Chapter 3

Coastal Geomorphology

3.1. Introduction

In the Indian context, modern day coastal processes along the coastline are controlled largely by three meterological seasons, viz., fair weather (February to May), southwest monsoon (June to September) and northeast monsoon (October to January) and include the action of monsoonal rainfall, winds, waves, tides, currents and extreme events. The Miliolites along the southern Saurashtra coast of India exhibit land–sea interaction in the form of cliffs, marine terraces, wave-cut platforms and marine notches (Pant and Juyal, 1993; Bhatt and Bhonde, 2006). The present chapter focuses on the geomorphic response of the Miliolite cliffs and platforms to the modern day coastal processes, which in turn, is controlled by the inherent mechanical and structural properties of the coast fringing Miliolite rocks. The coastal geomorphic response and its spatial variability are gauged through the analysis of the cliff and notch profiles. Besides, studies pertaining to the processes of coastal erosion of the Miliolite cliffs and platforms have also been carried out.

3.2. Miliolite cliffs and platforms

3.2.1. General characteristics

The Miliolites form spectacular cliffs all along the coastline of southern Saurashtra and range in height from 3 m to 15 m. The Miliolite cliffs of southern Saurashtra are non-plunging and have well-defined extensive shore platforms at their base which are horizontal to sub-horizontal **(Figure 3.1)** and thus attest to Type-B platform of Sunamura (1992). While the cliff sections in Gopnath and Babarkot are laterally extensive, those in Diu are interspersed with pocket beaches. The cliff forming Miliolites are buff colored, granular and thinly– to thickly cross-stratified (Facies 2) with dominance of thinly cross-stratified units (Facies 2a). The Miliolites are composed of very fine to fine (dominant) to medium moderately sorted and sub-angular to sub-rounded sand-sized grains. The cross-laminae dip at 21° to 34° mostly towards the land away from the sea. The Miliolite cliff section in Gopnath in the east is characterized by cross-stratified Miliolite units interspersed with laterally extensive paleosol horizons (Facies 5) **(Figure 3.1a)**. However, on moving towards the west, in Babarkot and Diu respectively, the paleosol horizons are not developed and the different dune building events are found superimposed upon one another giving rise to a monotonous, thick aeolian sedimentary package **(Figure 3.1b)**.

The fresh Miliolites are moderately hard to hard (intact rock strength ranging from 12.5 to 100 MPa) as observed by mechanical breaking from hammer blows using 1 kg geological hammer

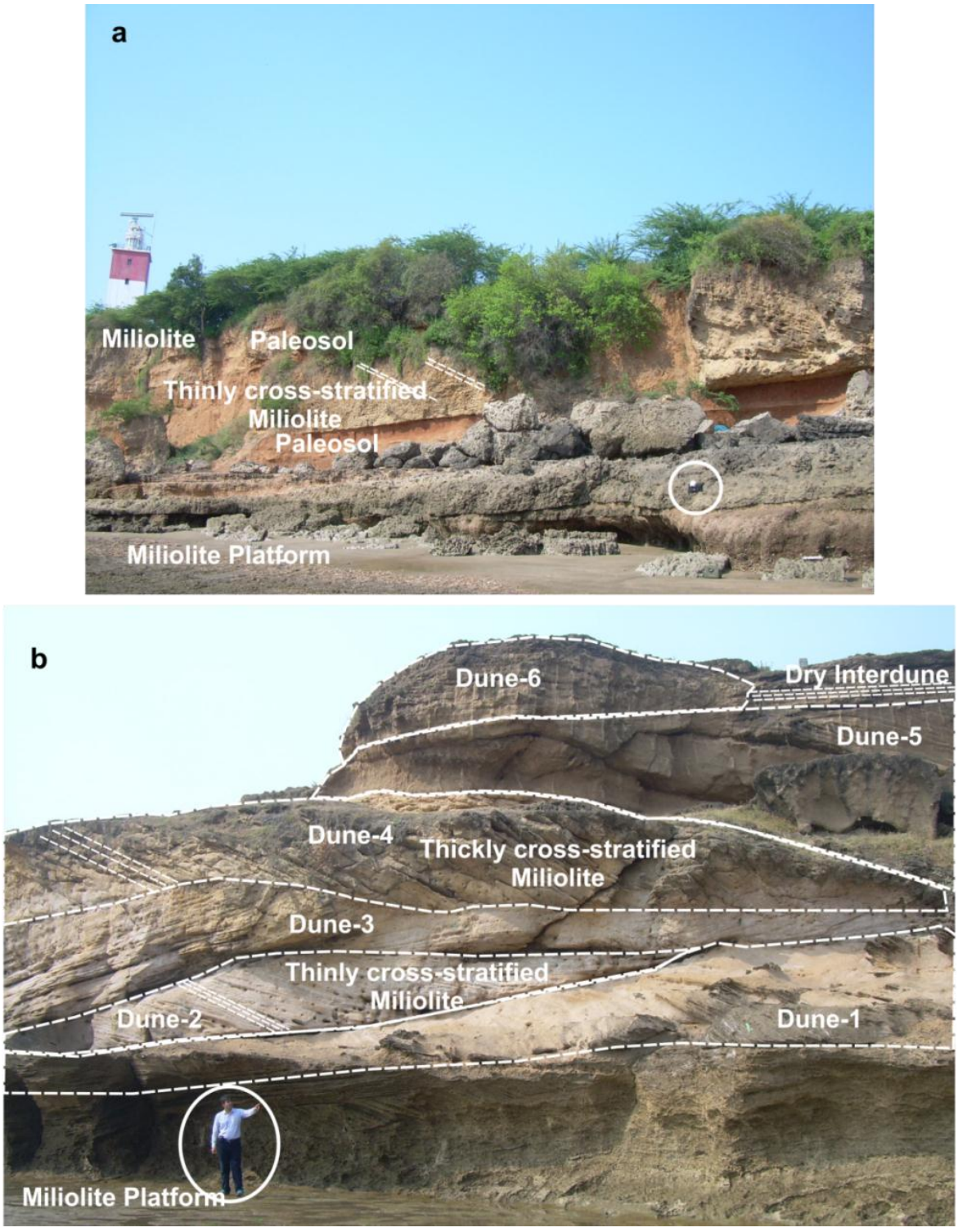

Figure 3.1. Nature of Miliolite cliffs: The Miliolite cliffs of southern Saurashtra are non-plunging and have well-defined extensive shore platforms at their base which are horizontal to sub-horizontal in nature. **a.** The Miliolite cliff section of Gopnath is characterized by the presence of cross-stratified units punctuated by different paleosol horizons. The thicknesses of the cross-stratified units vary from 2 m to 2.5 m. While the lower paleosol horizon exhibits a maximum thickness of 0.9 m, the upper paleosol horizon exhibits a maximum thickness of 0.4 m. Field bag (encircled) for scale (height 26 cm). **b.** The Miliolite cliff section of Babarkot is devoid of paleosol horizons and is characterized by vertical stacking of climbing dunes. The cross-stratified units vary in thickness from 1.3 m to 3 m. Human figure (encircled) for scale (height 172 cm).

following the 'simple means' test given by Hack and Huisman (2002). The cliff sections are characterized by N–S to ENE–WSW trending vertical joints **(Figure 3.2a)**. These joints are moderate to very open, large to very large, widely spaced and have an aperture ranging from 0.5 cm to 2 cm. The inner surfaces of the joints are smooth, irregular and possess large undulations. The joints are mostly clean in nature.

The cliff faces are devoid of any major vegetation except for shrubs and bushes which also abound on the top surface of the cliffs covered by modern day soil. Solution channels abound the top surface of the cliffs exposed to meteoric water and give it a honey-comb appearance **(Figure 3.2b)**.

The Miliolite cliffs along the coastal tracts of Saurashtra overlook the shore platform which occurs as a horizontal to sub-horizontal laterally extensive geomorphic unit. The shore platforms in Gopnath, Babarkot and Diu are rocky in nature, with the exception that the shore platform in Diu is interspersed by pocket beaches. The shore platform is composed of Miliolites, however in Diu, shell limestone (Facies 7) belonging to the Chaya Formation (Late Pleistocene after Mathur and Mehra, 1975) also forms an important lithological component. The platforms in Babarkot and Diu are highly rugged, possess an abraded topography and comprise numerous tidal pools of varying sizes (up to 70 cm wide) **(Figure 3.2c)**. The platform in Gopnath, however, is less rugged and since it lies in the gulf area, a major part of it remains covered with clay and silt brought in by tidal action. The shore platform is inhabited by littorinids, limpets, chitons, barnacles, lichens and filamentous algae **(Figure 3.2d, 3.2e)** and is transected by a number of vertical N–S to ENE–WSW trending joints **(Figure 3.2f)**.

3.2.2. Cliff profiles

Profiles of the cliff sections in the study area were generated using a handheld laser distance meter. A brief description of the typical profiles is furnished below.

(i) Cliff profiles in Gopnath

The Gopnath cliff profile has a typical 'L' shape **(Figure 3.3)** and cliffs in Gopnath range in height from 8 m to 15 m. In general, the cliff profile can be subdivided, from bottom towards the top of the cliff, into three distinct morphological sections, viz., a sloping base, the steep cliff face and an angular top. The base of the Gopnath cliff section (up to 5 m elevation) slopes seaward at an angle of ~25° and gives way to a steep (~90°), gently convex cliff face. The top 0.2 m of the cliff is rather angular in nature and stands out distinctly. The Gopnath cliff section is devoid of marine notches; however isolated, shallow sea caves are observed at the base of the cliff section. The base of the Gopnath cliff section, at places, is covered with boulders of Miliolite generated from cliff degeneration, which however, get removed rapidly by the erosive action of waves and tides.

Figure 3.2. Joints, solution channels and Miliolite platform. a. A north–south trending vertical joint is observed in the thinly cross-stratified Miliolite unit. The joint is moderately open, runs vertically for ~4 m and has an aperture of 0.5 cm. Human figure (encircled) for scale (height 172 cm). **b.** Solution channels formed by infiltration of meteoric water into the porous Miliolites abound over the top surface of the cliffs rendering a honey-comb appearance. Hammer (encircled) for scale (length 31 cm). **c.** Tidal pools of varying sizes abound the shore platform. The floor of the tidal pools is inhabited by littorinids and algae. Hammer (encircled) for scale (length 31 cm). **d.** Filamentous algae occur over the intertidal portions of the shore platform. Coin (encircled) for scale (diameter 2 cm). **e.** Limpets colonizing the shell limestone unit occurring over the shore platform in Diu. Coin (encircled) for scale (diameter 2 cm). **f.** E–W trending vertical joint passing along the shore platform. The joint aperture is very wide with highly irregular joint walls. Hammer (encircled) for scale (length 31 cm).

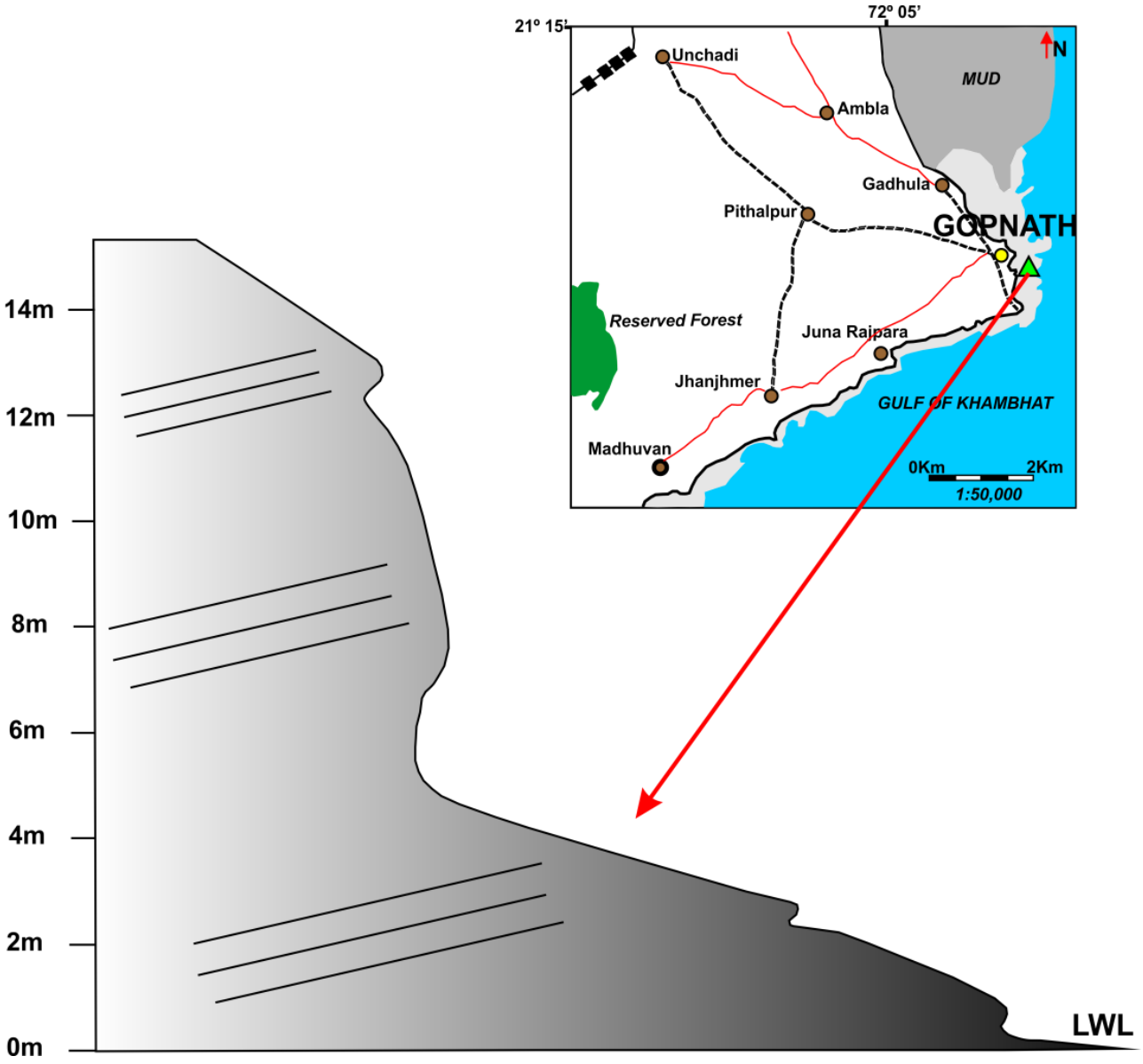

Figure 3.3. Gopnath cliff profile: The cliff profile in Gopnath generated by using a hand-held laser distance meter. The cliff is characterized by a typical 'L' profile with a base sloping towards the sea and a near vertical, gently convex cliff face followed up by an angular top. The foresets of cross-stratified Miliolites dip towards the land away from the sea. Cliff profiling was carried out with Low Water Line (LWL) as the datum.

(ii) Cliff profiles in Babarkot

The Miliolite cliffs in Babarkot are inadvertently characterized by sharp and angular concave bases and angular tops **(Figure 3.4)**. The cliffs range in height from 6 m to 15 m. A total of twelve numbers of cliff profiles were generated along the Babarkot coastline, but eight representative profiles are being presented here. A close examination of these cliff profiles indicates the presence of active marine notches (AN), surf notches (SN), raised platform (RP) and raised

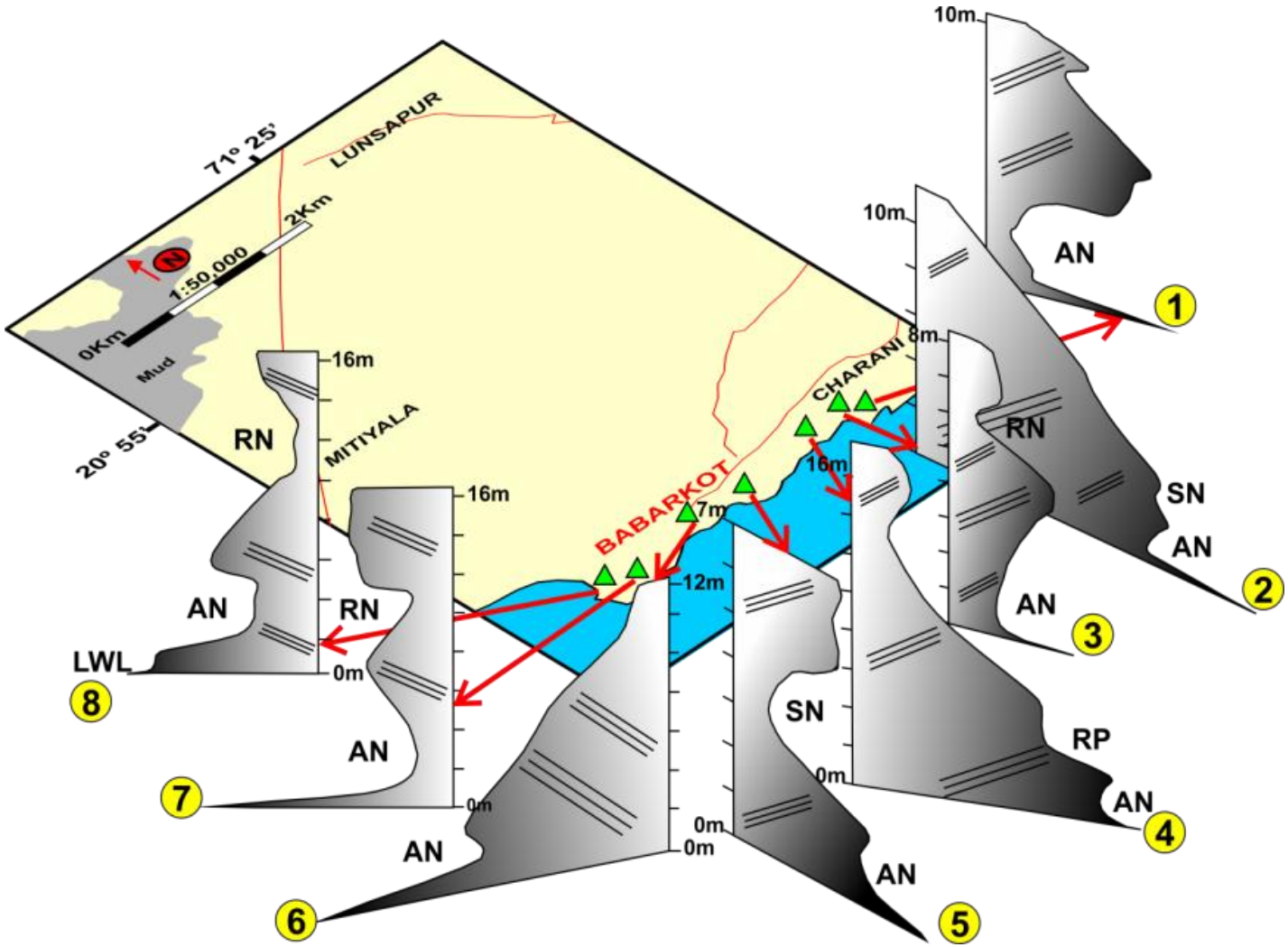

Figure 3.4. Cliff profiles in Babarkot: Cliff profiles in Babarkot are characterized by ubiquitous presence of active marine notches (**AN**) at their bases. The marine notches are asymmetrical in geometry. The heights of the cliffs vary from 8 m to 16 m and are characterized by angular tops. The foresets of cross-stratified Miliolites dip towards the land away from the sea. Besides active notches, the cliffs in Babrkot also exhibit the presence of raised notches (**RN**), raised platforms (**RP**) and occasional surf notches (**SN**). Cliff profiling was carried out with LWL as the reference datum.

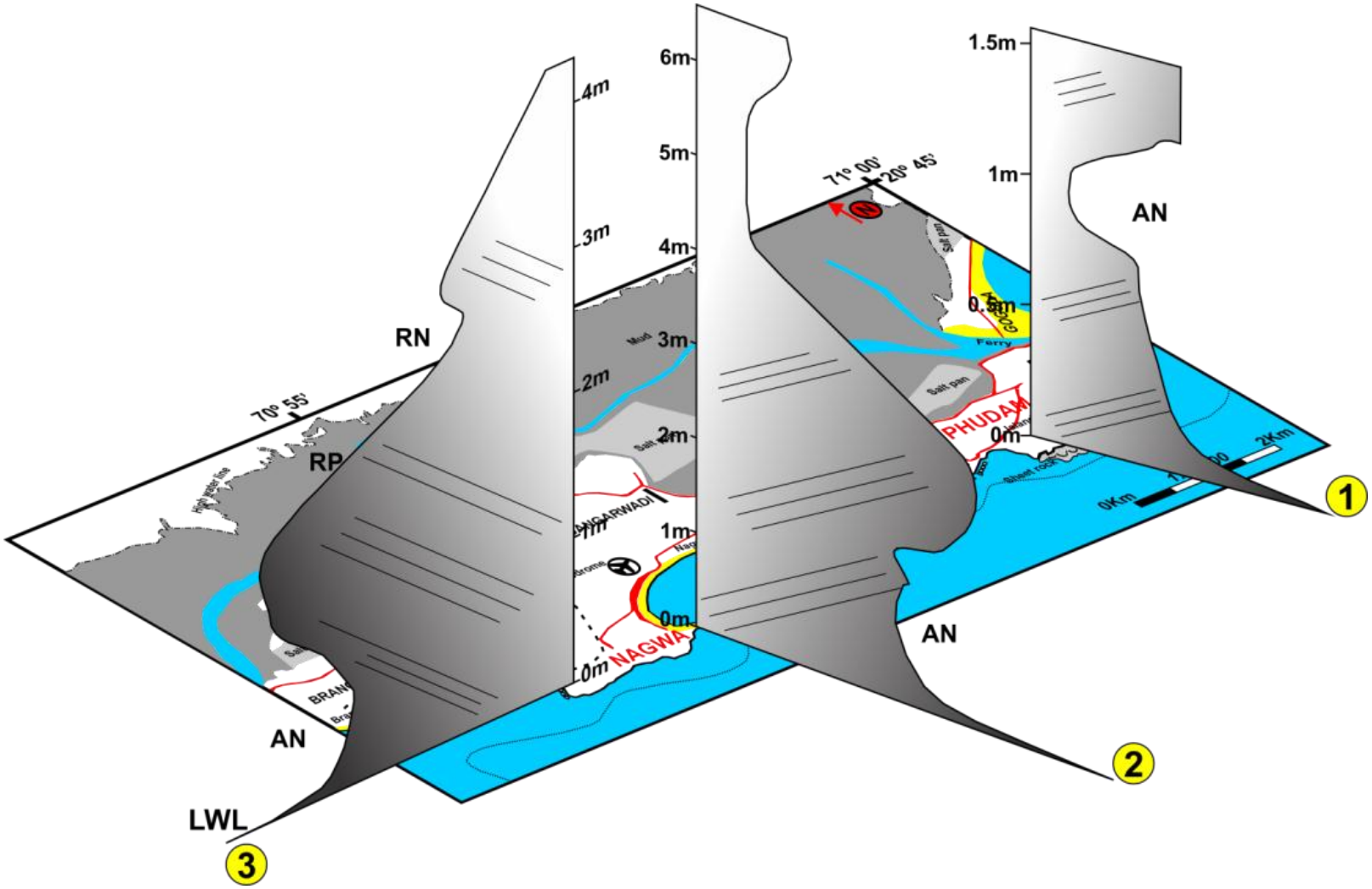

Figure 3.5. Cliff profiles in Diu Island: The Miliolite cliffs in Diu Island are characterized by sharp and angular concave bases and angular tops. A close examination of these cliff profiles indicate the presence of active marine notches **(AN)**, raised platform **(RP)** and raised marine notches **(RN)**. The foresets of cross-stratified Miliolites mostly dip towards the land away from the sea. Cliff profiling was carried out with LWL as the reference datum.

marine notches (RN). Raised platform (cliff profile no. 4) occur at an elevation of 2.5 m from the reference datum (low water line, LWL) and raised notches occur at two different elevations of ~6 m (cliff profile no. 3) and ~12 m (cliff profile no. 8), repectively and exhibit a depth of approximately 1 m. The cliff face occurs in two morphological variations, viz., (i) nearly vertical (as in cliff profile no. 3, 5, 7 and 8) and (ii) dipping towards the sea at an angle of ~20° to ~35° (as in cliff profile no. 1, 2, 4 and 6). Some of these dipping cliff faces have a gently convex shape (as in cliff profile no. 6). The base of the Babarkot cliff section, at places, is covered with boulders of Miliolite generated from cliff degeneration, which however, get removed rapidly by the erosive action of waves and tides.

(iii) Cliff profiles in Diu

Similar to the Babarkot area, the Miliolite cliffs in Diu Island are also inadvertently characterized by sharp and angular concave bases and angular tops **(Figure 3.5)**. The cliffs range in height from 3 m to 8 m. A close examination of these cliff profiles indicate the presence of active marine notches (AN), raised platform (RP) and raised marine notches (RN). Raised platform (cliff profile no. 3) occur at an elevation of 2 m from the reference datum (LWL) and raised notches (cliff profile no. 3) occur at an elevation of nearly 3 m from the reference datum and exhibit a depth of approximately 1 m. The cliff face is dipping towards the sea at an angle of ~20°. Locally, the base of the Diu cliff section is covered with boulders of Miliolite generated from cliff degeneration, which however, get removed rapidly by the erosive action of waves and tides.

3.2.3. Marine notches

A marine notch is an indentation or undercutting, a few centimeters to several meters deep, left by sea erosion in coastal rocks (Pirazzoli, 1986). According to Pirazzoli (1986), notches can be infralittoral, midlittoral and supralittoral, wherein, the midlittoral notches are further classified into tidal and surf notches with the latter being cut above high-tide level and is differentiated from the former by the presence of a well-defined surf bench.

The present day tidal notches in Babarkot and Diu were studied in details for their geometric variations. The notch parameters **(Figure 3.6a)** were measured following Pirazzoli (1986) and Sisma-Ventura *et al.* (2017) and are as follows: (i) Eo: height of the retreat point from reference datum; (ii) D: depth of retreat point; (iii) D_F: depth of floor; (iv) D_R: depth of roof; (v) H_R: height of roof from retreat point; (vi) H_F: height of floor from retreat point; (vii) H: height of the notch ($H_R + H_F$); (viii) Shape ratio: D/H and (ix) Asymmetry ratio: H_R/ H_F. The measured notch parameters are presented in **Table 3.1**.

As indicated by the tabulated notch parameters, the asymmetry ratio (H_R/H_F) is much greater than 1, indicative of the asymmetrical nature of the tidal notches. However, a comparison between

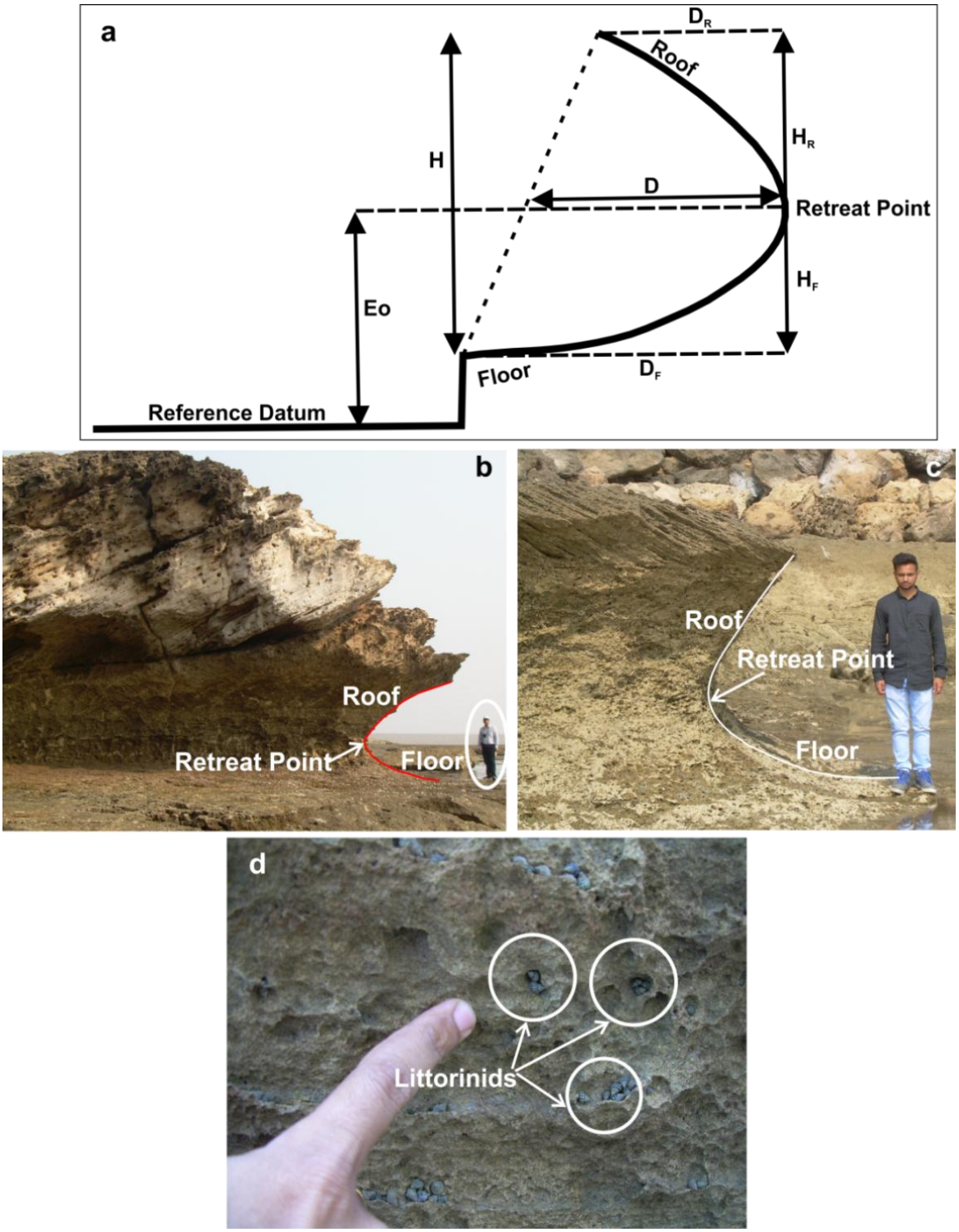

Figure 3.6. Marine Notches. a. Notch parameters as measured following Pirazzoli (1986). Eo: height of the retreat point from reference datum, D: depth of retreat point, D_F: depth of floor, D_R: depth of roof, H_F: height of floor from retreat point, H_R: height of roof from retreat point. **b.** Asymmetrical notch in Babarkot (Lat: 20°52'4.65"N, Long: 71°25'22.80"E) characterized by extended roof and short, steep floor. Human figure (encircled) for scale (height 172 cm). **c.** Asymmetrical notch in Babrkot (Lat: 20°52'3.06"N, Long: 71°24'49.82"E) characterized by short roof and extended floor. Human figure for scale (height 170 cm). **d.** Littorinids inhabiting the notch roof. The notch roof is intensely pitted due to spray action and bioerosion.

Table 3.1. Notch parameters (in meters; Reference datum: LWL) as measured in Babarkot and Diu Island

LOCATION	LAT/LONG	E_O	D	D_R	D_F	H_R	H_F	Height ($H= H_R+ H_F$)	Shape Ratio (D/H)	Asymmetry Ratio (H_R/H_F)
BABARKOT	20°52'4.65"/ 71°25'22.80"	0.80	1.78	12.99	1.25	14.42	0.71	15.13	0.18	20.31
	20°52'4.65"/ 71°25'22.80"	1.7	2.55	5.10	2.12	4.25	1.49	5.74	0.44	2.85
	20°52'4.65"/ 71°25'22.80"	0.98	1.91	2.45	1.57	1.76	0.98	2.74	0.70	1.79
	20°52'8.604"/ 71°25'7.00"	2.12	2.38	2.77	0.66	2.24	0.79	3.03	0.78	2.83
	20°52'3.066"/ 71°24'49.82"	0.43	0.72	0.6	0.82	0.96	0.43	1.39	0.52	2.23
DIU ISLAND	20°42'27.25"/ 70°59'3.96"	0.34	0.60	0.52	0.65	0.75	0.36	1.11	0.54	2.08
	20°42'5.86"/ 70°53'51.13"	0.47	1.27	1.74	1.17	1.17	0.47	1.64	0.77	2.48
	20°42'4.18"/ 70°54'31.36"	0.60	1.59	2.97	1.38	2.24	0.56	2.8	0.57	4

the D_R and D_F values for the different notches indicate that there are two principal types of asymmetrical notches established by the present study, viz., Type-A notches with extended roof and short, steep floor ($D_R > D_F$) and Type-B notches with short roof and extended floor ($D_R < D_F$) **(Figure 3.6b, c)**. However, field observations suggest that the Type-A notches are the dominant variety in both Babarkot and Diu. Further, it is observed that the Type-A notches differ among themselves in terms of the extension of their roofs (D_R and H_R values). A comparison between the Type-A notches of Babarkot and Diu reveals that the roofs in Type-A notches of Babarkot are more extensive compared to those in Diu. However, as far as the Type-B asymmetrical notches are concerned, there is not much variation in the geometric parameters as measured in Babarkot and Diu. In case of both Type-A and Type-B notches, the Babarkot notches are deeper (higher depth values, D) compared to those in Diu. In general, the retreat point is observed at a greater elevation (Eo) in notches in Babarkot compared to those in Diu. The shape ratio (D/H) for the notches does not show any linear relationship between the notch parameters, viz., the depth of the retreat point (D) and the height of the cliff (H). The D/H ratio of type-A and type-B notches of Babarkot and Diu ranges from 0.18 to 0.78.

The tidal notches are exposed to the open sea and are either isolated or laterally continuous in nature. The roofs and the floors of the notches are found to be highly irregular and pitted. While the roof of the tidal notches is colonized by littorinids and limpets, the floor is colonized by barnacles, limpets and algae **(Figure 3.6d)**.

3.3. Bioerosion and Bioconstruction

Kazmer *et al.* (2015) provided a practical guide for assisting field workers in identification and interpretation of frequently occurring bioerosional textures created in limestone by intertidal organisms along the rocky coasts of Langkawi Islands, Malaysia. In the light of his work, an attempt has been made in the present study to identify the different bioeroding and bioconstructional agents active along the Miliolite coasts of southern Saurashtra. Bioerosional and bioconstructional processes were studied in detail in Diu and Babarkot, however the rates of bioerosion could not be measured. Bioerosion over the coast is brought about by microorganisms such as algae and lichens as well as macrobioeroders such as limpets, littorinids, chitons and bivalves. Algae accommodate the upper intertidal zone at the cliff base. The buff colored Miliolites in the upper intertidal zone are progressively corroded due to microbial activity imparting a dark-colored pitted appearance **(Figure 3.7a)**. Lichens occur in the supratidal zone and bioerode the rock surface by etching tiny shallow holes while excreting oxalic and other acids at the rock surface (Adamo and Violante, 2000; Chen *et al.*, 2000) **(Figure 3.7a)**. Limpets (*Patella vulgata*) are gastropods with a conical uncoiled shell and a broad foot and occur in intertidal and lower

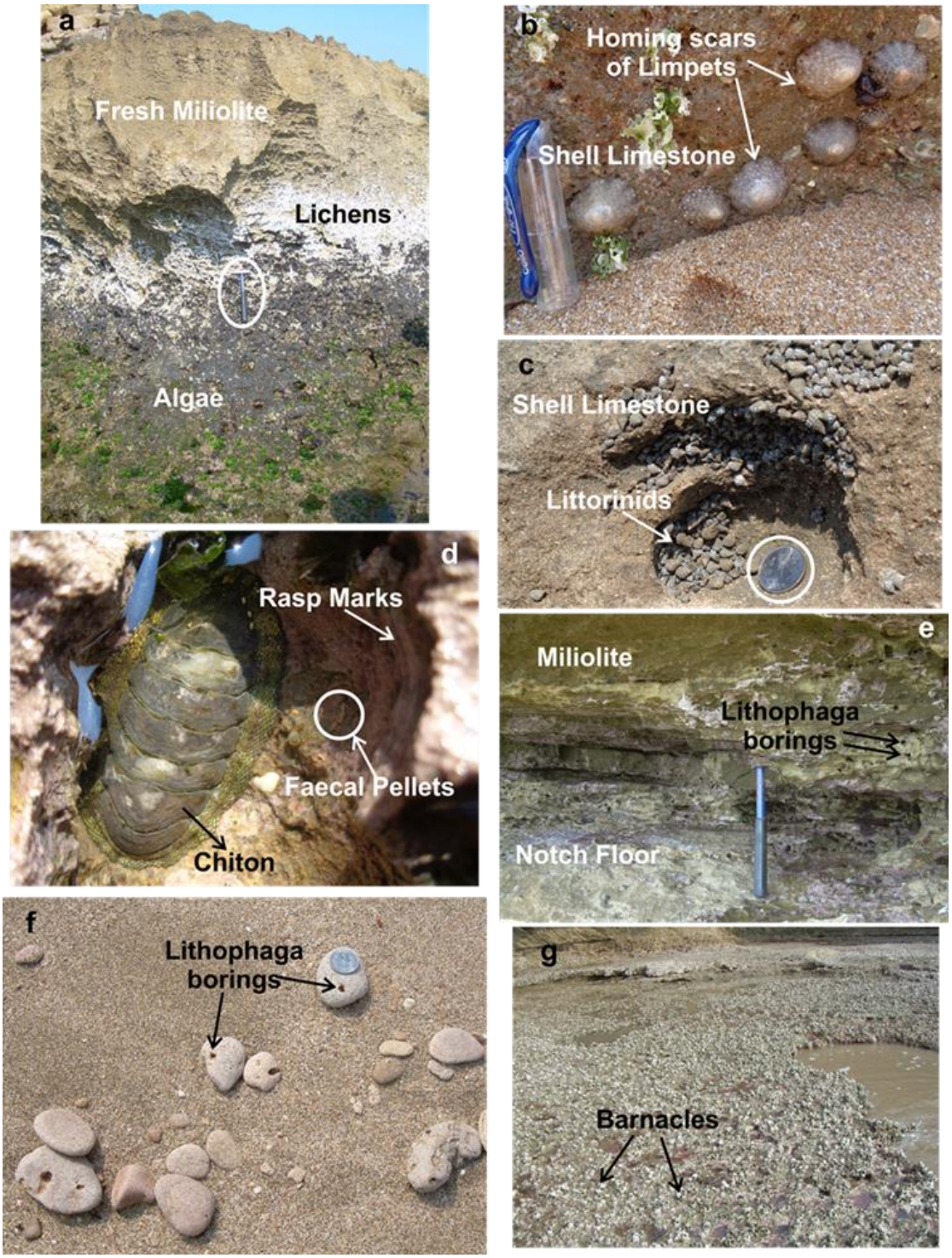

Figure 3.7. Bioerosion and Bioconstruction. a. Algae and Lichens inhabit the upper intertidal and the supratidal zones, respectively. Contrasting difference in the appearance of the fresh Miliolite located away from the reaches of the wave and tide actions and those infested by algae and lichens is quite evident. Hammer (encircled) for scale (length 31cm). **b.** Limpets in homing scars attached to the shell limestone on the shore platform. Pen cap for scale (length 3.5cm). **c.** Littorinids inhabiting the shell limestone on the shore platform. Coin (encircled) for scale (diameter: 2 cm). **d.** Chitons inhabiting the shore platform. Rasp marks and faecal pellets are highlighted. **e.** Lithophaga borings present on the inside walls of the active notches. Hammer for scale (length 31 cm). **f.** Lithophaga borings are observed over the isolated pebbles and cobbles littered over the shore platform. Coin for scale (diameter: 2 cm). **g.** Barnacles colonizing the shore platform.

supratidal zones. They possess radula with silica-containing teeth used to scrape algae off and from within rock substrate (Kazmer *et al.*, 2015) and thus cause mechanical wear and tear of the substrate. Homing scars are observed in the field corresponding exactly to the size and shape of an individual's shell **(Figure 3.7b)**. In a series of experiments designed to estimate the rate of erosion by limpets on chalk shore platforms, Andrews and Williams (2000) found that adult limpets consume about 4.9 grams of chalk a year and that, overall, limpets were responsible for lowering the platform by an average of 0.15 mm a year. Littorinid snails inhabit rocky shorelines and specialize in scraping biofilms and turf algae off exposed surfaces **(Figure 3.7c)**. They are also capable of scratching the rock with their radulas and consuming endolithic organisms as well (Kazmer *et al.*, 2015). Chitons are inhabitants of the intertidal zone and produce homing scars (large pits) that accommodate an individual animal's body size and represent its long term residence (Kazmer and Taborosi, 2012a) **(Figure 3.7d)**. Chitons are armed with a radula of extremely hard magnetite-capped teeth that allow them to easily remove layers of substrate while grazing on biofilms (Rasmussen and Frankenberg, 1990). Their rasp marks as observed in the field are in the form of parallel grooves engraved into the substrate **(Figure 3.7d)**. *Lithophaga* borings of circular to dumbbell shape are observed over the inner portions of the roofs of the present day notches and supratidal portions of the Miliolite cliffs **(Figure 3.7e)** as well as over the pebbles and cobbles littered over the shore platform **(Figure 3.7f)**.

Bioconstruction in the form of barnacle colonies (genus *Balanus*) is observed on the intertidal platforms as well as the upper intertidal portions of the Miliolite cliffs **(Figure 3.7g)**. The barnacle colonies act as bioprotecting agents by forming a cover over the exposed bedrock and minimizing its exposure to bioeroding organisms (Lace and Mylorie, 2013). However, according to Kleemann (2001) and Pappalardo *et al.* (2017) the barnacles can also simultaneously act as bioeroders, likely causing corrosion of the rock surface by fostering dissolution of the sandstone carbonate matrix. According to Antonioli *et al.* (2015) and Sisma-Ventura *et al.* (2017), platform with bioconstructions at their rims result into emaciated wave action over the adjoining cliffs, resulting into reduced mechanical damage at the cliff bases.

3.4. Marine and sub-aerial erosional processes

3.4.1. Erosion of the Miliolite platforms

As evidenced from field visits, the erosion of the platforms by tides and waves is actuated by mechanical abrasion as well as by the impact force of the breaking waves. Mechanical abrasion of the platform leads to the development of numerous tidal pools of varying sizes rendering the platform with a rugged topography. The tidal pools are generated by mechanical grinding of the platform by cobbles, pebbles and boulders entrained by tidal currents and entrapped by the tidal

Figure 3.8. Marine and sub-aerial erosion. a. Vertical grooves created on the walls of tidal pools by mechanical grinding caused by gravels entrapped by the tidal vortices. Pen cap (encircled) for scale (length 2.5 cm). **b.** Large portions of the shore platform get eroded by the breaking waves and tidal currents entering into the joint systems present in the platform. **c.** Mass wasting of the Miliolite cliffs is caused by widening of the vertical joints by dissolution processes due to passage of meteoric water along them. White cap (encircled) for scale (length 25 cm; width 21 cm). **d.** Subsequent detachment and toppling of a large block of Miliolite. **e.** Mass wasting of the Miliolite cliff is also caused by widening and deepening of dissolution channels which happen to reach up to the bedding palnes by progressive passage of meteoric water as well as by the undermining of the bedding plane due to flow and spreading of meteoric water along the same upon reaching down through the dissolution hollows.

vortices. The mechanical grinding leads to the formation of vertical grooves **(Figure 3.8a)** on the inner walls of the tidal pools near their bottom. Large portions of the shore platform also get eroded away due to the breaking waves and tidal currents entering into the joint systems present in the platform. The water entering with force inside the joints tend to widen them by putting pressure on the joint walls. The joints also get widened by dissolution of the parent rock material by water action. During these processes, whenever sets of joints intersect, large blocks of Miliolites are dislodged, eroded and washed away into the open sea leading to large scale mass wasting of the platforms **(Figure 3.8b)**.

3.4.2. Erosion of the Miliolite cliffs

The presence of active notches and occasional sea caves at the base of the Miliolite cliffs suggest towards the active role of the marine processes of erosion. According to Antonioli *et al.* (2015) marine notches are formed by mechanical erosion brought about by waves and tides as well as by biological agents, wetting–drying cycles and salt weathering. Sub-aerial erosive processes bring about large scale mass wasting of the Miliolite cliffs. The mass wasting of the Miliolite cliffs is brought into effect by two different sub-aerial erosional mechanisms. The first mechanism involves the widening of the already existing vertical joints through dissolution processes actuated by the passage of meteoric water along them and followed by subsequent detachment and toppling of a large block of rock **(Figure 3.8c, d)**. The second mechanism involves the development of vertical solution channels through meteoric water action over the exposed upper surface of the Miliolite cliffs which gradually get deepened and widened by progressive dissolution resulting from through flow of meteoric water. In due course of time, these channels happen to encounter one or more bedding planes allowing the meteoric water to spread along the same and cause large scale erosion through dissolution processes. At the same time, the vertical solution channels while widening laterally do coalesce with one another creating localized gaps or discontinuities within the parent rock body. At a certain point of time, lateral undermining of the substrate by flow of water along the bedding plane(s) and the gradual vertical detachment from the parent rock due to gaps generated within it by lateral coalescing of the solution channels, lead to dislodgement of a huge block of Miliolite **(Figure 3.8e)**. The mechanisms of Miliolite cliff erosion are presented through conceptualized models in **Figure 3.9**. Field observations suggest that at any given time, the sub-aerial mechanism of mass wasting involving widening of already existing vertical joints through dissolution processes actuated by the passage of meteoric water is more effective in destroying the Miliolite cliffs and generates huge blocks of dislodged Miliolite rock. The dislodged Miliolite blocks get accumulated over the platform near the base of the cliffs and thus protect the cliff base from further marine erosion. However, this protection is only temporary as the Miliolite blocks,

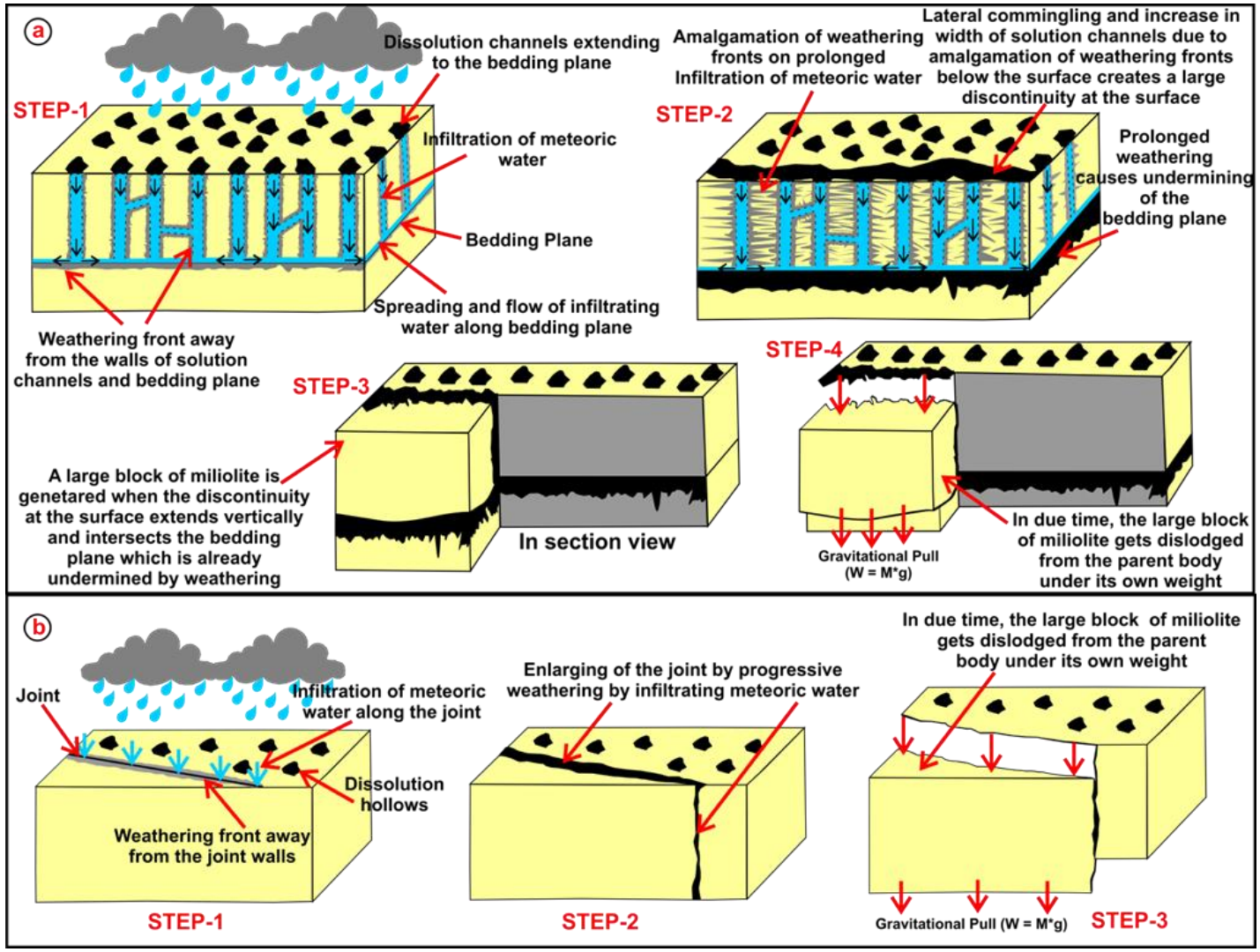

Figure 3.9. Mechanisms of sub-aerial processes of cliff erosion. a. Large scale mass wasting of the Miliolite cliffs caused by the interplay of progressive widening of dissolution channels by through flow of meteoric water and undermining of bedding plane by spread and flow of water along it by reaching down through the dissolution hollows. **b.** Large scale mass wasting of Miliolite cliffs caused by widening of joints through progressive seepage of meteoric water along them.

owing to their laminated nature and the vuggy porosity created by the passage of meteoric water, are easily worn down and washed away into the open sea by the action of waves and tidal currents. Thus, rapid wearing down of the debris accumulated at or near the cliff base allows the marine erosional processes to remain ever active over the cliffs and in combination with sub-aerial and biological erosional processes lead to continuous cliff retreat. This attests the Miliolite cliff system of coastal Saurashtra as belonging to the 'active' cliff stage of Emery and Kuhn (1982). Although the biological rates of erosion could not be measured, field visits clearly suggested that marine and sub-aerial processes of erosion have an upper hand over biological erosion in causing the retreat of the Miliolite cliffs.