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CARBONATE MICROFACIES FROM A PALEOCENE-EOCENE SUCCESSION OF AN ATTACHED PLATFORM – A CASE STUDY FROM THE SUB- HIMALAYA

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ABSTRACT

Well-developed Subathu succession is exposed in the Bilaspur tectonic Unit in the Sub-Himalaya. The Late Thanetian marine transgression across the Himalayan Foreland Basin (HFB) was from west to east over a peneplained basement with depressions that controlled the sedimentation. The sea first spread along the northern and southern margins and later the central part (Cuisian-Middle Lutetian). The northern extent of this sea was delimited by the Himalayan forebulge, while the southern margin was possibly delimited by the Mesoproterozoic Outer Limestone (e.g. Tundapathar, Malla, Morni) Wedges to which the HFB platform was attached.

Microfacies of mixed siliciclastic-carbonate sequence based on Wilson model distinguish three depositional sequences: A. Grainstone dominated with cortoid and grapestone (FZ 6) close to platform edge, at or above wave base (Ilerdian); B. Mud dominated representing open marine lagoon (FZ 7) grading to a restricted inner platform setting with stressed fauna in carbonaceous shales (FZ 8) (Early-Late Cuisian); C. Thick peritidal carbonate sequence which developed during the Late Cuisian-Early Lutetian carbonate shedding phase following the still-stand phase of Late Cuisian. The peritidal sequence is divisible in two parasequences: I- deeper subtidal passing upward into shallow upper subtidal sediments with major storm events which threw up coastal skeletal sediments on to the tidal flats and II-supratidal setting with frequent subaerial exposure. Two thick coal beds reported near Kalka indicate extensive marshy conditions in this sector.

Keywords: Subathu Formation, Palaeogene, Carbonate microfacies, Attached Platform

INTRODUCTION

The Late Thanetian-Late Lutetian Subathu Formation has multiple importance in the Himalayan Geology. For more than a century, till the discovery of the Cambrian fossils in the Tal Group in the nineteen eighties, the Subathu remained the only marine fossiliferous formation in the Lesser and Sub-Himalaya of Himachal Pradesh. It is not only the potential source rock for the hydrocarbon, but also the oldest unit in the Himalayan Foreland Basin (HFB) that chronicles various stages of collision of the Indian Plate with the Asian Plate. Hence, the Subathu Formation has been extensively studied by a galaxy of palaeontologists, oil geologists, petrologists, structural geologists, geochronologists and sedimentologists (for detailed references see Mathur and Juyal, 2000; Bhatia and Bhargava, 2006; Bhatia *et al*., 2013).

Though exposed as outliers and windows in the Lesser Himalaya, the main outcrops of the Subathu Formation are confined to the Palaeogene parautochtonous belt. This belt is exposed from Jammu in the NW to Dadhau in the SE (Fig. 1), and further east intermittently between Dadhau and Kill in the Himachal Pradesh. The parautochthonous belt has been subdivided into the Bilaspur and the Surajpur tectonic units. The Surajpur Unit is delimited by the MBT in North/NE and the Surajpur Thrust in South/SE. The Bilaspur Unit is framed by the Surajpur Thrust in NE and the Bilaspur Thrust (=Main Boundary Fault, *sensu stricto*) and extends from Kalka to the east of Sataun (Fig. 2a). Along the MBF appear outcrops of Mesoproterozoic limestones as wedges at Tundapathar, Malla, Morni, Kansar and Satuan in southern part, designated by the local names as Tundapathar, Morni, Sataun Limestone etc. Towards NW, the Bilaspur Limestone in Himachal and the Sirban Limestone in Jammu have identical setup.

The present paper describes and illustrates the carbonate microfacies of the Subathu Formation in the southern part of the Palaeogene parauthochthonous belt with a view to reconstruct the evolution of the Subathu Basin of the Bilaspur tectonic unit.

GEOLOGICAL SETUP

The Subathu Formation occurs over sequences varying in age from the Palaeoproterozoic to the Cretaceous and occupies various tectonic positions (Bhatia *et al*., 2013). Due to its occurrence over diverse basements, an extensive peneplanation and formation of bauxite prior to the deposition of the Subathu was suggested (Auden, 1934; Bhargava, 1976, p 217; Virdi, 1994). Since mere peneplanation could not explain identical facies of the Subathu over various older stratigraphic levels, folding prior to peneplanation was envisaged (Bhargava *et al*., 2011). The area thus peneplained was undulatory with macro depressions (Dey, 2011), which account for varying depths of the Subathu Basin.

The Palaeogene parautochthonous belt is not observed east of Dadahu. In several sections, a bauxite/lateritic horizon intervenes between the Subathu and the basement rocks. In the Bilaspur Tectonic Belt, this horizon has been recorded at the eastern bank of the Bithar-*ka-khala* on Sataun-Dak Pathar road, at Bhajon west of Sataun, and at Kansar (Dey, 2011). The presence of bauxite is interpreted to indicate the position of the Indian Plate in tropical latitudes (Virdi, 1993; Singh, B.P., *et al*, 2013) at the time of its formation.

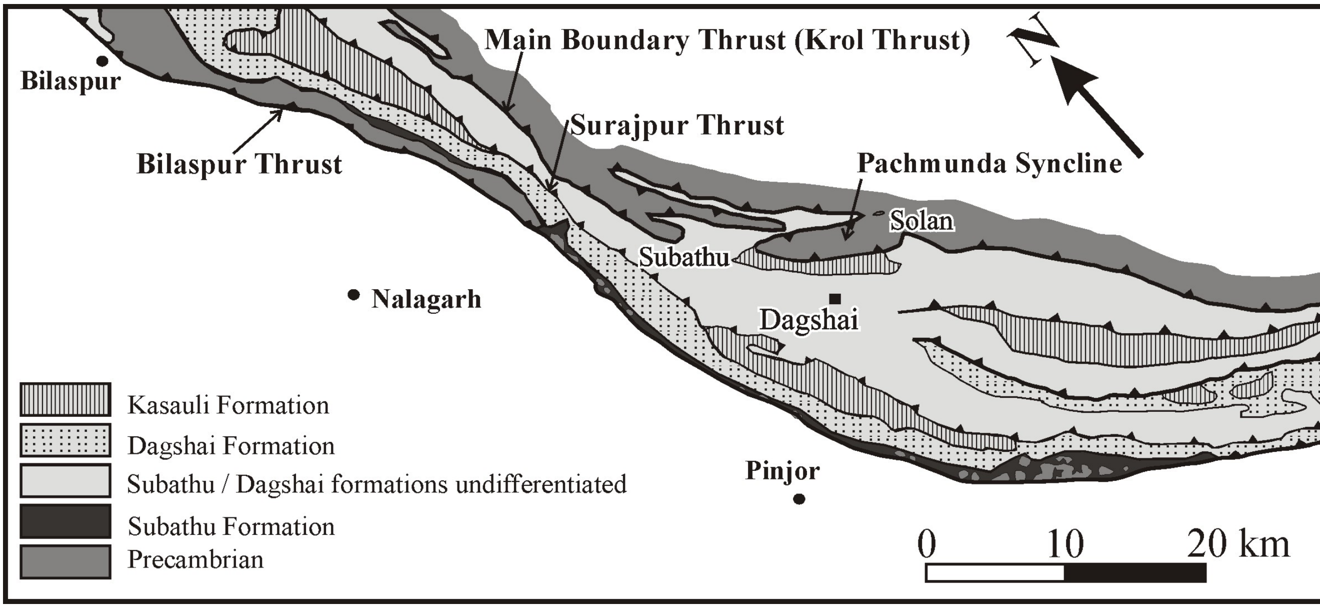

Fig. 1. Regional geological map of the Sirmur Group (Subathu, Dagshai and Kasauli) showing various tectonic elements (After Raiverman *et al*., 1983).

There is a near unanimity that the Subathu Formation was deposited in a shallow sea whose depth rarely exceeded 50 m. The view that the Subathu Formation represents calciturbidites (Bera *et al*., 2008), based on fauna, bedding features and carbonate microfacies has been refuted by Bhatia *et al*., (2013).

Most of the contributions cited above pertain to the Surajpur tectonic unit. Very little work has been carried out on the Bilaspur tectonic unit. Vohra *et al*. (1976) studied the Precambrian limestone deposits at Sataun. Siddaiah and Kumar (2007) reported an ash bed in the basal part and black pebbly limestone with fish remains in the middle part of the Subathu Formation exposed in the Koshalia river section close to Kalka town. Dey (2011) described the regional stratigraphic and structural set-up of the Precambrian carbonates designated as the Outer Limestone Belt (OLB) *vis-a-vis* the Subathu and Nahan formations in the Bilaspur tectonic unit. Based on the presence of a conglomerate bed and pisolitic horizon between the OLB and the Subathu Formation, Dey (2011) postulated an unconformity between these two sequences. Table 1 presents the tectono-stratigraphic set-up of the Bilaspur unit between Malla and Sataun.

Though broadly litho- and biofacies of the Subathu Formation are similar over the entire length, there are differences in various sections. Thus, it seems appropriate to subdivide the Palaeogene belt in sub-basin which has identical litho- and biofacies. The area between Sataun, Morni and Kalka (Fig. 2a) is one such sector that displays identical set-up. This sector is being named as Sataun-Morni-Kalka (SMK) Embayment.

CARBONATE MICROFACIES

The samples for the present microfacies studies were collected from two adjacent localities (H and I) near villages Kharak and Chhamla (Fig. 2b) (Bagi, 1993), exposed on either bank of the Ghaggar River. The area was mapped by Narain (1967), Lonial (1985) and subsequently by Bagi (1993). The section at Locality I on the left bank of the river measures approximately 340 m. On the right bank at Locality H, the exposed section is approximately 65 m thick, lower part of the section covering the Ilerdian-Early Cuisian sequence is concealed under the alluvial deposits. The carbonate beds numbered I-10 to I-23 were sampled and studied by HB for their foraminiferal and ostracode contents (Bagi, 1992). Only selected carbonate samples showing strikingly different microfacies and environmental setting as compared to those of the samples at

EXPLANATION OF PLATE I

1. Destructive cortoid. Note thick micritic envelope (ME). The external wall and the ornamentation of ***Assilina pomeroli*** Schaub have been completely destroyed presenting an irregular outline. . The internal chamber walls have also been completely destroyed. Note the solitary calcisphere (C) in the void created by destruction of internal laminae (Sample 1-10, matrix of fine grained grainstone). 2. Destructive cortoid (same Sample as Fig. 1). Note the destructive action by microbial activity forming a microbial crust (MC) on one side of the nummulitid test in contact with the sediments. On the opposite side the spiral laminae (SL) are relatively intact. 3. Oblique axial section of ***Assilina pustulosa*** Doneieux showing micritic filling and destructive action of microbes (MC) on one side of the test as in Fig. 2. Fine grained grainstone (G). Arrow (T) indicates top of the foraminifer during deposition. (Sample No. I-10). 4. Grapestone facies showing lobate micritised grains. Evidence of diagenetic crack and carbonate cement indicating subaerial exposure. Note calcite layer (Ca) binding the aggregate grains. Restricted shallow platform settings (SMF Type 7; Facies zone FZ 6; Sample I-11). 5. Aggregate grain lumps; note carbonate (Ca) grains, partially micritised forming the matrix. (Sample I-11). 6. Fragment of cross-section of coral ***Feddenia garkhalensis*** Mathur matrix mudstone. Note solitary calcisphere (C) and in situ algal peloids (AP). Possible symbiotic relationship with coral like the modern *zooxanthelle*? Lagoon with open marine setting below wave base. (Sample No. I-14)

Plate I

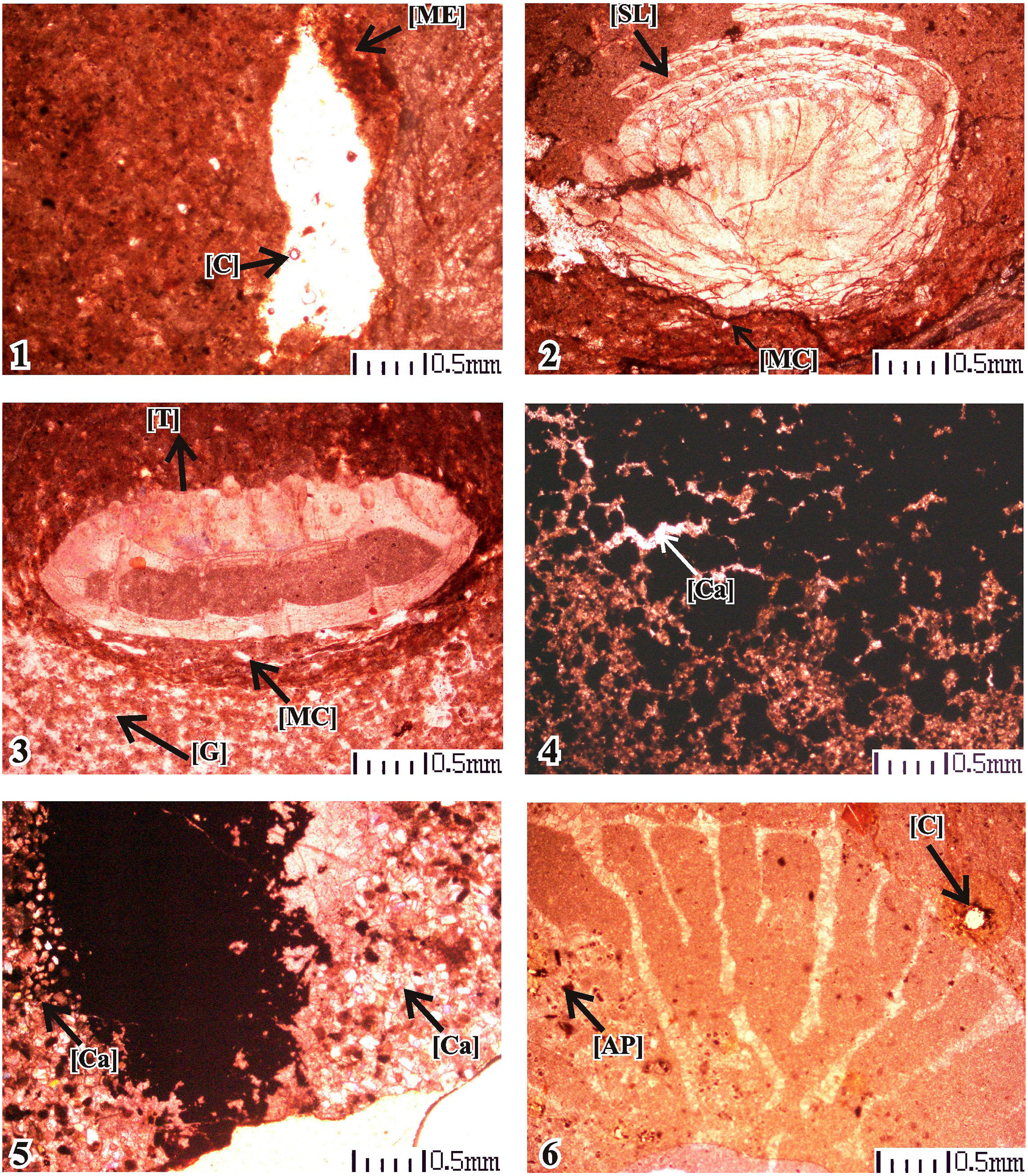
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Table 1. Tectono-stratigraphic sequence of the Sub-Himalaya between Sataun and Malla partially modified after Dey (2011).

Age	Geological Formation	Important rock types encountered
North		
Neoproterozoic -Lr Cambrian	Jaunsar, Blaini, Infra Krol, Tal (Inner Krol Belt)	Quartzite, slate, shale, carbonate beds, chert,
	South Tons/Chail Thrust	
Neoproterozic -Ediacaran	Blaini, Infra Krol, Krol (Outer Krol Belt)	Diamictite, shale, slate, Carbonate
	Krol Thrust	
Palaeogene	Dagshai (Late Eocene-Oligocene) Subathu (Paleocene-Mid. Eocene)	Purple/grey sandstone, shale Grey/olive green shale, grey sandstone, limestone ,
	Unconformity (conglomerate and pisolite)	
Mesoproterozoic	Outer Limestone	Bluish grey/massive/flaggy/stromatolitic limestone, shale/ phyllite, basal quratzite member
	Main Boundary Fault/Thrust	
Neogene	Nahan/Lower Siwalik (Middle Miocene)	Grey/green /light brownish sandstone, red clay
South		

Locality I were utilized from the locality H (Plate V, figs. 1-3 & 6) in the present work.

The stratigraphic section of the Subathu Formation exposed at Locality I is shown in Fig. 3. The basement rocks of the Tundapthar Limestone are not exposed at this locality. The basal part comprises mainly the black crumply shale with thin carbonate bands showing calcite veins and pyrite nodules. The rest of the section consists of a mixed siliciclastic-carbonate succession with centimetre to metre scale fossiliferous carbonate beds. The mixed siliciclastic-carbonate sequences represent interplay of eustatic changes, carbonate productivity, variation in sediment supply, tectonics and rate of erosion of sediments in the hinterland.

Winnowed fine-grained organic mud and silt from the adjoining sub-basin of Kalka, wherefrom thick sequence of coal, shale, limestone and volcanic ash are reported (Siddiah and Kumar, 2007), might have also affected the sedimentation pattern of the siliciclastic-carbonate succession near Morni.

DEPOSITIONAL SEQUENCES, 'SYSTEMS TRACTS' AND FACIES MODEL

Based on microfacies analysis of carbonate and the guidelines (Schlager, 2002) for identifying systems tracts from a single litholog as of Locality I SMK Embayment, the 340 m thick siliciclastic-carbonate succession is divisible into three shallowing-coarsening upward tidal sequences viz., A, B, and C (Fig. 3). Schlager (2002) suggested it is essential to first identify the platform edge *vis-à-vis* the postulated coastline and then to locate the (litholog) landward from the platform edge.

The Systems Tracts of the Early Palaeogene mixed siliciclastic-carbonate sequence of Locality I with respect to the postulated coastline and envisioned Platform edge are plotted in Figs. 3 and 4. The microfacies of the carbonate beds and their assignment to the revised Standard Microfacies Types (SMF) (Flügel, 2010, p. 681) shows that the Facies Zones in the SMK embayment arranged chronologically conform to the well-known and widely accepted Facies Model for the rimmed Carbonate Platform of the tropical and subtropical regions as proposed by Wilson (1975) and subsequently modified by Flügel (2010, Fig. 14.1, pp. 662-663). As postulated by Bhatia *et al*. (2013) the Subathu succession documented by Siddaiah and Kumar (2007) near Kalka, approximately 15-20 km from Morni and in strike continuation of the section at Chhamla, was palaeogeographically a part of the SMK Embayment, although we do not have any details of the microfacies or precise stratigraphical control of the sediments recorded from Kalka, nor are there any records of surface or borehole data to suggest connectivity between the two regions. The lithofacies of the basal 100 m of the Subathu Formation as provided by Siddaiah and Kumar (2007, Figs 1-3) from locality Kamli in the Koshalia River, southeast of Kalka, comprises two thick coal seams with an interbedded 1.5 m thick volcanic ash (tonstein) besides sandstone, carbonaceous shales with subordinate carbonate beds. A significant feature of this sequence is the occurrence of a black pebbly conglomerate with fish remains, approximately 65 m from the exposed base. The lithofacies recorded by Siddaiah and Kumar (2007) strongly suggests that the beds near Kalka can be assigned to the Facies Zone 9B of Wilson Model (1975).

The mixed siliciclastic-carbonate succession at Chhamla is divisible in three depositional sequences A, B, and C (Fig. 3).

MICROFACIES AND DEPOSITIONAL SETTING OF SEQUENCE A

Depositional sequence A: Two thin beds (samples I-10 and I-11) centimetre-scale thick occur in the basal part of this sequence. These beds represent grain-dominated microfacies.

Bed I-10 is assigned a Late Ilerdian age (SBZ 9, 52.5 Ma) because of the presence of age diagnostic foraminifera—*Assilina*

EXPLANATION OF PLATE II

1. ***Assilina spinosa*** fine grained grainstone. (Sample I-10). 2. ***Nummulites minutus*** Racey cortoid in Nummulitic wackestone with stubby filamentous coating (SMF 11; Sample No. I-15). All specimens Form 'A' except one 'B'. 3. Peloidal grainstone with large fragment of oyster shell. Tidal flat setting (SMF 18; Sample I-18). 4. Peloidal grainstone with abundant calcispheres (Same as Bed I-18). 5. Peloidal grainstone with axial section of ***Assilina placentula grande*** Schaub. Note the characteristic polar depression (PD), inset is the SEM photograph of stunted bivalve ***Corbula***. (Sample I-17b). 6. ***Nummulites praedisorbinus*** Schaub wacke/packstone (axial section, Sample I-16).

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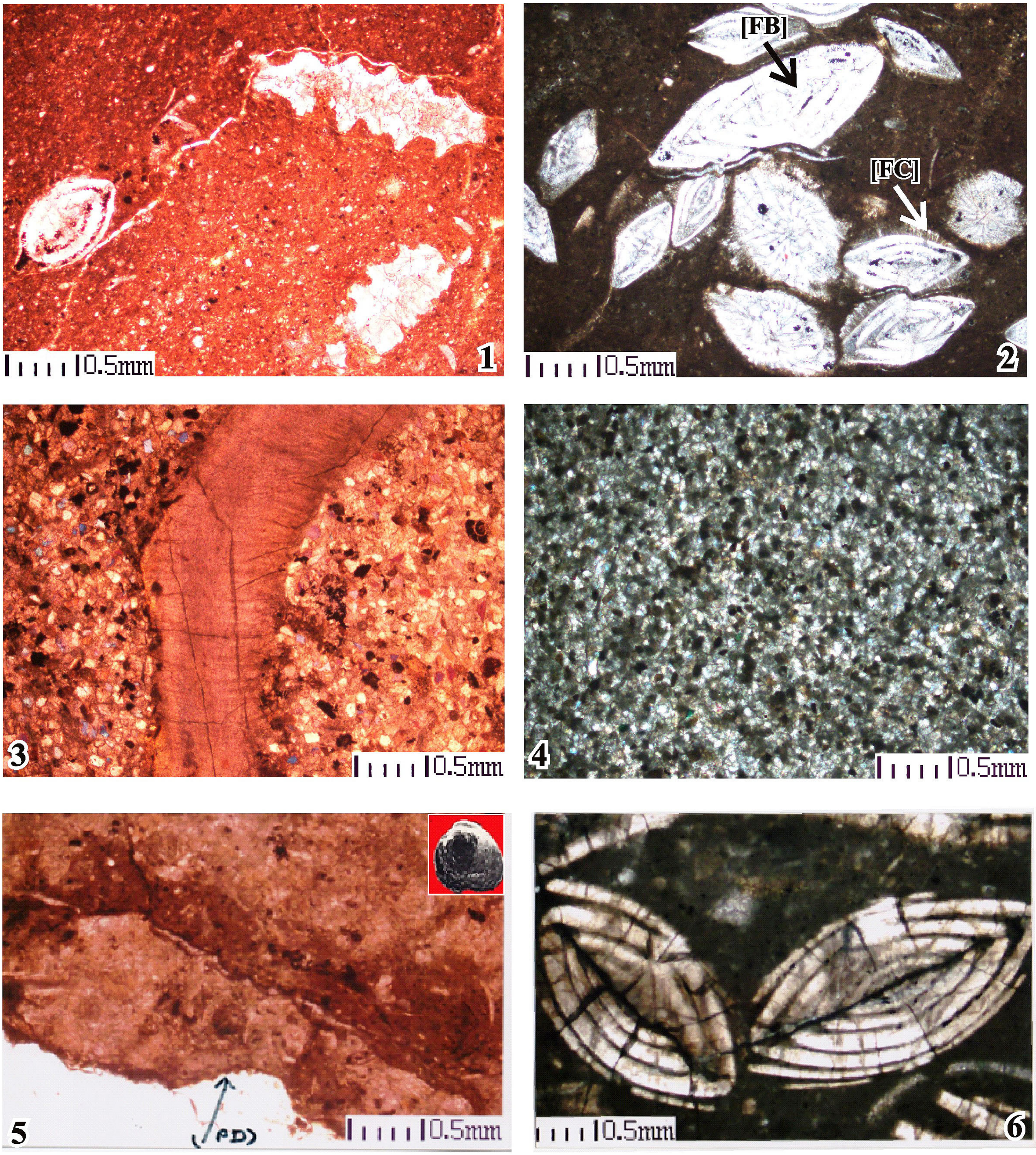
Plate II



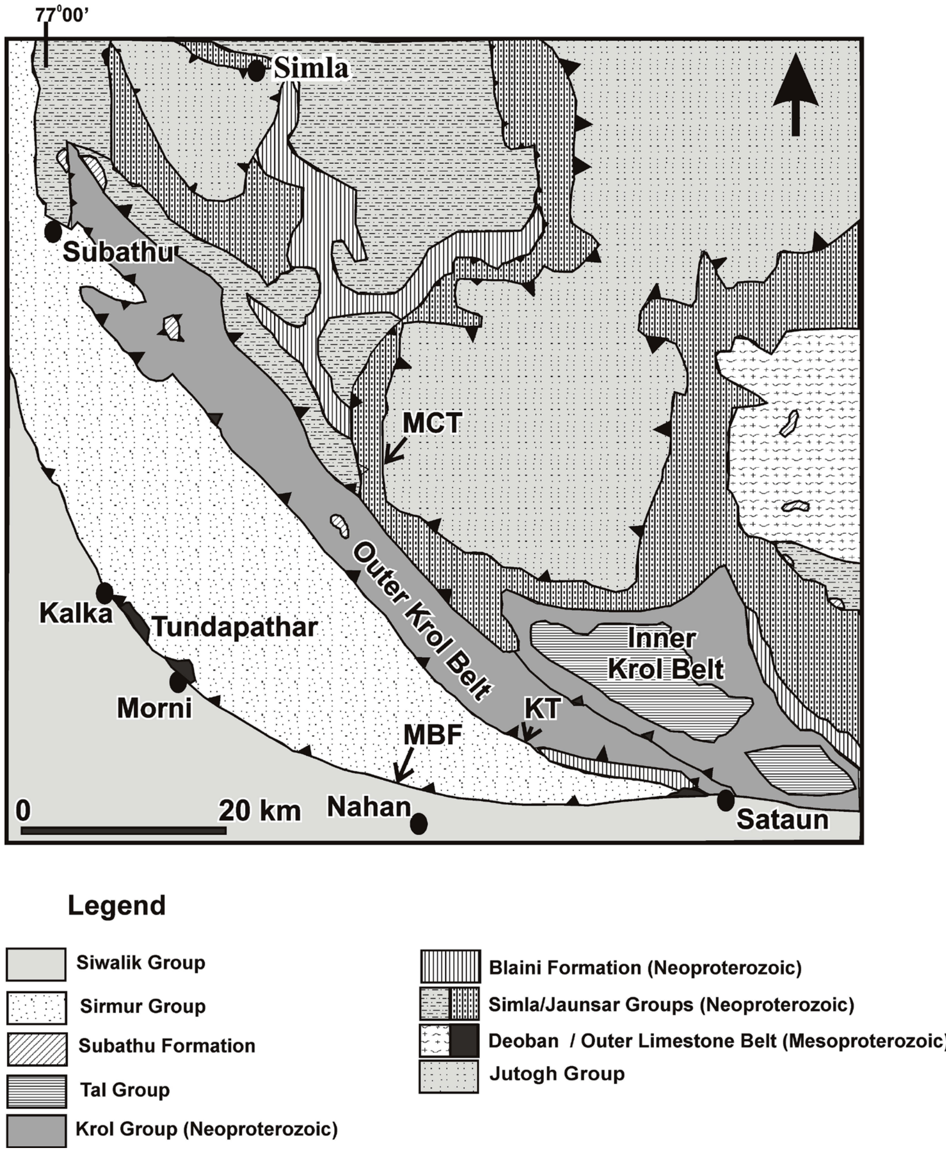


Fig. 2a. Geological map of a part of Himachal Pradesh, showing the Sataun-Morni-Kalka Embayment, Mesoproterozoic Outer Limestone Belt and outliers of the Subathu Formation outside the para-autochthonous Palaeogene belt.

pomeroli Schaub. This sample exhibits larger foraminifera bioclast coated with micritic envelope cortoid due to the destructive action of microbes (Pl. I, figs. 1-3, Pl II. fig. 1). Fig. 1 shows complete destruction of the walls, ornamentation and internal structure of the foraminifer, while Figs. 2 and 3 show partial destruction on only one side of unidentified foraminifer—the sediment bioclast interface.

Depositional setting: Shallow warm waters with constant water agitation, winnowed platform edge, at or above wave base characterised by bedded fine-grained grainstone and light-dependent boring organisms- cyanobacteria, representing SMF Type 11.

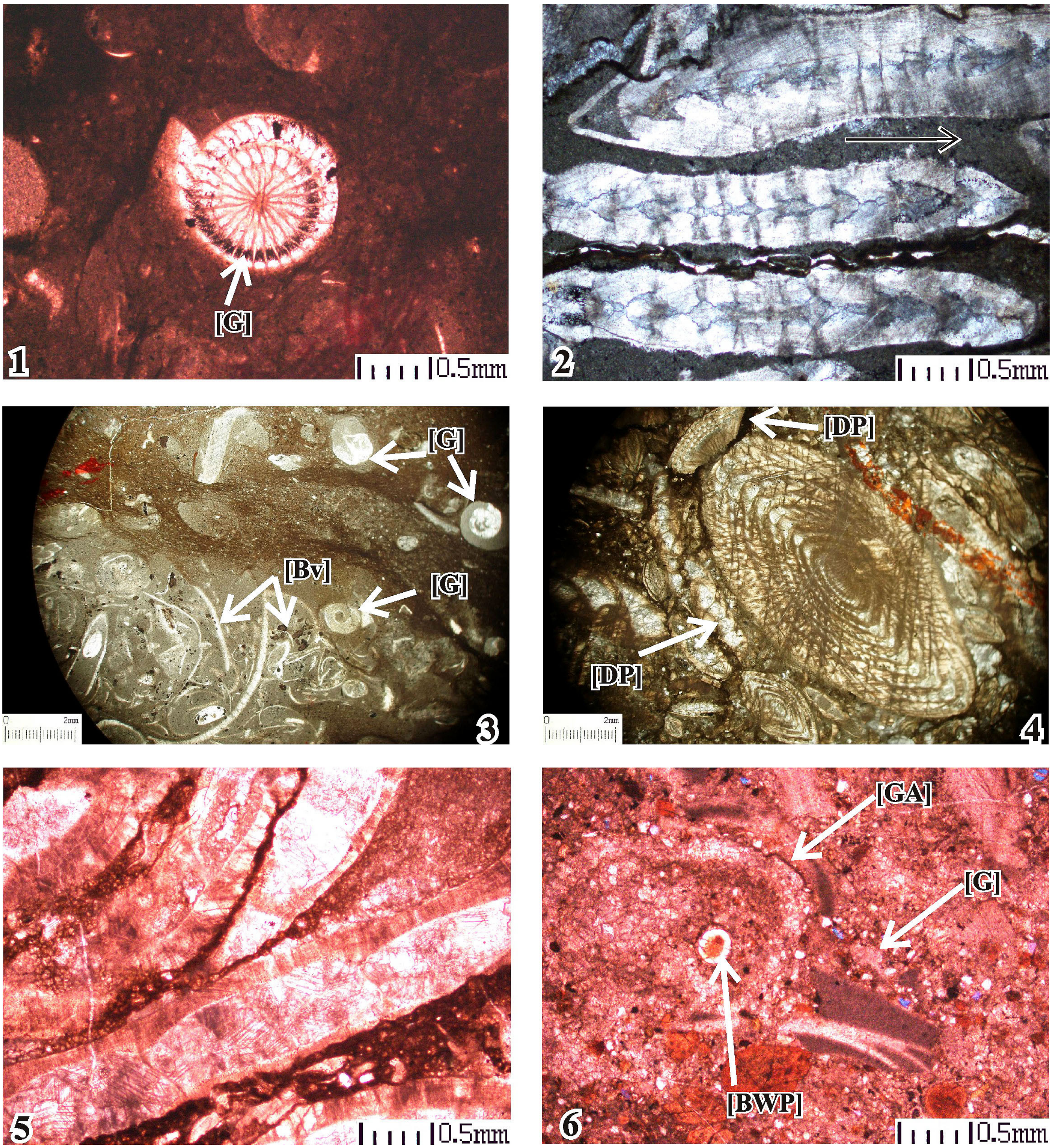
Bed I-11- The sample shows grapestone facies, early diagenetic cracks with vadose carbonate filling, possibly due to subaerial exposure (Pl I, Fig. 4) and aggregate micritised grains in lumps with mud peloids (Pl I, Fig. 5).

Depositional setting: Grapestone facies occurs preferentially on rimmed platforms, within a short distance behind the platform

EXPLANATION OF PLATE III

Fig. 1. Authigenic glauconite in equatorial section of an unidentified ***Nummulites*** in wackestone. Deeper subtidal setting below wave base. (Sample I-20A).
Fig. 2. Imbrication in ***Assilina cuvillieri*** Schaub (Form A) wackestone oriented parallel to the current direction. (Sample I-20B).
Fig. 3. Bivalve (Bv), gastropod (G) floatstone. Normal marine shallow subtidal setting (Sample I-20C). Fig. 4. ***Nummulites schaubi*** Racey. Note diagenetic peeling (DP) of outer spiral laminae due to attrition in the sole of the storm bed. Beach ridge setting (Sample I-21). Fig. 5. ***Assilina spira abrardi*** Schaub packstone showing imbrication. Matrix of bioclast fragments. Short term storm event at Beach ridge (Sample I-21). Fig. 6. Cryptalalgal (Gymnocodiacean algae GA) peloidal grainstone with fragment of a large *Black* and *White* (BW) peloid (*sensu* Flügel, 2010), the dark core is automicrite biologically induced metabolic process or by microbes. The white rim is composed of Mg-acicular magnesite, Tidal flat setting (Sample I-23).

Plate III



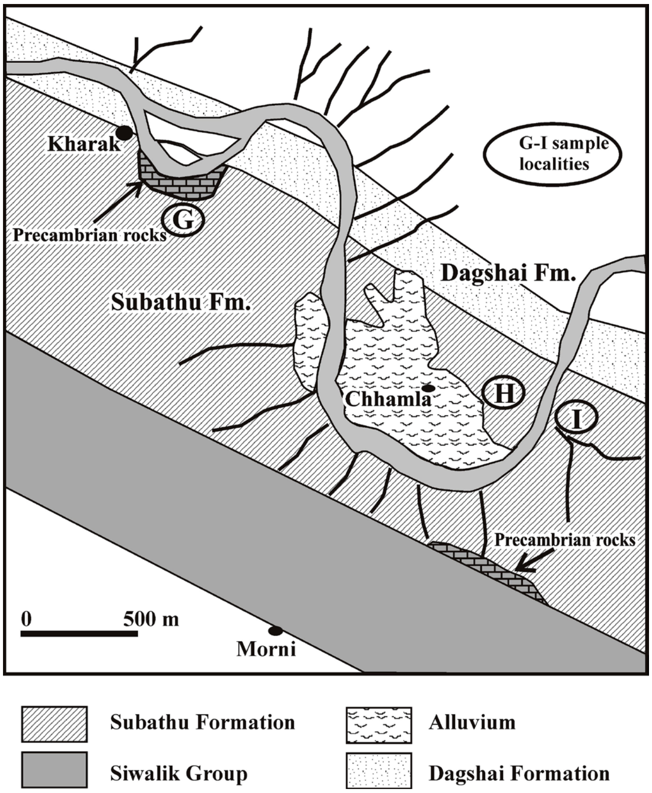


Fig. 2b. Map of Morni sector showing location of Chhamla and Kharak and localities H and I (After Lonial, 1983)

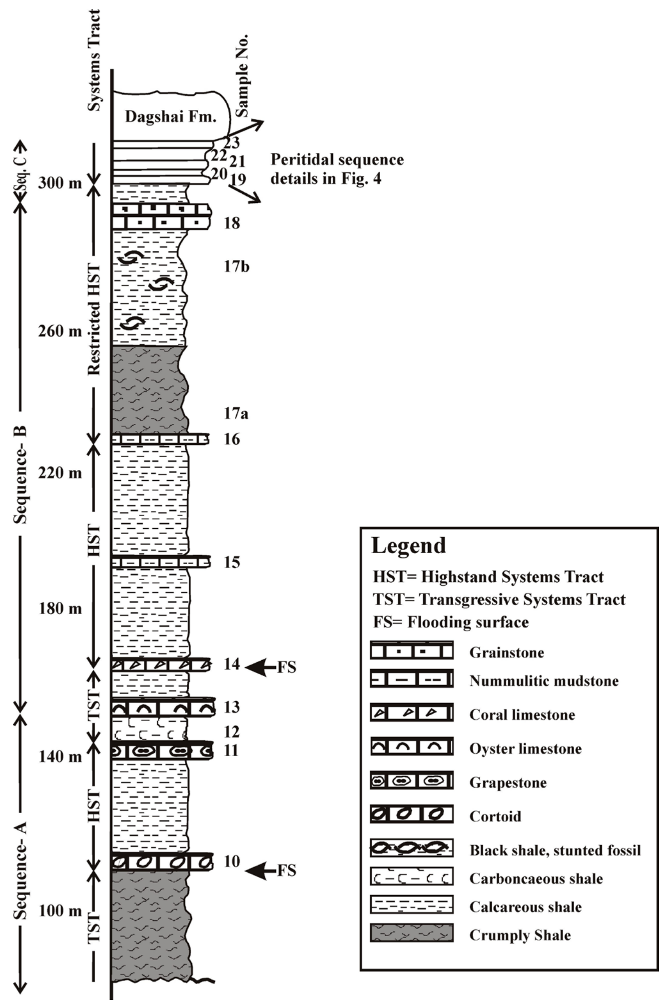


Fig. 3. Litholog of the Subathu Formation of the Locality I, Chhamla (Morni sector) showing various depositional sequences in their stratigraphic order.

edge, restricted shallow platform setting.

The depositional setting in the SMK embayment of attached platform is analogous to the setting in the Late Triassic (Rhaetian) Limestones of northern Calcareous Alps at Stemplate Tyrol, Austria. (Facies Zone 6, SMF Type 17; Flügel, 2010, Fig. 14.22).

MICROFACIES AND DEPOSITIONAL SETTING OF SEQUENCE B

This depositional sequence is assigned to Early Cuisian-Late Cuisian (SBZ-10 to SBZ 12, 52-49.5 Ma). Beds 12 and 13 represent TST and comprise carbonaceous shale and thick decimetre scale coquinite. Bed 14, which comprises a diagnostic species of coral, marks the initiation of the Early Cuisian flooding in the embayment. It is overlain by a thick succession of calcareous shale and two thick (decimetre scale) carbonate beds No. 15 and 16, displaying distinctive and contrasting microfacies containing characteristic species of *Nummulites*.

The Cuisian succession is divisible into two distinct units. Beds 14, 15 and 16 represent the Mud dominated open marine phase, while Beds 17a, b and 18 represent the restricted marine phase. The thick (meter-scale) Bed No. 18 of peloidal grainstone caps the sequence B.

Bed I-14 (Pl I, fig. 6): Matrix fine grained mudstone showing transverse section of the scleractinian coral *Feddinia garkhalensis* Mathur.

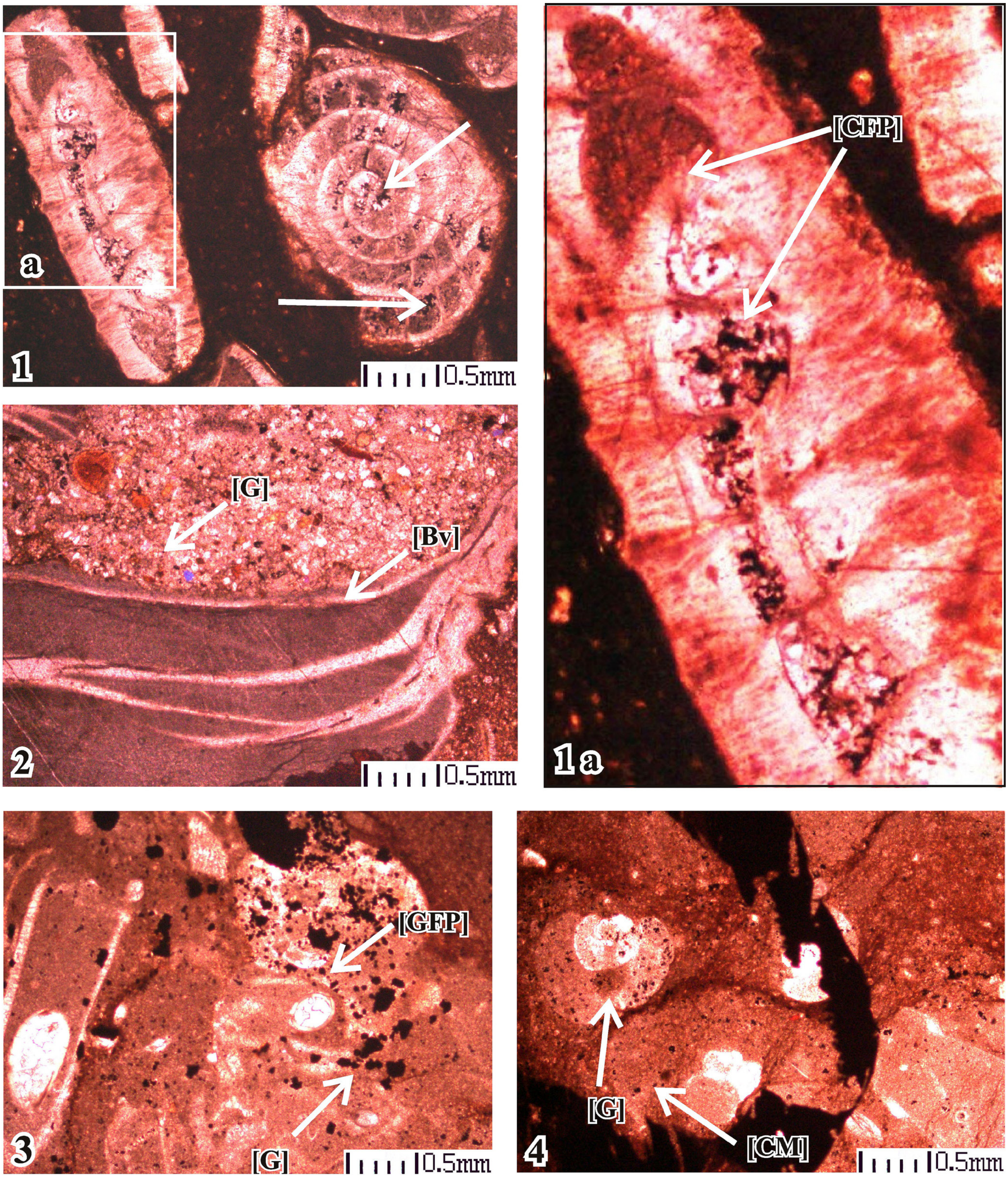
Depositional setting: Open marine lagoon, subtidal—Facies zone 7. According to Mathur and Juyal (2000) this is a zonal fossil of the Late Ypresian. Our record is, however, from the Early Cuisian.

Bed I-15 (Pl. II, fig. 2): The diminutive specimens of *Nummulites minutus* Racey show cortoid with coating of stubby filamentous microbes. The specimens are probably reworked from shallower parts of the lagoons. Racey (1992, 1995) first

EXPLANATION OF PLATE IV

1. In situ precipitation of pellets by microbial activity of algae/cyanobacteria in cavity-fill environment of ***Assilina suteri*** Schaub. Chambers are filled with irregularly shaped pellets (CFP). The white tubular portions are possibly fossilised microbes. The assiline chambers seem to be ideal micro cavities for microbes to thrive and precipitate micrite (peloid). Note both the equatorial and axial sections of ***A. suteri*** (Form A) occur in the same section. The rock can be classified as a wackestone with micritic matrix. Intertidal-subtidal setting. (Sample I-22C). 1a. Enlargement of demarcated part of 1. 2. Reworked bivalve (Bv) shells filled with fine grained micrite into coarse grained peloidal grainstone. Tidal flat setting. (Sample I-23). 3 & 4. Intraformational breccia, weakly lithified carbonate mud lithoclasts with gastropod (G) and their faecal pellets (GFP). The lithoclasts are reworked and redeposited by tidal currents in a tidal flat setting (details in text). (Sample I-23).

Plate IV



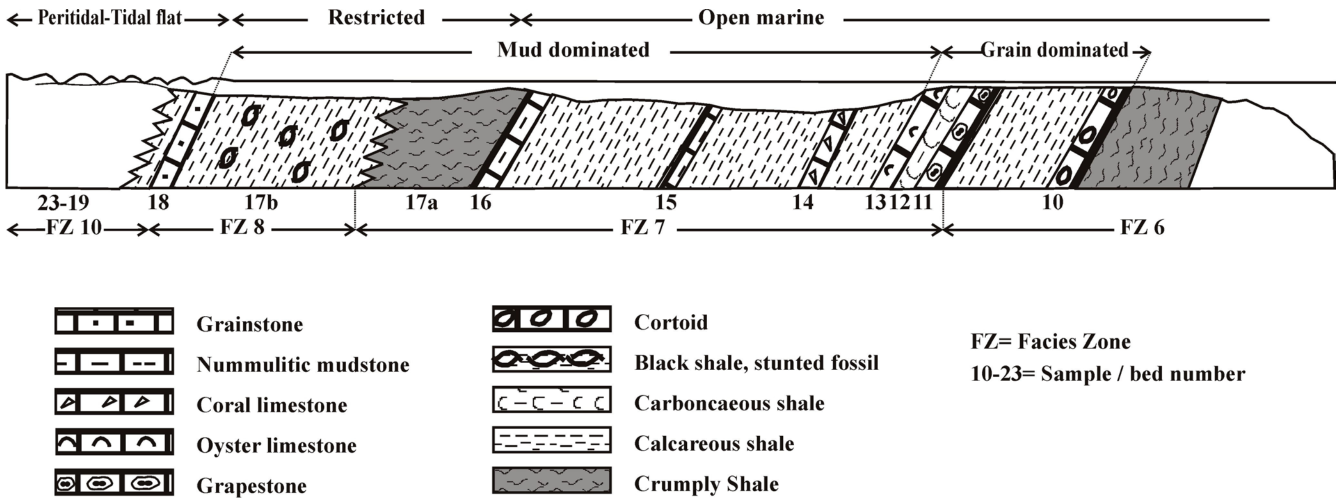


Fig. 4. Diagrammatic basin profile to show stacking of various depositional successions of the Subathu Formation in space and time in the Locality I, Chhamla (Morni sector).

recorded this species from the Late Cuisian-Early Lutetian of Oman. Our sample is from the Late Cuisian beds.

Depositional setting: Below wave base (FZ 7, SMF Type 11).

Bed I-16 (Pl. II, fig. 4): This sample exhibits axial sections of *Nummulites praediscorbinus* Schaub (FAD SBZ 12) in a wackestone (Pl. II, Fig. 6). The wackestone grades into fine grained peloidal grainstone with lamination of coarse grainstone representing SMF Type 16. Ecologically significant and opportunistic species of smaller foraminifera *Stainforthia dubia*, which was recorded from the Bed B-4 of succession B of the Subathu Formation of the Kaushalia River section (Bhatia *et al*., 2013), also occurs in Bed I-16 at roughly the same stratigraphic level.

Depositional setting: Platform interior tidal flat setting bordering towards restricted FZ 7-8 is indicated. *Stainforthia dubia* is known to occur in dysoxic/suboxic/anoxic environments.

Beds I-17a, 17b and I-18: Beds 17a and b (total thickness approximately 80 m) comprise black carbonaceous shales. Black shales of Bed 17a are crumply, devoid of any fossil and prominent bedding. The texture and sedimentary features of Bed 17b were first described by Lonial (1988), who distinguished two types of laminations in this bed. The two types generally occur as couplets. Facies similar to those recorded by Lonial (1988) from the Morni area are also known from the Late Triassic "Norian Seefeld Facies" Westal Quarry, Hallen, Austria (Flügel 2010, Fig. 12-10). The alternations of light and dark laminae are attributed to variation in oxygen level (ORB-2), anaerobic to disaerobic with stressed fauna (ORB-4) (Flügel 2010, p. 14). Lonial (1988) also tentatively identified the 'stunted bivalves' on the basis of growth lines and surface ornamentation to the genera *Corbula* (size range 2-4 mm) and *Venericardia* (size range 2-7 mm).

Bed I-18 (Pl. II, figs. 3-5): This metre-scale bed represents a light coloured peloidal grainstone (Pl. II, fig. 4) with skeletal fragments of oyster shell (Pl. II, fig. 3) and a large fragment (axial section) of the foraminifera *Assilina placentula grande* Schaub (Pl. II, fig. 5). This large-sized subspecies of *Assilina placentula* is known to range in age from Late Cuisian to Early Lutetian (SBZ 12-13), whereas the smaller species has a limited range of SBZ 10. Mathur and Juyal (2000) recorded this subspecies from several localities in the HFB with FAD at SBZ-12.The thin section illustrated by us (Fig. 4) shows a fine grained non-laminated peloidal grainstone with abundant peloids and calcispheres.

Depositional setting: Shallow restricted part of the basin—SMF Type 16, Fz 8—represented by non-laminated grainstone is indicated. Lenses of reworked shell fragments are interpreted to represent tidal flat setting (Pl. II, figs. 3-5).

THE TRANSITION FROM BED I-18 TO I-19-23 (SEQUENCE C)

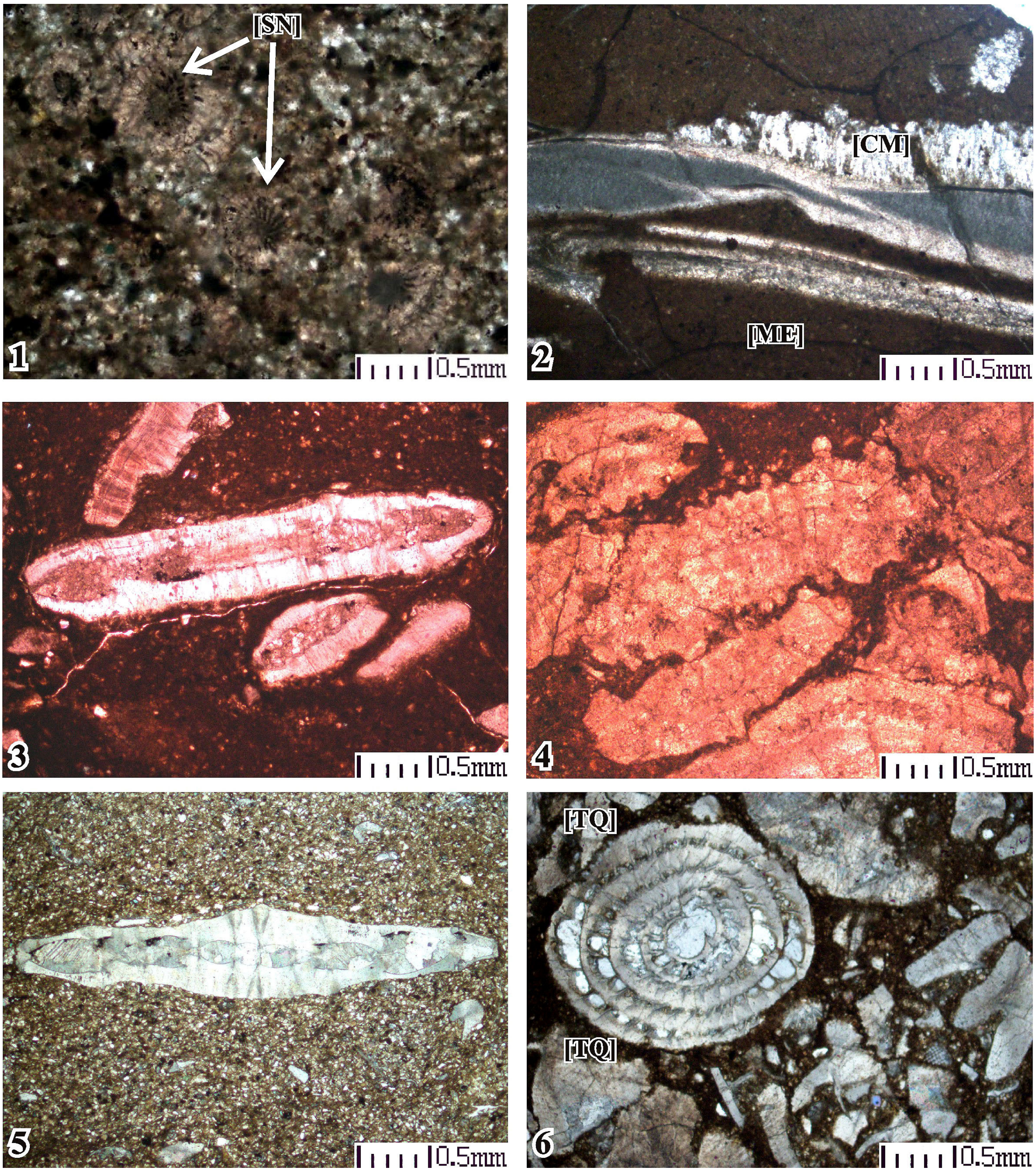
Although the grainstone bed I-18 is better grouped as a part of Depositional sequence B (Fig. 3, 4), its depositional history is closely linked with that of the overlying Sequence C (Fig. 5)

Approximately 20 m thick Sequence C represents a peritidal sequence (beds No. 19-23). It shows shallowing upward sequence from deeper subtidal through subtidal, intertidal and supratidal environment.

EXPLANATION OF PLATE V

Fig. 1. Peloidal grainstone with stunted (diminutive) nummulitid tests (SN). The proloculous is filled with authigenic glauconite (?). The juvenile tests either floated into an anoxic tidal flat environment or swept in by tidal current. Tidal flat setting. (Sample H-1). Fig. 2. Destructive and constructive activity of microbial organism in the formation of cortoid on a bivalve shell. Steps C-4 and C-5 in a three step model of Bathurst (1966) are visible: Calcified microbial filament (CM) and micritic envelope (ME), the finished cortoid has a fortuitous resemblance to the bristles of a 'tooth brush'. (Sample H-23). Fig. 3. ***Assilina*** sp. indet., (Form A) wackestone, imbrication due to short term storm event. (Sample H-9). Fig. 4. ***Assilina cuvillieri*** Schaub wackestone/packstone showing imbrication owing storm event on a beach ridge. (Sample No. I-19). Fig. 5. ***Assilina suteri*** sandy allochem with well sorted fine grained quartz sand and silt. Coastal setting. (Sample No. I-22c). Fig. 6. ***Assilina maior*** Heim (equatorial section, Form A) bioclast in sandy well sorted terrigenous quartz with micritic matrix. Note *in situ* microbial pellets in cavity chambers of the foraminifera. Locality H, the sample is homotaxial with Sample I-22, (Plate 4, Figs 1 & 2).

Plate V



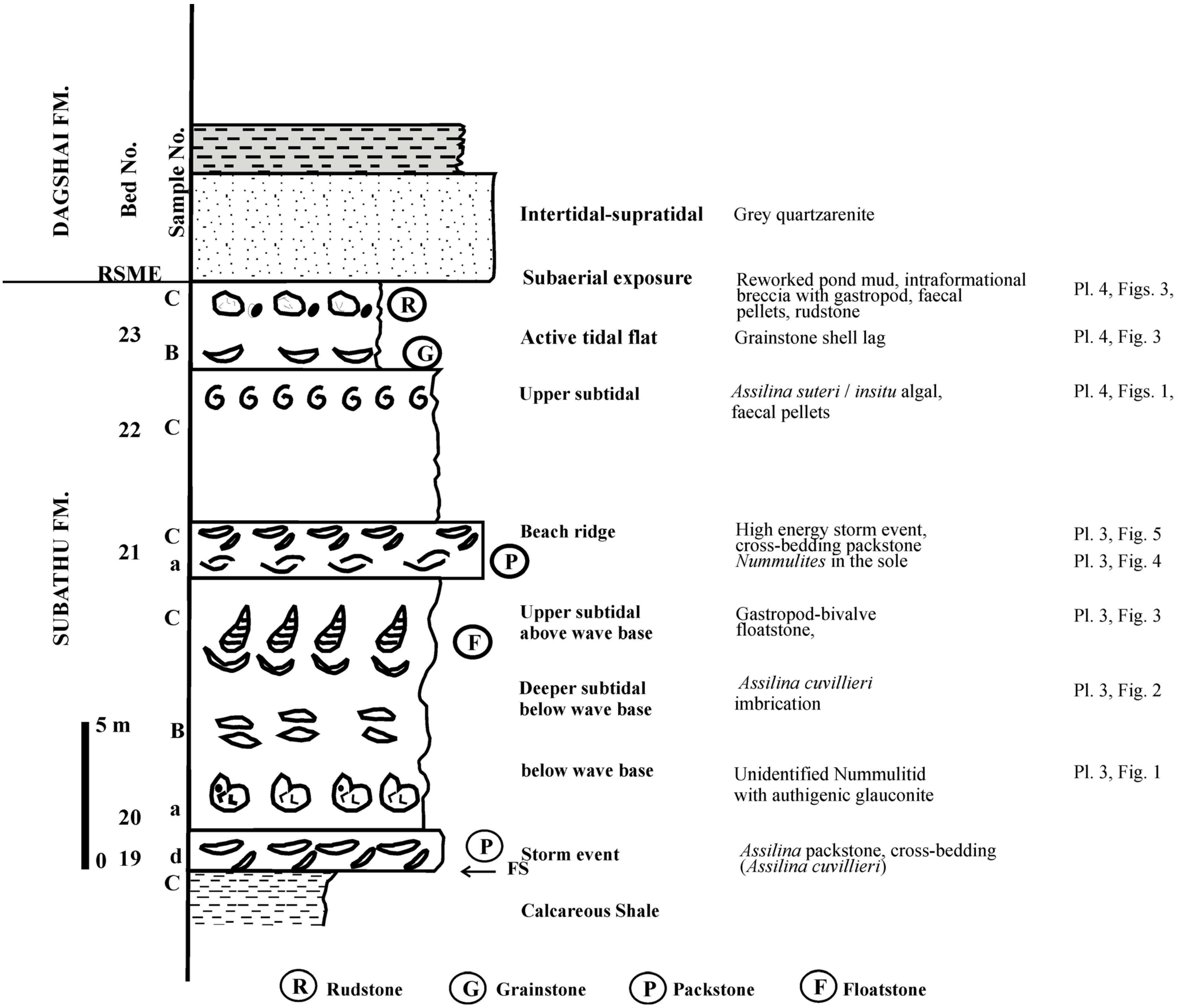


Fig. 5. Detailed litholog showing peritidal depositional sequence in the Depositional Sequence C of the Subathu Formation of the Locality I, Chhamla (Morni sector). Para sequence I-Beds 19-20; Parasequence II- Beds 21-23.

Thick carbonate beds in Highstand Systems Tract, similar to that encountered in the C Sequence (2 m thick peloidal grainstone; Bed I-18; Late Cuisian--49.5 Ma; SBZ 12), are attributed to carbonate shedding due to rate of sedimentation exceeding the sea level rise (cf. Flügel, 2010, p. 817).

MICROFACIES AND DEPOSITIONAL SETTING OF DEPOSITIONAL SEQUENCE C—THE PERITIDAL SEQUENCE

The peritidal sequence represented by beds I-19-I-23—a prograding upward tidal flat sequence is divisible into two parasequences—PI and PII. Detailed study of microfacies of closely spaced samples (cf. Hendersen, 1980) is essential as to enable to distinguish deeper subtidal (below wave base) and shallow subtidal (above wave base) facies besides intertidal and supratidal facies. These changes in facies reflect progradation of tidal flat primarily due to storm activities, their frequency and duration and periodic flooding of tidal flats owing to varying magnitude of transgressive events (cf. Coogan, 1974; Wilson, 1975; Ginsburg, 1976; Tucker, 1985).

Parasequence I: This parasequence commences with the deposition of 1.5 m thick flat marginal beach ridge (I-19) formed during major storm events which throw up coastal skeletal sediments on to the tidal flats.

The 1.5 m thick I-19 m bed comprises a laminated peloidal packstone with *Assilina cuvillieri* Schaub (SBZ-12; Late Cuisian) as the dominant biota (Pl. V, figs. 3 and 4).

The basal part of the overlying 6.5 m thick subtidal calcareous shales (I-20) indicates deposition below wave base (samples 20a and 20b). Microfacies of sample 20a (Pl. III, fig. 1) shows an unidentified *Nummulites* wackestone with authigenic glauconite filling the chambers; the sample 20b (Pl. III, fig. 2) shows a packstone with imbrication of flat *A. cuvillieri* (all cut in axial section). The imbrication is due to uni-wave directional current action below the wave base. These deeper subtidal deposits pass upward into shallow subtidal sediments (sample 20c), represented by bioclasts of gastropod-bivalve wackestone/

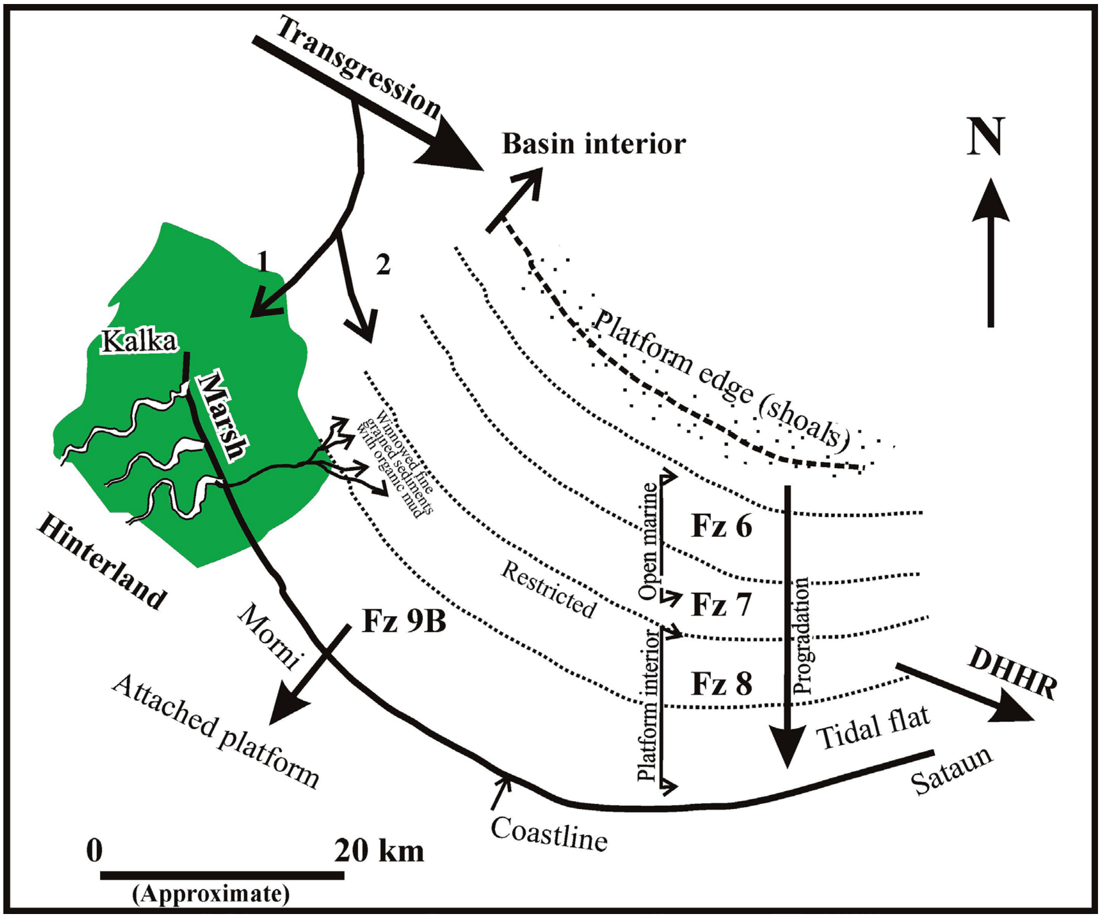


Fig. 6. Schematic diagram to illustrate postulated basin configuration SMK Embayment, facies model after Wilson (1975) and possible relation with the Kalka sub-basin, direction of marine transgression in the SMK and location of marsh with respect to Kalka (Not to scale).

floatstone (Pl. III, fig. 3). This microfacies is assigned to SMF Type 8. The floatstone bed caps the Parasequence I. The microfacies suggests that the overall depositional setting was in the distal, open platform where the Late Cuisian transgressive phase was intense and widespread resulting in the deposition of thin wackestone and packstone beds.

Parasequence II: It commences with the deposition of bed 21- an *Assilina sprira abrardi* packstone (SBZ 13; Early Lutetian) signifying beach ridge (Pl. III; figs. 4, 5). Two samples from this 2.5 m thick packstone bed were collected. Sample 21a from the sole of the bed (Pl. III. fig. 4) shows a large species of—*N. schaubi* Racey first described from Oman. The illustrated specimen shows the outer whorls of the species detached and partially damaged due to storm activity. The sample 21c from the upper part of the packstone shows the imbricated large specimens of *Assilina sprira abrardi* possibly due to storm events.

Bed-I-22 represents a 6.5 m thick bed lying immediately above the beach ridge (I-21) deposited in an upper subtidal setting. The bed is a laminated lime mudstone. A thin section from the top of the bed (sample 22c; Pl. IV, figs 1, 1a) shows axial and equatorial sections, both in the same slide of *Assilina suteri* Schaub with chambers almost completely filled with *insitu* microbial faecal pellets. *Assilina maior* Heim (equatorial section, Form A) bioclast in sandy well sorted terrigenous quartz with micritic matrix (Locality H, Pl. V, fig. 6) is homotaxial with Sample 22c). It is referred to SMF Type 19, FZ 8 and 9—Tidal Flats of attached platforms near coast platform interior.

Bed I-23—Two samples 23b (Pl. IV, fig. 2) and 23c (Pl. 4, Figs. 3, 4). The sample 23b illustrates reworking of algal fragments and large skeletal bivalves filled with fine-grained micrite and coarse grained peloidal grainstone (Pl. III, fig. 6) by tidal currents in active tidal flat setting. The sample 23c shows reworking and redeposition of partially lithified pond mud with faecal pellets, intraformational microbreccia. The samples from I-23 occurring at the top of Parasequence II indicate supratidal depositional setting with frequent subaerial exposure.

The Early Lutetian Cycle of this parasequence, in contrast to the Late Cuisian Cycle was deposited in the proximal part of the platform interior where tidal currents reworked and redisposited pond sediments, faecal pellets and skeleton remains of the biota as grainstone beds

BASIN CONFIGURATION

The HFB was created as a sequel to collision of the Indian and Asian plates during the Thanetian (~57.8 Ma), this being the age of the oldest sediment (=Kakara) in the HFB. According to Najman *et al*., (1994, Fig. 10a, b) and Virdi (1994, Figs 2a, b) the sea in HFB extended from the Indus Suture, covering the entire width of the Himalaya from north to south. If it were so, there would have been several outcrops of the Subathu right up to the Higher Himalaya at least in the windows. Thus, we consider the Indus and HFB as two separate basins, situated on either side of the rising mountain front (cf. Singh *et al*., 2015). Valdiya (1998), however, regarded the Palaeogene marine transgression from west to east.

During a major epeiric transgression in a vast craton, first the margins are flooded and then the central part (Flügel, 2010). In the HFB also a similar pattern is discernible. The sea transgressed from the western end through the Kalakot area in Jammu; it first invaded the northern and southern margins as revealed by the distribution of Thanetian sediments in these parts. The northern margin is dotted by the coal-bearing to carbonaceous Thanetian outcrops (=Kakara Member) at Kalakot, Subathu, Kog-Kalianpur, Kakara, Kurla and Sairi-Halog (Mathur and Juyal, 2000). At these localities stacks of Early Paleocene (Thanetian) represented by carbonaceous shales and coal interbedded with *Daviesina*-bearing beds are developed (Mathur and Juyal, 2000).

Along the southern margin, the basin floor for the Paleocene sea was constituted of the parautochtonous OLB falling in the present day Sub-Himalaya. This otherwise regionally peneplained area was undulating with 'macro depressions' (*sensu stricto* Dey, 2011). The sea transgressed in the Kamli area near Kalka and progressed towards Tundapathar, and Kharak and Chhamla in the Morni area and further east to Kansar and Sataun

The Thanetian outcrops at Kog-Kalianpur, Kakara, Kurla and Sairi-Halog over the Simla Group suggest extension of minor embayments North/NE of SMK in what now form the part of the Lesser Himalaya. The farthest outcrop in the north are the Subathu outliers over the Nilkanth Limestone of the allochthonous Inner Krol Belt, which has its roots north of the Deoban Antiform. The oolitic facies recorded in the Kakara Member of the Dogadda area (Prasad and Sarkar, 2002) of the Inner Krol Belt represents proximity to the northern limit of the Paleocene Basin, which was possibly demarcated by the Himalayan forebulge, which controlled and caused the formation of the HFB.

In the South, no outcrop of the Subathu Formation so far has been found below the Siwalik sediments i.e., S/SW of the Main Boundary Fault (*sensu stricto*) (= Bilaspur Thrust). The SMK Embayment seems to have been delimited along the Bilaspur Thrust by the Mesoproterozoic OLB, which possibly existed as promontory ridges to which the SMK platform was directly attached.

In the initial period of development, marshy conditions existed in several parts of the basin, which formed source material for coal deposits. In the Kamli (adjoining Kalka) section two thick coal seams (Siddaiah and Kumar, 2007) bear testimony to extensive marshy conditions in this sector (Fig. 6).

Above the coal seam occurs a black pebbly conglomerate with fish remains (Siddaiah and Kumar, 2007), signifying a subaerial exposure. A subaerial break more or less at this stratigraphic level and possibly coeval with the Kalka break, represented by grapestone facies (Bed 11), is present in the Morni sector, which can be dated as the latest Ilerdian. At this juncture, a direct connection seems to have been established between the Kalka sub-basin and Morni embayment (Beds 17-18) before the Middle Eocene.

Comparable litho- and biofacies of the Subathu Formation in the Surajpur and Bilaspur units suggest that these formed a unified basin prior to the thrusting of the Surajpur Unit in post-Kasauli time i.e., post-Burdigalian. The thrusting resulted in truncation of the sequences. For example, the younger part of the Kalka (Kamli) sequence belonging to the Bilaspur Unit (Siddaiah and Kumar, 2007) is preserved in the Kaushlia section of the Surajpur Unit. This is documented in the integrated 'Sequence Stratigraphy' of the succession from the Kakara to the Dagshai Formation (Bhatia *et al*., 2013). The Bilaspur unit being closer to the southern margin of the basin shows relatively shallower facies.

In Jammu sector three 'coal fields' are reported. These from northwest to southeast are: i) Kalakot, ii) Metka and iii) Mohogala. Coal in these areas originated from an angiosperm forest moor and limno-telematic depositional setting in a neritic environment (Singh and Singh, 1995). No similar studies are available for Kalka coal.

Detailed palaeontological and carbonate microfacies studies of the beds associated with coal and tonstein together with radiometric dating of ash beds are required in this crucial section to date these important events, which may form a link to interrelate the Bilaspur and Surajpur units.

The Early Palaeogene belt in the northwest at Jammu and Dharamsala is approximately 80 to 100 km wide. It narrows down to about 10 to 15 km in the southeast near Nahan and further narrows east of Sataun-Dakpathar (Uttrakhand), beyond which it abuts the Yamuna Tear Fault. According to Pal *et al*. (2000) the Delhi-Hardwar-Harsil Ridge delimited the eastern limit of the Early Palaeogene Basin. The Subathu outcrops in the Bidhalana and Pharat windows, situated between Mussoorie and Garhwal synforms, indicate that the Palaeogene belt is concealed below the Inner Krol Belt. The absence of the Palaeogene Belt in foot hill region east of Sataun, is therefore, due to concealment under the allochthonous Krol Belt.

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We dedicate this paper to the memory of the late Prof. B. S. Tewari, a celebrated palaeontologist and former President of the Palaeontological Society of India, who passed away in December 2016 at a ripe age of 93 years.

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