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Sedimentological analysis of a Late Quaternary coastal dune system: An example from Gopnath, south-east Saurashtra, Western India

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ABSTRACT

Coastal dune systems consisting of allochemical grains are important sedimentary archives of Pleistocene age in both of the hemispheres between the latitudes of 20° to 40°. The south Saurashtra coast in western India exhibits a large section of Middle Pleistocene aeolianites in the form of coastal cliffs, which is famous as ‘Miliolite’. Miliolites of Gopnath in south-east Saurashtra are the oldest known coastal aeolianite deposits (age >156 ka which corresponds to Marine Isotope Stage 6) in western India. Aeolian deposits of similar ages have also been reported from the Thar Desert in north-west India and from Southern Arabia which were largely controlled by the south-west monsoon wind system that affects the entire belt corresponding to Sahara–Sahel, the Arabian Peninsula and north-western India. Miliolite deposits in Gopnath are characterized by grainfall, grainflow and wind ripple laminations. At least three types of aeolian bounding surfaces have been identified. Five major facies have been identified which represent the dune and interdune relationship within the coastal aeolian system. The major dune bodies are identified as transverse dune types. The Gopnath aeolianites were deposited under dominantly dry aeolian conditions. Facies association reveals two different phases of aeolian accumulation, namely initiation of aeolian sedimentation after a prolonged hiatus and the establishment of a regularized aeolian sedimentation system. While initiation of aeolian sedimentation is marked by vast stretches of sheet sand with occasional dune bodies, the overlying thick, tabular, laterally extensive cross-stratified units manifest regular aeolian sedimentation. However, the dune building events in Gopnath were interrupted by development of laterally extensive palaeosol horizons. Eustasy and climate exerted the major allogenic controls on the aeolian sedimentation by affecting the sediment budget as well as influencing the sedimentation pattern.

Keywords Aeolianites, coastal dunes, Late Quaternary, Miliolite, Saurashtra, south-west Monsoon, Western India.

INTRODUCTION

A small subset of global dune systems consists of those from coastal areas where the chief component of sand-size grains comes from an organic source. Such coastal dunes are generally formed between 20° and 40° latitudes in both hemispheres, and have been termed ‘aeolianites’ (Brooke, 2001). Although in a strict sedimentological sense the term aeolianite, first coined by

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Sayles (1931) in Bermuda, describes any sediment deposited by the wind and subsequently lithified, the definition by Fairbridge & Johnson (1978) reflects the widely accepted use of the term to define dune calcarenite. Coastal aeolianites are formed by material from the deflation of beach deposits and subtidal sediments when exposed to wind during marine lowstand episodes (Abegg *et al.*, 2001). Numerous studies of extensive coastal and smaller island deposits in both hemispheres have shown that these aeolianites are predominantly Pleistocene in age (Brooke, 2001). In India, coastal aeolian deposits constitute a large section of the Saurashtra coast of Gujarat where they form coastal cliffs and ridges (as well as extending several kilometres inland) (Evans, 1900; Bhatt, 2003); they have also been reported from the coastal tracts of southern India (Gardner, 1983). The aeolianites of Saurashtra were first reported by Carter (1849) and introduced into the geological literature as 'Miliolites' or 'Miliolitic limestone' due to the preponderance of foraminifera of Genus *Miliolina*. This was later lithostratigraphically designated to the Miliolite Formation and Chaya Formation which were further subdivided into members (Mathur, 1987; Bhatt, 2000). The OSL ages of the coastal Miliolites in Saurashtra range from >156 ka (Gopnath in the east) to 45 ka (Makanpur in the west), with the units becoming younger in age on moving from east to west along the Saurashtra coast (Sharma *et al.*, 2017) covering a stretch of nearly 400 km (Fig. 1). Aeolian deposits of similar ages have also been reported from the Thar Desert in north-west India (Glennie & Singhvi, 2002; Glennie *et al.*, 2002; Singhvi & Kar, 2004) and from Southern Arabia (Glennie & Singhvi, 2002; Glennie *et al.*, 2002). Interestingly, the Late Quaternary to present aeolian deposition in Saurashtra, the Thar Desert and Southern Arabia is controlled by the south-west monsoon wind system which affects the entire belt corresponding to Sahara–Sahel, the Arabian Peninsula, north-western India and northern China (Zhongwei & Petit-Marie, 1994; Glennie *et al.*, 2002; Khadkikar, 2004; Singhvi *et al.*, 2012). The episodic glacial and interglacial phases during the past 200 kyr largely affected the intensity of the south-west monsoon wind system which in turn had its effect on the aeolian activities, processes and sedimentary records in the coastal and inland settings (Glennie & Singhvi, 2002; Glennie *et al.*, 2002; Singhvi & 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 south-west monsoon winds (Glennie & Singhvi, 2002; Singhvi & 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 & 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.

Considering the significance of Saurashtra Miliolites as a Late Quaternary sedimentary archive, a detailed sedimentological analysis is indispensable for unravelling and understanding the coastal dune building processes and controls that would augment the study of similar deposits in the Afro–Asian monsoonal belt in particular and the coastal belts in other parts of the world in general. This paper presents a case study of a a Late Quaternary coastal dune system from Gopnath in south-east Saurashtra which represents the oldest known Quaternary coastal aeolianite sequence in western India, deposited during the glacial epoch at *ca* 156 ka [Marine Isotope Stage (MIS) 6] (Sharma *et al.*, 2017). It aims at bridging the gap in understanding of the Saurashtra Miliolites from the viewpoint of aeolian depositional components, dune building processes and controls on sedimentation. While aeolian deposits of Proterozoic age from the Indian mainland have been studied in detail (Chakraborty, 1991; Bose *et al.*, 1999; Biswas, 2005; Basu *et al.*, 2014), the present study brings a new approach, hitherto unattempted, of looking into the aeolian deposits of Quaternary age occurring along the coastal tracts of peninsular India. The main objectives of this paper are: (i) to identify, describe and interpret the different aeolian facies; (ii) to gain an understanding of the aeolian architecture and facies succession; (iii) to gain an understanding of the aeolian depositional environment, dune morphology and morphodynamics; (iv) to identify the autogenic and/or allogenic controls on sedimentation and accumulation; and (v) to establish a model for the stratigraphic evolution of the Miliolite deposits.

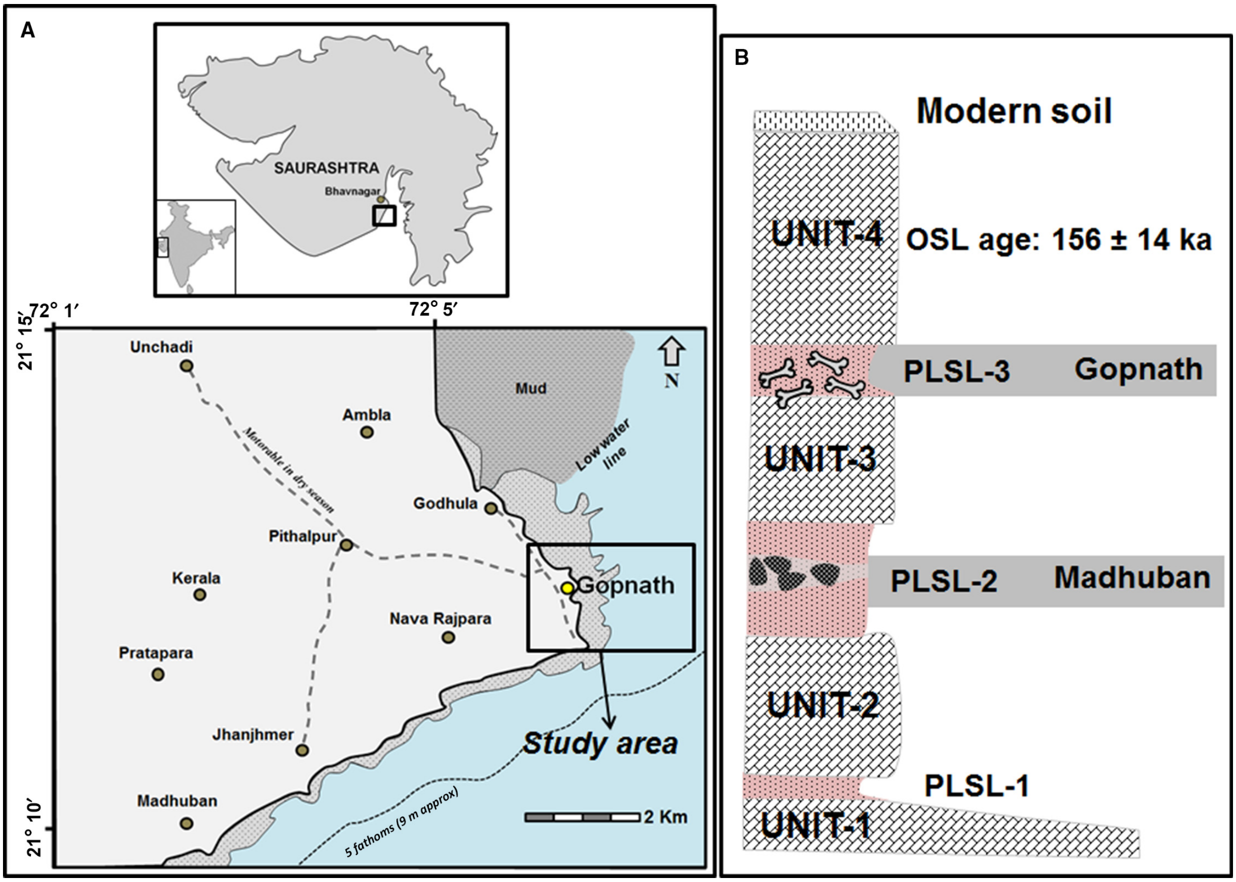

Fig. 1. Location map and composite aeolianite succession. (A) Location map showing the study area. Inset map shows the geographical position of the study area in western India. (B) Composite succession of coastal carbonate aeolianites and palaeosol horizons (PLSL1 to PLSL3) in Gopnath and adjoining areas (modified after Costa, 2015). The uppermost aeolianite unit in Gopnath bears an OSL age of 156 ± 14 ka (after Sharma *et al.*, 2017).

STUDY AREA

Gopnath is situated in the Gujarat state of western India and falls into the Talaja Taluka of Bhavnagar district (Latitude 21°11′N, Longitude 72°6′E), about 5·5 km south of the present mouth of the Shetrunji River (Fig. 1A). The Late Quaternary carbonate deposits occur as a wave-cut platform and cliff (*ca* 8 m high) along the coastal tract of Gopnath with the dune system extending seaward to an unknown depth. However, the waves have eroded the subaerial part considerably landward (>500 m) since the most recent Holocene transgression (Costa, 2015).

Along the coastal tracts of Gopnath and the adjoining area of Madhuban (Fig. 1B), the lowermost observable Miliolite unit comprises the expansive wave cut platform termed as Unit 1, which is exposed at low tide and exhibits a thin red palaeosol horizon (PLSL1) on top of it. Above this, Miliolite Unit 2 forms part of the proximal wave cut platform. The PLSL2 horizon (red palaeosol horizon) overlies this and in Madhuban area it bears a Late Acheulean lithic assemblage (Marathe *et al.*, 1995). Another carbonate Unit 3 is superimposed on the latter and above this lies PLSL3 which has furnished the first evidence of diverse Late Pleistocene vertebrate fauna in Gujarat (Costa, 2015). The sequence is capped by a distinct thick aeolianite, Unit 4, with Holocene soil at the surface (Fig. 1B). Patel & Bhatt (1995) interpreted these lithological variations in Gopnath cliff as indicative of palaeoclimatic fluctuations during Middle to late Upper Pleistocene.

Previously Khadkikar & Basavaiah (2004) identified three varieties of epikarst (Types 1 to 3) and five types of *terra rossa* (Types 1 to 5) besides cross-stratified Miliolites from Gopnath and adjoining areas. These authors also identified phreatophytic rhizoliths, freshwater gastropods and fossilized bones from *terra rossa* horizons of Gopnath. Khadkikar (2004) attributed the formation of *terra rossa* like soils to periods of increased rainfall leading to weathering, while prolonged periods of reduced rainfall but strong winds favoured the formation of parabolic dunes which deposited the aeolianites. Costa (2015), however, attributed the association of carbonate aeolianites and *terra rossa* to dune and interdune wetlands rather than a cyclical glacial–interglacial sequence. Khadkikar (2005) attributed the lamination types in Gopnath as grainfall deposits with an absence of grain avalanching either on account of high atmospheric humidity in coastal regions, or possibly due to the action of salt sprays and partial cementation. Khadkikar (2005) reported convex-up bedding geometries (dips in the range of 25 to 35° with NNE azimuth) from the Gopnath aeolianites, termed them as hump cross-bedding, and related this bedding geometry to sediment migration along an advancing parabolic dune nose or in some cases to an advancing lobe related to trough blow outs.

METHODOLOGY

The Gopnath cliff section runs for nearly 800 m north–south along the coast and possesses intermittent east–west right-angled bays. 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. 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. The Gopnath cliff section was laterally mapped in a horizontal by vertical 1 m by 1 m grid and the data was compiled as a series of two-dimensional panels. Each panel records the sedimentary structures, stratification types, latero-vertical extent of facies, spatial arrangement of sets of strata and bounding surfaces, and dip-azimuth readings from the cross-bedded units and bounding surfaces. Because of weathering and vegetation, the cliff section is not entirely mappable. However, a continuous 400 m stretch of the cliff section varying in height from 6 to 8 m could be mapped successfully. Based on the occurrence of different facies, their geometry, lateral extent and bounding surfaces facies associations were established to identify the different phases of aeolian sedimentation. Finally the results of facies analysis and aeolian architectural inputs, as obtained from lateral mapping, were integrated into a conceptual stratigraphic and depositional model for the aeolian succession in the study area.

AEOLIAN STRATIFICATION TYPES

Aeolian stratification types were studied in detail from the Gopnath cliff section and three different aeolian stratification types were distinguished.

Grainflow lamination

Description

Grainflow lamination (Fig. 2A) is the most common stratification type and constitutes *ca* 80% of the aeolianite deposits in Gopnath. Grainflow laminae are composed of dominantly medium-grained, moderately sorted, sub-rounded (dominant) to sub-angular sand size grains which sometimes exhibit crude inverse grading. Individual laminae possess thicknesses between 0·3 cm and 4·5 cm with an average around 1·0 cm. The grainflow lamination typically characterizes steeply dipping foresets with foreset dips between 25° and 34°. The foresets are tabular in nature and exhibit sharp angular upper and lower contacts. However, in a single vertical cliff section grainflow lamination has also been observed to constitute foresets with lower dip amount of 18°.

Interpretation

Grainflow lamination described here is very similar to grainflow lamination described by Hunter (1977) from small recent coastal dunes. The grainflow strata here are attributed to have been formed by avalanching on dune slip faces in the form of sand flow when deposition in zones of flow separation caused the slope angle to reach the initial angle of yield (Hunter, 1977).

Grainfall lamination

Description

Grainfall lamination (Fig. 2A) covers *ca* 10% of the aeolian deposits in Gopnath and is commonly intimately associated with grainflow

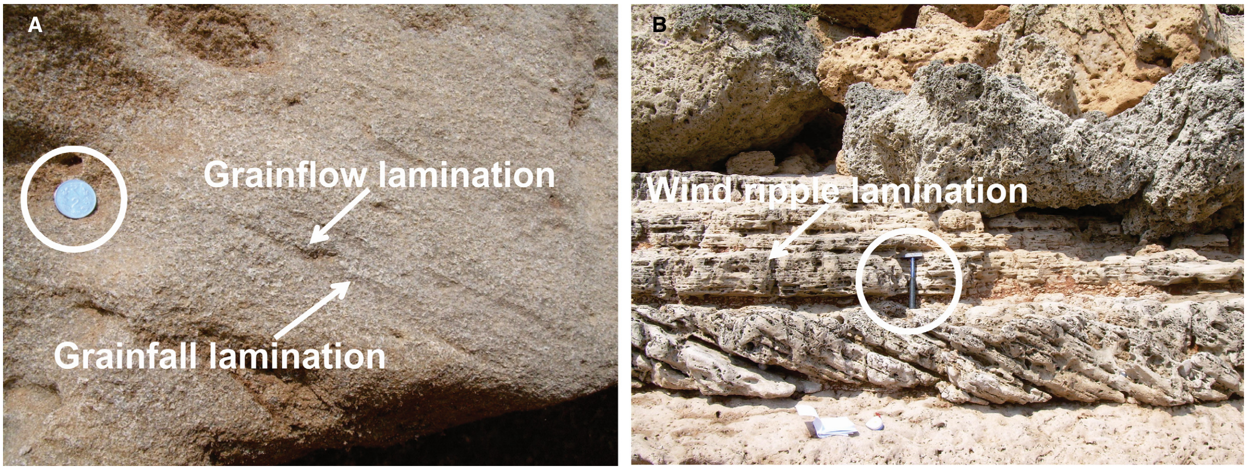

Fig. 2. Aeolian stratification types. (A) Grainflow and grainfall laminae in thickly cross-stratified Miliolite. Grainflow lamina is coarser, lighter in colour, heterogeneous and loosely packed compared to grainfall lamina. Coin for scale (diameter: 2·5 cm, encircled). (B) Wind ripple laminae are characterized by thin (1 to 3 mm), sub-horizontal, compact, laminae and lack ripple-foreset cross-lamination. Hammer for scale (length 31 cm, encircled).

strata. The grainfall lamination is 2 to 3 mm thick and is composed of moderate to well-sorted fine sand-sized grains. Individual grainfall laminae are tabular, dark coloured, homogeneous and exhibit compact packing of grains. Grainfall lamination essentially characterizes dune foresets which are 3·0 to 4·5 cm thick and dip between 30° and 34°.

Interpretation
The presence of grainfall lamination indicates that there must have been a zone of flow separation leeward of the dune crests because this stratification type, according to Hunter (1977), occurs on smooth leeward slopes in areas of flow separation. In this zone, previously saltating grains fall onto the surface because of the change in energy conditions around the lee face (Hunter, 1977; Clemmensen & Abrahamsen, 1983).

Wind ripple lamination

Description
Wind ripple lamination (Fig. 2B) accounts for *ca* 10% of the aeolianite deposits in Gopnath. Wind ripple laminae are very fine to fine to medium-grained, thin (1 to 3 mm) to thick (3 to 4 cm), composed of sub-angular to sub-rounded moderately sorted sand-size grains, compact, laterally extensive, tabular, horizontal to very gently dipping (5 to 7°) and lack ripple-foreset cross-lamination. Although extensive weathering has destroyed the internal fabric, in most cases, some fine scale interlaminations of dominantly fine-grained to dominantly medium-grained laminae are observed in places.

Interpretation
Wind ripple lamination described here is interpreted to belong to sub-critical climbing translatent strata of Hunter (1977). According to Hunter (1977) wind ripples occur on interdune flats, on the stoss sides of dunes and on lee slopes that are inclined less steeply than the angle of repose. Thicker laminae are deposited by subcritical climbing ripples where strong winds are present (Hunter, 1977).

AEOLIAN BOUNDING SURFACES

Field inspection and detailed mapping of the Gopnath cliff section permits the recognition of different bounding surfaces within the aeolianite succession, although different degrees of weathering might have obscured some of them. At least three types of bounding surfaces are recognized which have been compared to those described by Brookfield (1977) and Kocurek (1988).

Type-I surfaces (T1S)

These surfaces (Fig. 3A) are planar, horizontal to gently dipping surfaces which bound the

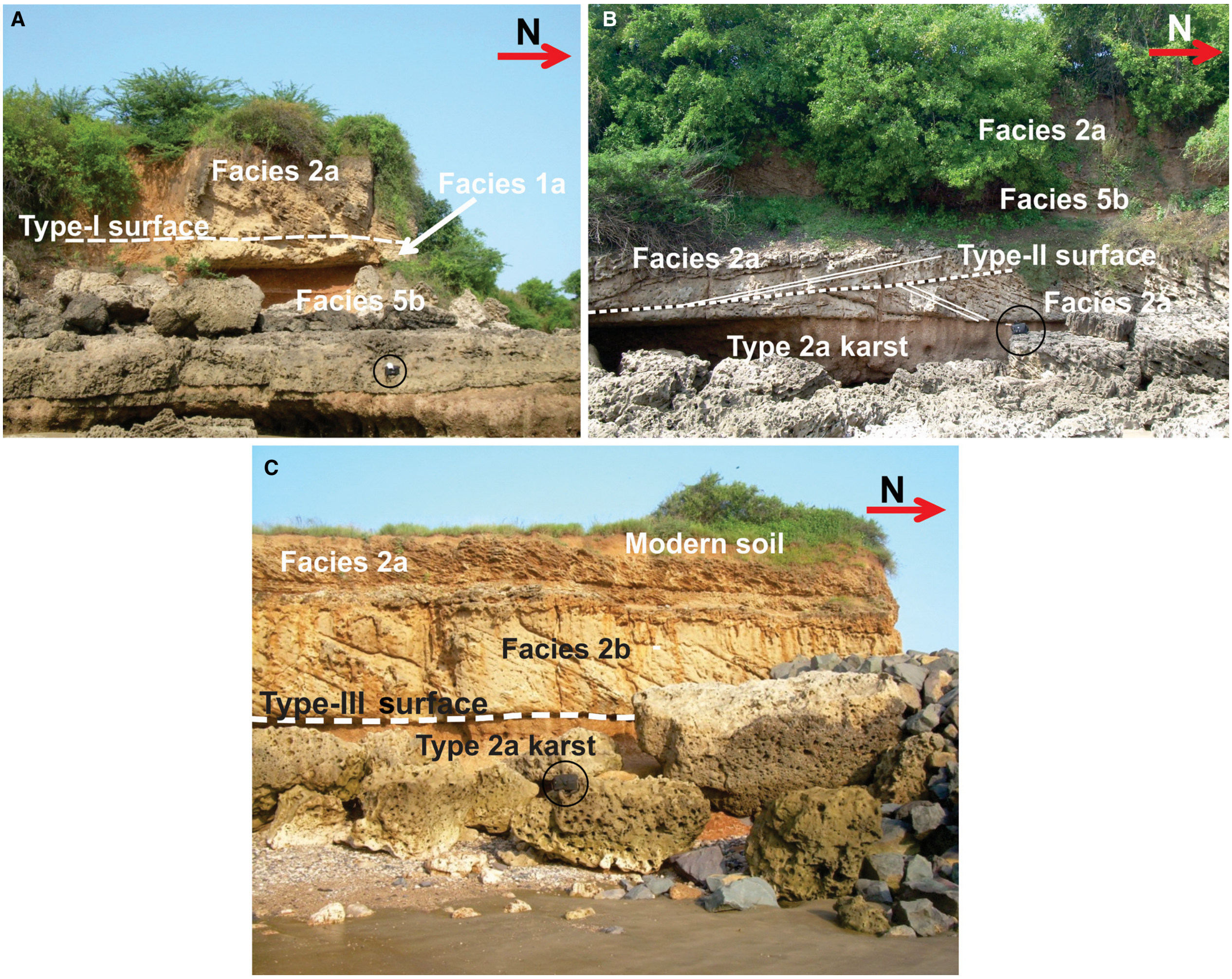

Fig. 3. Aeolian bounding surfaces. (A) Type-I surface is planar, horizontal and is marked at the contact between the thin plane stratified units (Facies 1a) (overlying the palaeosol horizon Facies 5b) and the overlying cross-stratified Miliolite unit (Facies 2a). Type-I surface thus represents the migration of primary bedforms in a dune field. Field bag (encircled) for scale (height 26 cm). (B) Type-II surface is planar, gently dipping and separates different dune units. Field bag (encircled) for scale (height 26 cm). (C) Type-III surface is a surface of unconformity and is marked at the top of the karstified unit which lies at the base of the aeolianite succession in Gopnath. While the karstified unit marks the cessation of dune building activities, the overlying cross-stratified Miliolites represent rejuvenation of aeolian activity after a prolonged gap. Field bag (encircled) for scale (height 26 cm).

different aeolian succession. The lateral continuity of the surfaces is often greater than 100 m and can exceed the length of the exposures that can be continuously traced for 400 m. Type-I surfaces are marked at the contact between the palaeosol horizons and/or plane stratified units (inferred to be interdune deposits as discussed later) and the overlying cross-stratified dune units. 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 & Howell (2000) and sand-drift surfaces of Scherer & Lavina (2005).

Type-II surfaces (T2S)

These surfaces (Fig. 3B) are planar to slightly concave upward, horizontal to gently dipping (10 to 12°), parallel to sub-parallel and bound different and successive dune sets within a single compound dune deposit defined by Type-I surfaces. Type-II surfaces show a maximum extent up to 35 m. Type-II surfaces are compared to the second-order surfaces of Brookfield (1977) which form in response to the migration of secondary bedforms over large-scale primary bedforms and also to superimposition surfaces of Mountney & Howell (2000).

Type-III surfaces (T3S)

A Type-III surface is a surface of unconformity (Fig. 3C) that marks the cessation of dune building activities indicated by the presence of relict, degraded dune topography as well as laterally extensive palaeosol horizons separating the different dune building events (discussed later) (Kocurek, 1988). A Type-III surface thus is marked at the top of the karstified unit (discussed later) which lies at the base of the aeolianite succession of the Gopnath cliff section. This surface is undulatory, laterally extensive and could be mapped for at least 400 m along the cliff section. In the vertical cliff section the contact between the successive aeolian succession and the intervening palaeosol layers is also marked as a Type-III surface. A Type-III surface as observed in Gopnath can be compared with super bounding surfaces (Kocurek, 1988) that form as a result of complete or partial termination of ergs or dune fields (Mountney & Howell, 2000). Supersurfaces are generated from a variety of factors or events, most notably changes in sand supply, water table or erg activity, each of which may in turn be driven by the underlying mechanisms of climate change, tectonic subsidence/uplift and sea-level change (Kocurek & Havholm, 1993; Mountney & Howell, 2000).

FACIES

The Gopnath Formation has been classified into five facies and eleven sub-facies (Table 1) based on lithology, internal stratification and unit morphology.

Facies 1: Plane laminated facies

The plane laminated facies is characterized by horizontal stratification and is sub-divided into two sub-facies on the basis of laminae thickness.

Sub-facies 1a: Thin plane laminated facies
The thin plane laminated facies (Fig. 4A) is characterized by horizontal laminae 1 to 3 mm thick and occurs as tabular to isolated lensoidal bodies; tabular units laterally extend for 24 m to >200 m and lensoidal units show lateral extension of 7 to 10 m. The thickness of the unit varies between 20 cm and 1·5 m. This facies is buff to greyish to greyish white in colour and variously weathered. The thin planar laminae are very compact and composed of very fine to fine and medium sand size grains which are sub-rounded and exhibit moderate sorting. Moreover, there exists some fine scale interlamination of dominantly fine-grained to dominantly medium-grained laminae within the unit. The thin plane laminated facies exhibits sharp horizontal upper and lower contacts. Depending upon the architecture, the upper contact of this facies unit variously underlies either the cross-stratified Miliolite or karst facies or modern day soil. Similarly, the lower contact is marked either by underlying cross-stratified Miliolite or palaeosol.

Sub-facies 1b: Thick plane laminated facies
The thick plane laminated facies (Fig. 4B) is characterized by thick plane laminae of 3 to 4 cm thickness and occurs as tabular to isolated lensoidal bodies; tabular units extend laterally for >140 m with lensoidal units showing lateral extension of 42 to 59 m. The thicknesses of the units vary between 60 cm and 1·5 m. This facies is buff coloured, variously weathered and shows development of vugs. The thick planar laminae are composed of fine to medium-grained, moderately sorted, sub-angular to sub-rounded (dominant) sand size grains. Internal gradation of grains could not be studied due to destruction of internal fabric by differential weathering and leaching. The thick plane laminated facies exhibits sharp horizontal upper and lower contacts. The lower contact is marked either by underlying karst facies or palaeosol; while the upper contact of this facies unit underlies cross-stratified Miliolite.

Interpretation
Thin plane laminated Miliolites without recognizable ripple foreset cross-lamination but showing bimodal grain sorting and compact grain packing suggest that sub-facies 1a is composed of subcritical climbing translatent strata formed due to migration and climbing of wind ripples under conditions of net sedimentation (Hunter, 1977; Kerr & Dott, 1988). However, ripples formed by strong winds can deposit thick subcritically climbing translatent strata (Hunter, 1977) as observed in sub-facies 1b. According to Scherer & Lavina (2005), horizontal strata like these can be ascribed to two diverse depositional settings: (i) interdune areas where they develop under meta-saturated depositional conditions (Mountney & Thompson, 2002; Mountney & Jagger, 2004); and

Table 1. Facies classification, brief-description and interpretation for facies encountered in the study area.

Facies	Sub-facies	Brief description	Interpretation
Facies 1: Plane laminated facies	Thin plane laminated facies	Buff to greyish to greyish white in colour; characterized by very compact thin planar laminae (1 to 3 mm) composed of sub-rounded and moderately sorted very fine to fine to medium sand size grains; occurs as tabular (lateral extension: 24 m to >200 m) to isolated lensoidal bodies (lateral extension: 7 to 10 m) with thickness varying between 20 cm and 1·5 m; variously weathered	Subcritical climbing translatent strata formed due to migration and climbing of wind ripples under condition of net sedimentation indicative of deposition in interdune areas or as sand sheets
	Thick plane laminated facies	Buff coloured; characterized by thick planar laminae (3 to 4 cm) composed of fine to medium-grained, moderately sorted, sub-angular to sub-rounded (dominant) sand size grains; occurs as tabular (lateral extension: >140 m) to isolated lensoidal bodies (lateral extension: 42 to 59 m) with thickness varying between 60 cm and 1·5 m; variously weathered	
Facies 2: Cross-stratified facies	Thinly cross-stratified facies	Greyish white to buff coloured; characterized by 0·3 to 1·5 cm thick tabular and angular grain flow cross-laminae composed of moderately sorted sub-angular to sub-rounded (dominant) fine to medium (dominant) with minor coarser sand size grains; occurs as tabular (lateral extension: 70 m to >220 m) to lensoidal bodies (lateral extension: 7 to 56 m) with thickness varying between 40 cm and 2·5 m; cross-laminae dips: 25 to 28° towards 10 to 30°; variously weathered	Deposits of migrating dunes with abundant slip faces
	Thickly cross-stratified facies	Greyish white to buff coloured; characterized by 3·0 to 4·5 cm thick tabular and angular grain flow cross-laminae composed of moderately sorted sub-rounded (dominant) to rounded medium (dominant) to coarse sand size grains; lensoidal in geometry (lateral extent: 52 m to >140 m) with thickness varying between 2·0 m and 2·5 m; cross-laminae dip: 30 to 34° towards 45°; variously weathered	

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Table 1. (continued)

Facies	Sub-facies	Brief description	Interpretation
Facies 3: Tabular sets of low angle cross-laminae	–	Greyish white in colour; characterized by very compact paper thin (<1 mm) horizontal to sub-horizontal strata composed of moderately sorted sub-angular to sub-rounded very fine to fine sand size grains; occurs as tabular bodies of thicknesses varying between 20 cm and 60 cm; dip of the cross-laminae mostly varies between 5° and 7° with dip direction varying between 20° and 150°; variously weathered	Subcritical climbing translatent strata formed due to migration and climbing of wind ripples under conditions of net sedimentation indicative of deposition in interdune flats
Facies 4: Karst facies	Type-1, Type-2 and Type-3 karsts (after Khadkikar & Basavaiah, 2004). In the present study Type-2 karst is further sub-classified into Type-2a, Type-2b and Type-2c karsts	Type-2a karst: occurs in a 1·0 to 1·5 m thick unit which is brownish in colour with pipe form cavities 10 to 12 cm long and 1·5 to 3·0 cm wide. Type-2b karst: occurs in a 1·8 to 2·0 m thick unit which is buff coloured with pipe form cavities being smaller in length (5 to 8 cm) and thinner in width compared to Type-2a karst. Type-2b karst is also characterized by horizontal pipe form cavities which form discontinuous features of 3·5 to 5·0 cm length. Type-2c karst: buff coloured and characterized by very elongated is vertical pipe form cavities which extend throughout the thickness of the unit (*ca* 1 m). The vertical pipe form cavities vary in length from 40 cm to 1 m, in width from 2 to 5 cm and in thickness from 2 to 3 cm	Karstification is attributed to dissolution processes. The variation in the length of pipe form cavities across the three varieties of Type-2 karst may be attributed to variation in the percentages of soluble fraction within the parent rock material or variations in internal fabric or different durations of exposure or variation in meteoric water flux or different permutation/combination of all the above
Facies5: Palaeosol facies	Sub-facies 5a to 5d	Sub-facies 5a: brick red in colour, lensoidal in geometry and shows maximum thickness of 70 cm, moderately hard, internally structureless with carbonate clasts present within it. Sub-facies 5b: brown to light brown in colour, tabular in geometry, 20 to 40 cm thick, internally structureless and possesses a sucrosic appearance. Sub-facies 5c: brownish red in colour, lensoidal in geometry (maximum thickness: 90 cm), moderately hard to hard and is internally characterized by residual carbonate clasts, concretions and rhizocretions. Sub-facies 5d: buff coloured, internally structureless, tabular in geometry (thickness *ca* 40 cm)	The palaeosol facies indicate lengthy episodes of landscape stability exposing the sediments to physical, biological and chemical modification leading to development of soil horizons

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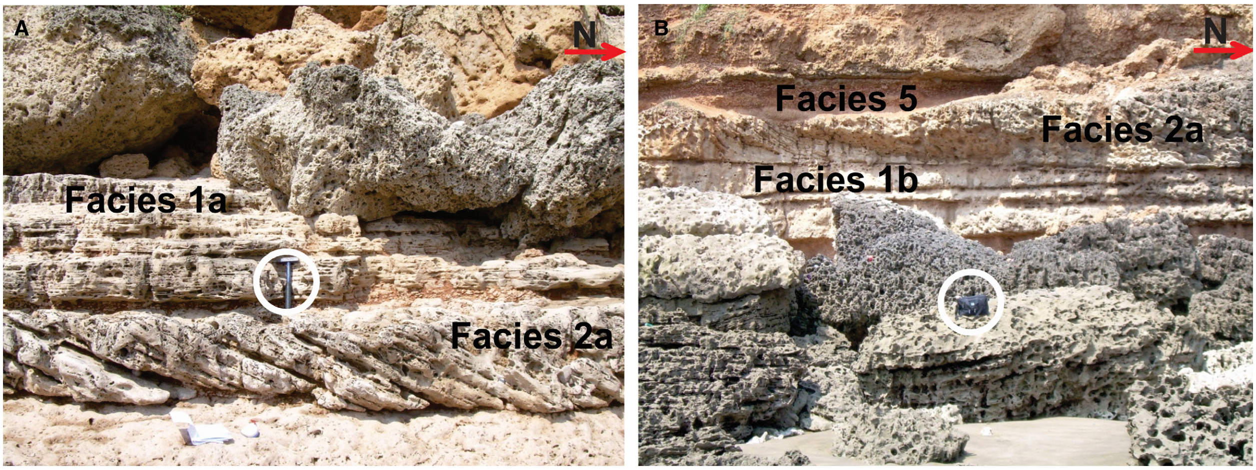

Fig. 4. Plane Laminated Facies. (A) Thin plane laminated facies (Facies 1a) is characterized by horizontal 1 to 3 mm thick laminae. Hammer (encircled) for scale (length 31 cm). (B) Thick plane laminated facies (Facies 1b) is characterized by thick plane laminae of 3 to 4 cm thickness. Field bag (encircled) for scale (height 26 cm).

(ii) aeolian sand sheets formed because of limited wind energy or sand availability precluding aeolian dune formation (Trewin, 1993; Veiega *et al.*, 2002; Biswas, 2005).

Facies 2: Cross-stratified facies

The cross-stratified facies is characterized by tabular, angular cross-laminae of 0·3 to 4·5 cm thickness. The cross-laminae dip at angles of 25 to 34° with dominant northerly azimuths. The cross-stratified facies is sub-divided into two sub-facies on the basis of the thickness of the cross-laminae.

Sub-facies 2a: Thinly cross-stratified facies

The thinly cross-stratified facies (Fig. 5A) is characterized by 0·3 to 1·5 cm thick cross-laminae and occurs as tabular to lensoidal bodies; tabular units laterally extend for 70 m to >220 m with lensoidal units showing lateral extension of 7 to 56 m. The thickness of the unit varies between 40 cm and 2·5 m. This facies is greyish white to buff coloured, variously weathered and shows development of vugs. The thin cross-laminae are composed of sub-angular to sub-rounded (dominant) fine to medium (dominant) with minor coarser sand size grains which are moderately sorted and are of grainflow origin. Although no gradation within the cross-laminae is observed, in places a crude inverse grading is observed. The cross-laminae are tabular and angular in nature; however, in places they exhibit tangential lower contacts. The cross-laminae commonly show dips between 25° and 28° towards 10 to 30°, but in a single instance within an isolated lensoidal body a dip of 22 to 24° towards 160° was observed. The thinly cross-stratified facies exhibits unimodal dip distribution with NNE mean wind flow direction (Fig. 5B). The thinly cross-stratified facies exhibits sharp horizontal upper and lower contacts. While the lower contact is marked either by underlying karst facies or by palaeosols, the upper contact of this facies unit underlies either the thin plane stratified facies or modern day soil. Some deformed and contorted cross-strata are also observed within the facies. In east–west cliff sections, nearly perpendicular to the dip direction of cross-laminae, the thinly cross-stratified facies exhibits up-arched stratification which was reported by Khadkikar (2005) as convex-up bedding.

Sub-facies 2b: Thickly cross-stratified facies

The thickly cross-stratified facies (Fig. 5A) is characterized by 3·0 to 4·5 cm thick foreset laminae and the sets occur with lensoidal geometry and show a lateral extent of 52 m to >140 m. The thickness of the unit varies between 2·0 m and 2·5 m. This facies is greyish white to buff coloured, variously weathered and shows development of vugs. The thick cross-laminae are composed of sub-rounded (dominant) to rounded medium (dominant) to coarse sand size grains which are moderately sorted. The individual laminae do not show any grain-size gradation. The cross-laminae of thickly cross-stratified facies is

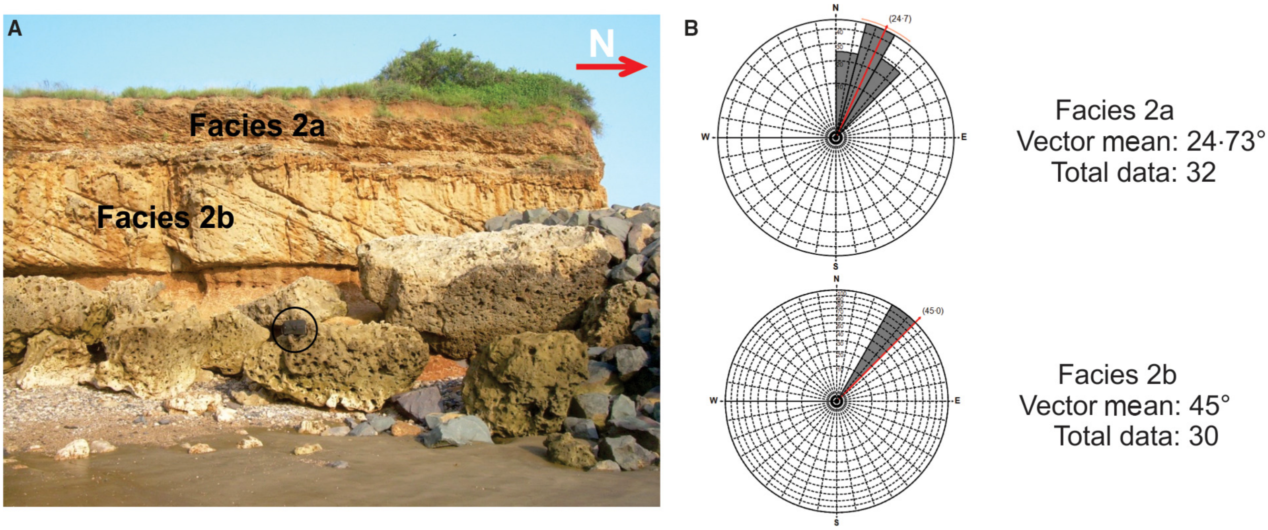

Fig. 5. Cross-stratified facies. (A) Thinly cross-stratified facies (Facies 2a) is characterized by thin, tabular cross-laminae which are dominantly angular in nature. Thickly cross-stratified (Facies 2b) facies is characterized by thick (3·0 to 4·5 cm), tabular cross-laminae with angular contacts. Facies 2a and Facies 2b exhibit sharp upper and lower contacts. Field bag (encircled) for scale (height 26 cm). (B) Rose plots for Facies 2a and 2b show a unimodal dip azimuth distribution with N25°E and N45°E mean flow direction.

marked by alternation between thicker medium to coarse-grained grainflow laminae and thinner, homogeneous, dark coloured, fine-grained grainfall laminae. The cross-laminae are tabular and angular in nature and dip between 30° and 34° towards 45°. The thickly cross-stratified facies exhibits unimodal dip distribution with north-easterly mean wind flow direction (Fig. 5B). The thickly cross-stratified facies exhibits sharp horizontal upper and lower contacts. While the lower contact is marked by underlying karst facies, the upper contact of this facies underlies either thinly plane stratified facies or palaeosol.

Interpretation

The cross-stratified facies are interpreted to be deposits of migrating dunes with well-developed avalanche slip faces indicated by a high percentage of grainflow strata (Kocurek & Dott, 1981). The angular foresets probably represent smaller dunes where grainflows frequently reached the bottom of the lee faces (Kocurek & Dott, 1981; Clemmensen & Abrahamsen, 1983; Chakraborty, 1991). Thicker grainflow laminae alternating with thinner grainfall layers in sub-facies 2b indicate intermittent avalanching over the lee face of depositing dunes owing to low wind velocities and wind stress insufficient to rework the grainfall deposits (Reineck & Singh, 1973; Kocurek & Dott, 1981). The absence of grainfall laminae in sub-facies 2a indicates frequent avalanching over the lee face of depositing dunes due to higher wind velocities (Reineck & Singh, 1973). The tangential nature of some of the foresets indicates the presence of wind-ripples near the toe of facies 2a dunes. The deformed cross-strata suggest slumping on the dune lee face as a result of sand wetting by dew or rain or by cementation (Scherer & Lavina, 2005).

Facies 3: Tabular sets of low angle cross-laminae

This facies, occurring mostly on the Gopnath shore platform is characterized by very compact paper thin (<1 mm) sub-horizontal strata and occur as tabular bodies of thicknesses varying between 20 cm and 60 cm (Fig. 6A). The laminations are composed of sub-angular to sub-rounded, moderately sorted, very fine to fine sand size grains. However, the internal gradation of grains could not be ascertained due to heavy weathering and leaching caused by tide and wave action. The unit is greyish white in colour, variously weathered and possesses vuggy porosities. The facies is underlain by karst facies with a sharp contact (Fig. 6B). The extremely thin laminations give a foliated papery appearance to the unit and make it visibly distinct from other facies in the study area. The dip of the low angle

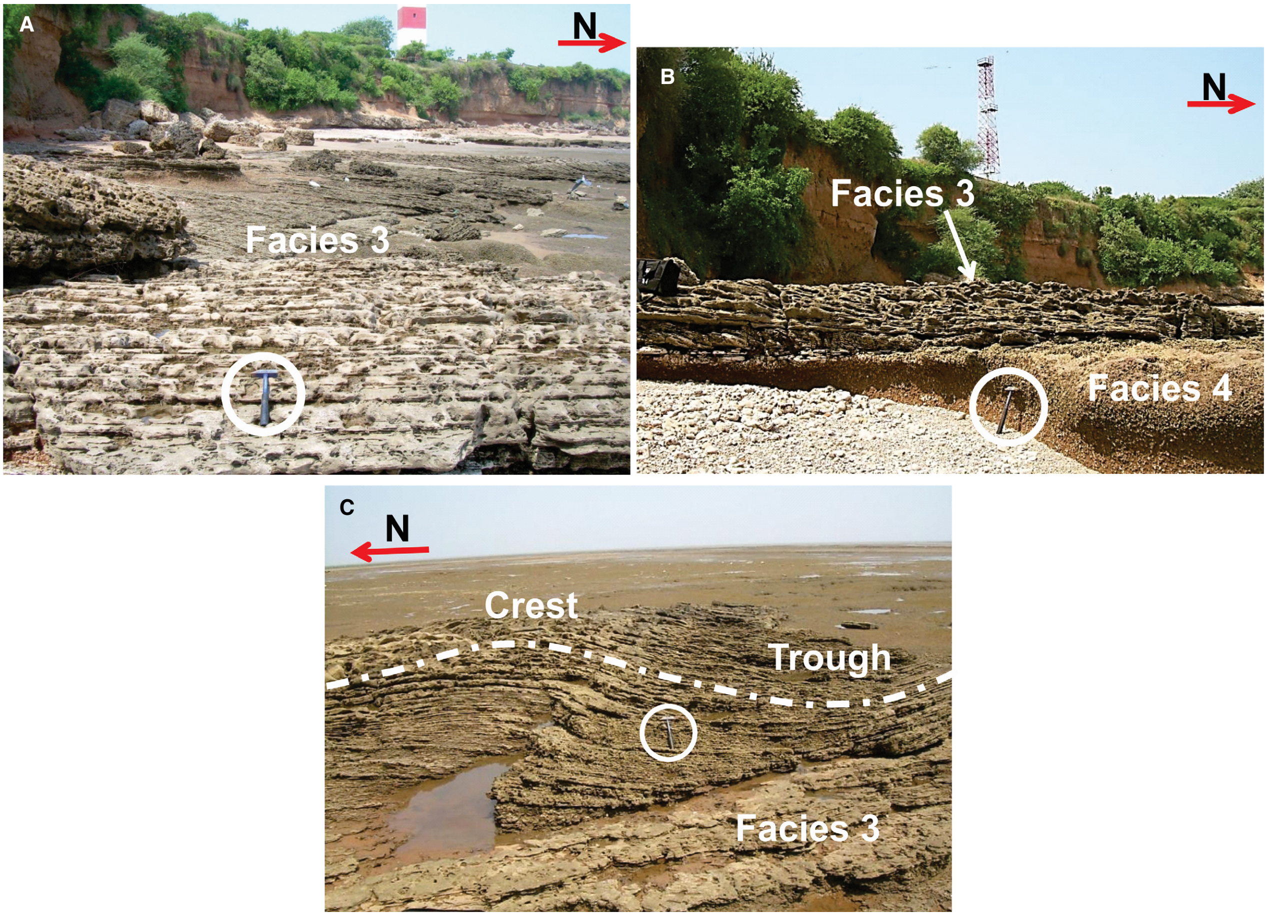

Fig. 6. Tabular sets of low angle cross-laminae. (A) Tabular sets of low angle cross-laminae (Facies 3) are characterized by very compact, paper thin (<1 mm), sub-horizontal strata and occur as tabular bodies. Hammer (encircled) for scale (length 31 cm). (B) Facies 3 is underlain by karst facies and exhibits a sharp contact. Field bag (encircled) for scale (height 26 cm). (C) Megaripple form preserved within Facies 3 shows a sinuous crestline and represents the remnant of isolated dunes occurring in interdune areas. Hammer (encircled) for scale (length 31 cm).

laminae mostly varies between 5° and 7° with dip direction varying between 20° and 150° within a short traverse across the shore platform. A megaripple form with a sinuous crest line is also found preserved within the unit (Fig. 6C) with the plunge of the crest axis being 22° towards 50°.

Interpretation

The extremely thin, tabular, low angled cross-strata with close compact packing are ascribed as subcritical climbing translatent stratification (Hunter, 1977) deposited by migration and climbing of wind ripples on interdune flats (Hunter, 1977; Kocurek & Dott, 1981). The preserved megaripple form is interpreted to be remnant of smaller isolated dunes occurring in the interdune areas. The wider range of dip azimuths (20 to 150°) may be attributed to frequent changes in wind direction due to variations in pressure gradient within the interdune area resulting from closely spaced dunes (Walker & Hesp, 2013).

Facies 4: Karst facies

The karst facies in Gopnath and adjoining areas have been vividly described and classified by Khadkikar & Basavaiah (2004) into Type-1, Type-2 and Type-3 karsts. However, in the present study a closer look into the outcrop sections of Gopnath allowed further classification of Type-2 karst into sub-facies. Type-2 karst as defined by Khadkikar & Basavaiah (2004) possesses nearly circular planform shaped cavities which extend down vertically to form pipes of 3 to 7 cm diameter with very small or negligible lateral interconnectedness. In the present study three sub-facies have been identified, namely: Type-2a, 2b and 2c karsts (Fig. 7A and B). Type-2a karst occurs in a 1·0 to 1·5 m thick unit which is brownish in colour with pipe form cavities 10 to 12 cm long and 1·5 to 3·0 cm wide. The Type-2a karst is marked by the presence of abundant residual carbonate clasts which are elliptical in plan form with small and large axis ranging between 4 to 9 cm and 5 to 10 cm, respectively. The residual carbonate clasts are found mostly with their long axis parallel to the stretch of the facies. Type-2b karst occurs in 1·8 to 2·0 m thick unit which is buff coloured with pipe form cavities being smaller in length (5 to 8 cm) and thinner in width compared to Type-2a karst. Type-2b karst is also characterized by horizontal pipe form cavities which form discontinuous features 3·5 to 5·0 cm long. Type-2c karst is buff coloured and is characterized by very elongated vertical pipe form cavities which extend throughout the thickness of the unit (*ca* 1 m). The vertical pipe form cavities vary in length, width and diameter between 40 cm to 1 m, 2 to 5 cm and 2 to 3 cm, respectively. From stratigraphic point of view, it appears that Type-2a karst is overlain by Type-2b karst which in turn is overlain by Type-2c karst. While sedimentary structures have been completely obliterated in Type-2a and Type-2c karsts, in Type-2b karst some faint relict cross-laminae are observed in places which bear an

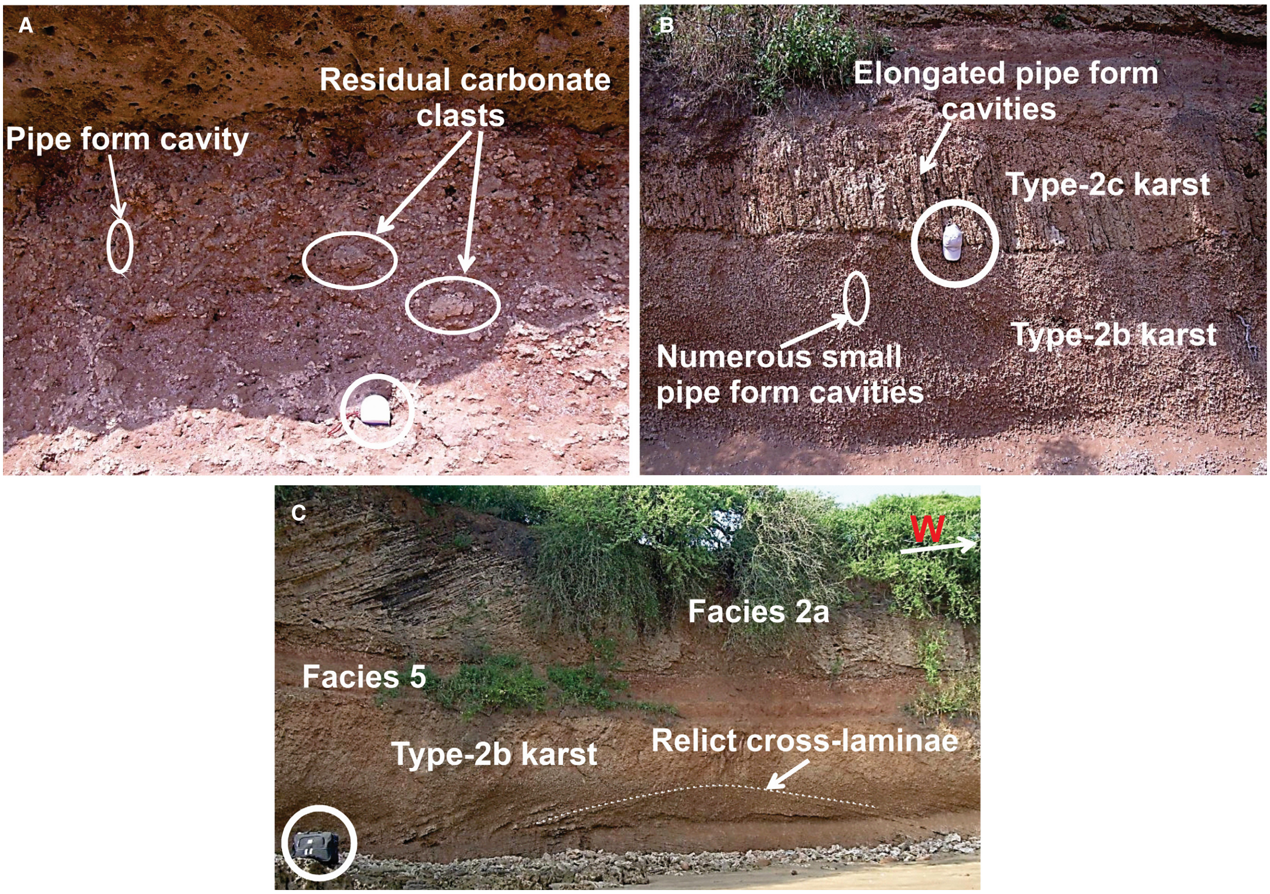

Fig. 7. Karst facies. (A) Type-2a karst is brownish in colour with pipe form cavities 10 to 12 cm long and 1·5 to 3·0 cm wide and is marked by the presence of abundant residual carbonate clasts which are elliptical in plan form. The residual carbonate clasts are found mostly with their long axis parallel to the stretch of the facies. Measuring tape (encircled) for scale (width 5·7 cm). (B) Type-2b karst is buff coloured with pipe form cavities being smaller in length (5 to 8 cm) and thinner in width compared to Type-2a karst. Type-2c karst is buff coloured and is characterized by very elongated vertical pipe form cavities which extend throughout the thickness of the unit (*ca* 1 m). The vertical pipe form cavities vary in length, width and thickness between 40 cm to 1 m, 2 to 5 cm and 2 to 3 cm, respectively. White cap (encircled) for scale (width 21 cm). (C) Faint relict cross-laminae observed in Type-2b karst which bear an arcuate appearance in the east–west cliff section. Field bag (encircled) for scale (height 26 cm).

arcuate appearance in the east–west cliff section (Fig. 7C).

Interpretation

The formation of karst is attributed to solution processes with the Type-2 karst forming in zones dominated by pipe flow water movement with coalescing of the vertical pipe network causing the formation of much larger pipe cavities (Khadkikar & Basavaiah, 2004). The variation in the length of pipe form cavities across the three varieties of Type-2 karst may be attributed to variation in the percentages of soluble fraction within the parent rock material or variations in internal fabric or different durations of exposure or variation in meteoric water flux or different permutation/combinations of all of the above. Type-2a karst, owing to its brownish colour compared to Type-2b and Type-2c karsts, seems to show a greater degree of pedogenesis (Khadkikar & Basavaiah, 2004) indicating longer exposure to meteoric conditions. The longer pipe form cavities of Type-2c compared to Type-2a and Type-2b karsts may be attributed to variation in the internal fabric of the parent rock material resulting in development of better fluid passageways in case of Type-2c karst.

Facies 5: Palaeosol facies

The palaeosol facies in the study area is subdivided into four sub-facies, namely sub-facies 5a, 5b, 5c and 5d (Fig. 8A to D). Sub-facies 5a is brick red in colour, lensoidal in geometry and shows maximum thickness of 70 cm. The unit is moderately hard and internally structureless with carbonate clasts present within it. The unit possesses sharp upper and lower contacts. While the lower contact is marked by underlying Facies 3, the upper contact underlies Facies 2a. Sub-facies 5b is brown to light brown in colour, 20 to 40 cm thick, internally structureless and possesses a sucrosic appearance. The unit possesses sharp upper and lower contacts and is tabular in geometry. While the upper contact underlies either Facies 2a or Facies 1a, the lower contact is marked by underlying Facies 1b of Facies 2a. In a north–south traverse along the cliff, sub-facies 5b passes below another palaeosol horizon (sub-facies 5c) forming stacked palaeosol horizons and pinches out further southward. Towards the north, palaeosol sub-facies 5b merges with Facies 2a (Figs 9 and 12). Sub-facies 5c is brownish red in colour, lensoidal in geometry (maximum thickness: 90 cm), moderately hard to hard and is internally characterized by residual carbonate clasts, concretions (internal concentric zonation) and rhizocretions. The unit possesses sharp upper and diffused lower contacts. While the upper contact underlies Facies 1a, the lower contact is marked by underlying Type-2c karst. A similar palaeosol layer occurring at the base of the Miliolite cliff section in Madhuban (8 km south-west of Gopnath) has yielded a Late Acheulean lithic assemblage (Marathe *et al.*, 1995). Sub-facies 5d is buff coloured and is internally structureless. The unit is tabular in geometry (thickness *ca* 40 cm) with sharp upper and lower contacts. While the upper contact underlies Facies 2a, the lower contact is marked by underlying Facies 1b. This unit has yielded vertebrate remains (Costa, 2015) of terrestrial tortoises (*Geochelone* sp.), soft-shelled aquatic turtles (*Nilssonia* sp.), dog-like carnivores (*Canis* sp.), equids (*Equus cf. E. sivalensis* and *Equus cf. E. hemionus*), rhinoceros *(Rhinoceros cf. R. unicornis*) and bovines (*Boselaphus* sp., *Bubalus* sp., *Bos* sp. and *Sivacobus sankaliai*). In addition, numerous shells of the snail *Zootecus insularis* are also found in this unit (Costa, 2015). *Zootecus insularis* is an arid land, terrestrial snail species that prefers moist locations near lakes or rivers (Costa, 2015). From a taphonomic point of view the vertebrate remains of Gopnath do not indicate a role of humans and animals in their accumulation, exhibit minimal post-mortem disturbance and modification and also do not show any preferential orientation (Costa, 2015). Further fossils unaffected by recent erosive action of the intertidal splash zone at Gopnath are found to be surprisingly fresh. The overall freshness of the remains and lack of animal modification suggested that the vertebrate remains were buried rapidly following death (Costa, 2015).

Interpretation

The palaeosol facies indicate lengthy episodes of landscape stability exposing the sediments to physical, biological and chemical modification leading to development of soil horizons (Kraus, 1999). According to Khadkikar (2004) and Khadkikar & Basavaiah (2004) the palaeosol horizons represent breaks in carbonate deposition due to interglacial wetter climatic conditions which favoured palaeosol development. However, immature soil development can take place during pauses in the deposition of an aeolianite package and form in a very short time (hundreds or thousands of years) compared to mature soils (tens of thousands to hundreds of thousands of years)

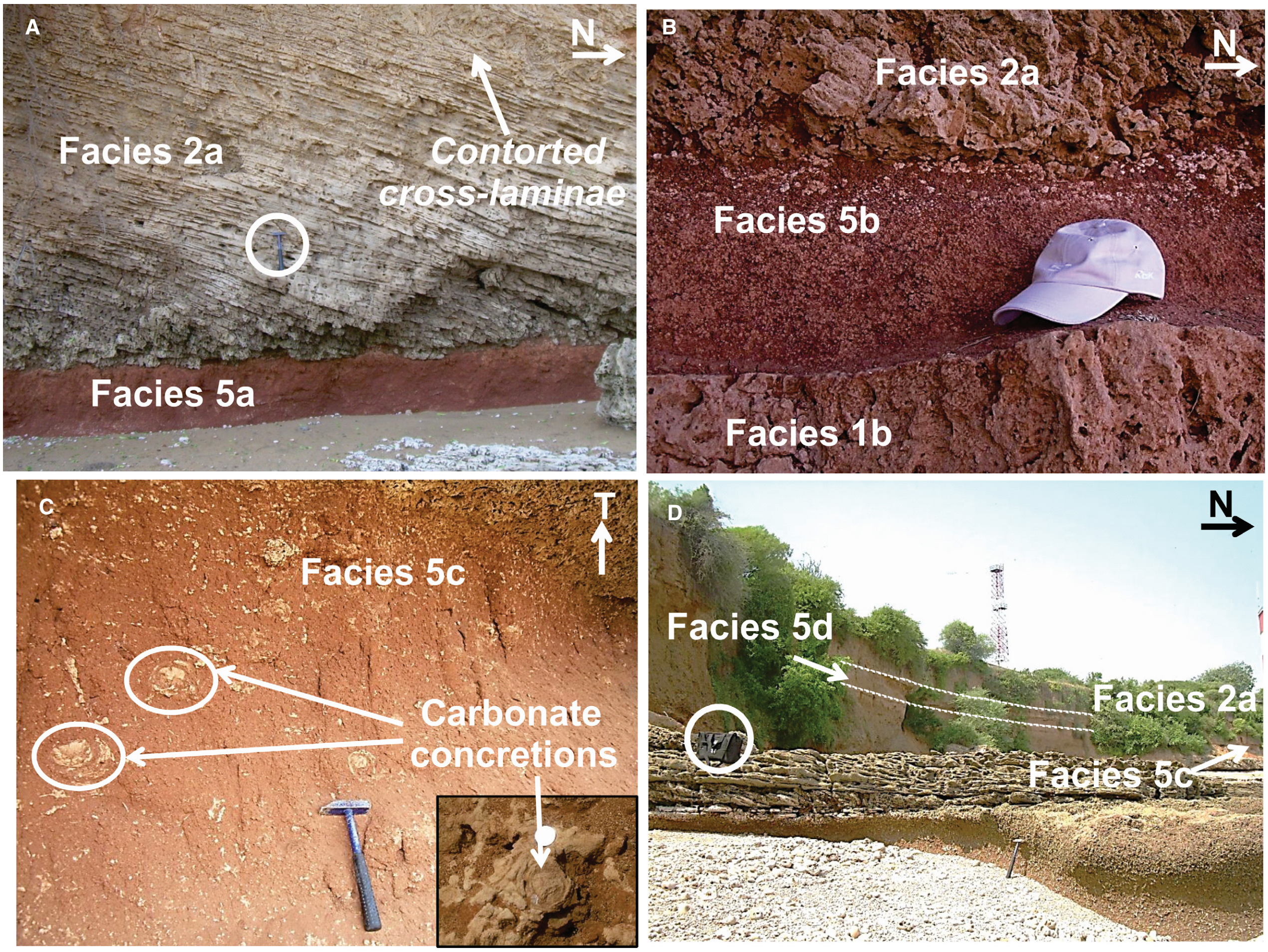

Fig. 8. Palaeosol facies. (A) Palaeosol Facies 5a is brick red in colour, internally structureless and possesses sharp upper and lower contacts. Hammer (encircled) for scale (length 31 cm). (B) Palaeosol Facies 5b is brown to light-brown in colour, internally structureless, has a sucrosic appearance and possesses sharp upper and lower contacts. White cap for scale (width 21 cm). (C) Palaeosol Facies 5c is brownish red in colour, internally characterized by the presence of residual carbonate clasts and concretions and possesses sharp upper and lower contacts. Hammer for scale (length 31 cm). (D) Palaeosol Facies 5d is buff coloured, internally structureless and possesses sharp upper and lower contacts. Field bag (encircled) for scale (height 26 cm).

(Mylorie & Carew, 2010; Kelly *et al.*, 2011). The Gopnath fossil assemblage as recovered from palaeosol sub-facies 5d represents a grassland/marsh ecosystem (Costa, 2012). *Zootecus insularis* is an arid land, terrestrial snail species that prefers moist locations near lakes or rivers (Costa, 2015). Wetter climatic conditions during interglacials could result in the development of wetlands or confined body/bodies of water and growth of vegetation, supporting the wide variety of vertebrate and invertebrate taxa as observed in Gopnath. However, the long-term surficial weathering required for development of mature soils would not have resulted in such a good preservation of the fossil record. Hence, the palaeosol sub-facies 5d is ranked as a protosol and represents a short break in aeolian sedimentation compared to prolonged landform stabilization during development of mature soils. The colour variation among the different palaeosol sub-facies may be attributed to varying concentration of hematite. Hematite is released as an authigenic mineral phase during weathering (Khadkikar & Basavaiah, 2004) of the Miliolites.

DISCUSSION

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 & Dott, 1981; Kocurek & Havholm, 1993; Mountney & Thompson, 2002; Scherer & Lavina, 2005) indicate that the different dune–interdune sequences interspersed by development of palaeosol horizons 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 & 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 & Lavina, 2005). The dune–interdune and palaeosol sequence (Figs 9 to 13) as observed in the Gopnath cliff system suggests episodic switching between drier and wetter climatic conditions.

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 & Abrahamsen, 1983). The thick and laterally extensive cross-stratified units of the Gopnath cliff system 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 & Abrahamsen, 1983; Kerr & Dott, 1988). The dominance of grainflow strata in Gopnath aeolianites links them, at least qualitatively, to large crescentic dunes (Kerr & 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 & Hunter, 1982). Paucity of third order surfaces (Brookfield,

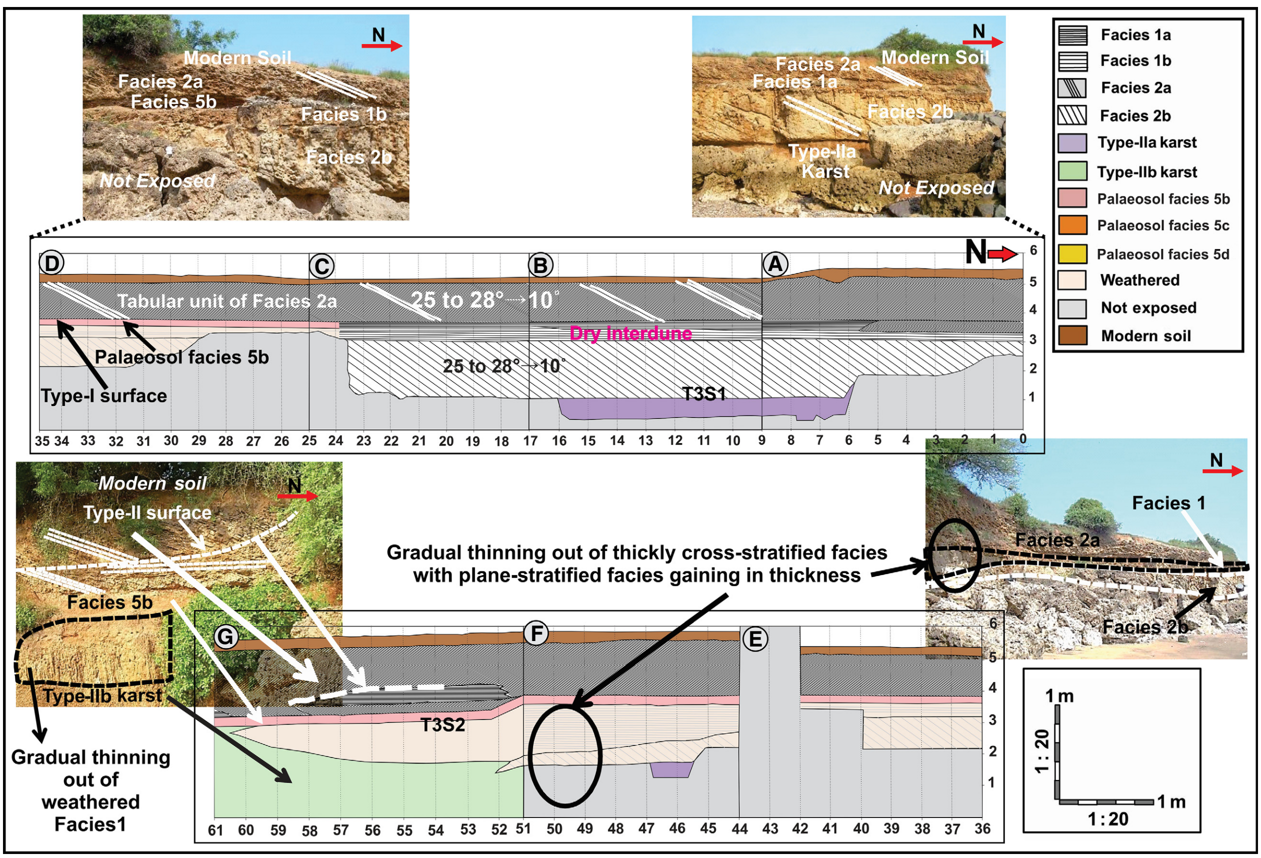

Fig. 9. Panel diagram depicting facies occurrences, their geometry, lateral extent and bounding surfaces in a north–south cliff section. Legend and scale remains the same for the successive panel diagrams.

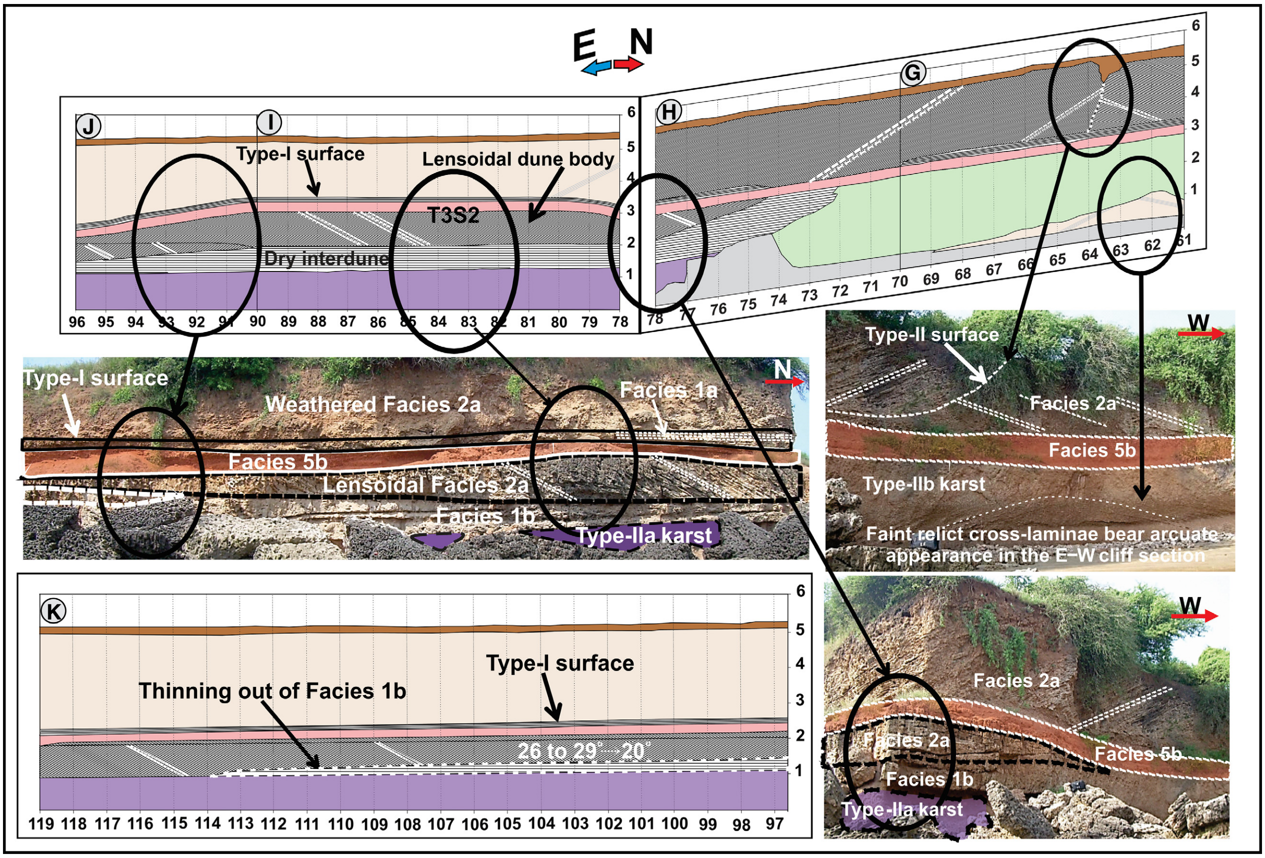

Fig. 10. Continued lateral mapping along east–west (G) and (H) and north–south (I) to (K) cliff sections. Convex-up bedding is observed in the lower portion of the east–west panel (G). While moving from the base towards the top of the cliff section, facies association of lensoidal dune bodies and interdune facies gives way to laterally extensive tabular cross-stratified units.

1977; Kerr & Dott, 1988) indicates infrequent lee-slope erosion and reactivation (Kerr & Dott, 1988).

Thus the existing understanding that the Gopnath aeolianites 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 (Fig. 12) 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 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 & 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).

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 (Figs 9 to 13). The basal weathered aeolianite is exposed only in pockets (Figs 9, 10, 11 and 13) 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 & Basavaiah, 2004). Thus the upper surface of the basal weathered aeolianite is a surface of unconformity named here as T3S-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

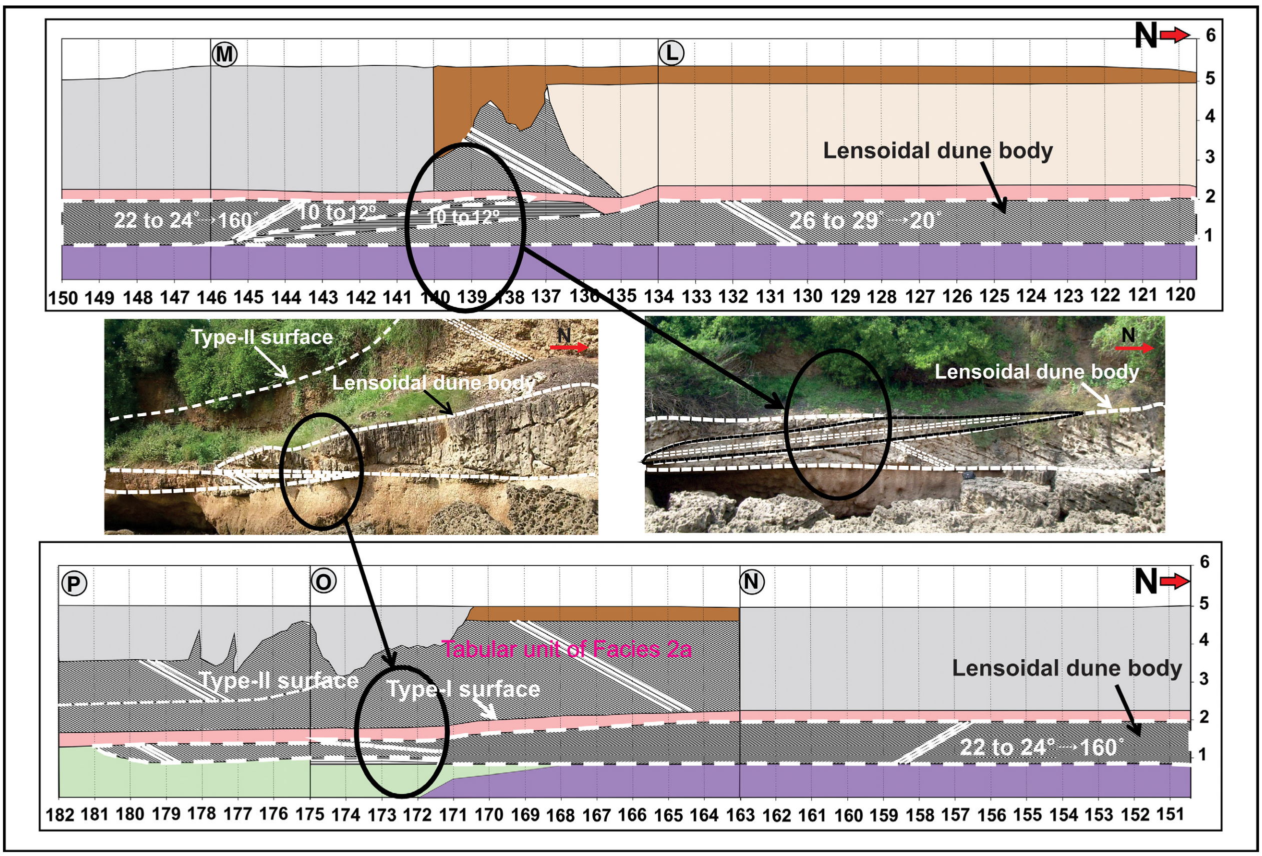

Fig. 11. Continued lateral mapping along the north–south cliff section (L) to (P) shows superimposition of lensoidal dune units with varying foreset dip azimuths indicative of variations in palaeowind directions. (L) to (P) also depict the architectural elements of the overlying laterally extensive tabular cross-stratified unit.

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 palaeosol 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 (Figs 9 to 13). 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 & Hunter, 1982):

$$\overline{H} \cong \sqrt{\frac{TD}{I}}, I = 15,$$

where, H is dune height, T is bed thickness and D is the downcurrent extent of individual cross-stratified beds or downcurrent depositional extent (Clemmensen & Abrahamsen, 1983) and occurs in the range of 0·63 to 2·63 m. Where one dune body climbs over another, the superimposition surface (Type-II surface) dips 10 to 12° (Fig. 11). While palaeosol 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, palaeosol Facies 5b merges with Facies 1a towards the north (Fig. 9) and passes below palaeosol Facies 5c towards the south (Figs 12 and 13) forming stacked palaeosol horizons. The

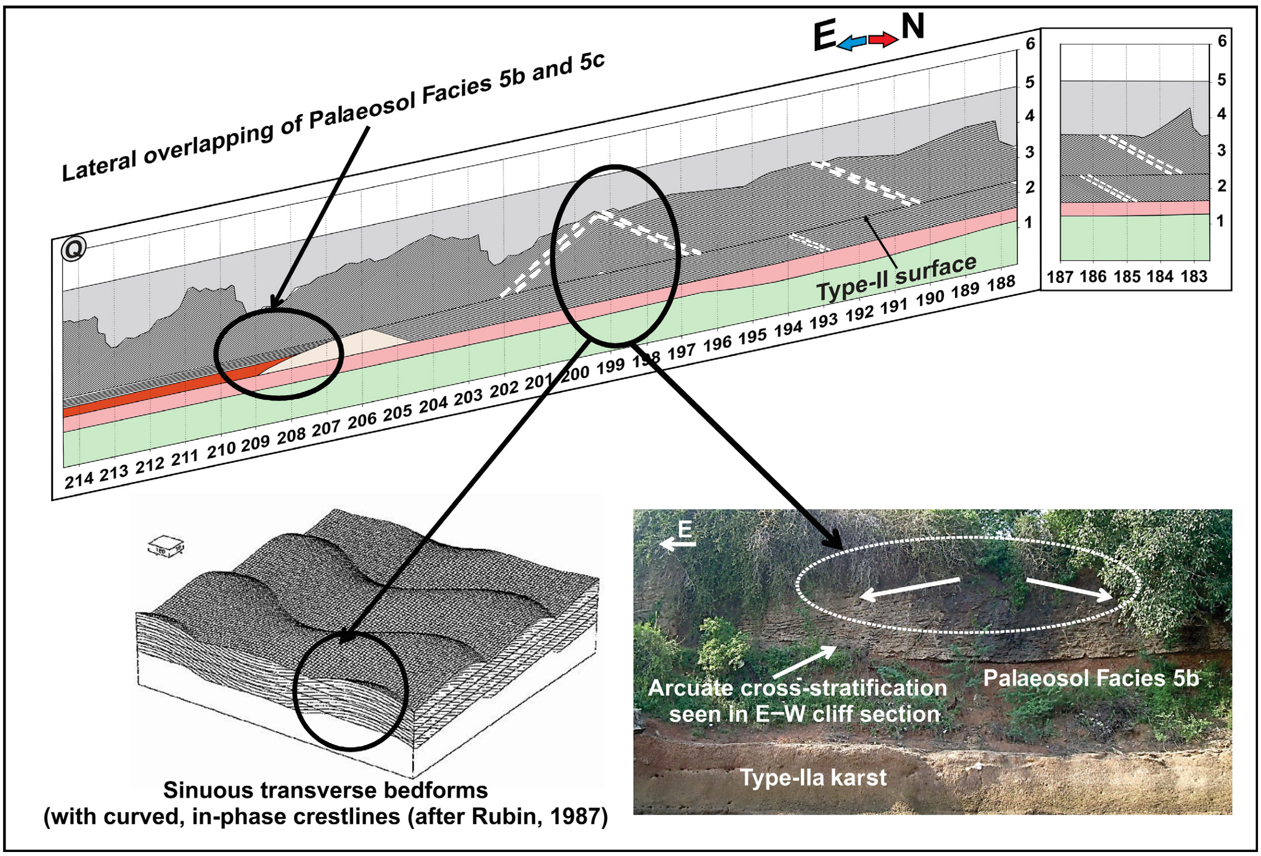

Fig. 12. Continuation of lateral mapping along north–south (P) and east–west (Q) cliff sections. Lateral overlapping of palaeosol Facies 5b and 5c is observed in (Q). Convex up bedding as seen in section perpendicular to dominant transport direction indicates deposition by transverse dunes with sinuous crestlines (Rubin, 1987).

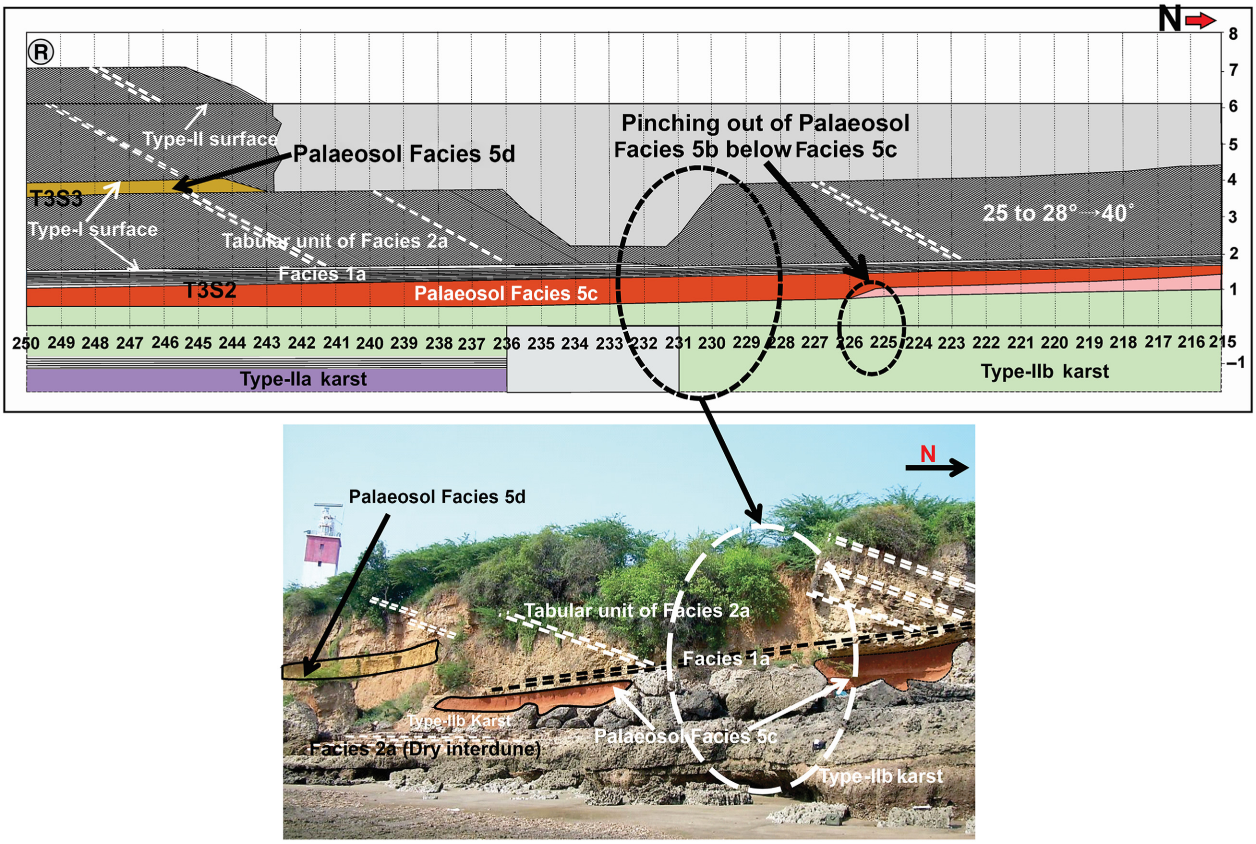

Fig. 13. Continuation of lateral mapping into the north–south cliff section (R). Pinching out of Palaeosol Facies 5b below Facies 5c is observed in the panel diagram. In the vertical succession, the bedforms are bounded by nearly horizontal planar surfaces exhibiting zero angle of climb.

base of the stacked palaeosol horizons defines a Type-III surface (T3S-2).

Facies association B overlies the stacked palaeosol horizons belonging to Facies 5b and 5c. This facies association comprises vertically stacked thinly cross-stratified facies (Facies 2a) with an intervening palaeosol 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 to 70 m. The height of the depositing dunes is estimated (Rubin & 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 to 35 m (Figs 11, 12 and 13). The intervening palaeosol Facies 5d represents a short break in aeolian sedimentation and defines a Type-III surface (T3S-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 (Figs 9 to 13). For dry aeolian systems, as in the present case, this suggests that interdune hollows existed simultaneously with dune forms (Mountney & Howell, 2000). A conceptual depositional model for the sedimentary succession is presented in Fig. 14.

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 & Lavina, 2005). As far as the aeolian succession in Gopnath 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,

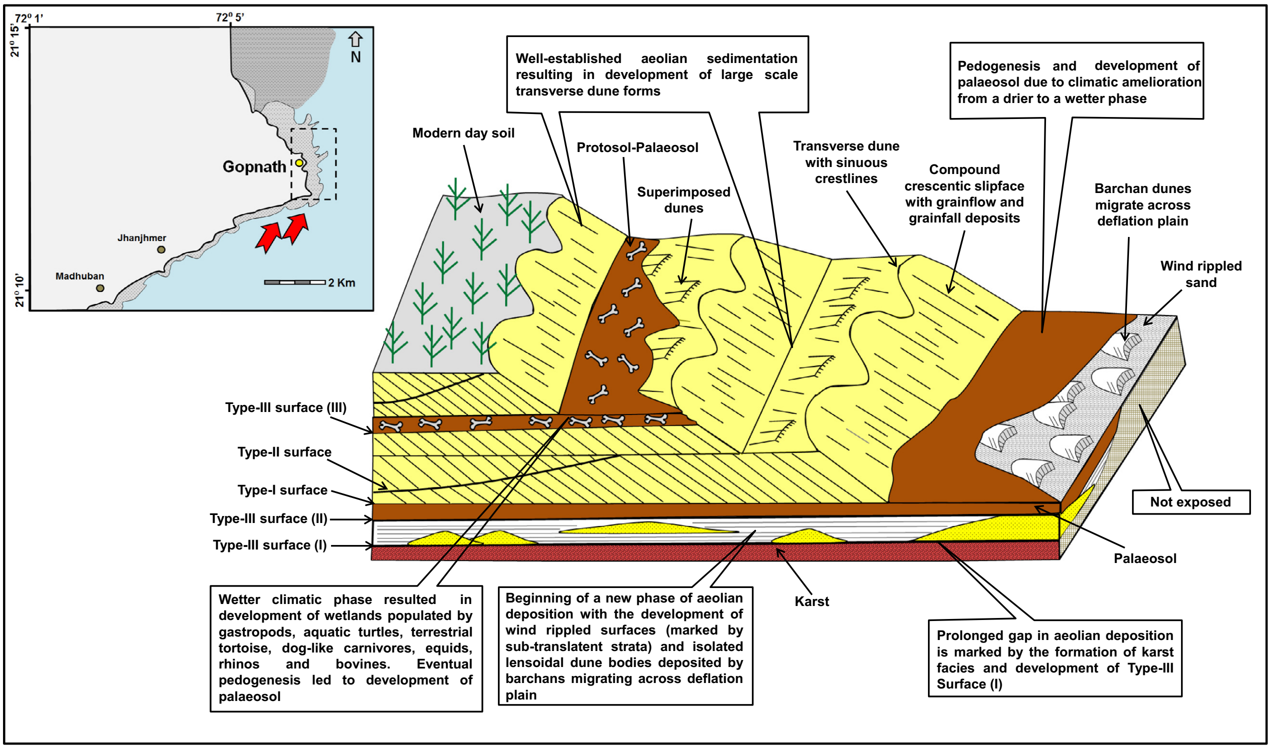

Fig. 14. Conceptualized depositional model for aeolinite sedimentation in the study area encompassing the Gopnath cliff system. The dominantly north-easterly dip azimuths indicate deposition by a south-westerly wind system as shown in the inset figure.

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 dune building events in Gopnath 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 Gopnath aeolianites under dominantly dry conditions indicates that the moisture content of these winds was significantly lowered during eustatic lowstands which could only be regained during eustatic highstands leading to dune stabilization and regional pedogenesis. 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 & 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 sedimentary succession in Gopnath, 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 sedimentary succession in Gopnath exhibits a changeover from a period of subdued to enhanced aeolian activities across the surface of the unconformity (T3S-1) that lies at the base of the Gopnath cliff section. The development of T3S-1 might be attributed to the destruction of an earlier existing coastal 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 palaeosol horizons (belonging to Facies 5b and 5c) blanketing the aeolian events of Facies association A 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 lowstand resulting in laterally extensive dune building which, however, was momentarily paused by a eustatic highstand resulting in the development of a protosol–palaeosol horizon belonging to Facies 5d.

CONCLUSIONS

1 The aeolianite units in Gopnath 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.
2 Late Quaternary dune building events in Gopnath took place under dominantly dry aeolian conditions.
3 The aeolian succession in Gopnath was deposited by transverse dune systems.
4 Eustasy and climate both went ‘hand in hand’ in depositing the Late Quaternary aeolianite succession in Gopnath. 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 and eventual pedogenesis.
5 The dominantly dry dune building events in Gopnath 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 and regional pedogenesis.

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