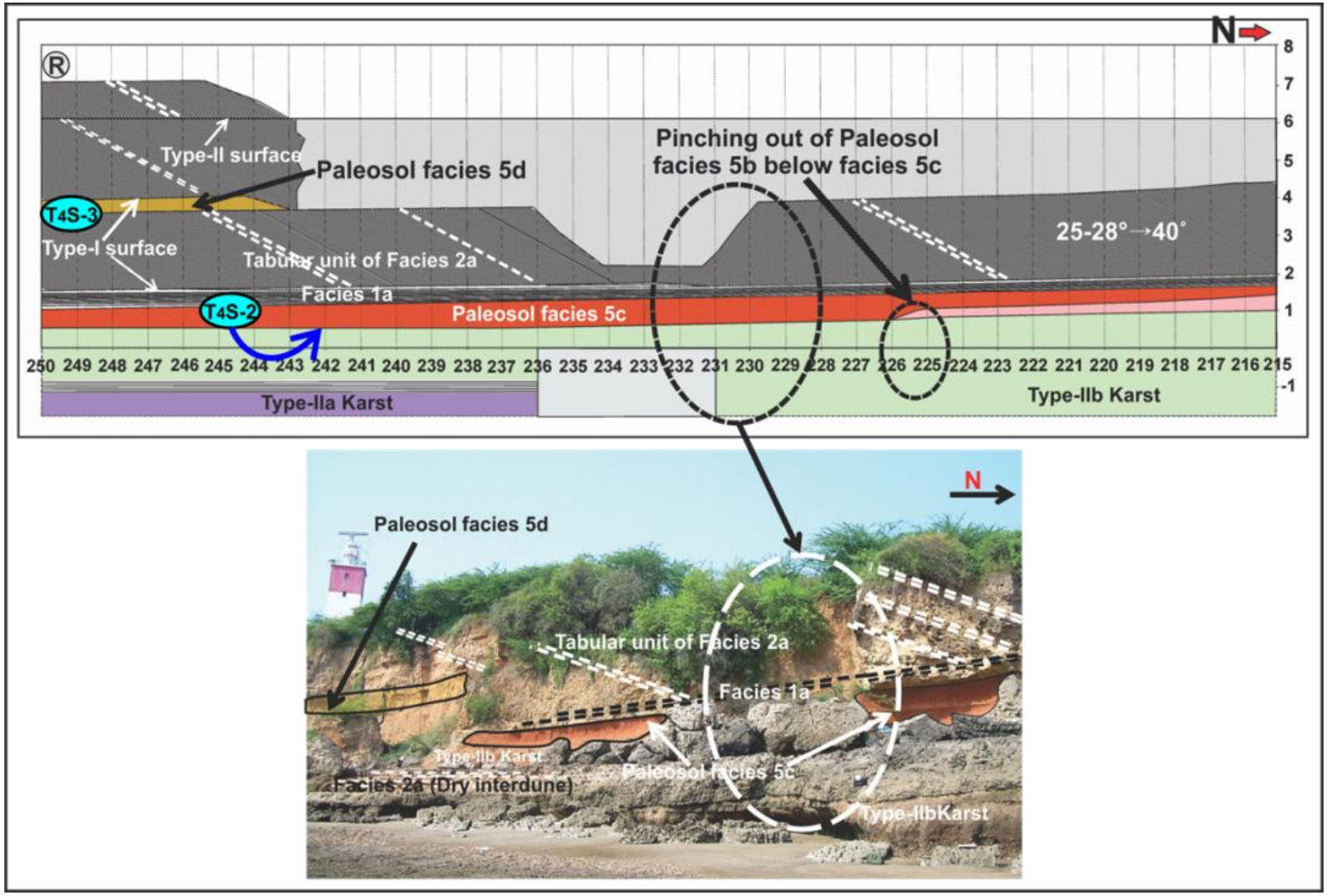

Figure 4.5. Lateral facies mapping. Continuation of lateral mapping into the north–south cliff section (R). Pinching out of Paleosol Facies 5b below Facies 5c is observed in the panel diagram. In the vertical succession, the bedforms are bounded by nearly horizontal planar surfaces exhibiting zero angle of climb.

Veiega *et al.*, 2002; Biswas, 2005). The minimum height of the depositing aeolian dunes is calculated using the formula (Rubin and Hunter, 1982):

$$\overline{H} \cong \sqrt{\frac{T\,D}{I}}, \text{ I=15 (Rubin and Hunter, 1982; Wilson, 1972),}$$

where, H is dune height, T is bed thickness, I is bedform spacing-to-height ratio (bedform index) and D is the down-current extent of individual cross-stratified beds or down-current depositional extent (Clemmensen and Abrahamsen, 1983). The value of bedform index (I) was determined from present day examples which best replicate the depositional conditions in the study area. In the present case bedform index was determined from the height (H) and bedform spacing (L) of the modern day barchans (H: 2 m–15 m; L: 100 m–300 m) and transverse dune (H: 5 m–50 m; L: 500 m–1000 m) types *(biologydiscussion.com/ecology/sand-dunes)* of the Thar Desert where the aeolian activities are governed by the same SW Monsoon wind system which has been regulating the aeolian activities in southern Saurashtra from the Late Quaternary to the recent times. Since, for transverse dunes, dune height increases with bedform spacing (Lancaster, 1988); a comparision of these parameters as observed in the Thar Desert with the aeolian bedform elements of Wilson (1972) reveals that modern dunes with spacings of 300 m can attain heights of about 20 m leading to bedform index (I) values of 15. The lensoidal cross-stratified units in Facies association A show a maximum thickness in the range of 0.6 m to 2.0 m and extend laterally for 10 m to 56 m. The height of the depositing dunes, thus, occurs in the range of 0.63 m to 2.63 m. Where one dune body climbs over another, the superimposition surface (Type-II surface) dips 10° to 12° **(Figure 4.3)**. While paleosol Facies 5a occurs only in a small lenticular pocket, Facies 5b occurs as a laterally extensive tabular unit (maximum thickness: 40 cm, lateral extent: *ca* 200 m). The base of Facies 5b is marked either by underlying Facies 2a or Facies 1a. While moving southward in a north–south traverse along the cliff section, paleosol Facies 5b merges with Facies 1a towards the north and passes below paleosol Facies 5c towards the south **(Figures 4.1, 4.5)** forming stacked paleosol horizons. The base of the stacked paleosol horizons defines a Type-IV surface (T4S-2).

Facies association B overlies the stacked paleosol horizons belonging to Facies 5b and 5c. This facies association comprises vertically stacked thinly cross-stratified facies (Facies 2a) with an intervening paleosol horizon belonging to Facies 5d. The individual sets of cross-stratified units are tabular, exhibit a maximum thickness of 2.5 m and extend laterally for 60 m to 70 m. The height of the depositing dunes is estimated (Rubin and Hunter, 1982) to be 3.4 m. The individual sets of cross-strata are bounded by Type-II surfaces which are planar to slightly concave upward and extend laterally for 20 m to 35 m. The intervening paleosol Facies 5d represents a short break in aeolian sedimentation and defines a Type-IV surface (T4S-3). The dune units occurring above it represent renewed aeolian activities and the contact between them defines a Type-I surface. In the

vertical succession, the bedforms are bounded by nearly horizontal planar surfaces, thus exhibiting zero angle of climb. For dry aeolian systems, as in the present case, this suggests that interdune hollows existed simultaneously with dune forms (Mountney and Howell, 2000).

Compared to the oldest Miliolite record in Gopnath, aeolian sedimentation pattern happened to be completely 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 and as discussed earlier, 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 Miliolite units; however, compared to the wind directions (dominantly NNE) that existed during the times of deposition of Gopnath Miliolites, the mean wind flow direction during the times of deposition of the relatively younger Babarkot Miliolites varied widely from NE to SE and to SSW indicating frequent changes in wind direction **(Figure 4.6)**. Thirdly, the height of the depositing dunes is estimated (Rubin and Hunter, 1982) to be in the range of 0.2 m to 2.8 m (maximum thickness of 0.4 m to 2.06 m and lateral extension for 2.5 m to 60 m) which is comparatively smaller than those responsible for depositing the older Gopnath aeolianites. Fourthly, the Miliolite succession in Babarkot is characterized by superimposed dune forms identified by distinct cross-stratified sets (or co-sets) separated by Type-II surfaces (T_2S) **(Figure 2.2b)**. Occasional presence of reactivation surfaces (T_3S) is also observed within sets defined by Type-II surfaces **(Figure 2.2c)**. The younger Miliolite succession of Babarkot, thus, 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.

As far as the youngest Miliolite succession in Diu is concerned, the cross-stratified Miliolite succession (Facies 2) rests over the shell limestone facies (Facies 7) separated by thin plane laminated Miliolite facies (Facies 1a). The contact between Facies 1a and Facies 2 thus defines a Type-I surface (T_1S) indicative of initiation of dune migration. 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 (T_4S-5) **(Figure 2.2f)** which is attributed to MIS-5 high sea stand (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

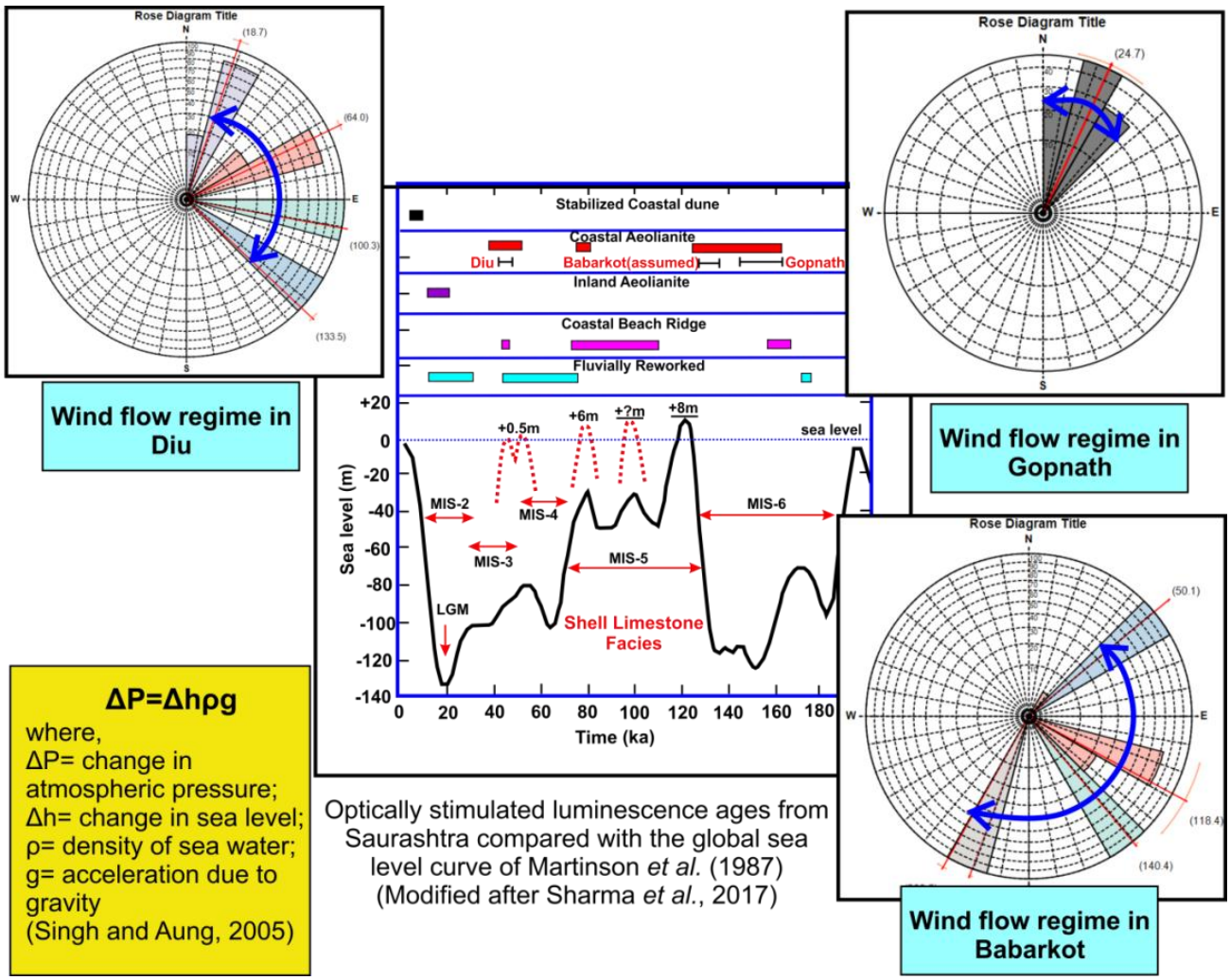

Figure 4.6. Wind regime. The available OSL ages from Gopnath and Diu when compared with the global sea level curve (after Sharma, *et al.*, 2017) reveals that while Gopnath Miliolites were deposited during MIS-6 lowstand, Diu Miliolites were deposited during the phase when the sea level was falling down post MIS-3 highstand. Keeping this in the background when we compare the paleowind directions observed in Gopnath and Diu, the latter shows wider spread in dip azimuths indicative of a then existing chaotic wind regime during the deposition of the Diu Miliolites. This can be attributed to fluctuations in atmospheric pressures due to eustatic changes (Singh and Aung, 2005) as the Diu Miliolites were deposited in a transitional phase between MIS-3 and MIS-2. The paleowind regime during the deposition of Babarkot Miliolites was more diversified compared to that of Gopnath and Diu which in turn is indicative of major fluctuations in atmospheric pressures attributed to major oscillations of the sea level. In absence of available OSL ages for Babarkot Miliolites, occurrence of MIS-5 highstand deposits (refer text), proliferation of Type-II surfaces and major fluctuations in atmospheric pressures as revealed from the spread of the dip azimuths, it is assumed that the Babarkot Miliolites were deposited during the transitional phase from MIS-6 lowstand to MIS-5 highstand.

direction (NE to ESE) **(Figure 4.6)** 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.

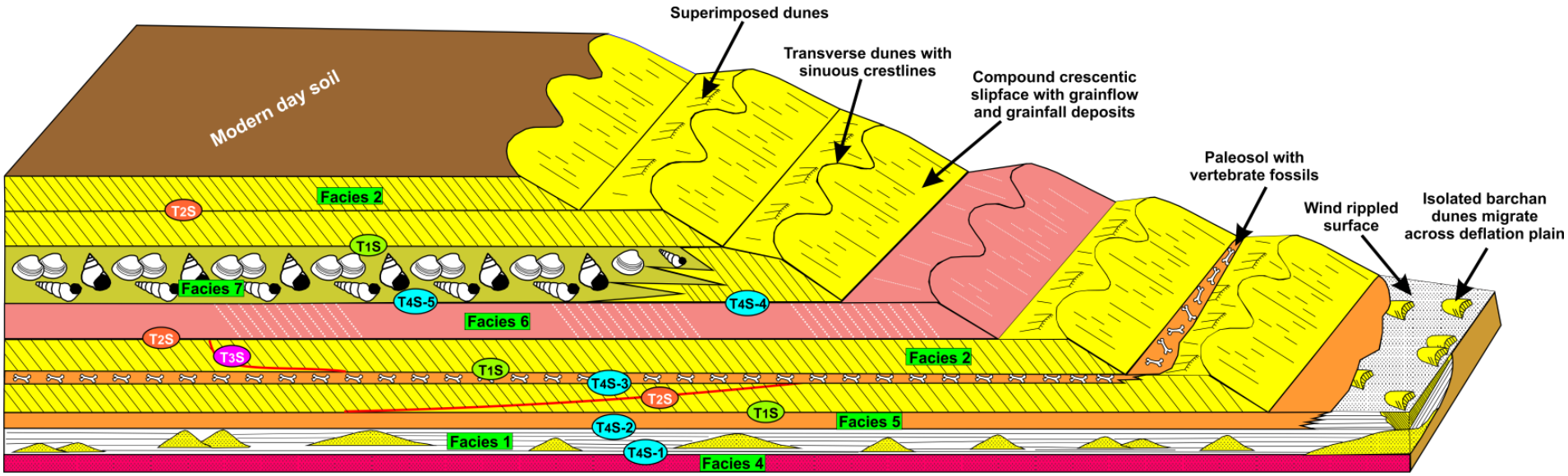

Figure 4.7. Stratigraphic evolution of the coastal Miliolites of southern Saurashtra. A conceptualized model for the stratigraphic evolution of the coastal Miliolites of southern Saurashtra is presented here. The oldest record of aeolian sedimentation in southern Saurashtra is characterized by the occurrence of karst facies (Facies 1) at the base which is overlain by a vertically stacked association of plane stratified (Facies 1), cross-stratified (Facies 2) and paleosol facies (Facies 5). The pinkish buff colored Miliolite facies (Facies 6) marks a pronounced hiatus during the deposition of the younger aeolian events. The younger aeolian events were deposited under essentially dry climatic conditions marked by redundancy of the wetter climatic phases as evidenced from the absence of paleosol horizons which could be frequently observed in the older Miliolites. The younger aeolian events were thwarted by the MIS-5 high sea stand resulting into the destruction of the pre-existing Miliolite topography and deposition of the shell limestone facies (Facies 7). The shell limestone facies forms an integral part of the shore platforms in Diu area and similar facies have also been reported from Sarakeshwar near Babarkot (refer text). Declining sea levels post-MIS-5 high sea stand re-exposed the coastal tracts and the shelfal regions to aeolian activities and resulted into rejuvenation of the aeolian sedimentary processes which in turn resulted into deposition of vertically stacked aeolian succession. T_1S: Type-I surface; T_2S: Type-II surface; T_3S: Type-III surface; T_4S: Type-IV surface.

A conceptualized model depicting the stratigraphic evolution of the coastal Miliolites of south Saurashtra is presented in **Figure 4.7**.

4.2.4. 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). These factors modify sediment supply, sand availability, fluvial and aeolian transport capacity and water table position, thus influencing the aeolian system sedimentary regime (Scherer and Lavina, 2005). As far as the aeolian succession in southern 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 (Glennie *et al.*, 2002; Khadkikar, 2004), and consequently the periods of fluvial and aeolian activities, respectively (Juyal *et al.*, 2006). However, it is worth mentioning that the extensive dune building events in southern Saurashtra during the Late Quaternary 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 southern Saurashtra aeolianites under dominantly dry conditions indicates that the moisture content of these winds was significantly lowered during eustatic low stands. The vast amount of palaeo-environmental information on the south-west monsoon, as gathered from the Quaternary sedimentary archives of south-western India (e.g. Glennie *et al.*, 2002; Singhvi and Kar, 2004; Khadkikar, 2004; Juyal *et al.*, 2006) has mostly been generated by linking the occurrence of aeolian and non-aeolian sedimentary accumulations to the intensity of the south-west monsoon which varied during glacial and interglacial periods, as deduced from the ages of the sediments by comparing them with the global sea-level curve. The Late Quaternary Miliolite succession of southern Saurashtra, however, not only provides the scope of relating them to eustatic controlled changes in the intensity of the south-west monsoon, but also to understanding the nature of eustatic change from the preserved sedimentation patterns.

The coastal Miliolite record of southern Saurashtra when seen from the oldest (in Gopnath) to the youngest (in Diu) is punctuated by a number of unconformity surfaces (T4S-1–5) which indicate temporal breaks in the aeolian sedimentation history of the area. The oldest Miliolite record as observed in Gopnath rests over the surface of unconformity (T4S-1) that lies at the base of the Gopnath cliff section and exhibits a changeover from a period of subdued to enhanced aeolian activities across the unconformity surface. The development of T4S-1 might be attributed to the

destruction of an earlier existing dune system due to eustatic rise which inhibited dune building processes by curtailing the sediment availability for aeolian entrainment. This, accompanied by enhanced moisture content of the Indian monsoon winds, led to higher amounts of precipitation and eventual karstification of the dune deposits. The deposition of the overlying aeolianite succession is attributed to re-availability of sediments for aeolian entrainment under falling eustatic levels. Facies association A, however, indicates that the eustatic fall was relatively small and short-lived. This inference is drawn from the fact that a relatively small and temporal fall in eustatic level would generate only a small sediment supply which could only be worked out by prevailing winds into vast interdunes with isolated small dunes as observed in Facies association A. The paleosol horizons (belonging to Facies 5b and 5c) blanketing the aeolian events of Facies association A (corresponding to unconformity surface T4S-2) represent a break in aeolian activities and eventual landscape stabilization due to eustatic rise resulting in curtailment of sediment supply as well as climatic amelioration from a drier to a wetter phase due to enhanced moisture contents of the south-west monsoon wind system. Facies association B, resting over Facies association A, indicates a major and prolonged eustatic low stand resulting in laterally extensive dune building, which, however, was momentarily paused by a eustatic high stand resulting in the development of a protosol–paleosol horizon belonging to Facies 5d (and corresponding unconformity surface T4S-3). Moving westwards along the southeren Saurashtra coast to the younger Miliolite units in Babarkot, a distinct unconformity surface (T4S-4) is observed separating the older Miliolite (Facies 6) from the fresher Miliolite units lying above, which in comparision to the underlying older unit exhibit a wide range of mean wind flow direction and proliferation of superimposed dunes. However, the non-development of paleosol horizon corresponding to T4S-4 as against the Type-IV surfaces in the underlying older Miliolite suggests that the break in aeolian sedimentation corresponding to T4S-4 was short lived and did not lead to karstification and eventual paleosol formation. The lack of karstified and/or pedogenized horizons corresponding to T4S-4 also suggests an overall dry climatic conditions with limited precipitation. The overlying dune sequence as discussed earlier comprises superimposed dune forms with a wide range of mean wind flow direction and proliferation of Type-II surfaces indicating a chaotic wind regime which might be attributed to variations in atmospheric pressures over the then existing coastal tracts of southern Saurashtra. The MIS-5 high sea stand (~120–80 ka, Martinson *et al.*, 1987) eroded the pre-existing Miliolite limestone sequences and deposited the bioclast rich beach ridges (shell limestone facies) and associated dunes including the favoured growth of coral reefs in suitable coastal segments (Bhonde, 2004). At Balana (near Sarakeshwar), located in the vicinity of Babarkot, Bhatt and Patel (1998) have reported an 8 m–high cliff comprising of porous, coarse grained, planar cross-stratified Miliolite limestone with mega shell fragments of gastropods, pelecypods, barnacles and older limestone gravels. This unit occurs

at stark distinction from the other adjoining Miliolites and has been stratigraphically correlated with the shell limestone unit corresponding to MIS-5 high sea. In Diu area, a clear cut irregular contact surface between the below lying older Miliolites and the shell limestone facies has been observed. This surface, thus, attests to a surface of unconformity and has been termed here as T4S-5. At places, and as discussed earlier, residual clasts of older Miliolites are found embedded within the shell limestone facies. Eustatic lowstands post MIS-5 high sea stand re-exposed the sediments of the shelfal regions to aeolian entrainment and the ensuing aeolian depositional processes led to deposition of the stacked Miliolite succession of Diu Island.

The available OSL ages from Gopnath and Diu when compared with the global sea level curve (after Sharma *et al.*, 2017) reveals that while Gopnath Miliolites were deposited during MIS-6 lowstand, Diu Miliolites were deposited during the phase when the sea level was falling down post MIS-3 highstand **(Figure 4.6)**. Keeping this in the background, when we compare the mean paleowind directions observed in Gopnath and Diu, the latter shows wider spread in dip azimuths indicative of a then existing wind regime which was quite different (more chaotic) from that prevailing during the times of deposition of the Gopnath Miliolites. This can be attributed to fluctuations in atmospheric pressures due to eustatic changes (Singh and Aung, 2005) as the Diu Miliolites were deposited in a transitional phase between MIS-3 and MIS-2. The paleowind regime during the deposition of Babarkot Miliolites was more diversified compared to that of Gopnath and Diu which in turn is indicative of major fluctuations in atmospheric pressures attributed to major oscillations of the sea level. In absence of available OSL ages for Babarkot Miliolites, occurrence of MIS-5 highstand deposits (as in Balana near Sarakeshwar), prolific occurrences of Type-II surfaces and major fluctuations in atmospheric pressures as revealed from dispersion of dip azimuths, it is assumed that the Babarkot Miliolites were deposited during the transitional phase from MIS-6 lowstand to MIS-5 highstand.

4.3. Geomorphological analysis of the cliff and notch profiles

4.3.1. Cliff profiles and relative role of marine and sub-aerial erosion

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 erosional processes (SA) over marine erosional processes (M), the cliff profile gradually changes from vertical (M>>SA) → sloping (M>SA) → convex-up (M=SA) → concave-up (M<SA). 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 typical 'L-shaped' (vertical cliff profile) cliff profile in Gopnath suggests that marine erosion is much more dominant in the area compared to the sub-aerial processes of erosion. The existence of an angular top indicates towards the presence of a resistant capping at the top. The absence of marine notches in Gopnath cliff section might possibly be attributed to the larger tidal range in Gopnath which allows the sea to approach, rest at the cliff base and carry out its erosional activities only for short durations of time and not as frequently as in cases where tidal ranges are smaller. Secondly, the base of the Gopnath cliff comprises karst and paleosol horizon (as evidenced from lateral facies mapping) which is easily eroded away by the tidal currents and breaking waves facilitating continuous cliff collapse and recession. The analysis of Babarkot and Diu cliff profiles indicates that where 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. Since the cliffs are composed of the same parent material, the degree of exposure to marine erosional processes seems to be the controlling factor in determining the relative importance of marine erosion over sub-aerial erosion in shaping the cliff profiles. The degree of exposure to the marine processes appears to be determined by the orientation of the coastline with respect to the incoming waves (dominantly SW to SSW, Chowdhury *et al.,* 2019) and tidal currents as well as the clearance at the base of the cliffs. Where the coastline is oriented perpendicular to the incoming waves and tidal currents, erosion at the cliff base by marine processes is maximized due to direct impact of the incoming waves and tidal currents. However, in any other angular relationship of the coastline with the incoming waves and tidal currents, a component of the latter could only reach the cliff base, thus, reducing the overall strength of impact at the cliff base. From the study of the tidal notches in La Paz Peninsula (southern Baja, Mexico), Trenhaile *et al.* (2015) highlighted the fact that coastline morphology do affect the strength of the incoming waves. As observed in the field, hindrance at the base of the cliff in the form of talus accumulation and bioconstruction rims formed at the edge of the platform (Antonioli *et al.*, 2015; Sisma-Ventura *et al.*, 2017) tend to impede the strength of the incoming waves and tidal currents. Field observations suggest that the extent to which solution channels can develop within the Miliolites and the presence or absence of joints and joint spacing cast influence over the rate of sub-aerial erosion.

4.3.2. Notch geometry and geomorphological inferences

The geomorphic 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 which might be attributed to stronger wave and tide activities. Based on a comprehensive analysis of the tidal notches in Mediterranean Sea, Antonioli *et al.* (2015) established that increased wave action results in an increased notch depth. Although, Babarkot and Diu both face the open sea and belong to the same seasonal belt, the coastal slope map furnished by Mahapatra and Ramakrishnan (2015) for the Saurashtra coast clearly indicates that the coastal slope in Diu area is lower compared to that in Jafrabad–Babarkot area. This accounts for the difference in the intensity of wave and tide activities in Babarkot and Diu, wherein, steeper coastal slopes in Babarkot allows the waves and tidal currents to retain their energy while moving shoreward and have a greater impact over the cliff bases.

(iii) Notch heights (H): The variation in the heights (H) of the tidal notches might be attributed to the degree of their exposure to the waves and the corresponding upward limit of sea sprays and splashes, wherein, the height of the notches increases with the increasing exposure to the open sea (Takenaga, 1968; Pirazzoli, 1986).

(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 such as those with bioconstructions at their rims might result into lowering of the D/H values for a given tidal range (Antonioli *et al.*, 2015; Sisma-Ventura *et al.*, 2017).

(v) Notch elevations (Eo): Notches develop at a variety of elevations in relation to the mean sea level according to their mode of formation which partly reflects the wave regime, tidal range and rock type (Trenhaile *et al.*, 2015). The tabulated notch parameters **(Table 3.1)** indicate that the Babarkot notches commonly occur at greater elevations compared to the Diu notches with respect to the datum. Since the rock type is the same and the tidal ranges are similar in Babarkot and Diu, it appears that 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. Further, according to Trenhaile *et al.* (2015), notches produced by wave quarrying or abrasion, and particularly by spray- or splash induced weathering (salt or chemical weathering or wetting and drying) can develop over a greater range of elevations depending on the degree of exposure and the nature of the substratum.

4.4. Tectono-eustatic changes: Inferences from raised notches and platforms

Evidences from continents for sea level changes during the Late Quaternary include occurrences of depositional and erosional events. The presence of coast parallel beach ridges, aeolianites, higher occurrences of dead coral reefs, shell limestone and tidal flats suggest an oscillating Late Quaternary sea level along the Saurashtra coast (Bruckner, 1989; Patel, 1991). The available geochronological data obtained on coral reefs and oyster from the Saurashtra coast indicate the existence of two major high sea stands 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 stand 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 stand 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 T4S-5 in Diu area as well as the occurrence of residual clasts of recrystallized Miliolite facies (Facies 6) within shell limestone facies (Facies 7) exposed on the platforms along the Diu coast. At Balana (near Sarakeshwar), located in the vicinity of Babarkot, Bhatt and Patel (1998) have reported an 8 m–high cliff comprising of porous, coarse grained, planar cross-stratified Miliolite limestone with mega shell fragments of gastropods, pelecypods, barnacles and older limestone gravels. This unit occurs at stark distinction from the other adjoining Miliolites and has been stratigraphically correlated with the shell limestone unit corresponding to MIS-5 high sea. Since, the coastal Miliolites in Diu occur over the shell limestone facies (Facies 7) which in turn possesses the relicts of older pinkish buff colored Miliolite facies (Facies 6) encountered in Babarkot, it is evident that the Miliolite sequences of Babarkot were deposited prior to the MIS-5 high sea stand.

Pant and Juyal (1993) generated a composite cross-section of the cliffy coast between Babarkot and Diu and indicated the presence of 5 sets of raised marine terraces (T0-T4) at elevation between 13 m (T4) and 20 m (T0) above MSL; distorted notch at an elevation of ~12 m above MSL; ripple notches just below the distorted notch at an elevation between 8 m and 9 m above MSL; marine notch (and associated platform) at an elevation of ~3 m above MSL (Notch 2); and present day active notch (Notch 1) **(Figure 4.8)**. The marine terraces were attributed to falling sea level after the last interglacial high sea stand (at about ~120 ka) of ~7 m. The landmass emerged in a pulse after the formation of terraces and then became stable so as to enable the waves to cut a notch. This accounts for the occurrence of the notch at 4 m below the terrace T4. A series of events

of tectonic uplift followed the formation of this notch. Emergence of landmass is evident from the bulging of the notch wall. Landmass rose continuously after the formation of distorted notch and the emergence became pulsating as evidenced by the occurrence of ripple notches below the distorted notch. Following this, the landmass continuously emerged till the formation of Notch 2 (and associated platform) and remained stable during the formation of the same. A major tectonic uplift during the Holocene resulted into emergence of Notch 2 and positioning at ~3 m above the present day sea level.

In keeping with the observations made by the earlier workers, the present author recorded the occurrence of raised platforms and three instances of raised notches along the Babarkot–Diu coastline. One instance of raised platform and raised notch occur at an elevation of ~3 m above LWL in Babarkot and Diu (cliff profile no. 4 and cliff profile no. 3 in **Figure 3.4** and **Figure 3.5,** respectively), while the other two instances of raised notches occur at elevations of ~6 m **(**cliff profile no. 3 in **Figure 3.4)** and ~12 m **(**cliff profile no. 8 in **Figure 3.5)** above the LWL in Babarkot, respectively. The observations in the present study are mostly in tandem with those of Pant and Juyal (1993) except for the occurrence of the notch at the elevation of ~6 m above the datum which has been termed here as Notch 3 following the nomenclature of Pant and Juyal (1993) **(Figure 4.8)**. Earlier, occurrence of prominent notches at elevation in the range of 4 m to 5 m from the present day biological mean sea level (BMSL) around Jafrabad and Babarkot area were reported by Bhatt and Bhonde (2006) together with less prominent notches at an elevation of 5 m (from the present day BMSL) in Diu area. Previously, Pant and Juyal (1993) had envisaged a continuous emergence of the landmass after the development of the ripple notches till the formation of Notch 2. However, the occurrence of Notch 3 in between the set of ripple notches and Notch 2 indicates that the emergence of the landmass post development of the ripple notches was not continuous, and rather, was halted during the formation of Notch 3. Mathur *et al.* (2004) invoked a 2 m 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 ka and 3.3 ka (Juyal *et al.*, 1995). The oyster bed occurring at 1 m above MSL near Khada Bandar has yielded a 3.47 ± 0.11 ka 14C ages (Bhatt, 2004). 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 above the present day notches (Notch 2 of Pant and Juyal, 1993) suggest their formation during the mid-Holocene and subsequent tectonic uplift in the order of 1 m within duration of nearly 3 ka. This observation accords well with that of Banerji *et al.* (2015).

The morphodynamic events that took place along the southern Saurashtra coastline in a time window of ~120 ka to ~3 ka were classified by Pant and Juyal (1993) into stages. However, the

incorporation of Notch 3 in between the set of ripple notches and Notch 2, allows for three stage classification of the morphodynamic events. Referring to **Figure 4.8**, the different stages are as follows:

Stage-I: witnessed landform emergence at varying rates generating features like distorted notch (Notch 4) and ripple notches. Landform stability was attained during the formation of Notch 3. Stage-I witnessed an upthrow of ~7 m (difference between the elevation of T4 and Notch 3).

Stage-II: witnessed the emergence of Notch 3 above the effective range of wave action and the up throw continued till the formation of Notch 2 and the associated platform. Stage-II witnessed an upthrow of ~3 m (difference between the elevation of Notch 3 and Notch 2).

Stage-III: witnessed the emergence of Notch 2 and the associated platform above the effective range

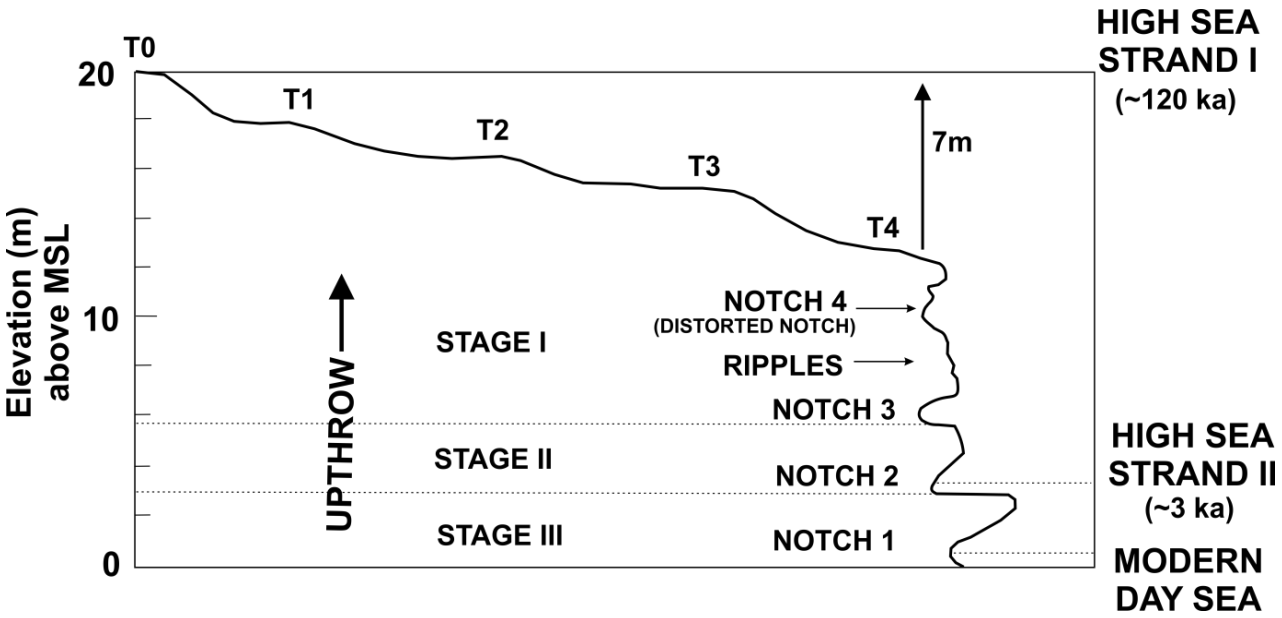

Figure 4.8. Composite cross-section of cliffy coast between Babarkot and Diu. The marine terraces were attributed to falling sea level after the last interglacial sea level high (~120 ka) of ~7 m (above the present sea level). Stage-I witnessed landform emergence at varying rates generating features like distorted notch (Notch-4) and ripple notches. Stage-I witnessed an upthrow of ~7 m (difference between elevation of T4 and Notch-3). Landform stability was attained during the formation of Notch-3. Stage-II witnessed the emergence of Notch-3 above the effective range of wave action and the up throw continued till the formation of Notch-2 and the associated platform. Stage-II witnessed an upthrow of ~3 m (difference between elevation of Notch-3 and Notch-2). Stage-III witnessed the emergence of Notch-2 and the associated platform above the effective range of wave action and the up throw continued till the formation of Notch-1. Notch-2 lies at an elevation of ~3 m from the present day sea level and considering its formation during the mid-Holocene high sea level of about 2 m, the landform emergence during this stage was ~1 m *(Modified after Pant and Juyal, 1993).*

of wave action and the up throw continued till the formation of Notch 1. Notch 2 lies at an elevation of ~3 m from the present day sea level and considering its formation during the mid-Holocene high sea level of about 2 m, the landform emergence during this stage was ~1 m.

The above discussion might give an impression that the tectonic movements along the southern Saurashtra coast were the sole agent in shaping the coastal geomorphology, especially, in the past 120 ka. However, Pant and Juyal (1993) emphasized that sea level did fluctuate during the formation of the terraces and the notches as also suggested by the global sea level curve of this period. But, in 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.