*Chapter 2*

# Sedimentological Analysis

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## 2.1. Introduction

On moving from east to west along the southern Saurashtra coastline, the Miliolite sequences progressively become younger in age from Gopnath (OSL age: > 156 ka) to Diu Island (OSL age: ~45 ka) (Sharma *et al.*, 2017). Thus, spanning over a time interval of ~100 ka, the Miliolite sequences over the three sectors are expected to serve as a repository of the temporal variations in aeolian depositional processes and controls in southern Saurashtra. For proper understanding of the aeolian depositional processes and controls, it is a pre-requisite to understand their fundamental expressions in the form of stratification types, bounding surfaces and facies. However, it is worth mentioning that before the initiation of the present study no clear-cut definition of these fundamental expressions of the aeolian sedimentary processes existed in the literature pertaining to the aeolianites of Saurashtra. Hence, a need was felt to define, describe and quantize the same which in turn would serve as the building blocks for erecting the Late Quaternary aeolian sedimentation history of southern Saurashtra. Since the Gopnath Miliolites represent the oldest record of aeolian sedimentation in southern Saurashtra, it forms the foundation for building up the aeolian sedimentation history in the region. Hence, a detailed lateral mapping of the Miliolite succession (400 m mappable section) 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. This allowed for gauging the changes in aeolian depositional processes and controls over southern Saurashtra with the deposition of the younger Miliolite units. The following sections describe the different stratification types, bounding surfaces and facies as observed in the study area.

## 2.2. Aeolian stratification types

Three different aeolian stratification types were distinguished, viz., (i) Grainflow lamination, (ii) Grainfall lamination and (iii) Wind ripple lamination. A detailed description of these stratification types is furnished below.

(i) Grainflow lamination

Grainflow lamination **(Figure 2.1a)** is the most common stratification type and constitutes *ca* 80% of the aeolianite deposits in the study area. Grainflow laminae are composed of dominantly medium grained, moderately sorted, sub-rounded (dominant) to sub-angular sand-sized grains

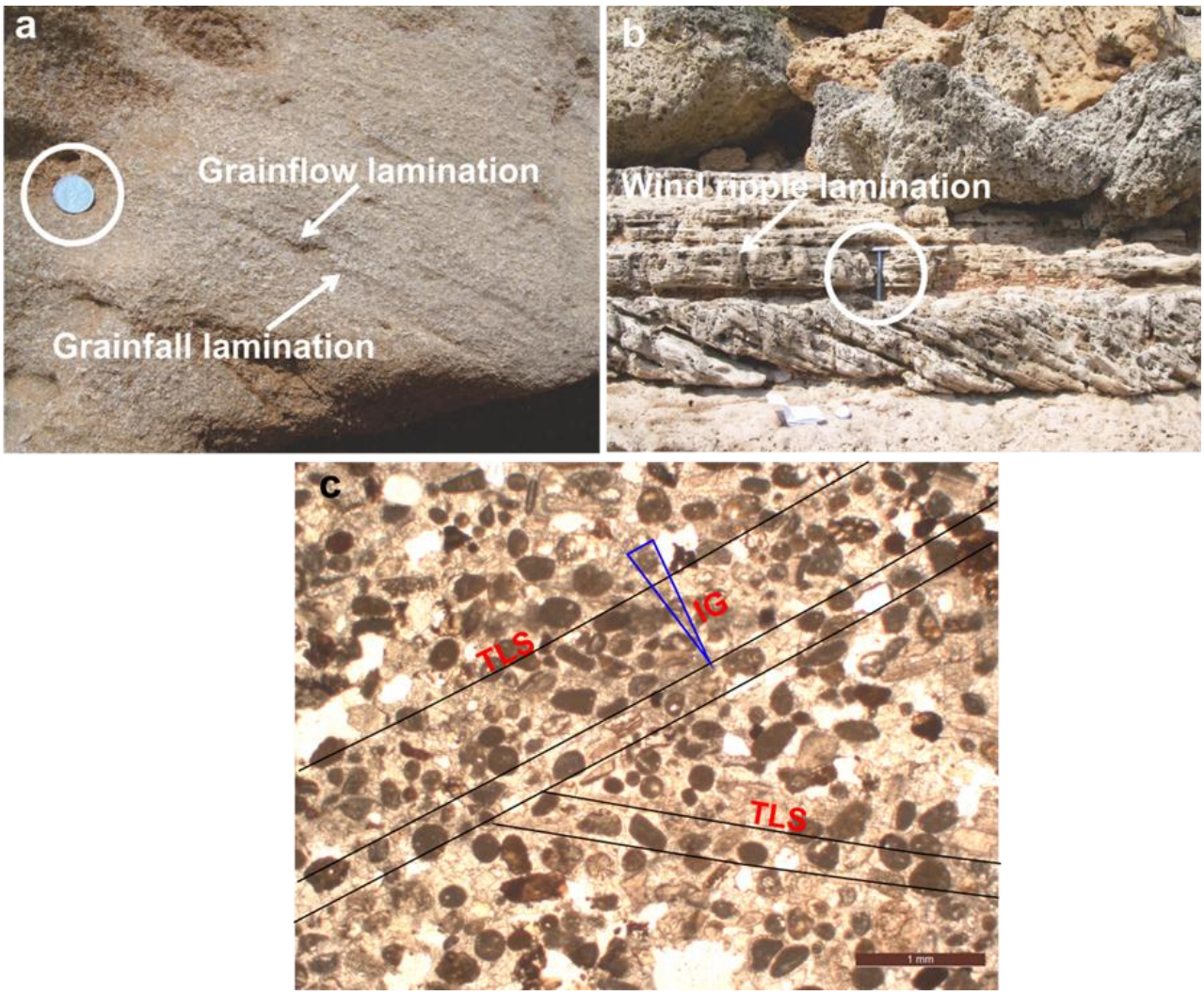


**Figure 2.1. Types of aeolian stratification. a.** Grainflow and Grainfall laminae in thickly cross-stratified Miliolite facies (Facies 2b). Grainflow lamina is coarser, lighter in color, heterogeneous and loosely packed compared to grainfall lamina. Coin (encircled) for scale (diameter: 2.5 cm). **b.** Wind ripple laminae are characterized by thin (1 mm to 3 mm), gently dipping, compact, laterally extensive and tabular stratification. Hammer (encircled) for scale (length 31 cm). **c.** Microscopic examination of the wind ripple laminae reveals the presence of translatent strata (TLS) and inverse grading (IG).

which sometimes exhibit crude inverse grading. Individual laminae possess thicknesses ranging from 0.3 cm to 4.5 cm with an average around 1 cm. The grainflow lamination typically characterizes steeply dipping dune foresets with foreset dips varying from 25° to 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).

(ii) Grainfall lamination

Grainfall lamination **(Figure 2.1a)** covers *ca* 10% of the aeolianite deposits in the study area and is commonly intimately associated with grainflow strata. The grainfall lamination is 2 mm to 3 mm thick and is composed of moderate to well sorted fine sand-sized grains. Individual grainfall laminae are tabular, dark colored, homogeneous and exhibit compact packing of grains. Grainfall lamination essentially characterizes dune foresets which are 3 cm to 4.5 cm thick and possess dips in the range of 30° to 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 on to the surface because of the change in energy conditions around the lee face (Hunter, 1977; Clemmensen and Abrahamsen, 1983).

(iii) Wind ripple lamination

Wind ripple lamination **(Figure 2.1b)** accounts for *ca* 10% of the aeolianite deposits in the study area. Wind ripple laminae are very fine to fine to medium-grained, thin (1 mm to 3 mm) to thick (3 cm to 4 cm), composed of sub-angular to sub-rounded moderately sorted sand-sized 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. Microscopic examination of the wind ripple laminae reveals the presence of translatent strata and inverse grading **(Figure 2.1c)**.

*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).

## 2.3. Aeolian bounding surfaces

Field inspection and detailed mapping allowed the recognition of different bounding surfaces within the aeolianite succession. Four types of bounding surfaces are recognized which have been compared to those described by Brookfield (1977) and Kocurek (1988).

(i) Type-I surfaces ($T_1S$)

These surfaces are planar, horizontal to gently dipping surfaces which bound the different aeolian succession **(Figure 2.2a)**. The lateral continuity of the surfaces is in the order of 100 m and can even exceed the length of the exposures that can be continuously traced for. Type-I surfaces are marked at the contact between the paleosol 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 and Howell (2000) and sand-drift surfaces of Scherer and Lavina (2005).

(ii) Type-II surfaces ($T_2S$)

These surfaces **(Figure 2.2b)** 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 and Howell (2000).

(iii) Type-III surfaces ($T_3S$)

These surfaces are infrequently encountered concave upward surfaces which occur as discontinuities in the lateral sequence of cross-strata within a set **(Figure 2.2c)**. The underlying cross-strata are truncated against this surface, whereas, those that occur above, overlie it conformably. The dip of these surfaces is in the order of $10^{o}$, while the lateral extension is in the order of 6 m. Type-III surfaces are compared to the third order surfaces of Brookfield (1977) which are reactivation surfaces indicative of changes in character of the wind, either its velocity or direction, to which the cross-bedded units could not fully respond. According to Brookfield (1977), third order surfaces may simply be due to natural and possible seasonal changes in wind distribution and velocity or may be due to longer term local airflow changes caused by configurational changes in dune patterns and their consequent alteration of the local airflow patterns.

(iv) Type-IV surfaces ($T_4S$)

A Type-IV surface is a surface of unconformity that marks the cessation of dune building activities indicated by the presence of relict, degraded dune topography (karstified unit) as well as


**Figure 2.2. Types of bounding surfaces. a.** Cliff section from Gopnath exhibiting the presence of Type-I surface (T1S). Field bag (encircled) for scale (height 26 cm). **b.** Cliff section from Babarkot exhibiting the presence of Type-II surfaces (T2S). Human figure for scale (height 172 cm). **c.** Cliff section from Babarkot exhibiting the presence of Type-III surface (T3S). Human figure (encircled) for scale (height 172 cm). **d.** Type-IV surface (T4S) 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. Field bag (encircled) for scale (height 26 cm). **e.** An example of Type-IV surface (T4S) from Diu, wherein, the contact between the older cross-stratified Miliolite facies (Facies 6) and the Shell limestone facies (Facies 7) is clearly discernible. Field bag (encircled) for scale (height 26 cm). **f.** An example of Type-IV surface (T4S) from Gopnath, wherein, T4S is marked at the contact between the dune building events (Facies 2a) and the overlying paleosol horizons (Facies 5). Field bag (encircled) for scale (height 26 cm).

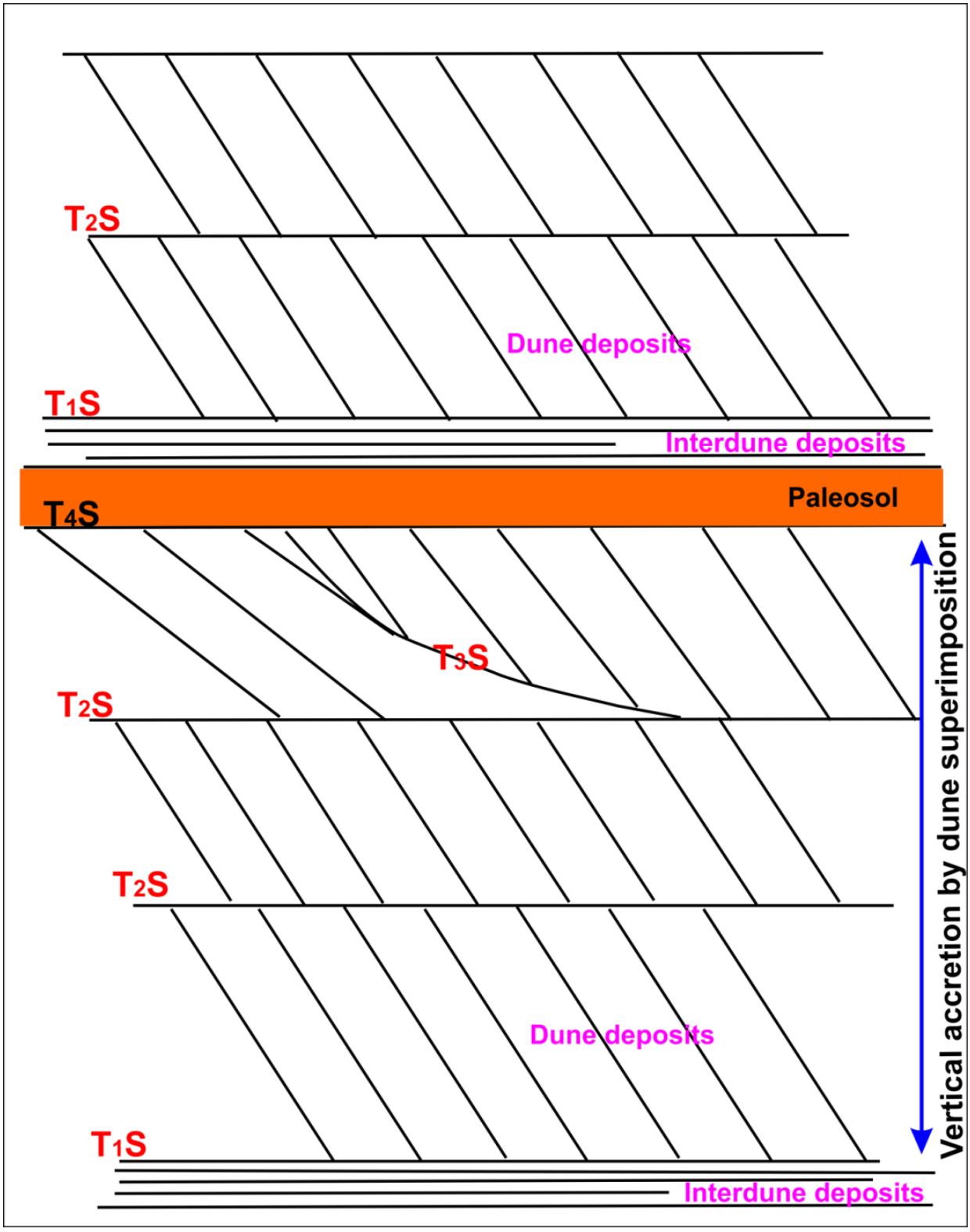


**Figure 2.3. Hierarchy of bounding surfaces.** Type-I surfaces (T1S) form in response to the migration of primary bedforms within an erg system. Type-II surfaces (T2S) form in response to the migration of secondary bedforms over large-scale primary bedforms and are bounded by Type-I surfaces. Type-III surfaces (T3S) are reactivation surfaces that indicate changes in the character of the winds. Type-IV surface (T4S) is a surface of unconformity and represents cessation of dunal activities *(Modified after Zavalia et al., 2005)*.

laterally extensive paleosol horizons separating the different dune building events (discussed later) (Kocurek, 1988) **(Figure 2.2d, e)**. A Type-IV surface 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 in Gopnath, the contact between the successive aeolian succession and the intervening paleosol layers is also marked as a Type-IV surface. The contact between the older Miliolites (Facies 6 as discussed later) and the overlying shell limestone facies (Facies 7 as discussed later) in Diu area is also marked as a Type-IV surface **(Figure 2.2f)**. This contact surface is pretty sharp and highly irregular. A Type-IV surface as observed in Gopnath as well as in Diu 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 and Howell, 2000). Super surfaces 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 and Havholm, 1993; Mountney and Howell, 2000). In a typical aeolian succession, the different bounding surfaces discussed above exhibit a vertical order of occurrence known as 'hierarchy'. The hierarchy of the bounding surfaces encountered is shown in **Figure 2.3**.

## 2.4. Aeolian facies

The aeolianite succession in the study area has been classified into seven facies and eleven sub-facies based on lithology, internal stratification and unit morphology **(Table 2.1)**.

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 **(Figure 2.4a)** is characterized by horizontal laminae 1 mm 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 m to 10 m. The thickness of the unit varies from 20 cm to 2 m. This facies is buff to greyish to greyish white in color and variously weathered. The thin planar laminae are very compact and composed of very fine to fine and medium sand-sized 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 paleosol.

*Sub-facies 1b: Thick plane laminated facies*

The thick plane laminated facies **(Figure 2.4b)** is characterized by thick plane laminae of 3 cm to 4 cm thickness and occurs as tabular to isolated lensoidal bodies; tabular units extend laterally

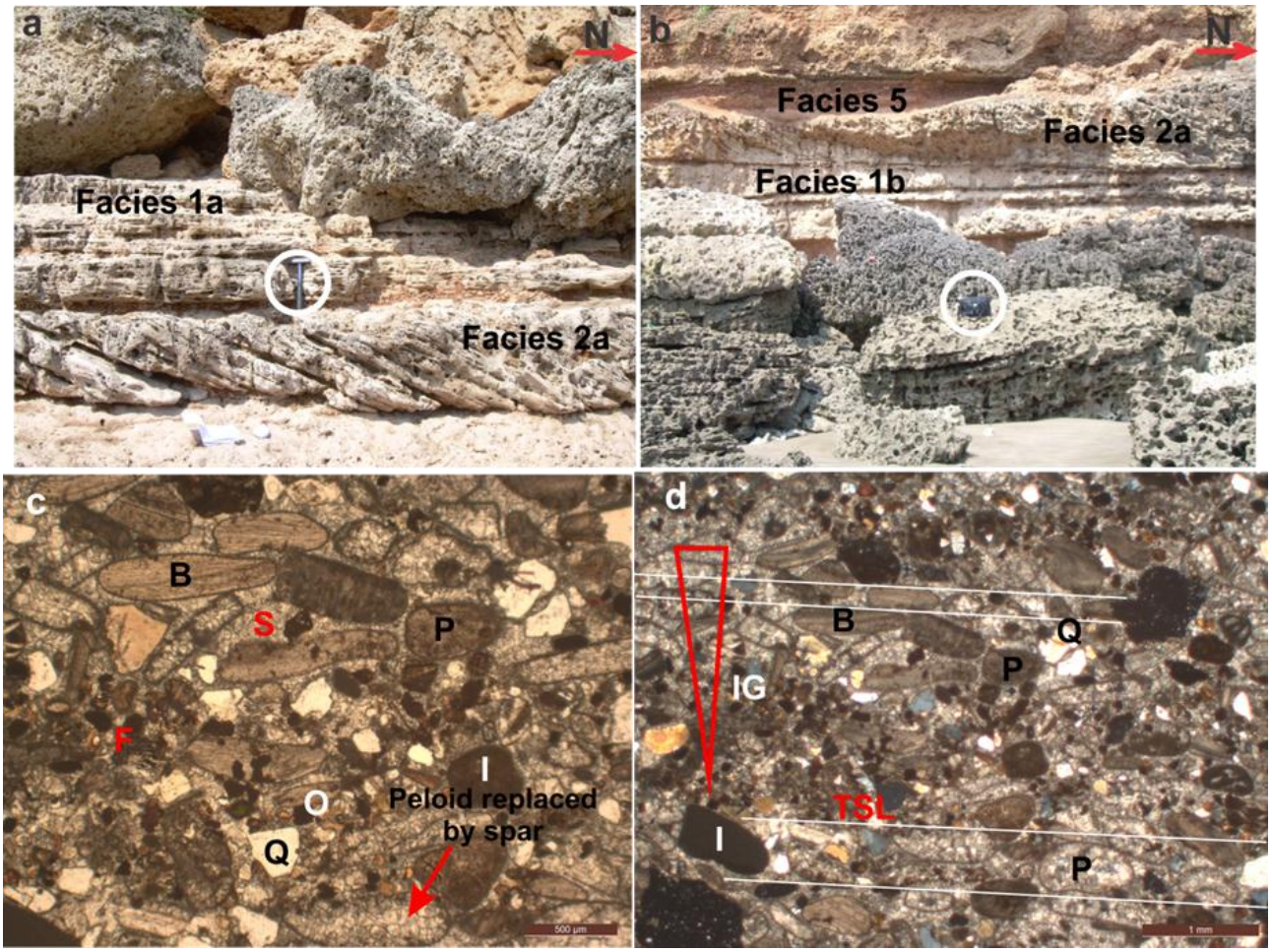


**Figure 2.4. Plane Laminated facies. a.** Thin plane laminated facies (Facies 1a) is characterized by horizontal 1 mm to 3 mm thick laminae. Hammer (encircled) for scale (length 31 cm). **b.** Thick plane laminated facies (Facies 1b) is characterized by thick plane laminae of 3 cm to 4 cm thickness. Field bag (encircled) for scale (height 26 cm). **c.** Microscopic examination of the plane laminated facies reveals the presence of bioclasts (B), peloids (P), foraminiferal tests (F), intraclasts (I), opaque minerals (O) and quartz (Q) grains as the chief allochemical components which are bound together by sparry (S) cement. Advanced diagenesis is indicated by spar internally replacing most of the peloid grains with the external morphology being only preserved. **d.** Microscopic examination of the plane laminated facies reveals that internally these are characterized by the presence of translatent strata (TSL) and exhibit inverse grading (IG).

for >140 m with lensoidal units showing lateral extension of 42 m to 59 m. The thicknesses of the units vary from 60 cm to 1.5 m. This facies is buff colored, 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-sized grains. Internal gradation of grains could not be studied due to destruction of rock 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 paleosol (as in Gopnath) or cross-stratified Miliolite (as in Babarkot and Diu); while the upper contact of this facies unit underlies cross-stratified Miliolite.

Petrographic analysis of the plane laminated facies indicates that the allochemical and orthochemical components constitute 60% to 70% and 40% to 30% of the whole rock, respectively. The allochemical components include peloids (60% to 80%), ooids (and composite ooids), larger bioclasts, foraminiferal tests, intraclasts, quartz grains and accessories (pyroxenes, opaques, heavy minerals). The orthochemical component is dominated by spar. Thus, the plane laminated facies can be termed as 'pelsparite' (Folk, 1959). Extensive diagenesis has led to internal replacement of most of the peloid grains with spar, with the external morphology being only preserved **(Figure 2.4c)**. The plane laminated facies is internally characterized by the presence of translatent strata and inverse gradation of grains **(Figure 2.4d)**.

*Interpretation*

Thin plane laminated Miliolites without recognizable ripple foreset cross-lamination but showing bimodal grain sorting (inverse grading in thin sections) 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 and Dott, 1988). However, ripples formed by strong winds can deposit thick sub-critical climbing translatent strata (Hunter, 1977) as observed in sub-facies 1b. According to Scherer and Lavina (2005), horizontal strata like these can be ascribed to two diverse depositional settings: (i) interdune areas where they develop under metasaturated depositional conditions (Mountney and Thompson, 2002; Mountney and Jagger, 2004); and (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 0.2 cm to 4.5 cm thickness. The cross-laminae dip at angles of 21º to 34° with dominant north-north- easterly to south-south-westerly 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 **(Figure 2.5a)** is characterized by 0.2 cm to 1.5 cm thick

**Table 2.1.** Facies classification, brief description and interpretation

| Facies | Sub-facies | Brief Description | Interpretation |
|---|---|---|---|
| Facies 1: Plane laminated facies | Thin plane laminated facies | Buff to greyish to greyish white in color; characterized by very compact thin planar laminae (1–3 mm); composed of sub-rounded and moderately sorted very fine to fine to medium sand-sized grains; occurs as tabular (lateral extension: 24 m to >200 m) to isolated lensoidal bodies (lateral extension: 7 m to 10 m) with thickness varying from 20 cm to 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 colored; characterized by thick planar laminae (3–4 cm) composed of fine to medium grained, moderately sorted, sub-angular to sub-rounded (dominant) sand-sized grains; occurs as tabular (lateral extension: >140 m) to isolated lensoidal bodies (lateral extension: 42 m to 59 m) with thickness varying from 60 cm to 1.5 m; variously weathered. | |
| Facies 2: Cross-stratified facies | Thinly cross-stratified facies | Greyish white to buff colored; characterized by 0.3–1.5 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-sized grains; occurs as tabular (lateral extension: 70 m to >220 m) to lensoidal bodies (lateral extension: 7 m to 56 m) with thickness varying from 40 cm to 2.5 m; cross-laminae dips: $25^{o}$–$28^{o}$ towards $10^{o}$–$30^{o}$; variously weathered. | Deposits of migrating dunes with abundant slip faces |
| | Thickly cross-stratified facies | Greyish white to buff colored; characterized by 3–4.5 cm thick tabular and angular grain flow cross-laminae composed of moderately sorted sub-rounded (dominant) to rounded medium (dominant) to coarse sand-sized grains; lensoidal in geometry (lateral extent: 52 m to >140m) with thickness varying from 2 m to 2.5m; cross-laminae dip: $30^{o}$–$34^{o}$ towards $45^{o}$; variously weathered. | |

| Facies | Sub-facies | Brief Description | Interpretation |
|---|---|---|---|
| Facies 3: Tabular sets of low angle cross-laminae | ---- | Greyish white in color; characterized by vey compact paper thin (<1 mm) horizontal to sub-horizontal strata composed of moderately sorted, sub-angular to sub-rounded, very fine to fine sand-sized grains; occurs as tabular bodies of thicknesses varying from 20 cm to 60 cm; dip of the cross-laminae mostly varies from 5º to 7º with dip direction varying from 20º to 150º; 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 flats |
| Facies 4: Karst facies | Type-1, Type-2 and Type-3 karsts (after Khadkikar and 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 1–1.5 m thick unit which is brownish in color with pipe form cavities of length 10–12 cm and width 1.5–3 cm. Type-2b karst: occurs in 1.8–2 m thick unit which is buff colored with pipe form cavities being smaller in length (5–8 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 3.5–5 cm length. Type-2c karst: buff colored and characterized by very elongated vertical pipe form cavities which extend throughout the thickness of the unit (~1 m). The vertical pipe form cavities vary in length from 0.4–1 m, width from 2–5 cm and thickness from 2–3 cm. | Karstification is attributed to dissolution processes. The variation in the length of pipeform 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 |
| Facies 5: Paleosol facies | Sub-facies 5a-d | Sub-facies 5a: brick red in color, 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 color; tabular in geometry; 20–40cm thick; internally structureless and possesses sucrosic appearance. Sub-facies 5c: brownish red in color; lensoidal in geometry (maximum thickness: 90 cm); moderately hard to hard and is internally characterized by residual carbonate clasts, concretions, rhizocretions. Sub-facies 5d: buff colored; internally structureless; tabular in geometry (thickness: ~40 cm). | The paleosol facies indicate lengthy episodes of landscape stability exposing the sediments to physical, biological and chemical modification leading to development of soil horizons |

| Facies | Sub-facies | Brief Description | Interpretation |
|---|---|---|---|
| Facies 6: Pinkish buff colored Miliolite facies | ---- | Buff to pinkish in color; hard to very hard; extremely compact; composed of sub-angular to sub-rounded, very fine to fine (dominant) sand-sized grains; internally characterized by cross-laminae of 0.2–0.5 cm thickness; unit thickness ranges from 1.5 m to 5.2 m. | Extremely compact and hard to very hard nature is indicative of strong diagenetic cementation and at places, even possible re-crystallization. This facies might indicate a temporal break in aeolian sedimentation in the region which allowed for extensive diagenetic alteration of the pre-existing Miliolites |
| Facies 7: Shell limestone facies | ---- | Grey to greyish white in color; medium to coarse to very coarse grained; poorly sorted; composed of siliciclastics and enriched in bioclasts (molluscan shells, corals, etc.); horizontal to sub-horizontal (dipping landward away from the sea) in nature; varies in thickness from 0.2 m to 3 m. | Bioclastic shore deposits |

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 m to 56 m. The thickness of the unit varies from 40 cm to 12 m (in Diu). This facies is greyish white to buff colored, 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-sized 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 from 21° to 28°. The thinly cross-stratified facies exhibits unimodal dip distribution with mean wind flow direction being NNE in Gopnath **(Figure 2.5b)** and NE to SE in Babarkot and Diu with some instances of SSW mean wind flow direction being recorded in Babarkot. The thinly cross-stratified facies exhibits sharp horizontal upper and lower contacts. While the lower contact in Gopnath is marked either by underlying karst facies or by paleosols, in Babarkot and Diu, it is marked by the pinkish buff colored Miliolite facies (Facies 6) and the shell limestone facies (Facies 7), respectively. 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 **(Figure 2.5c)**. 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) from Gopnath as convex-up bedding **(Figure 2.5d)**. In Babarkot, a single unit (maximum thickness ~6 m) of this facies exhibits the presence of numerous vertical cylindrical burrow-like features which run downwards from the top of the unit cutting across the dune foresets. At their terminal ends, some of these burrows exhibit distinct bifurcation **(Figure 2.5e)**. The length of the vertical burrow-like features varies from 0.4 cm to 7.7 cm and the diameter is in the order of 4 mm. The unit also exhibits common occurrence of deformed and contorted cross-strata **(Figure 2.5e)**.

*Sub-facies 2b: Thickly cross-stratified facies*

The thickly cross-stratified facies **(Figure 2.5a)** is characterized by 2 cm to 4.5 cm thick foreset laminae and the sets occur with lensoidal to tabular geometry and show a lateral extent of 52 m to >140 m. The thickness of the unit varies from 1 m to 2.5 m. This facies is greyish white to buff colored, variously weathered and shows development of vugs. The thick cross-laminae are composed of sub-rounded (dominant) to rounded medium (dominant) to coarse sand-sized grains which are moderately sorted. The individual laminae do not show any grain-size gradation. The cross-laminae of thickly cross-stratified facies is marked by alternation between thicker medium to coarse-grained grainflow laminae and thinner, homogeneous, dark colored, fine-grained grainfall laminae. The cross-laminae are tabular and angular in nature and exhibit dip amounts of 30° to 34°

towards 0º to 45°. The thickly cross-stratified facies exhibits unimodal dip distribution with north-easterly mean wind flow direction **(Figure 2.5b)**. The thickly cross-stratified facies exhibits sharp horizontal upper and lower contacts. While the lower contact is marked by underlying karst facies (as in Gopnath) or thinly cross-stratified facies (as in Babarkot), the upper contact of this facies underlies either thin- or thick-plane stratified facies or paleosol.

Petrographic analysis of the cross-stratified facies indicates that the allochemical and orthochemical components constitute 60% and 40% of the whole rock, respectively. The allochemical components include peloids (70%), ooids (and composite ooids), larger bioclasts, foraminiferal tests, intraclasts, quartz grains and accessories (pyroxenes, opaques, heavy minerals). The orthochemical component is dominated by spar. Thus, the cross-stratified facies can be termed as 'pelsparite' (Folk, 1959). Extensive diagenesis has led to internal replacement of most of the peloid grains with spar, with the external morphology being only preserved. Preferential alignment of the long axis of the peloidal grains is observed along with inverse grading of the allochemical components **(Figure 2.5f)**.

*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 and Dott, 1981). The angular foresets probably represent smaller dunes where grainflows frequently reached the bottom of the lee faces (Kocurek and Dott, 1981; Clemmensen and Abrahamsen, 1983; Chakraborty, 1991). Thicker grainflow laminae alternating with thinner grainfall layers in 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 and Singh, 1973; Kocurek and Dott, 1981). The absence of grainfall laminae in Facies 2a indicates frequent avalanching over the lee face of depositing dunes due to higher wind velocities (Reineck and 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 and Lavina, 2005). The presence of burrow-like features within a unit belonging to Facies 2a (as observed in Babarkot) might indicate enhanced faunal activities which might be attributed to frequent precipitation as also observed by the common occurrence of deformed and contorted cross-strata attributed to frequent sand wetting. According to Clemmensen and Abrahamsen (1983), such trace fossil bearing aeolian units might be attributed to have been deposited during periods when there was an unusually high and stable groundwater level. The restriction of burrows to a particular dune unit indicates that conditions favourable for invertebrate colonization of the aeolian landscape were only rarely achieved (Clemmensen and

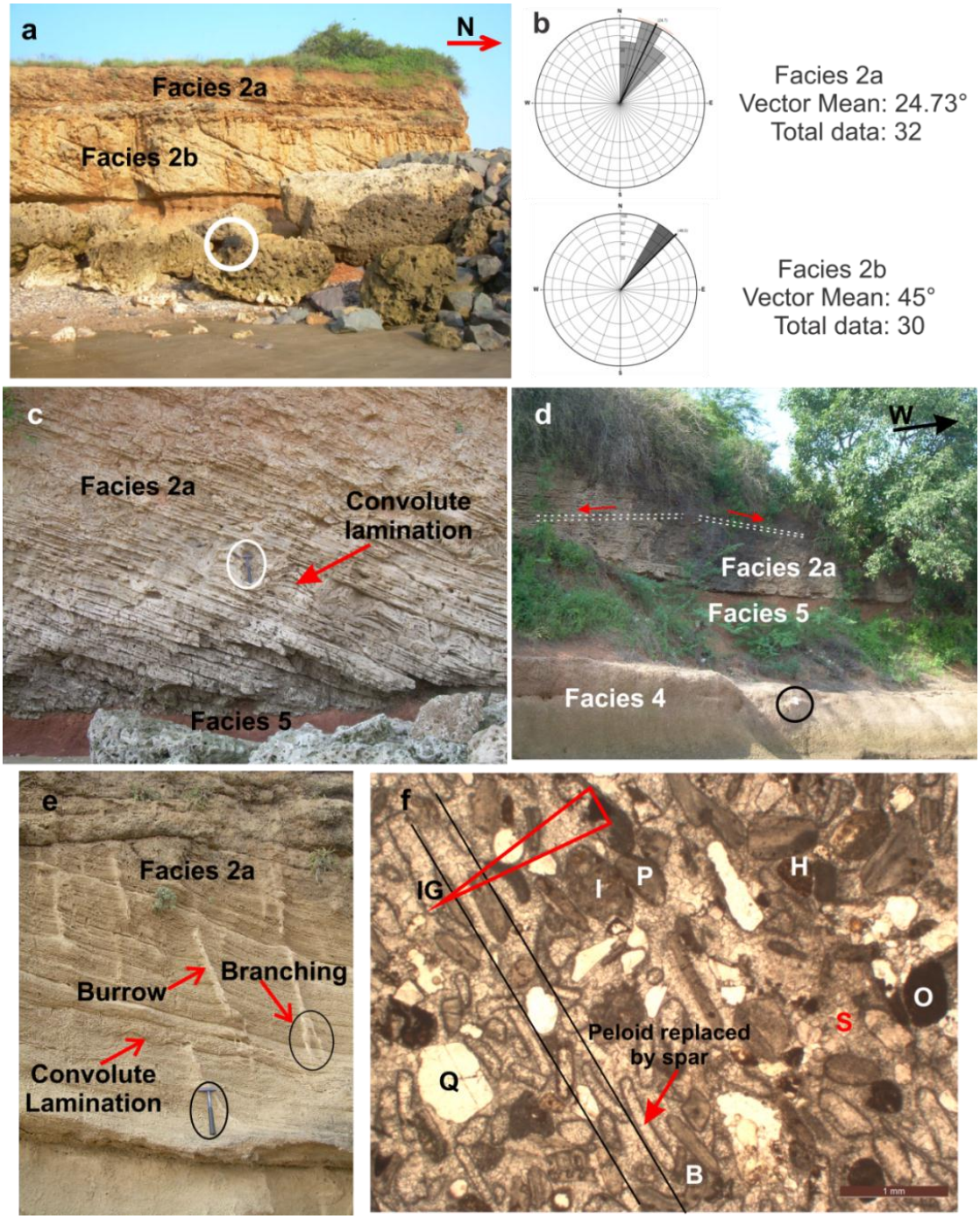


**Figure 2.5. Cross-stratified facies. a.** Thinly cross-stratified facies (Facies 2a) and Thickly cross-stratified (Facies 2b) facies from Gopnath cliff section. Field bag (encircled) for scale (height 26 cm). **b.** Rose plots for Facies 2a and 2b show unimodal dip azimuth distribution with N25°E and N45°E mean wind flow direction, respectively. **c.** Deformed and contorted cross-strata (convolute lamination) observed in Facies 2a. Hammer (encircled) for scale (length 31 cm). **d.** Up-arched stratification observed in Facies-2a in an east–west cliff section at Gopnath. White cap (encircled) for scale (width 21 cm). **e.** Cylindrical burrows observed in a single unit of Facies 2a at Babarkot. Hammer (encircled) for scale (length 31 cm). **f.** Bioclasts (B), peloids (P), intraclasts (I), heavy minerals (H) and quartz (Q) grains are the chief allochemical components bound together by sparry (S) cement. Spar internally replaces most of the peloid grains with external morphology being preserved. Preferential alignment of the long axis of the peloidal grains (marked by black line) probably along the dune foresets is observed along with inverse grading (IG) of the allochemical components.

Abrahamsen, 1983).

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 from 20 cm to 60 cm **(Figure 2.6a)**. The laminations are composed of sub-angular to sub-rounded, moderately sorted, very fine to fine sand-sized 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 color, variously weathered and possesses vuggy porosities. The facies is underlain by karst facies (Facies 4) with a sharp contact **(Figure 2.6b)**. The extremely thin

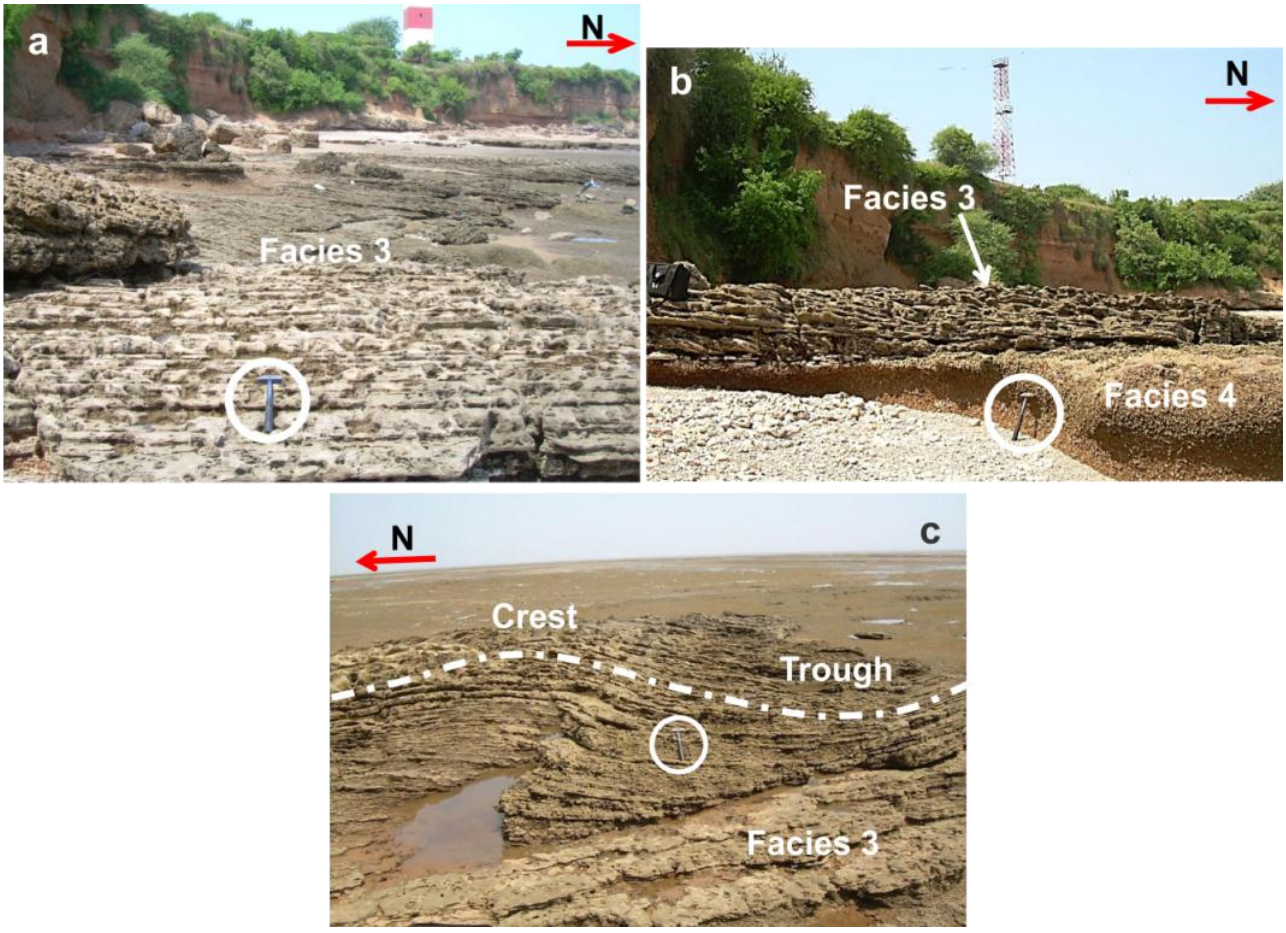


**Figure 2.6. Tabular sets of low angle cross-laminae. a.** Tabular sets of low angle cross-laminae (Facies 3) are characterized by very compact, paper thin (<1 mm), sub-horizontal strata and occur as tabular bodies. Hammer (encircled) for scale (length 31 cm). **b.** Facies 3 is underlain by karst facies 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).

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 laminae mostly varies from 5° to 7° with dip direction varying from 20° to 150° within a short traverse across the shore platform. A mega-ripple form with a sinuous crest line is also found preserved within the unit **(Figure 2.6c)** 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 and Dott, 1981). The preserved mega-ripple 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 and Hesp, 2013).

Facies 4: Karst facies

The karst facies is exclusively found in Gopnath and adjoining areas and have been vividly described and classified by Khadkikar and 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 and Basavaiah (2004) possesses nearly circular planform shaped cavities which extend down vertically to form pipes of 3 cm to 7 cm diameter with very small or negligible lateral interconnectedness. In the present study three sub-facies have been identified, viz., Type-2a, 2b and 2c karsts. Type-2a karst occurs in 1 m to 1.5 m thick unit which is brownish in color with pipe form cavities 10 cm to 12 cm long and 1.5 cm to 3.0 cm wide **(Figure 2.7a)**. The Type-2a karst is marked by the presence of abundant residual carbonate clasts which are elliptical in planform with small and large axis ranging from 4 cm to 9 cm and 5 cm 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 m to 2.0 m thick unit which is buff colored with pipe form cavities being smaller in length (5 cm to 8 cm) and thinner in width compared to Type-2a karst **(Figure 2.7b)**. Type-2b karst is also characterized by horizontal pipe form cavities which form discontinuous features 3.5 cm to 5.0 cm long. Type-2c karst is buff colored and is characterized by very elongated vertical pipe form cavities which extend throughout the thickness of the unit (*ca* 1 m) **(Figure 2.7b)**. The vertical pipe form cavities vary in length, width and diameter ranging from 40 cm to 1 m, 2 cm to 5 cm and 2 cm 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

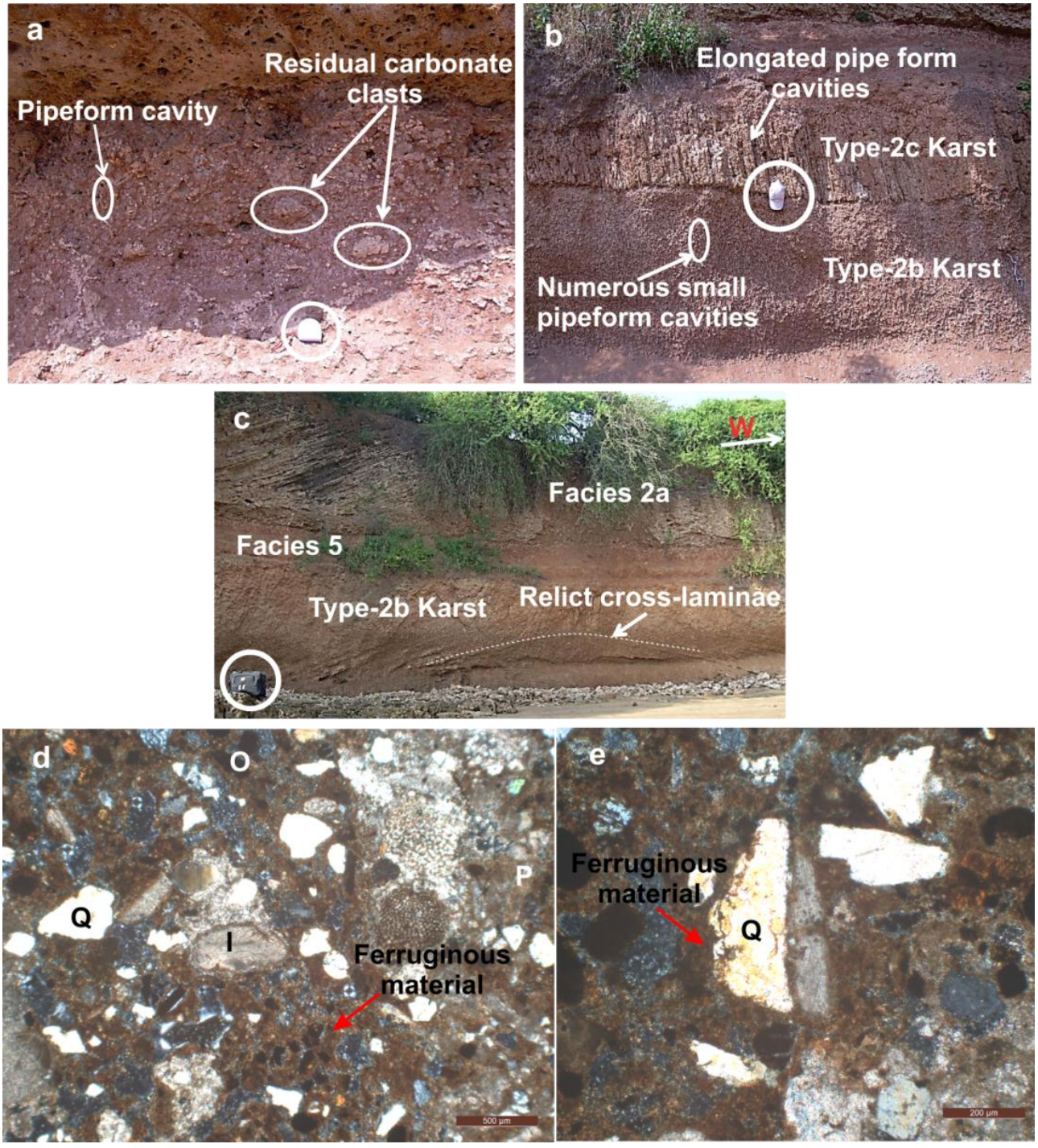


**Figure 2.7. Karst facies. a.** Type-2a karst. Measuring tape (encircled) for scale (width 5.7 cm). **b.** Type-2b karst and Type-2c karst. White cap (encircled) for scale (width 21 cm). **c.** Faint relict cross-laminae observed in Type-2b karst which bear an arcuate appearance in the east–west cliff section at Gopnath. Field bag (encircled) for scale (height 26 cm). **d.** Karstification leading to complete destruction of the internal fabric of the Miliolites and replacement of labile allochemical components by ferruginous materials. The more resistant quartz grains (Q) and opaque minerals (O) are left out as residuals. Rare intraclasts (I) and peloidal grains (P) are observed with diffused grain boundaries. **e.** A closer look at how the quartz grains (Q) are getting disintegrated and replaced by ferruginous material during karstification which eventually leads to pedogenization.

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 arcuate appearance in the east–west cliff section **(Figure 2.7c)**.

Microscopic examination reveals that during the process of karstification the entire fabric of the parent rock as well as the labile allochemical components are replaced by ferruginous materials. The more resistant quartz grains and opaque minerals are left out as residuals **(Figure 2.7d)** which also with time get disintegrated and replaced by ferruginous material **(Figure 2.7e)**.

*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 and 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 color compared to Type-2b and Type-2c karsts, seems to show a greater degree of pedogenesis (Khadkikar and 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: Paleosol facies

The paleosol facies in the study area is subdivided into four sub-facies, viz., sub-facies 5a, 5b, 5c and 5d and are exclusively observed in the Miliolite succession at Gopnath. Sub-facies 5a is brick red in color, 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 **(Figure 2.8a)**. Sub-facies 5b is brown to light brown in color, 20 cm 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 or Facies 2a **(Figure 2.8b)**. In a north–south traverse along the cliff, sub-facies 5b passes below another paleosol horizon (sub-facies5c) forming stacked paleosol horizons and pinches out further southward. Towards the north, paleosol sub-facies 5b merges with Facies 2a. Sub-facies 5c is brownish red in color, lensoidal in geometry (maximum thickness: 90 cm), moderately hard to hard

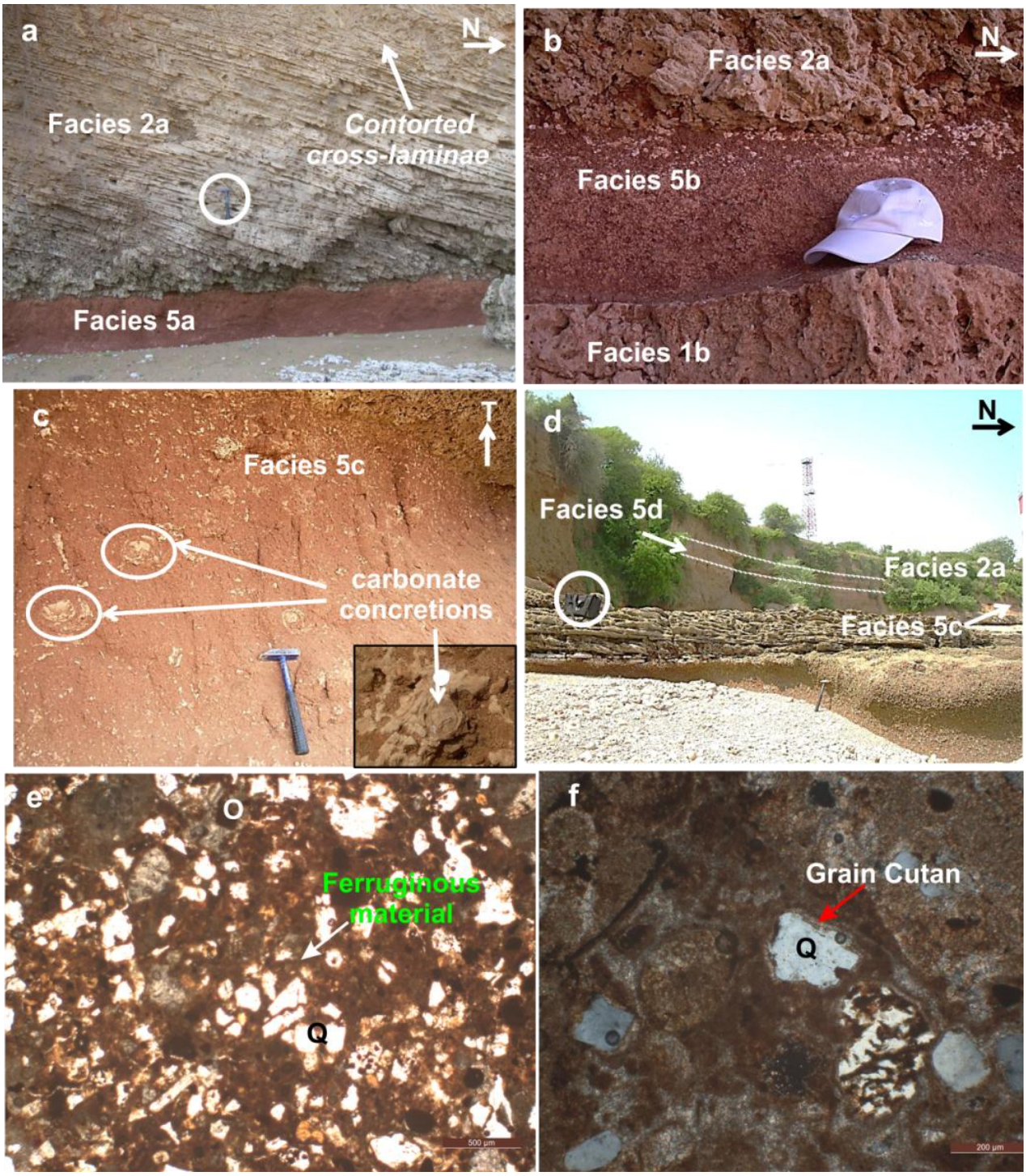


**Figure 2.8. Paleosol facies. a.** Paleosol Facies 5a is brick red in color, internally structureless and possesses sharp upper and lower contacts. Hammer (encircled) for scale (length 31 cm). **b.** Paleosol Facies 5b is brown to light brown in color, internally structureless, has a sucrosic appearance and possesses sharp upper and lower contacts. White cap for scale (width 21 cm). **c.** Paleosol Facies 5c is brownish red in color, 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.** Paleosol Facies 5d is buff colored, internally structureless and possesses sharp upper and lower contacts. Field bag (encircled) for scale (height 26 cm). **e.** Microscopic examination of the paleosol facies reveals the ubiquitous presence of ferruginous material along with relict quartz (Q) and opaque (O) minerals. No internal fabric is evident. **f.** Microphotograph of grain cutan observed in the paleosol facies.

and is internally characterized by residual carbonate clasts, concretions (internal concentric zonation) and rhizocretions **(Figure 2.8c)**. 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 paleosol 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 colored and is internally structureless **(Figure 2.8d)**. 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 any 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).

Microscopic examination of the paleosol facies reveals the presence of extensive ferruginous material with relict quartz and opaque minerals. The internal fabric of the parent rock is observed to be completely destroyed **(Figure 2.8e)**. A typical textural feature is the presence of mineralized rims all along the filler boundary, which in paedological terms, is known as cutan or more specifically grain cutan **(Figure 2.8f)**. It is found to be composed of radially arranged poorly crystalline chalcedonic material with a sharp contact between the cutan and the detrital grains. A lack of continuity between the adjacent cutanic materials is also observed.

*Interpretation*

The paleosol 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 and Basavaiah (2004) the paleosol horizons represent breaks in carbonate deposition due to interglacial wetter climatic conditions which favoured paleosol 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) (Mylorie and Carew, 2010; Kelly *et al.*, 2011). The Gopnath fossil assemblage as recovered from paleosol 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 inter-glacials 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 paleosol 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 color variation among the different paleosol sub-facies may be attributed to varying concentration of ferric oxide (hematite). Hematite is released as an authigenic mineral phase during weathering (Khadkikar and Basavaiah, 2004) of the Miliolites. The sharpness of the boundary between the cutan and the detrital grains, radial arrangement of the silica crystals and lack of continuity between the adjacent cutanic materials suggest that these are of illuviation type– formed by movement of the cutanic material in solution or suspension and subsequent deposition (Roy, 1964).

Facies 6: Pinkish buff colored Miliolite facies

This facies is observed in Babarkot and is buff to pinkish in color, hard to very hard, extremely compact, composed of sub-angular to sub-rounded very fine to fine (dominant) sand-sized grains and is internally characterized by cross-laminae of thickness ranging from 0.2 cm to 0.5 cm which exhibit NNW dips of 10° to 15°. The unit exhibits a thickness in the range of 1.5 m to 5.2 m. The unit occurs at the base of the Miliolite succession in Babarkot and is overlain by Facies 2a with a sharp contact **(Figures 2.9a, b)**.

Petrographic examination of Facies 6 reveals rampant sparitization and complete obliteration of internal fabric. Some relict allochemical grains can only be observed **(Figure 2.9c)**.

*Interpretation*

The extremely compact, hard to very hard nature and rampant sparitization with complete obliteration of the internal fabric is indicative of extensive compaction and strong diagenetic cementation. The occurrence of this Miliolite facies might indicate a temporal break in aeolian sedimentation in the region which allowed for extensive diagenetic alteration of the pre-existing Miliolites.

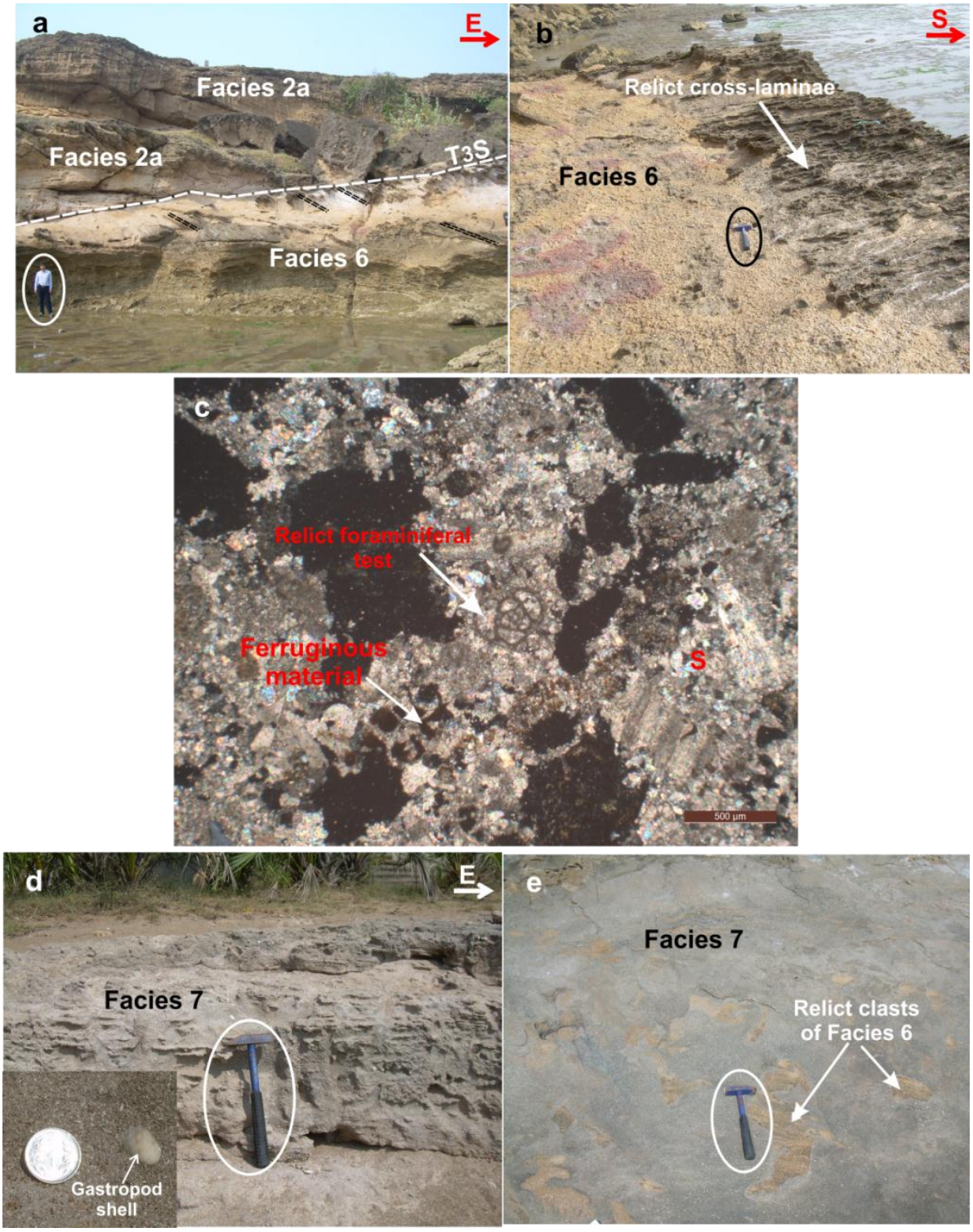


**Figure 2.9. Pinkish buff colored Miliolite facies and Shell limestone facies. a.** Pinkish buff colored Miliolite facies. Human figure (encircled) for scale (height 172 cm). **b.** Surficial view of Facies 6 exhibiting typical pinkish buff color with relict cross-laminae. In comparision to the overlying younger Miliolites, the denuded and compact nature of the facies is quite evident. Hammer (encircled) for scale (length 31 cm). **c.** Microphotograph of Facies 7 shows rampant sparitization (S) and complete obliteration of internal fabric. Relict foraminiferal test with chambers filled with spar is observed in the central part. **d.** Shell limestone facies (Facies 7). Hammer (encircled) for scale (length 31 cm). **e.** Angular to sub-angular residual clasts of older Miliolites (Facies 6) found within Facies 7.

Facies 7: Shell limestone facies

The shell limestone facies is observed exclusively in Diu Island. The facies is grey to greyish white in color, medium to coarse to very coarse grained, poorly sorted, composed of siliciclastics and enriched in bioclasts (molluscan shells, corals, etc.) **(Figure 2.9d)**. The unit is horizontal to sub-horizontal (dipping landward away from the sea) in nature and varies in thickness from 0.2 m to 3 m. The shell limestone at places also possesses angular to sub-angular residual clasts of older Miliolites (Facies 6), with the clast size (long axis) varying from 2 cm to 60 cm **(Figure 2.9e)**. At places, the contact between the shell limestone and the underlying older Miliolites is clearly discernible. Facies 7 is overlain by Facies 1a which gives way to a thick sedimentary package of Facies 2a.

*Interpretation*

The shell limestone facies has been interpreted as bioclastic shore deposit (Bhatt and Patel, 1998). The occurrence of residual clasts of older Miliolite within the shell limestone facies indicates towards destruction and erosion of the pre-existing Miliolite sequences due to marine invasion.