Journal of the Palaeontological Society of India
Volume 58(1), June 2013: 21-38

ISSN 0522-9630

SEQUENCE STRATIGRAPHIC FRAMEWORK OF THE PALEOGENE SUCCESSION OF THE HIMALAYAN FORELAND BASIN: A CASE STUDY FROM THE SHIMLA HILLS

S.B. BHATIA[1], O.N. BHARGAVA[2], BIRENDRA P. SINGH[3] and HARMEET BAGI[4]

[1]441, SECTOR 6, PANCHKULA 134109
[2]103 SECTOR 7, PANCHKULA 134109
[3]CAS GEOLOGY DEPARTMENT, PANJAB UNIVERSITY, CHANDIGARH 160014
[4]5333 PARKHIGHLAND BLVD. #9, CONCORD, CA 94521, U.S.A.
E-mail: sudhashi0903@gmail.com; onbhargava@gmail.com; v_ruh@rediffmail.com; harmeetbagi@aol.com

ABSTRACT

The Subathu Formation (Late Thanetian-Early Priabonian) of the Himalayan Foreland Basin constitutes a 2nd order depositional sequence with a subaerial unconformity at the base and a tidally influenced transitional sequence at the top. Three 3rd order T-R successions - A, B and C are recognized. Succession A (late Thanetian-late early Cuisian) includes seven facies association (FA) and commenced with transgression (TST; A.1), followed by MFS and a condensed section (A.2; P4, SBZ 4-9), carbonate-siliciclastic coarsening upward sequence (A.3-4; HST), tectonically driven deposits (A.5-7), formation of back barrier lagoon with tidal inlet inhabited by sharks, ray fish; poor circulation in the lagoon caused mortality of the vertebrate fauna (A.6) and Early stage base level rise (A.7).

Succession B. (Middle-Upper Cuisian, SBZ 11-12) includes seven FAs, B.1. Minor flooding surfaces, B.2-3. Coarsening upward succession, tidalflat, subtidal setting, B.4. Muddy tempestites, in inner shelf, B.5-6. Several benthic foraminifera and crabs indicate rise in sea level, B.7. Amalgamated sequence of proximal tempestites of shoreface in inner shelf setting.

Succession C. (Early Lutetian-Early Priabonian) constitutes four FAs, C.1. Begins with flooding marked by *Assilina spira abrardi* zone, succeeded by Biotic condensation (C.2) passing into the Passage Bed (C.3; FSST) displaying textural inversion in delta influenced setting, and coastal sand (C.4; White Quartzarenite).

Conformably overlying basal part of the Dagshai Formation comprises three tidally influenced parasequences (D.1-3; LST) separated by two calcrete levels.

The C.4 and D.1 mark tidally influenced transgressive ravinement surfaces.

Keywords: Paleogene, Himalayan Foreland Basin, Sequence Stratigraphy, Subathu Formation, Basal Dagshai, Tidal influence

INTRODUCTION

The well-known adage, "First impression is usually the last impression", seems to hold good for the significant observations and studies of Medlicott (1864) who opined that the Paleogene succession of the Himalayan Foreland Basin, comprising the Subathu, Dagshai and Kasauli formations, constitutes a continuous conformable sequence designated by him as the 'Sirmur Series'. Scores of geologists who have traversed across the succession in the Lesser Himalaya have broadly agreed with Medlicott's observations. These three formations have distinctive lithology and facies, indicating transition from shallow marine through estuarine to fluvial environments.

In the context of the theme of our present work, important contributions were made by Singh, I.B. (1978), Raiverman (1979), Srivastava and Casshyap, (1983), Batra (1989), Bagi (1992), Najman *et al.*, (1994), Singh, B.P. (2003, 2010, 2012, 2013), Singh and Andotra (2000) and Prasad and Sarkar (2002).

Bhatia and Bhargava (2005) presented a regional correlation of the entire suite of the Paleogene sediments from Nepal in the east to the Sulaiman Range in Pakistan in the southwest and also provided palaeontological and other evidences demonstrating biochronological continuity of the Paleogene sequence (Bhatia and Bhargava, 2006). This comprehensive regional correlation provides an integrated picture of the geological history of the entire Paleogene Foreland Basin and briefly discusses the event and sequence stratigraphy during the Paleogene.

A few recent publications deal in detail on the facies and depositional environment of the Paleogene succession. Bera *et al.* (2008, 2010) identified shelf, mixed deltaic lobe, shoreface and subaerial alluvial plain facies associations in the Subathu Formation. Singh, B.P. (2012) argued that the Subathu succession was deposited in a shallow marine setting mainly in subtidal to shoreface areas.

The Himalayan Foreland Basin (HFB) has a vast geographical extent; its sediments display structural and tectonic complications that lack continuous sections in the outcrops. We have, thus, restricted the scale of our sequence stratigraphic framework to a limited geographical extent and availed of lithostratigraphic vertical profile as exposed in Jammu in the northwest and at selected localities in the Shimla Hills.

The present paper on the sequence stratigraphic framework of the Paleogene sequence is a sequel to the earlier publications of Bhatia and Bhargava (2005, 2006, 2008) referred to above and is based on well-established chronostratigraphy of the sequence and the vertical and lateral facies analysis.

STRATIGRAPHIC AND STRUCTURAL SETTINGS

The Paleogene rocks of the HFB, sandwiched between the Siwalik Group in the south along the Main Boundary Fault (*sensu stricto*) and Precambrian rocks in the north along the Main Boundary Thrust extend from Kashmir in the west to Arunachal Pradesh in the east. The absence of these rocks in certain sectors (e.g. Darjeeling) is due to concealment below the overlying thrust sheets rather than to lensing out of the basins as suggested by some workers.

In the Himachal Pradesh sector the Paleogene sequence of the Himalayan Foreland Basin, designated as the Sirmur Group, is divisible into Subathu, Dagshai (=Lower

Dharamsala=Lower Murree) and Kasauli (=Upper Dharamsala=Upper Murree) formations. Of these, the Subathu Formation including the Kakara Member occurs at several tectonic levels (Auden, 1934; Bhargava, 1976; Najman *et al*., 1994). Najman *et al.* (1994) regard the Subathu outcrop resting over the Simla Group at Halog to occupy the highest tectonic level. Auden (1934) and Bhargava (1976), however, consider the Subathu sequence over the Krol and Tal to represent the highest tectonic level. Pre-tectonic restoration of these deposits reveals that the Krol Belt occupied the farthest position with respect to the lowest parautocthonous belt. The HFB Sea, thus, extended far to the north over the extensively peneplaned and folded area (Bhargava *et al.,* 2011) that now forms the Lesser Himalaya, possibly as embayments. In these embayments, the Subathu sequences were deposited over various Precambrian rocks and locally over the Cambrian, Permian and Cretaceous rocks. At many localities a bauxite/laterite horizon intervenes between the Subathu and the older rocks denoting a major subaerial unconformity. Towards the end of the Subathu sedimentation the sea level fell, embayments obliterated and the sea was confined to the main parautochthonous belt where the Subathu Formation is conformably succeeded by the Dagshai and the Kasauli formations.

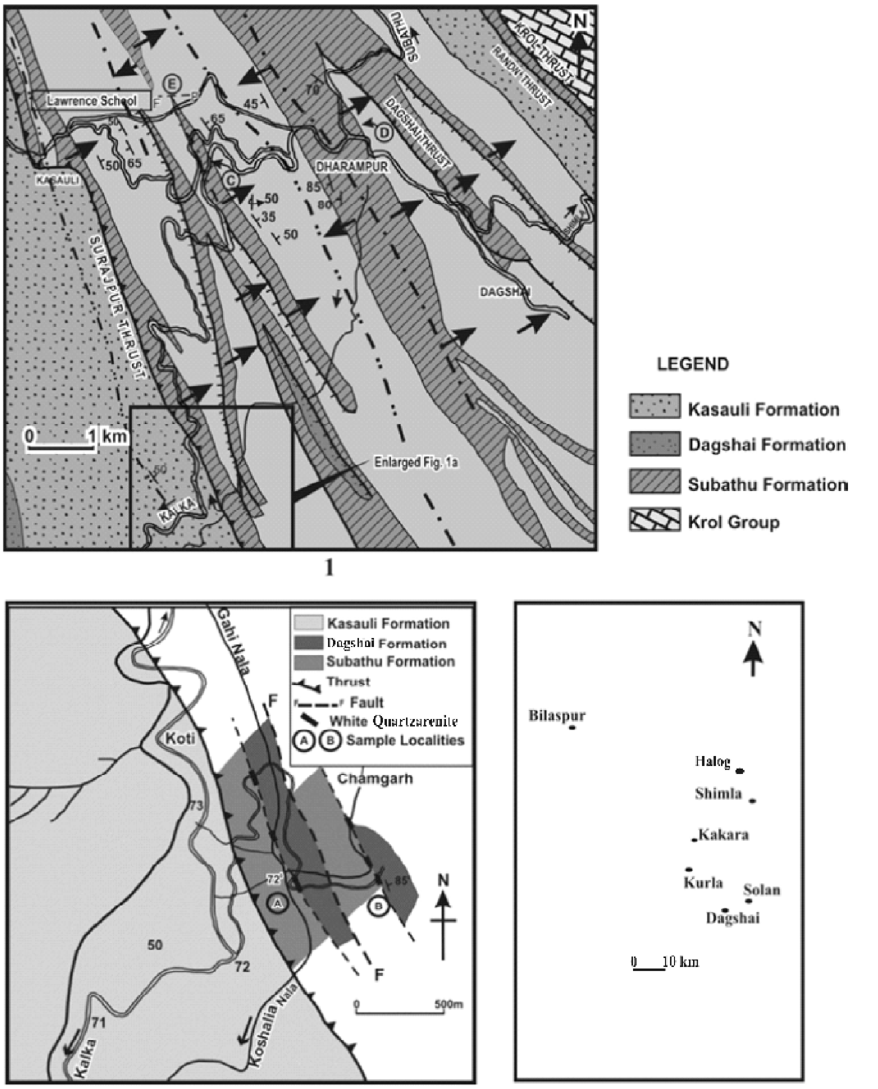


Fig. 1. Geological map of part of the Shimla Hills showing the Paleogene sequence between Surajpur and Ranon thrusts (modified after Bagi, 1992).
1a. Enlarged map of a part of the Paleogene sequence near Koti, Kalka-Shimla Highway (NH 22) showing collection localities A & B (after Bagi, 1992).
1b. Map showing locations of Kakara, Halog and other important localities referred to in the text (after Mathur and Juyal, 2000).

In the Shimla Hills, the Paleogene rocks strike NW-SE and generally dip in NE direction. Three main thrusts traverse the Paleogene sequence (Karunakaran and Ranga Rao, 1979). These thrusts, which divide the Paleogene succession in three distinct units, from south to north are: (i) Bilaspur Thrust, (ii) Surajpur Thrust and (iii) Ranon Thrust. In addition, another thrust viz. the Dagshai Thrust has been identified in the Kalka-Solan section (Fig. 1). The present paper mainly deals with the rock succession between the Surajpur and Dagshai thrusts (Figs. 1-2).

The spatial repetition of the Subathu, Dagshai and Kasauli formations has been largely explained due to folding accompanied by reverse faults. Dubey *et al.,* (2001) suggested that in the first stage early basement faults were formed during the tensional phase. Increased displacement along the basin margin faults led to subsidence of the basin. Mukhopadhayay and Mishra (2005) opined that the spatial repetition is due to thrusting; with increased compression the thrusts propagated into the basin and caused thrust-propagated folds. Baruah *et al*. (2011), based on field data and seismic profile, have proposed a balanced section that shows two-tier decollement system.

SEQUENCE MODEL AND CHRONOSRATIGRAPHIC FRAME WORK

The Kakara-Subathu-Dagshai succession (Bhatia and Bhargava, 2005, 2006), which exhibits a complete transition from marine through tidal to fluvial facies, represents a second order depositional sequence (*sensu* Mitchun, 1977). This depositional sequence has a subaerial unconformity (sequence boundary) at the base—contact of Subathu Formation with the underlying Proterozoic sequences, and a conformable transition zone at the top—between the youngest beds of the Subathu Formation (Facies association C.4, discussed below)—the distinctive white quartzarenite (henceforth WQ) and the overlying tidal-estuarine-fluvial Dagshai Formation at the top.

Several workers (Singh, I.B. 1978; Srivastava and Casshyap, 1983; Singh B.P., 2000) recognised the tidal and estuarine signatures in the basal part of the Dagshai Formation. Bera *et al.,*(2008, Fig. 7) described in the Gahi river section

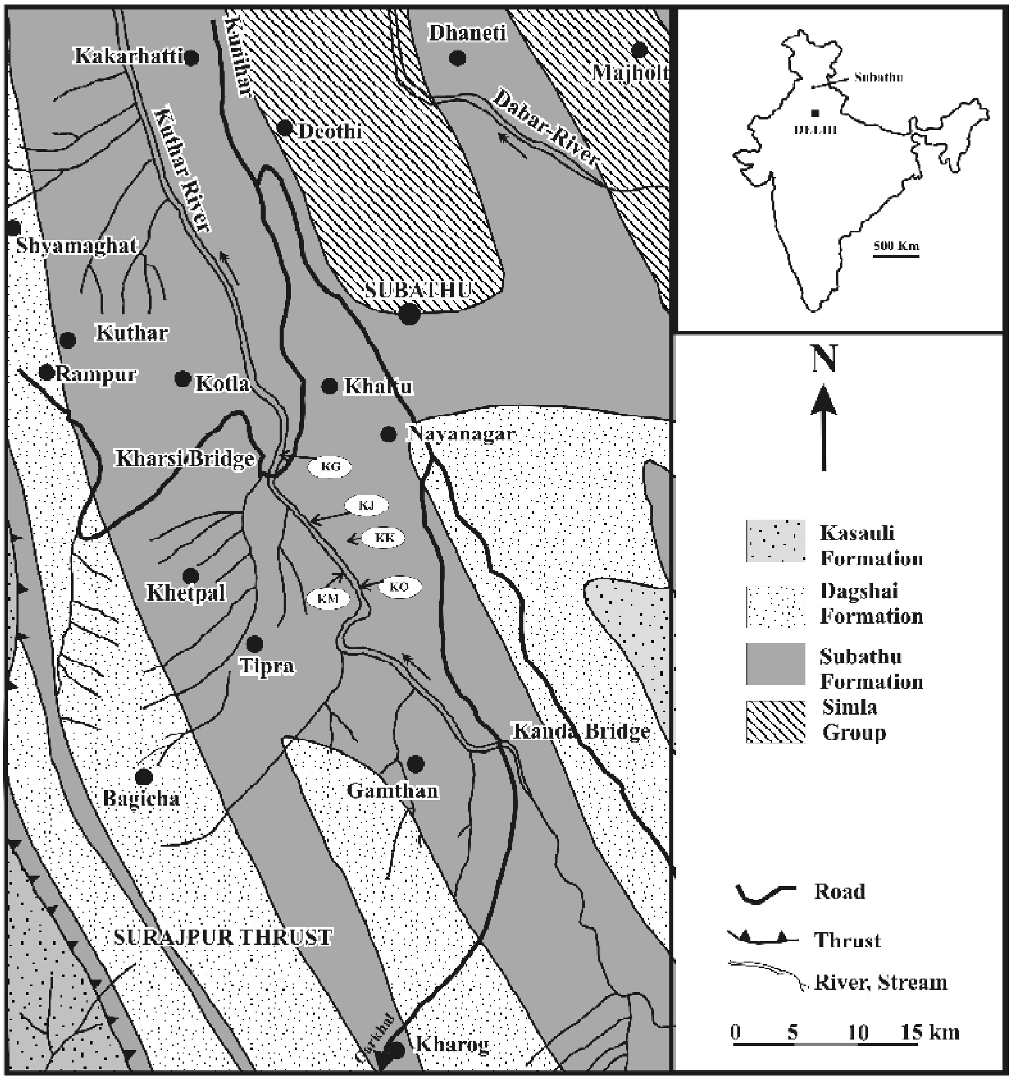


Fig. 2. Geological map of the Paleogene succession around the Subathu type area and the Kuthar river section showing important sample locations of Loyal (1990) (modified after Kishor and Loyal, 2006).

Assilina spira abrardi-bearing limestone as calciturbidite followed by WQ representing upper foreshore to shoreface deposits with a thin intervening grey shale (Facies E_1). This juxtaposition of two contrasting facies is untenable as it violates the Walther's Law of facies. Further, Bera *et al.* (2008) consider *Assilina spira abrardi* as a reworked fossil from the craton. Throughout the Tethyan Basin and also in the Shimla Hills *Assilina spira abrardi* occurs in the faunal zone SBZ 13 (Serra-Kiel *et al.,* 1998), overlying the SBZ 12 (with *Assilina cuvillieri* and *A. laxispira*) (Mathur and Juyal, 2000). The interpretations of Bera *et al.* (2008) are, therefore, untenable and have been rejected by Singh, B.P. (2010) who argued that the early Himalayan Foreland sequences were deposited in shallow marine setting (water depth <55 m) mostly in subtidal and foreshore areas. Singh, B.P. (2010) identified three broad facies in the Subathu Formation, viz. I, II and III. The bedding features studied by us in the Koshalia river section (Fig. 3), a critical study of pre-existing literature and supplemented with field checks have enabled us to construct a comprehensive sequence stratigraphic framework in the present paper. The Subathu Formation represents a second order depositional sequence whose deposition commenced in the Late Thanetian ~56.5 Ma as a regional transgression in the Lesser Himalaya and continued till Late Bartonian-? Early Priabonian (Bhatia and Bhargava, 2005, 2006)—a duration of approximately 17 Ma, and consists of three distinct 3rd order T-R successions designated here as A, B and C in that chronological order. The conformable Dagshai succession, which was deposited in continuity of the Facies Association C.4 in tidal, estuary/fluvial setting is considered as a separate succession and designated as D. Since no complete vertical profile of these succession exists at any one locality, we have computed a lithocolumn (Fig. 4) based on data from Bagi (1992), Mathur and Juyal (2000), Loyal (1990), Kumar and Loyal (2006) and Siddaiah and Kumar (2007, 2008). The composite litholog (Fig. 4) shows the entire Succession A with basal subaerial unconformity (SU). Details of parts of the Succession A are also exhibited at Kakara (Fig. 5). Based on foraminiferal biostratigraphy and other age diagnostic biota, the chronostratigraphic range of Succession A is estimated from the Late Thanetian to late Early Cuisian (*sensu* Schaub, 1981) (~56.5 Ma -51.5 Ma), a duration of approximately 5 Ma, spanning larger foraminiferal benthic zones SBZ-4 to SBZ-10. In the Shimla Hills this sequence is best developed and exposed between Kakarhatti and the Kanda Bridge in the Kuthar river section (Figs. 2, 4) that flows along the trace of axis of the Kuthar anticline—younging in the upstream direction.

This litholog (Fig. 4) also illustrates the facies association of the basal part of the Succession B in continuity with the lithofacies A.7, which it overlies conformably. The Succession B ranges from ~51.5 Ma to 49 Ma—a duration of approximately ~2.5 Ma, representing Middle and Upper Cuisian, i.e. SBZ 11 and SBZ 12. The basal part of the Succession B is represented by facies associations B.1—B.4.

Typical representation of the upper part of the Succession B containing index larger benthic foraminifera of SBZ 11 and SBZ 12 corresponding to the Zone VI of Mathur and Juyal (2000), is best exposed in the upper part of the Koshalia river section (Figs. 1,3). Downstream from the bridge this succession measures 110 m (Fig. 3). This section exposes the upper part of the Succession B (B.5-B.7) and the entire set of beds of the Succession C and part of the Succession D. The Succession C

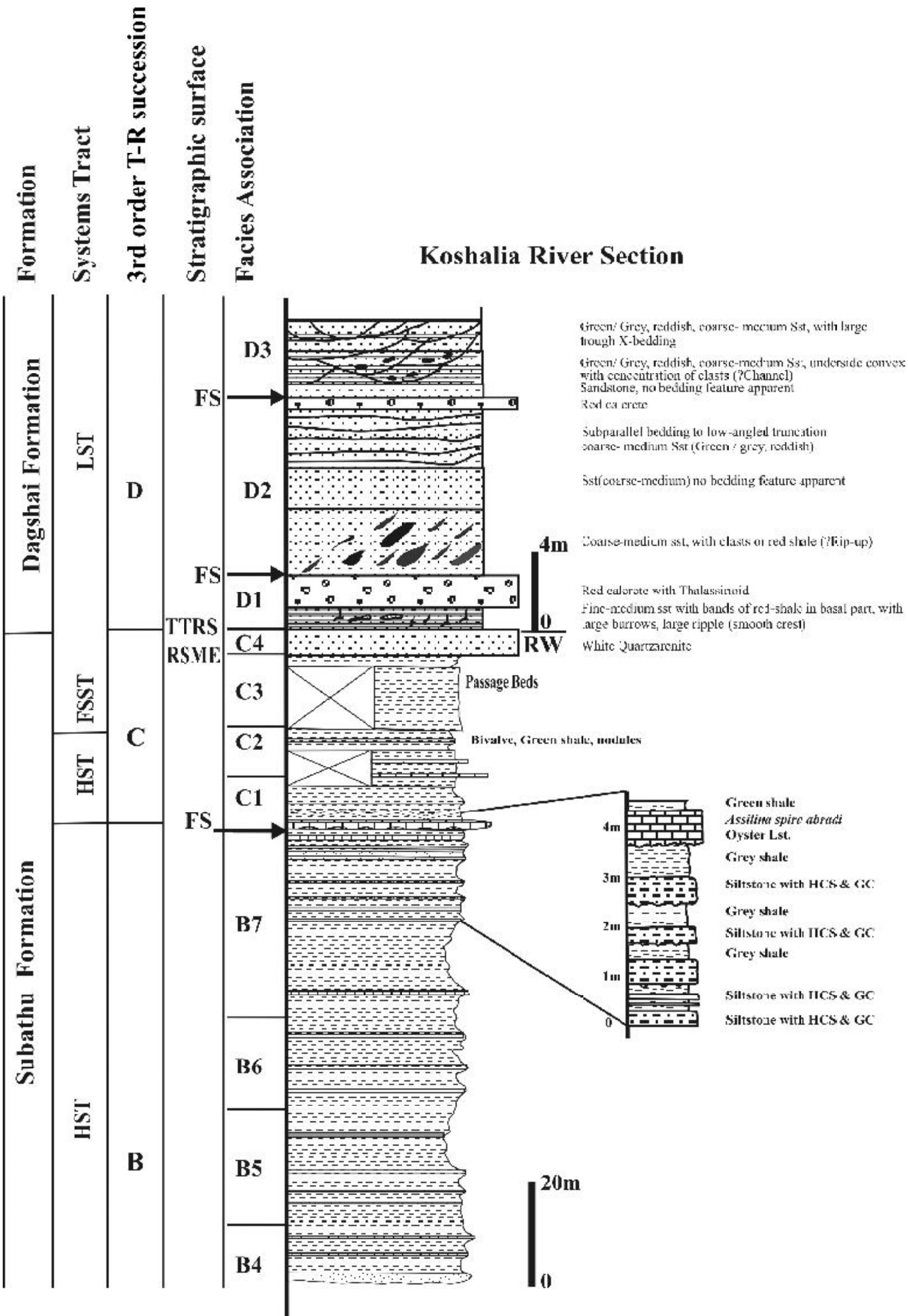


Fig. 3. Lithostratigraphic section of the Successions B (in part), C (Subathu Formation) and part of D (Dagshai Formation) in the Koshalia River section showing sequence stratigraphic surfaces and systems tracts. FS-Flooding surface, FSST-Falling Stage Systems Tract, HSST-Highstand Systems Tract, LST-Lowstand Systems Tract, RSME Regressive surface of marine erosion, RW-Late Highstand Systems Tract regressive wedge, TST-Transgressive System Tract, TTRS-Transgressive tidal ravinement surface.

ranges in age from Early Lutetian (*sensu* Schaub, 1981) to Late Bartonian -?Early Priabonian (~49 Ma-41.5 Ma), spanning a duration of approximately 8.5 Ma. The base of this 110 m section is demarcated by a thrust. The section further downstream, beyond the confluence of the Gahi and the Koshalia rivers, is traversed by several thrusts causing repetition of fossiliferous beds. This tectonically complicated section thus is not included in the present study as it is difficult to tie up top of the facies association B.4 (Fig. 4) of the Kuthar river section with the basal part of the Facies association B.5 of the Koshalia river section (Fig. 3).

SUBATHU FORMATION: FACIES ASSOCIATION, SEQUENCE STRATIGRAPHIC SURFACES AND SYSTEMS TRACTS

Succession A

Facies association A.1: This facies association (a part of Transgressive Systems Tract), constitutes the basal part of the Subathu succession, wherever the unconformable base is exposed, it corresponds to the biostratigraphic Zone I of Mathur and Juyal (2000) (*non*-Danian succession ? Singtali Formation). This facies association, corresponding with Facies Association I of Singh, B.P. (2012), comprises dominantly of carbonaceous shale, coal seams and oyster-bearing limestone (Pl. I, fig. A). This facies is best developed in the Kalakot area (J&K), where it rests over the Mesoproterozoic Sirban Limestone along a prominent subaerial unconformity marked by a bauxite layer in the Jammu area (Singh, B.P. 2003.; Singh and Singh, 1995) and an intervening Chert Breccia (Singh, B.P. 2012)- reinterpreted by Siddaiah and Shukla (2012) as a rhyolite.

Facies association similar to the one at Kalakot has recently been recorded from two localities in the Shimla Hills (Siddaiah and Kumar, 2007, 2008) in the vicinity of Subathu and in the lower Koshalia River. These records are significant in as much as the coal at these localities is interbedded with kaolinised volcanic ash *(tonstein)* and overlain by the biostraigraphically significant foraminifer *Daviesina* (see discussion following facies). This helps to constrain the timing of the volcanic activity in the foreland basin to Late Thanetian. Facies association A.1 also occurs at the base of the Kakara section (Fig. 5), where a 10 m thick

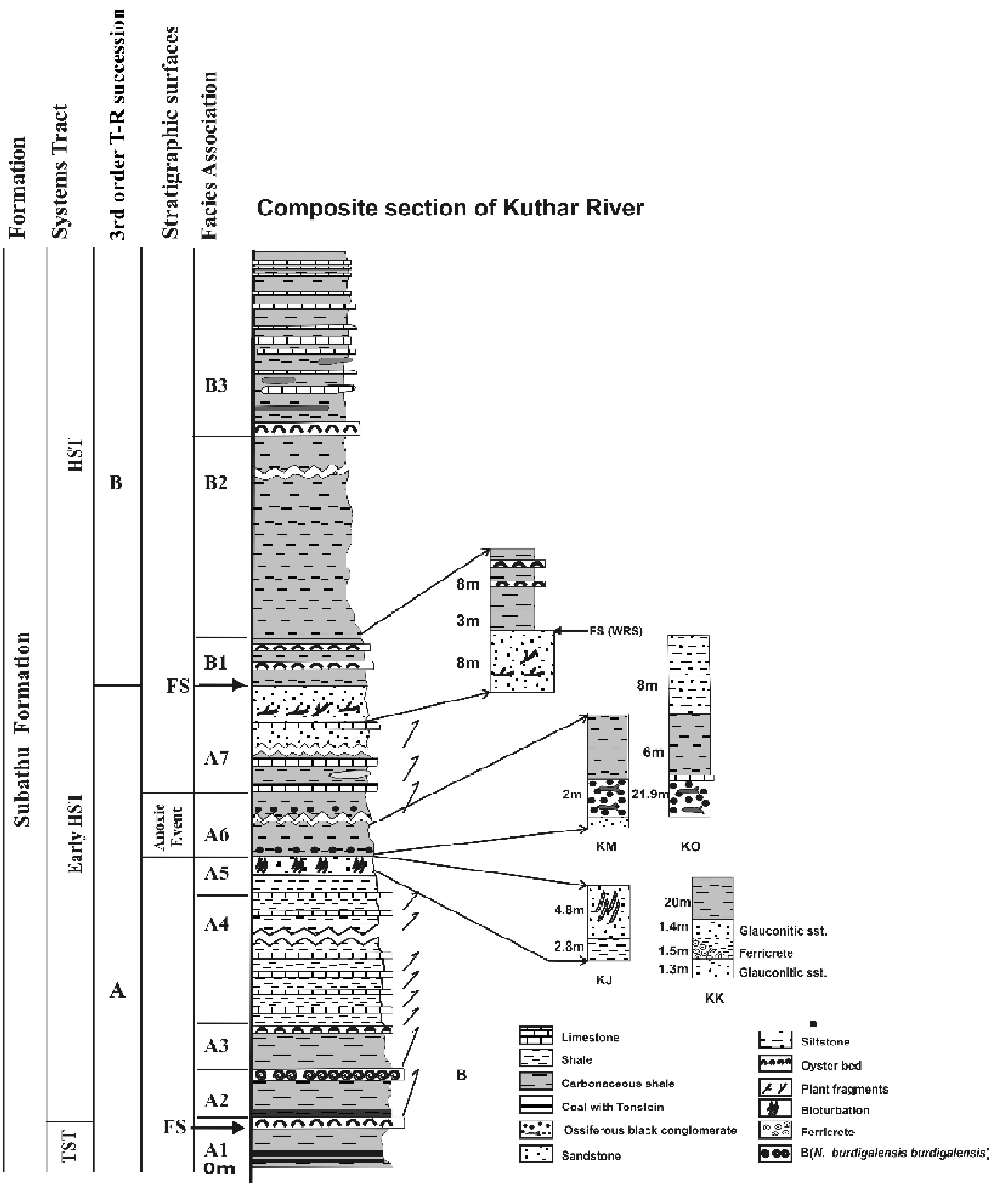


Fig. 4. Composite lithostratigraphic section of the Succession A and part of Succession B of the Subathu Formation in the Kuthar River Section showing stratigraphic surfaces (not to the scale) (based on data retrieved from Mathur, 1978; Loyal, 1990; Kishor and Loyal, 2006; Siddaiah and Kumar, 2008). HST-Highstand Systems Tract, FS-Flooding Surface, TST-Transgressive Systems Tract.

succession of carbonaceous mudstone and limestone (?oyster-bearing) rests with a subaerial unconformity, manifested by an intervening bauxite, over the Neoproterozoic Simla Group.

Interpretation: This facies marks the initial transgression in the Lesser Himalaya during the Late Thanetian and forms part of the Transgressive System Tract (TST). Apart from the significance of volcanism during the transgression, the occurrence of kaolinite in the ash bed as recorded by Siddaiah and Kumar is noteworthy (cf. Ketzer *et al.*, 2003).

The maceral and microlithotype of the coal shows that the plant debris came from the low forest in limno-telematic brackish water estuarine setting (Singh and Singh, 1995). The oyster-bearing limestone heralds beginning of marine environment.

Facies association A.2: The A.1 facies is followed by mixed carbonate and siliciclastic facies (A.2) designated as the "Kakara Facies", since it is best developed at Kakara (*sensu* Kakara Member this paper = Kakara Series, Srikantia and Bhargava, 1967). It corresponds to the Faunal Zone II of Mathur and Juyal (2000) (Fig. 5) and also to a part of Facies Association II of Singh (2012). The occurrence of this facies as detached outliers over different Precambrian basements, which now occupy different tectonic levels as at Halog (see location map 1b), northwest of Shimla and other distant localities inthe Simla and Jammu Hills (Rajpur Formation, Singh and Andotra, 2000), is attributed to their deposition when the Subathu Sea had acquired its maximum extent and paleobathymetry (50 m) and its embayments extended to distant areas.

The A.2 facies comprises fine grained greenish-grey fossiliferous limestone, interbedded with subordinate pale brown shale and mudstone. According to Srikantia and Sharma (1970) limestone which occurs as lenticular bands within green shale is of two types; i) fossiliferous limestone and ii) fossiliferous phosphatic limestone. The phosphatic nodules occur in varying sizes. Pyrite, limonite, haematite and glauconite are the important accessories in the limestone. The shale contains 20-25% P_2O_5.

The bluish limestone is a pelagic packstone/wackestone with scattered pelagic and other benthic foraminifera (Pl. II, figs. A-F) and belongs to SMF type 3 (Wilson, 1975).

Biota: A rich biota is recorded from this lithofacies association (Bhatia and Syed, 1988; Mathur and Juyal, 2000). The important taxa being: *Daviesina garumnensis* (Tambareau), *D. tenuis* (Tambareau), *D. ruida* (Schwager), *D. khatyahi* Smout, *D. langhami* Smout, *D. danieli* Smout, *Lockhartia hunti* Davies, *Rotalia trochidiformis* Lamarck, *Pseudohastigerina*

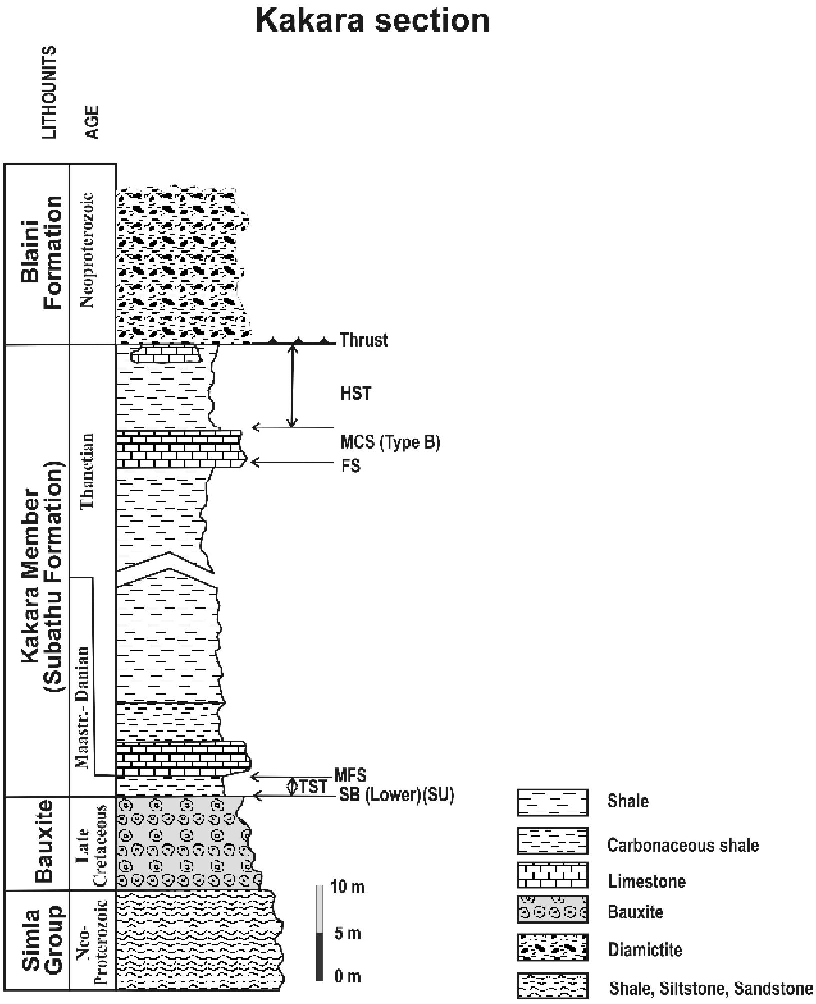


Fig. 5. Lithostratigraphic section of the Subathu Formation in Kakara type section depicting sequence stratigraphic surfaces and system tracts (based on data after Mathur and Juyal, 2000). HST-Highstand Systems Tract, MCS- Mid-cycle Condensed Shell Bed, MFS-Maximum Flooding Surface, SB-Sequence Boundary, SU-Subaerial unconformity, TST-Tragressive Systems Tract.

micra (Cole), *Alveolina minervensis* Hottinger and echinoid spines.

Interpretation: The above mentioned biota comprising scattered pelagic and larger benthic foraminifera and other fossils occurs concentrated in the bluish packstone and sporadically elsewhere in the succession marks the MFS. The 60 m thick succession of biomicritic limestone and green brown shale includes a shell bed rich in biota that ranges in age from Zone P_4 and SBZ 4-SBZ 9, a span of nearly 3.5 Ma, and may represent a stratigraphic condensation (*sensu* Baraboshkin, 2009) and mid cycle condensed shell beds (*sensu* Abott and Carter, 1994; Carter, 1998), marking the transition from TST to Early HST. Though this succession may consist of several hemicycles but overall it represents an HST setting. The A.2 facies association belongs to hemipelagic shallow water type (*sensu* Barbaboshkin, 2009), which accumulated on the middle to outer shelf of submerged platform or uplifts outside the influence of deltaic or various other types of continuous sedimentation (cf. Einsele, 1992) with limited or deficient supply of terrigenous sediments.

Facies association A.3: This facies association overlies the Facies association A.2 and represents a shoaling/shallowing up phase and corresponds to the Zone III of Mathur and Juyal (2000). There is an abrupt and sharp change in the lihologies and the biota from the underlying A.2 Facies association. The Facies A.3 is best observed in the sections at Subathu/Kuthar river section (Figs. 2, 4). In the Kuthar river section, this facies shows two prominent cream to bluish coloured bioclastic packstones separated by siliciclastic shale and siltstone. Shoaling/shallowing up sequences are generally formed due to tidal flat progradation (Miall, 2000).

Biota: This facies association is characterized by the following diagnostic Early Cuisian taxa (SBZ 10):

N. burdigalensis burdigalensis de la Harpe, *N. partschi* de la Harpe, *N. rotularius* Deschayes, *N. subramondi, Assilina spinosa* Davies, *A. plana* Schaub, Dasycladacean algae—*Cyanopolia* sp, *Distichoplax* sp, Echinoid—*Cyamidia numulitica* and several species of ostracoda (for details see Mathur and Juyal 2000). The lower carbonate bed marked B (Fig. 4) is characterized by the first appearance (FAD) of the diagnostic Early Cuisian (*sensu* Shaub, 1981) taxon *Nummulites burdigalensis burdigalensis* (Pl. III, figs. B, Pl. IV. fig. B) and other Early Cuisian (SBZ 10) taxa.

Interpretation: The microfacies association (SMF Type 12) with above mentioned biota suggests formation of the carbonate shoal in a rimmed shallow shelf, close to shelf break, where depths are shallow (<20 m) as in the south Florida shelf (Tucker, 1985; Einsele, 2000). A shoaling/shallowing of sequence (regression) similar to the one from the Facies A.2 (paleobathymetery 50 m) and A.3 (paleobathymetery <20 m) of the Shimla Hills also occurs in the homotaxial Naredi Formation of western Kutch (Chattoraj *et al.*, 2009).

The Facies associations A.4-A.7 are well exposed in the Kuthar River section and extend along the strike for over a distance of approximately 7 km. These facies roughly correspond to the Subzones IIIa, IIIb and IIIc of Mathur (1978, 1979). It is difficult to estimate the precise thickness of these facies associations from the data available as the sequence occurs as disconnected outcrops on either bank of the river (Mathur, 1978; Loyal 1990). These facies associations are described below.

Facies association A.4: This facies association comprises mixed carbonate and siliciclastic facies and corresponds to Zone IIIa of Mathur (1978). The dominant rock types are grey-green shale interbedded with fossiliferous grey limestone rich in oyster and other mollusks and nummulitics. The shale is sporadically glauconitic and also pyritic. The beds are best exposed for a distance of about 3 km along strike between the Bridge B3 and Bridge B2 (Kharsi Bridge) at localities KA to KH Unit II (Fig. 2) (Loyal, 1990).

The rhythmic alternation of carbonate and siliciclastic sediments may be related to base-level changes or changing supply of siliciclastic sediments from the land.

Biota: Besides the occurrence of unidentifiable oyster and the zonal fossils *Cordiopsis subathooensis* and *Turritella subathooensis* d'Archaic and Haime, several large benthic foraminifera like *Nummulites rotularius* Deschayes, *Assilina plana* Schaub—both species restricted to SBZ 10 are also recorded.

There are two records of significant vertebrate fossils from the supposed Zone IIIc (Mathur, 1978) of the oyster-rich limestone that include the oldest global records of sirenians—*Isatherium subathuensis* Sahni and Kumar (1980) and the cetacean *Himalayacetus subathuensis* (Bajpai and Gingerich, 1998)—both new genera and species. In our opinion these vertebrate fossils are from Zone IIIa and not Zone IIIc. The coordinates of the collecting locality given by Bajpai and Gingerich (1998) appear to be erroneous as according to us their locality falls close to the Bridge B2 (Fig. 2) in the vicinity of locality KG of Loyal (1990). Sahni and Kumar's (1980) locality X1 also appears to be close to locality KG (downstream from the prominent meander of the Kuthar River). Bhatia and Bhargava (2005, pp. 116-117) have discussed the age of *H. subathuensis vis-à-vis Pakicetus* from the Kuladana Formation of Pakistan.

Interpretation: Sahni and Kumar (1980) and Bajpai and Gingerich (1998) visualized an open shoreline setting in shallow marine environments, where ancestors of *Ishatherium subathuensis* and *Himalayacetus subathuensis* evolved and thrived. Sahni and Kumar (1980) regarded the presence of "oyster banks all along the high energy strand line environment of the Subathu Sea". We consider the depositional environment of the Facies association A.4, as a wave dominated open shoreline with fluctuating base level.

The termination of the deposition of the Facies A.4 Association coincided with the collision of the Indian Plate with the Kohistan Island Arc, which changed the basinal conditions, as is evident by the overlying facies associations (A.5-A.7) described below:

Facies Association A.5: It corresponds to Zone IIIb of Mathur (1978) and Zone IV of Mathur and Juyal (2000) and is best represented by sections at localities KI to KK (Loyal, 1990) (Fig. 2). At these localities, the sequence is predominantly of red shale with interbedded conglomerate/iron-rich paleosol that rests over the coarse-grained green sandstone with glauconite. The top of the ferricrete may represent a subaqueous transgressive surface and not as a sub-aerial disconformity as the overlying sequence (A.6) is also marine. The red shale at the locality KK followed by limestone consisting of iron oxide and phosphatic nodules becomes micro-conglomeratic at localities KM and KO and may represent a flooding surface. The red conglomerate contains isolated teeth of shark (Loyal, 1990; see detailed list below). The petrography of the red beds at localities KJ and KK comprising splintery shale, conglomerate, oval shaped ferruginous concretions (ferricrete) and limonitic stains on the green sandstone, so well described by Loyal (1990, p. 14), suggests that they belong to 'Type 7' – Shpattered Red Beds of Clark's (1962) field interpretation of Red Beds.

Interpretation: The Facies Association A.5 was deposited under anaerobic conditions in subtidal part of the lagoon that was relatively deeper and barred as compared to the one at Locality KK and contains terrestrial mammalian and reptilian remains. The occurrence of red shale with large chunks of gypsum in the Kuthar River section as at locality (Stop 4, about 50 m downstream from Kharsi Bridge, Kumar and Loyal, 2006, p. 28) points to precipitation of gypsum in the back barrier shallow water lagoon. Overall the facies A.5 represents depositional setting as Early High Stand Systems Tract - Back Barrier Island Lagoon (with occasional subaerial exposure). The depositional event seems to coincide with global LSW TA2-2.7 between ~51.5 Ma-51 Ma.

Facies association A.6: It comprises predominantly greyish black shale with pyrite, grey limestone, black conglomerate, sporadically with coquina and subordinate purple and variegated shale. This facies association is well developed at the adjoining localities KM, KN and KO (upstream of the Kharsi Bridge B2 and *not downstream* as mentioned by Loyal, 1990). At the locality KO (also known as Muddy Boots locality, Kumar and Loyal, 1987), the limestone consisting of iron oxide and phosphatic nodules and becomes micro-conglomeratic.

Biota: A comprehensive list is provided by Loyal (1986), Kumar and Loyal (1987), Loyal (1990) and Blas *et al.,* (2004).

Some of the important taxa are mentioned below: ***Selachi*** (Shark)—8 genera and 10 species (including *Galeocerdo* sp, *Galeorhinus* sp), **Reptilia** *Pristichampsus* sp**;** ***Batoidea*** (Rays and skates)—4 genera and five species including *Subathurura casieri* (n. gen., and n. sp.), *Dasyatis rafinesquei* (n. sp.), ***Holostei***—one genus and 5 species including *Pycnodus bicolestata*; ***Telostei***—4 genera and 4 species including *Kankotodus capettai*.

Interpretation: Deposition of the Facies Association A.6 probably corresponds to the early Cuisian anoxic event which had an impact on the vertebrate fossil fauna. The greyish black shale and black conglomeratic limestone of Facies Association A.6 have the largest and most diverse late Early Cuisian vertebrate fauna in the HFB. These include disarticulated remains of animals from diverse environments and habits such as shallow open marine, coastal waters, bottom dwellers, brackish bays, terrestrial and fresh water. In the Kuthar section these mixed faunal assemblages are usually associated with transgressive lag deposits. Wave action relocated the remains of marine animals in shallow water and beaches; while the river currents and flooding transported and deposited the remains of upland terrestrial mammals and reptiles in the shallow sea. The sedimentation took place in a back barrier lagoon with a narrow tidal inlet with poor circulation leading to mass mortality of the prolific vertebrate fauna of the lagoon. This surmise is based on the fact that the prolific vertebrate fauna of A.6 of the Kuthar river section is not replicated elsewhere in the HFB.

Facies association A.7: This facies association corresponds roughly to the Zone IIIc of Mathur (1978) and Facies II (part) of Loyal (1990). It is best exposed for a distance of approximately 2 km upstream from the prominent meander-loop of the Kuthar River (collecting localities KP-KV; Loyal, 1990) up to Kanda Bridge (Fig. 2). The facies association includes variegated grey, yellow and green shale showing good bedding with intercalated lenticular (cm scale) grey limestone beds, red shale with thin micro-conglomerate and green medium to coarse grained sandstone. The facies association, as exposed along the northeastern bank of the river at localities KS-KT-KU seems to be a deposit of tidal complex and barrier system affected by sea level changes,

Changes in facies are presented in chronological order in Table 1.

Table 1: Interpretation of facies variation and biota of subfacies of Facies Association A.7 due to early rise in sea level resulting in migration (transgressive) of barrier island complex landward. (Based on data from Mathur, 1978; Loyal, 1990; Kumar and Loyal, 2006).

Lithofacies	Depositional environment	Biota
B.1. Green shale with well preserved bedding and cm scale two shell beds.	Subtidal Inner Shelf Succession B	Hiatal concentration of bivalves, fragmentary remains of Selachians
---------------------------------	---------------FS—WRS-----	----------------------------
5. Fine to medium grained green sandstone.	Lower Shoreface	Plant debris
4. Variegated shale	Brackish water marsh to fresh water ponds	*Neocyprides bhatiai* Mathur, *Ilyocypris khoslai* Mathur, *Chara gyrogonites* (Mathur)
3. Finely laminated grey shale, interbedded limestone, mostly lenticular	Tidal flat, subtidal	*Nummulites,* oyster, coquina, *Venericardia* sp
2. Red shale with lenticular micro-conglomerate	Lagoonal mud with channel lag	Fragmentary remains of reptiles and mammals
1. Medium to coarse grained green sandstone	Channel sand (in let)	X

The base level changes during the deposition of A.5-A.7 were tectonically driven as a sequel to the collision of the Indian Plate and the Kohistan Island Arc along the Main Mantle Thrust (Tahirkhelli *et al.,* 1997) coinciding with the global sea level changes LSW ~51.5-50 Ma; TA 2-2.7) during the late Early Cuisian. The collision "resulted in changes in the dynamics of the sedimentary basins and depositional conditions…." (Siddiqui, 2009, p. 455). Restricted marine evaporate trough were formed in Kohat and Potwar in NW Pakistan. Jatta gypsum and salt of Mami Khel were deposited in these restricted troughs (see also Bhatia and Bhargava, 2005). The impact of the collision was less in the Subathu Sub-basin (present area of study), where the Facies Associations A.5-A.7 were deposited in a wave dominated Back Barrier Island lagoon (BIL) complex, which had a narrow inlet. The diverse interactive environments of BIL like salt marshes in back barrier lagoon, inlet delta, the shoreface, tidal flats, small river estuaries and marshes with fresh water ponds are reflected in various rock-types and diverse biota of the facies association A.5, A6 and A.7.

Succession B

The Succession B can be classified into seven facies associations described below. Facies Associations B.1 to B.4 are exposed in the Kuthar river section and B.5 to B.7 in the Koshalia river section.

Facies association B.1: This facies association, which rests conformably over the green sandstone bed of the Facies Association A.7 represents a lag deposit with plant debris, comprises 8 m thick green shale with well preserved bedding and two dark grey centimeter scale shell beds rich in bivalve. The base of this facies association marks a flooding surface.

Biota: Unidentifiable oysters, *Cordiopsis subathuensis* d'Archaic and Haime and bone fragments of selachians.

Interpretation: This facies association represents inner shelf environment with subtidal carbonate shoals.

Facies association B.2: The association comprises approximately 110 m thick monotonous sequence of grey-green shale coarsening upwards with thin intercalations of several siltstone bands, and calcareous shale/limestone couplets. Approximately 8 m from the top of the measured section there is a prominent 3.5 m thick limestone bed rich in oysters and other mollusks.

Interpretation: This facies association was deposited in a tidal flat to sub-tidal setting.

Facies association B.3: This facies (approximately 12 m) includes 3.5 m limestone rich in oyster and other molluscs. Grey shale with thin limestone band couplets form the bulk of the sequence. The limestone bands are rich in *Nummulites rotularius* and *Assilina* sp.

Interpretation: The litho- and biofacies of this facies association indicates deposition in a tidal flat complex, mainly in subtidal setting with oscillation in the base level.

Facies association B.4.: Well developed in the basal part of the section in the Koshalia River section (Fig. 3) this FA comprises 15.5 m of grey to greyish black mudstone with thin (cm scale) bands of siltstone and limestone. The shale is fissile and locally pyritic. The siltstone beds show horizontal burrows. The succession exhibits typical proximal muddy tempestites with hummocky cross stratification with displaced small-sized larger benthic foraminifera as tempestite layers (Pl. IV, fig. C).

Biota : The mudstone contains a rich assemblage of smaller and larger benthic foraminifera (Bagi, 1992). The larger foraminifera include characteristic late Early Cuisian (SBZ 10) taxa including *Nummulites planulatus* Lamarck, *N. praelucasi* Douville, *Assilina placentula* (Deshayes), *Dictyoconides flemingi*, *Trochammina* sp, *Textularia punjabensis* Haque,

EXPLANATION OF PLATE I

A. Coal seam forming the basal part of the Subathu Formation, exposed along an un-metalled road to Kalakot. The first limestone bed appears about 4.5 m above the base; 7 m from base limestone contains foraminifers (Photograph courtesy Dr Kishor Kumar, Wadia Institute of the Himalayan Geology).

B. Distant view of the Red beds and white quartzarenite (Subathu Formation) and the Dagshai Formation, exposed near the bridge along the road from the NH 22 to the Koshalia River section (File photograph by H. Bagi in 1992, presently landslide and thick vegetation have covered the outcrop of the Red beds).

C. Close-up view of the above.

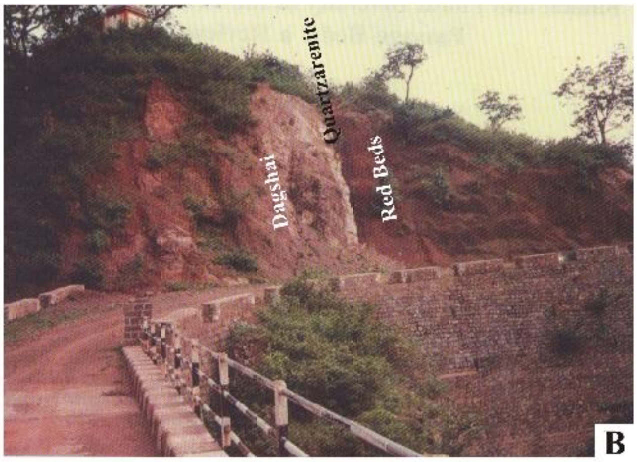
D. Close-up of the underside of the white quartzarenite with trace fossil ***?Ophiomorpha***. Note red shale partings in the basal part of the quartzarenite.

E. Hummocky cross stratification in the siltstone/fine grained sandstone bed occurring below the ***Assilina spira abrardi*** Bed in the Koshalia River section, Facies Association B.7.

F. Gutter cast at the sole of the siltstone bed shown in Fig. E.

Plate I


A



B

C


D


E

F

Triloculina trigonula (Lamarck), *Stainforthia dubia* Haque, *Stianforthia* sp and *Cibicides lobatulus* (Walker and Jacob).

Interpretation : The occurrence of muddy tempestite, pyrite and ecologically significant genus *Stainforthia* are interesting. The extant species of *Stainforthia* occur in a wide range of suboxic/dysoxic/anoxic conditions (Patterson *et al*., 2000). According to Moodley *et al.,* (1997), *S. fusiformis* (Williamson) is an opportunistic species and can colonise areas formerly anoxic. We interpret deposition of this facies in the inner shelf, at or close to fair weather wave base, prone to periodic storms and oxygen-free zone.

Facies association B.5: The overlying 20 m thick succession of mudstone and interbedded limestone (packstone/wackestone) and muddy marl (?mud drapes) contain several species of larger benthic foraminifera, especially abundant *Nummulites* sp. ex gr. *N. tobeleri* (S.B.Bhatia, unpublished data) and an indeterminate species of crab belonging to the genus *Glyphithyreus* Reuss (Pl. V, fig. J).

Interpretation: The random orientation of the crab cephalothorax, chelae and large Nummulites (biconvex >8 mm) suggests their trapping by sediments on a steep shelf slope facilitated by non-calcareous sea-grass or algae.

Facies Association B.6: This facies association, approximately 17 m thick, comprises mudstone with prominent 50 cm thick carbonate buildup towards the top rich in larger foraminifera (Bagi, 1992) has a splintery, marly lithology. This sequence is of middle and early Late Cuisian age (SBZ 11, 12).

Biota: *Assilina laxispira* de La Harpe, *A. cuvillieri* Schaub, *A. placentula grande* Schaub, *A. papillata* Nuttall, FAD of *Nummulites beaumonti* d'Archaic and Haime (Pl. V, figs. A-I) and bryozoan genus *Steginoporella*.

Interpretation: The facies represents a period of decreased terrigenous input and a probable rise in sea level.

Facies Association B.7: This 23 m thick succession represents a coarsening upward succession of greyish mudstone with a number of cream-coloured siltstone and sandstone intercalations indicating slow progradation and gradual increase in siliciclastic input. In the top 3.5 m of this sequence, the siltstone beds show distinct tempestite evidences manifested by gutter cast (Pl. I, fig. F) and hummocky cross stratification (Pl. I, fig. E). This part so far has not yielded any fossil.

Interpretation: The presence of stacked proximal tempestites and intercalated mudstone indicate deposition of the amalgamated sequence in a high energy zone of shore face and inner shelf setting. The sequence may correspond to the regressive phase TA2-2.9 at the Cuisian/Lutetian boundary.

Succession C

Facies association C.1: It is 1-1.5 m thick foraminiferal packstone and represents an abrupt change in facies from the underlying mudstone/silt dominated B.7 Facies. The tests of the dominant large-sized (>8 mm) flat assiline—*Assilina spira abrardi* Schaub are mostly oriented parallel to the bedding plane (Pl. IV, fig. A).

Biota : The biota is dominated by large benthic foraminifers. The following are important taxa (Pl. IV, fig. A): *Assilina spira abrardi* Schaub, *A. hamzehi* Mojab, *Nummulites obesus*, d'Archaic and Haime, *N. lehneri* Schaub, *N. gallensis*, Heim, and *N. praediscorbidus* Schaub, besides oysters.

Interpretation : The *Assilina-Nummulites* packstone represents a within trend flooding surface (cf. Catuneanu *et al.,* 2009). The large size-sized nummulitid taxa thrived in high beach to open marine setting in carbonate shoals (Luterbacher, 1984), indicating deepening of the basin denoted by a flooding surface (FS) during the early Lutetian global highstand TA3-3.2. The facies represents a transgressive deposit with a Transgressive ravinement surface (Pl. IV fig. E).

Facies association C.2: Only about 6 m section of this facies association, which comprises green shale intercalated with hard limestone bands with small disc-shaped assilines *(Assilina* packstone) and calcareous nodules containing fragments of bivalve at certain level, is exposed in the Koshalia River section. However, better exposures of this facies are available at locality B and Kharag (Fig. 1b, Morni Hills, Bagi, 1992). At the latter locality, a 1.5 m thick packstone bed occurs about 12 m above the *Assilina spira abrardi* bed. Approximately 12 m higher up in the succession, occurs a 1.5 m thick sandstone bed (tempestite) with hummocky cross stratification and ripple bedding in the upper part. 3.5 m thick splintery shaly marl caps the sequence.

Biota: The Assilina packstone encloses in abundance *Assilina major* Heim, *A. cuvillieri* Schaub and *A. medanica* Schaub, besides *Nummulites discorbinus*, which occurs commonly in green shale in all sections of C.2 Facies**.**

Interpretation: The hard *Assilina* packstone bed with assilines of Cuisian age, *Assilina major* with *Nummulites discorbinus* (SBZ 14-16) is considered by us as a mid-cycle condensed shell bed (MCS) which includes biotic erosion, redistribution and compaction "during periods of nondeposition" (Baraboshkin, 2009; Hillgaertner, 1998). Deposition took place in a water depth of 20-50 m. *Nummulites discorbinus* signifies SBZ 14-16, *A. medanica* Kirthar age and *A. papillata* Middle Lutetian age. The age of this association is determined by *Nummulites discorbinus*—being the youngest taxon. The older taxa represent reworked fossils derived from older rocks, exposed and immersed during the flooding associated with C.2. The silt with hummocky cross-stratification and ripple bedding at the top represents proximal tempestite deposits.

Facies association C.3: This facies association was earlier described as the Passage Bed (Bhatia and Mathur, 1967). It is made up of variegated sequence of predominantly red shale siltstone and sandstone with local oyster beds and mudstone rich in diverse fauna comprising terrestrial vertebrates, brakish water ostracodes, epifaunal molluscs and nautilus (Bhatia 2000; Bhatia and Bhargava, 2006). Besides, fresh water alga *Pediastrum* and chara *Raskyella peckii* are also known. The carbonate microfacies showing textural inversion (Pl. 4, fig D)

EXPLANATION OF PLATE II

All samples are from the Kakara Facies A.2, Halog (coll. C.M.Ahuja)

Figs. A. Wackestone with ***Hastigerina micra;*** B. ***Alveolina minervensis***, Equatorial section (ES) X 50; C. a. ***Daviesina garumnensis*** ES X45; b. Unidentifiable planktonic foraminifera X45; D. ***Daviesina danieli* X45**; E. ***Daviesina ruida*** ES X50: F. ***D. tenuis*** AS X75.

Plate II

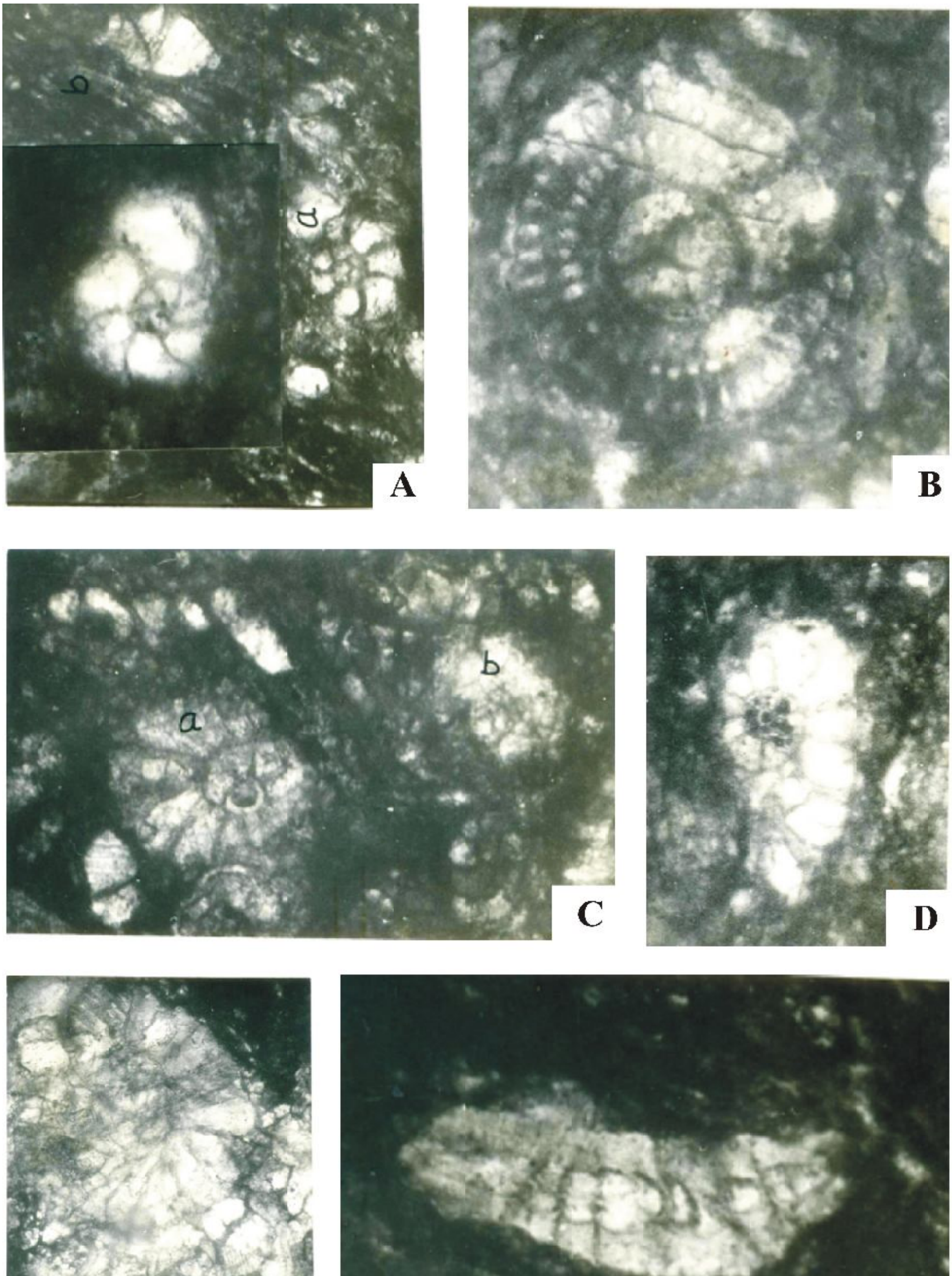
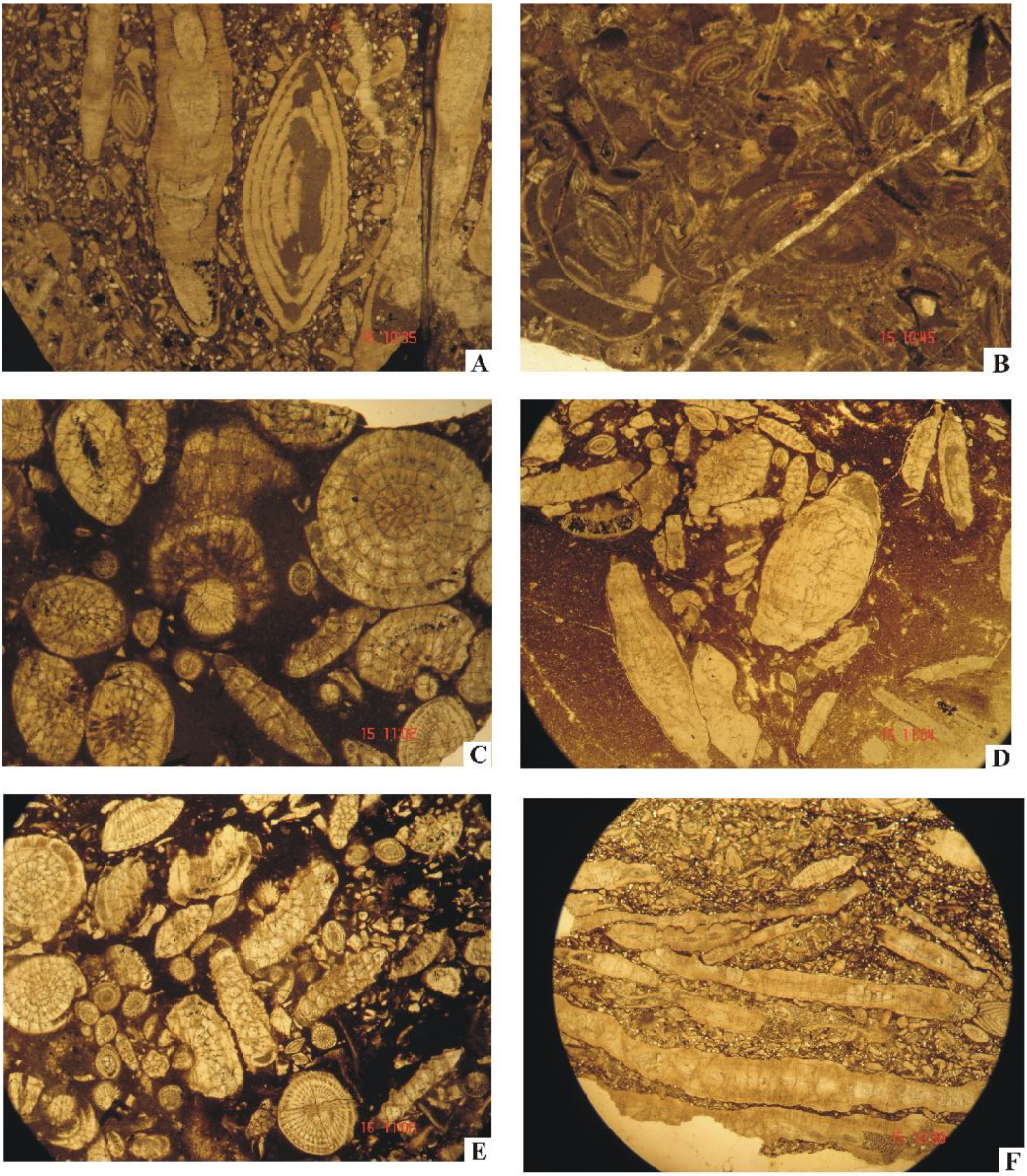


Plate III

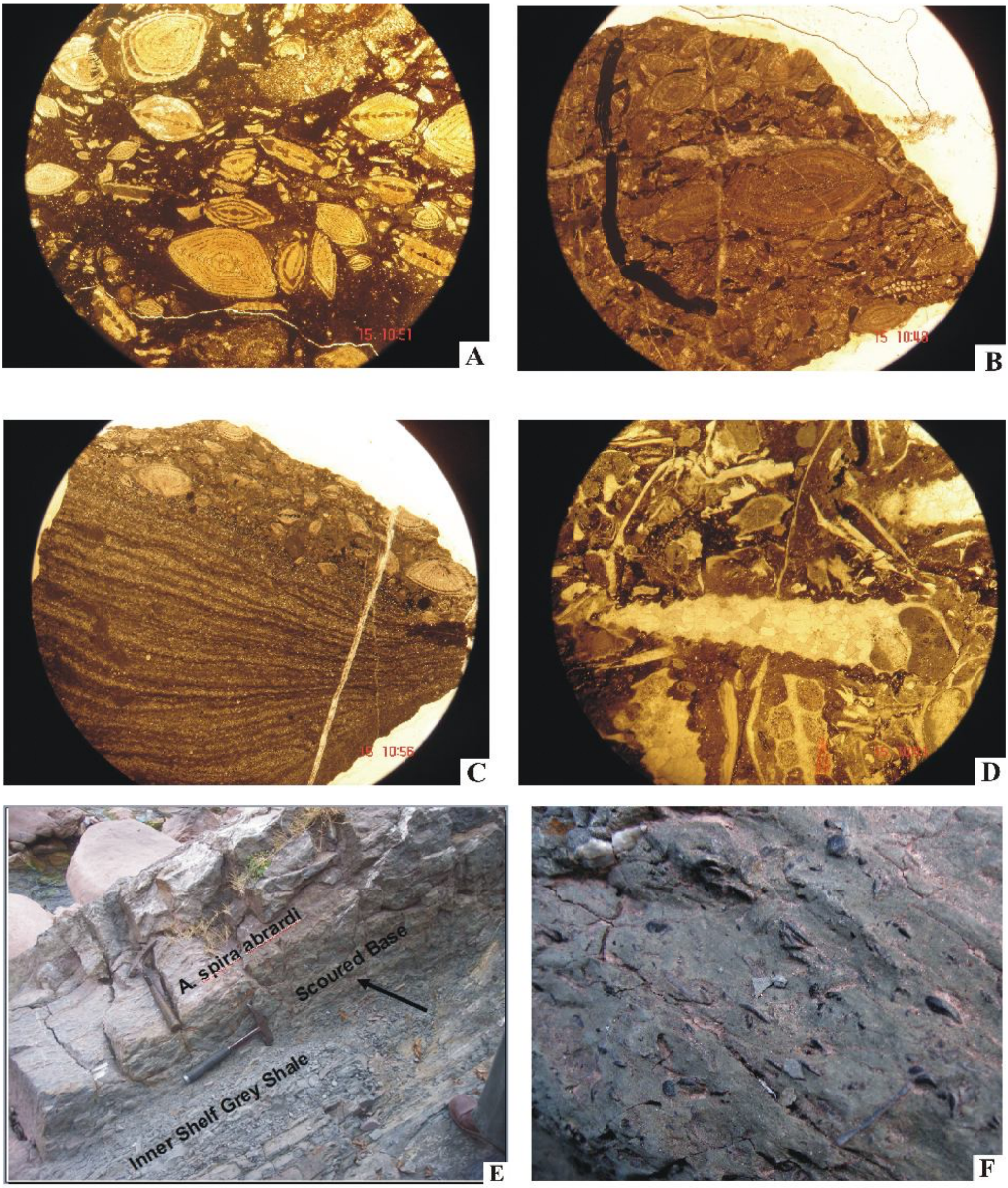


BHATIA, BHARGAVA, SINGH AND BAGI

EXPLANATION OF PLATE III

All samples (except B) are from the Koshalia River section (Coll. HB) Figs. A. ***Assilina spira abrardi*** bed with ***Nummulites lehneri***, FA C.1; B. Well packed packstone showing *N. burdigalensis* Bed, Sample F_3, Kuthar River Section; C & E. ***Assilna*** packstone showing equatorial, random and commuted (E) sections of ***A. major***. FA C.2; D. Packstone showing equatorial and random sections of ***A. cuvillieri***, FA B.6; F. Axial sections of ***Assilina spira*** *abrardi*, Form A, Facies C.1.

Plate IV

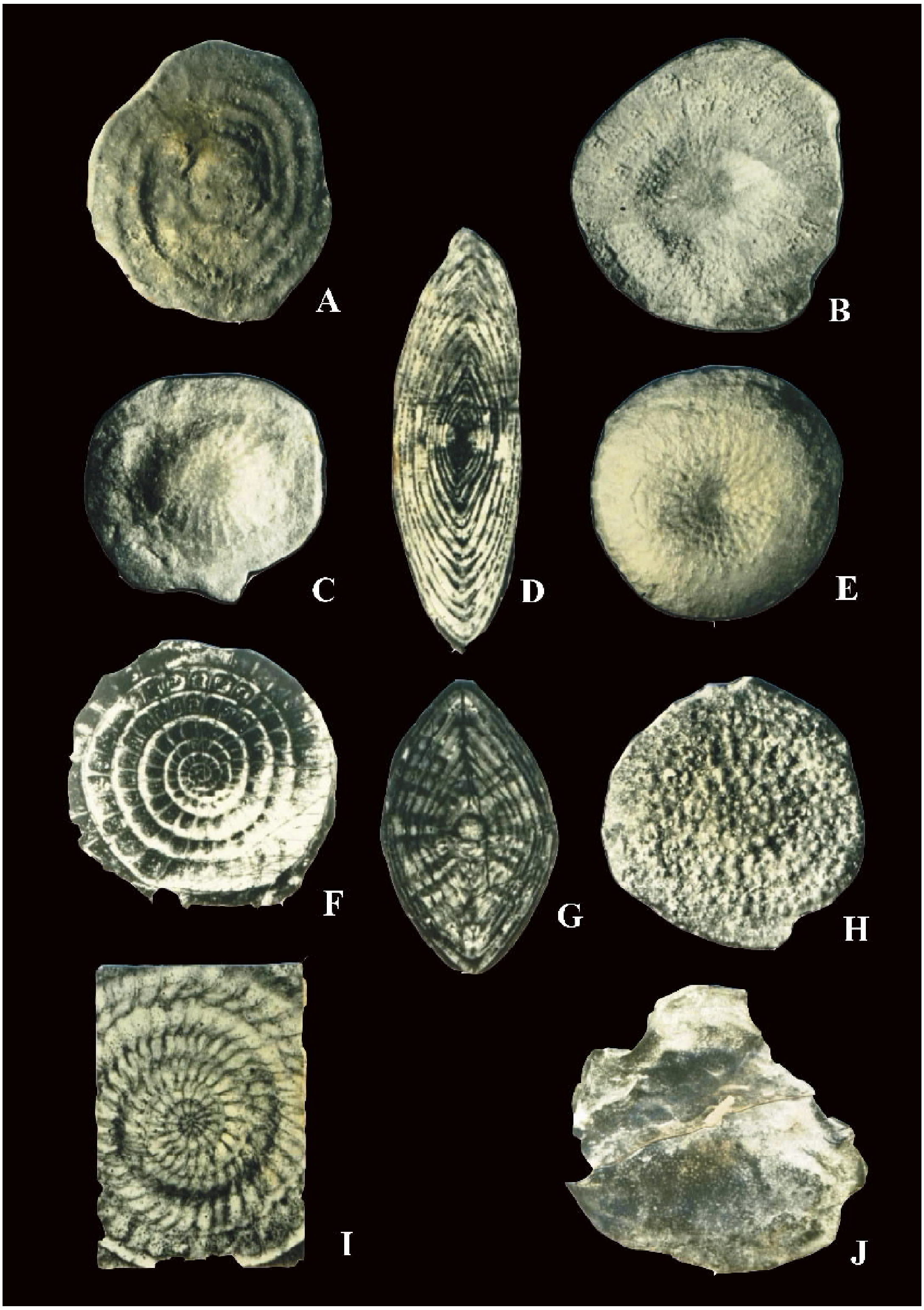


BHATIA, BHARGAVA, SINGH AND BAGI

EXPLANATION OF PLATE IV

Figs. A. ***Nummulites*** and ***Assilina*** packstone/grainstone, ***A. spira abrardi*** Bed sample with *A. hamzehi* and ***N. praediscorbinus*** (Sample F.18, Subathu type area, Coll. HB); B. Foraminifera and algal packstone showing ***N. burdigalensis burdigalensis*** and dasycladacean alga (Sample F.3, Subathu type area, Coll. HB); C. Photomicrograph of siltstone/fine sandstone showing hummocky cross stratification and a tempestite layer of assorted foraminifera in FA B.4, Koshalia River Section. X5; D. Packstone showing coated and worn bioclasts (textural inversion SMF 10, locality B, Coll HB) in FA C.3, X5; E. ***Assilina spira abrardi*** Bed showing scoured base the surface marks the transgressive ravinement surface and MFS, FA C.1, Koshalia River Section; F. Rip-off shale clasts in the Dagshai Sandstone. (FA D.2), Koshalia River Section. X5

Plate V



BHATIA, BHARGAVA, SINGH AND BAGI

EXPLANATION OF PLATE 5

Figs A. ***Assilina laxispira*** (EV)- D=11.1; B. ***A. papillata*** – EV-D=11.1, C. ***A.Cuvillieri*** Ev – D5.8; D. ***Nummulites obesus*** AS, Form B- D=11.7; E. ***A. placentula grande*** EV-D=7.2; F. ***A. Cuvillieri*** ES-D=4.5; G. ***Nummulites toberi*** AS Form A D=3.3; H. ***A. medanica*** EV Form A-D=4.5; I. ***N. praelucassi*** ES-D=2.3; J. ***Glyphithyreus*** X1.

includes i) gastropod packstone made up of turreted gastropod with a few ostracodes in dark homogenous micritic matrix and ii) bioclastic packstone/grainstone (SMF 12, Wilson, 1975) containing foraminifera, bryozoa, bivalves, subrounded to rounded litho and bioclasts in fairly well bedded layers of micrite.

Interpretation: The extremely diverse assemblage of biota (see Bhatia, 2000) makes it difficult to interpret the depositional setting. However, admixture of fresh water, brackish, coastal and high energy fauna with normal and marine fauna suggests deposition in a river-dominated system in a deltaic setting. The deposition took place during late Highstand Systems Tract.

Facies association C.4: The facies association termed here as WQ and is classified as the youngest bed of the Subathu Formation. Several previous authors designated it as White Sandstone and classified it with the Dagshai Formation (Auden, 1934; Srivastava and Casshyap, 1983; Bhatia, 2000, Bera *et al*., 2008). This facies association is not exposed in the Kohsalia river valley; presently its contact with the underlying red beds (Passage Beds) is best observed in the road section above the valley. This too, however, is obscured by vegetation and thick debris. However, in 1992 an excellent section could be observed along the road (Pl. I, figs. B-C). At the base as well as upper part of the white quarzarenite occur thin red shale partings (Pl. 1 Fig. D). Trace fossil ?*Ophiomorpha* also occurs at its base (Pl. I, fig. D). The WQ is fine to medium grained, shows parallel to sub-parallel bedding and ripple cross lamination. Petrologically, the arenite comprises clean-washed quartz, fragments of chert and chalcedonic silica. Approximately 70% of quartz grains are angular to subrounded and moderately to well-sorted. Rare fragments are of glauconite and pisolitic laterite. The heavies are constituted of zircon, rutile and magnetite (Srivastava and Casshyap, 1983).

The nature of the contact of this facies with the Dagshai Formation is discussed in the following pages.

Interpretation: The WQ seems to have had a complex sedimentological history (cf. Bera *et al.,* 2008, 2010). It is beyond the scope of this paper to confirm whether Bera *et al's.,* (2008, 2010) interpretations are valid regionally. More area needs to be examined to work out the Sedimentology of WQ in space and time. However, in view of its extensive development in the Shimla Hills, the WQ is broadly interpreted to be a coastal sand barrier deposit at the shore face. The contact of WQ with the overlying Dagshai sediments seems conformable. However, equivalent of this contact in the Kohat section of Pakistan is unconformable (Bhatia and Bhargava, 2005).

TRANSITION FROM SUBATHU TO DAGSHAI AND SEQUENCE STRATIGRAPHIC SURFACES

The stratigraphic position as also the age of the prominent WQ (i.e. White sandstone of Auden, 1934), which forms the youngest unit (C.4) of the Succession C is controversial (see Bhatia and Bhargava, 2005, 2006, 2007, 2008). Bhatia and Mathur (1965) considered this unit together with the underlying red and green shale (C.3) as the “Passage Beds” between the Subathu and the Dagshai formations (for fuller discussions refer Bhatia, 2000). The present study on sequence stratigraphy favours its classification with the Subathu Formation. The palaeontological and field evidences demonstrate a biochronological continuity from the marine Subathu (Late Thanetian- Middle Lutetian) through the Passage Beds (Late Lutetian to Late Bartonian/?Early Priabonian; Bhatia and Bhargava, 2006). Subsequently Bera *et al*., (2008) without any cogent evidence interpreted a ?3 Ma break between the Subathu and the Dagshai formations. More recently Jain *et al*. (2009) based on fission track date of detrital zircons suggested a >10 Ma gap between these two formations. Based on the studies of diagenetic changes in the Dagshai sediments, Raiverman (2002, 2006, 2007) observed that these sediments experienced heating up to 200-300^0 C. Thus the >10 Ma hiatus concluded by Jain *et al.,* (2009) on the premise that the Dagshai sediments never reached the annealing temperature of zircons in the range of 175-250^0 C is questionable.

Our present work on the sequence stratigraphy (see below) provides additional evidences to support a continuous deposition from the marine Subathu Formation to the lower part of the Dagshai Formation (Pl. I, fig. D). The most significant facies change is between the Red Beds (C.3) and the WQ (C.4). This prominent stratigraphic surface has a strong physical expression and when viewed from a distance appears sharp (Pl. I, fig B), but a close examination reveals the presence of the red shale partings in the basal as well as upper part of the WQ (Pl. I, Fig. D). The trace fossil ?*Omhioporpha* occurs at the base of the WQ in the Koshalia river section (Pl. I, fig. D). This surface represents a Regressive Surface of Marine Erosion (RSME) (*sensu* Plint, 1988).

DAGSHAI FORMATION: FACIES ASSOCIATION, SEQUENCE STRATIGRAPHIC SURFACES

The Dagshai Formation rests over the WQ along a transgressive tidal ravinement surface (TTRS) (*sensu* Catuneanu, 2006). For the purpose of this study we examined only 16 m of the basal part of the Lower Dagshai Succession (D) of the Koshalia river section. This 16 m succession is divisible into three parasequences designated as D.1, 2 and 3, separated by two levels of paleosol (calcrete) representing periods of non-deposition.

Facies association D.1: It is composed of following sequence in descending order:

1d. 0.94 m thick red calcrete horizon with light grey *kankar* and doubtful *Thalassinoides,*

1c. 0.60 m sandstone greenish sandstone, free of bioturbation and any partings. Bedding features include parallel to subparallel bedding, rare large smooth crested ripples followed by mottled zone due to bioturbation. Minor pebbly lenses in upper part,

1b. 0.60 m sandstone with red shale/clay partings that pinch along the strike,

1a. 2 m fine to medium grained greenish sandstone with reddish tinge, with partings of red shale and fairly large size burrows. The bioturbated parts are filled with white sandy material, finer than the host rock. Rare tests of foraminifera *Linderina* occur in its basal part (in Bhatia and Bhargava, 2006),

Since A, B and C horizons are not clearly definable; the calcrete horizon is considered to be a partially pedoginised/ truncated surface.

Interpretation: This part of the sequence is regarded to represent coastal sandflat deposits with scattered mudflats that were frequented by crabs. Large-sized burrows seem to be substrate controlled. A prolong exposure led to formation of red calcrete in a warm-arid climate. This part of sequence shows evidence of gradual progradation of the coast. Ranga Rao, (1986) estimated 10 Ka? for the formation of calcrete in the Lower Murrees (=Dagshai Formation).

Facies association D.2: It has the following sequence:

2d. 1 m thick red calcrete,

2c. 2.2 m thick coarse to medium grained greenish/grey-reddish sandstone showing subparallel bedding and low angle truncation,

2b. 1.5 m Coarse-medium greenish sandstone,

2a. 2.2 m thick, coarse to medium grained greenish sandstone with distinct red tinge, with subrounded to subangular clasts of red shale (Pl. IV, fig. F)

Interpretation: The 2.2 m sandstone marks a flooding event in a coastal part over a partially pedogenised surface, the currents of invading sea ripped off clasts from the underlying red shale (Pl. IV, fig. F). The 1.5 m sandstone possibly marks the most important flooding surface of this cycle (though still very shallow), followed by progradation of sandflat environment with deposition of subparallel bedded sandstone. Further fall in the sea level caused the formation of the second level of the calcrete.

Facies association D.3: The sequence of this parasequence is:

3c. >2 m greenish, grey, red-tinged, coarse-medium sandstone with large-scale cross-bedding and trough cross-bedding.

3b. 2.2 m greenish, grey, red tinge, coarse-medium sandstone (2.5 m) constitutes this cycle. Bottoms of several beds are convex; along the trough clasts of red shale, green siltstone/sandstone are concentrated.

3a. 0.80 m sandstone.

Interpretation: The unit represents another flooding event restoring sandflat conditions with channels and channel lag.

Overall, the sedimentation of the Lower Dagshai sediments referred above took place in a coastal 'Low Accommodation Setting' with multiple palaeosol and flooding surfaces (= Tidal Transgressive Surface of Catuneanu, 2006, p. 202, 253). Presence of tidal bedding features and occurrence of marine foraminifera in basal part of the Dagshai point to the existence of coeval shore line during the Subathu-Dagshai transitional period. As the seismic data are not available it will be hazardous to comment on the distance of the shoreline from the Paleogene outcrops.

The bedding features and sedimentologic interpretations recorded in the present paper are in broad harmony with those made earlier by Singh, I.B. (1978), Srivastava and Casshyap (1983) in the Shimla Hills and by Singh and Singh (1995) in the Jammu area.

CONCLUSIONS

1. Biochronologic and lithostratigraphic continuity from the Subathu to the Dagshai was documented by Bhatia and Bhargava (2005, 2006, 2008). This is further supported by the Sequence Stratigraphy of the Subathu Formation to the Dagshai showing a gradual evolution of the basin with no significant break.
2. The index fossil-bearing horizons occur in perfect stratigraphic order, which are globally correlatable. The idea that these beds represent calciturbidites and have no stratigraphic bearing is untenable. The silty/sandy beds show hummocky cross-stratification and gutter cast. There is no evidence of turbidites in the Subathu sequence.
3. Our study of litho- and biofacies suggest that that maximum paleobathymetry of 50 m is shown by the Kakara facies, the remaining Subathu sequence was much shallower.
4. The Facies Associations A.4 and D.1 mark tidally influenced transgressive ravinement surfaces indicating early base level rise in LST

ACKNOWLEDGEMENTS

We deem it a great privilege to have been invited by the Palaeontological Society of India, Lucknow to contribute this paper in a volume to honour Prof. B.S.Tewari. A nascent draft abstract of this paper was critically reviewed by Dr S. K. Biswas (Mumbai) about two years back. The present manuscript is considerably improved as result of thorough and critical review by Prof. I. B. Singh. We are grateful to Dr Kishor Kumar, Wadia Institute of the Himalayan Geology, Dehradun and Dr B.P. Singh of Banaras Hindu University for generously providing literature, the former also provided a copy of the field photograph of the coal seam outcrop near Kalakot. Thanks are also due to Dr Ritesh Arya for arranging the logistics for field work and to Prof. Rajiv Patnaik, Panjab University and Shri Ram Ratan, Geological Survey of India for photomicrography.

REFERENCES

Abott, **S.T**., and **Carter, R.M.** 1994. The sequence architecture of mid-Pleistocene (0.35-0.95 Ma) cyclothems, Castlecliff section, Newzealand: Facies Development during a period of known orbital control on sea level cyclicity, p. 367-394. In (Eds. De Boer, P.L. and Smith, D.G.), *Orbital Forcing control on sea level cyclic sequences*. International Association of Sedimentologists, Special Publication, **19**: 367-394.

Auden, J.B. 1934. The geology of the Krol Belt and associated formations. *Records of the Geological Survey of India*, **67** (4): 357–454.

Bagi, H., 1992. *Contribution to the ostracodes and smaller foraminifera of the Subathu Formation of parts of Shimla Hills region*. Unpublished PhD Thesis, Panjab University, Chandigarh, 265pp.

Bajpai, S and **Gingerich, S.** 1998. A new Eocene archaeocete (Mammalia, Cetacea) from India and the time of origin of whales. *Proceedings of the National Academy of Sciences, USA*, **95**: 15464–15468.

Baruah, M. and **Joshi, G**. 2011. Section balancing in the area south of Solan, H.P., India for reinforcing subsurfacing model related to ongoing Hydrocarbon Exploration in the area. *Journal of Indian Association of Sedimentologists*, **30**(1): 1-10.

Batra, R.S. 1989. A reinterpretation of the geology and biostratigraphy of the Lower Tertiary formations exposed along the Bilaspur–Shimla Highway, Himachal Pradesh, India. *Journal of the Geological Society of India*, **53**: 503–523.

Bera M.K., Sarkar, A., **Chakraborty, P.P**., **Loyal, R.S** and **Sanyal, P**. 2008. Marine to continental transition in Himalayan foreland. *Bulletin Geological Society of America*, **120** (9/10): 1214–1232; doi: 10.1130/B26265.

Bera, M.K., A. Sarkar, A., Chakraborty, P.P., Ravikant, V. and **Choudhury, A.K.** 2010. Forced regressive shoreface sandstone from Himalayan foreland: Implications to early Himalayan tectonic evolution. *Sedimentary Geology*, **229**: (4): 268-281 doi:10.1016/j.sedgeo.2010.06.013.

Bhargava, O.N. 1976. Geology of the Krol Belt and associated formations: a reappraisal. *Memoirs Geological Survey of India*, **106**(1): 167-234.

Bhargava, O.N., Frank, W. and **Bertle, R.** 2011. Late Cambrian deformation in the Lesser Himalaya. *Journal of Asian Earth Sciences*, **40**: 201–212.

Bhatia, S.B. 2000. Faunal and floral diversity in Subathu–Dagshai Passage Beds: a review. *Himalayan Geology*, **21**: 87–98.

Bhatia, S.B. and **Bhargava, O.N.** 2005. Regional correlation of the Paleogene sediments of the Himalayan Foreland Basin. *Palaeontological Society of India (Special Publication)*, 105–123.

Bhatia, S.B. and **Bhargava, O.N.** 2006. Biochronological continuity of the Paleogene sediments of the Himalayan foreland basin:

Paleontological and other evidences. *Journal of Asian Earth Sciences,* **26:** 477–487. doi:10.1016/j.jseaes.2004.10.007.

Bhatia, S.B. and **Bhargava, O.N**. 2008. Reply to Y. Najman, 2007, Comment on "Biochronological continuity of the Paleogene sediments of the Himalayan Foreland Basin: Paleontological and other evidences" – Bhatia, S.B., Bhargava, O.N., 2006. Journal of Asian Earth Sciences 26, 477–487. *Journal of Asian Earth Sciences*, **31**: 87-89.

Bhatia, S.B. and **Mathur, N.S.** 1965. On the occurrence of pulmonate gastropods in the Subathu–Dagshai passage beds, near Dharampur, Simla Hills. *Bulletin of the Geological Society of India,* **2** (2): 33–36.

Bhatia, S.B. and **Syed, A**., 1988. Early Tertiary Microfossils from the Lesser Himalaya with Particular Reference to the Thanetian–Ypresian Boundary, *National Seminar on Stratigraphic Boundary Problems in India. Jammu University, Jammu,* pp. 48–49 (Abstract).

Blas, X.P., **Loyal, R.S., Schleich H.H.** and **Agrasar, E.C**. 2004. Pristichampsine cranial remains from the basal red bed facies of the Subathu Formation (Himachal Pradesh), India and some paleobiogeographic remarks. *PalArch Vertebrate Palaeontology*, **3**: 1-8.

Boraboshkin, E.Y. 2009. Condensed Sections: Terminology, Types, and Accumulation Conditions. *Moscow University Geological Bulletin*, **64** (3): 153-160.

Boyd, R., Diessel, C.F.K., Wadsworth, J., Leckie, D., and **Zatlin, B.A**. 1999. Development of non-marine sequence stratigraphic model. *American Association of Petroleum Geologists Annual Meeting Texas, Official Program,* A15

Carter, R.M. 1998. Two models: global sea-level change and sequence stratigraphic structure. *Sedimentary Geology*, **122**: 23-36.

Catuneanu, O. 2006. *Principles of Sequence Stratigraphy*. Elsevier, 375p.

Catuneanu, O., V. Abreu,V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M. Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen O.J,. Miall A.D., Neal, J.E., Nummeda, D., Pomar,L l., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., and **Winker, C**. 2009. Towards the standardization of sequence stratigraphy. *Earth-Science Reviews*, **92**(1-2): 1-33.

Chattoraj, S.L., Banerjee, S. and Saraswati, P.K. 2009. Glauconite from Late Paleocene-Early Eocene Naredi Formation, western Kutch and their genetic implications. *Journal of Geological Society of India*, **73**(4): 567-574.

Clark, J. 1962. Field interpretation of red beds. *Bulletin Geological Society of America*, **73** (4): 373-420

Dubey, A.K., Misra, R., and **Bhakuni, S.S.** 2001. Erratic shortening from balanced cross-sections of the western Himalayan Foreland basins: causes and implications for basin evolution. *Journal of Asian Earth Sciences*, **19**: 765-775.

Einsele, G. 1992, *Sedimentary basins: Evolution, facies, and sediment budget*: Germany, Springer-Verlag.

Flügel, E. 1982. *Microfacies of Limestones*. Springer, 163p.

Hillgaertner, H. 1998. Discontinuity surface on a shallow-marine carbonate platform (Berriasian, Velanginian, France, Switzerland). *Journal of Sedimentary Research*, **68** (6): 1093-1108.

Hunt, D., and Tucker, M.E. 1992. Stranded parasequences and the forced regressive wedge systems tract: Deposition during base level fall: *Sedimentary Geology*, **81**: 1–9, doi: 10.1016/0037-0738(92)90052-S.

Jain, A.K., Lal, N., Sulemani, B., Awasthi, A.K., Singh, S., Kumar, R. and **Kumar, D**. 2009. Detrital-zircon fission-track ages from the Lower Cenozoic sediments, NW Himalayan foreland basin: Clues for exhumation and denudation of the Himalaya during the India–Asia collision. *Geological Society of America Bulletin* **121:** 519–535.

Karunakaran, C. and **Ranga Rao, A.R**. 1979, Status of exploration for hydrocarbons in the Himalayan region—Contribution to stratigraphy and structure: *Geological Survey of India, Special Publication*, **41**: 1–66.

Ketzer., J.M., Morad, S., and **Amorosi, A**. 2003. Predictive diagenetic clay-mineral distribution in siliciclastic rocks within a sequence stratigraphic framework, p. 43-61. In: *Clay mineral cements in sandstones* (Eds. Worden, R.H. and Morad, S.), Special Publication International Association of Sedimentologists, **34**.

Kumar, K. and Loyal, R. S. 1987. Eocene Ichthyofauna from the Subathu Formation, northwestern Himalaya, India. *Journal of Palaeontological Society of India*, **32**: 60-84.

Kumar, K. and Loyal, R. S. 2006. *Excursion Guide on Sub Himalayan Paleogene succession of Shimla Hills (Subathu-Dagshai-Kasauli formations) in Stratotype Area, Solan District, Himachal Pradesh.* Wadia Institute of Himalayan Geology.

Loyal, R.S. 1986. Vertebrate biostratigraphy of the type area of Subathu Formation (Eocene), Subathu, Himachal Pradesh, India. *Tertiary Research*, **7**(4): 129-132.

Loyal, R.S. 1990. Lithostratigraphy of the basal Subathu Formation (upper Paleocene-Middle Eocene) exposed in the stratotype Kuthar River, Subathu, Himachal Pradesh, India with introductory notes on physiography and tectonics. *Tertiary Research*, **12**: 1-16.

Mathur, N.S. 1978. Biostratigraphical aspects of the Subathu Formation, Kumaun Himalayas. *Recent Researches in Geology,* **5**: 96–112.

Mathur, N.S. and **Juyal, K.P.** 2000. *Atlas of Early Paleogene invertebrate fossils of the Himalayan foothill belt*. Monograph of the Wadia Institute Himalayan Geology, **1**.

Medlicott, H.B. 1864. On the geological structure and relation of the southern portion of the Himalayan Range between the rivers Ganges and Ravee. *Memoirs of the Geological Survey of India,* **3**(2): 212p.

Miall, A.D. 2000. *Principles of Sedimentary Basin Analysis*. 3rd Edition. Springer, 616p.

Mitchun Jr., R.M. 1977. Seismic stratigraphy and global changes of sea level, part 11: Glossary of terms used in seismic stratigraphy. In: Payton, C.E. (Ed.), *Seismic Stratigraphy— Applications to Hydrocarbon Exploration*. Memoir American Association of Petroleum Geologists, **26**: 205–212.

Moodley, L., Vander, Z. and Bengel, P. van. 1997. Differential response of benthic microfauna to anoxia with special reference to foraminifera (Protista, Sarcodina). *Marine Ecology Process Series*, **158**: 151-163.

Mukhopadhyay, D.K., and **Mishra, P**. 2005. A balanced cross section across the Himalayan frontal foreland belt, Subathu area, Himachal Pradesh, India: thrust sequence, structural evolution and shortening. *Journal of Asian Earth Sciences*, **25**: 735-746.

Najman, Y., Clift, P., Johnson, M.R.W., Robertson, A.H.F. 1994. Early stages of foreland basin evolution in the Lesser Himalayas, North India, p. 541-558. In: *Himalayan Tectonics* (Eds. Trelor, P.J., and Searle, M.P.), Geological Society London Special Publication, **74**.

Najman Y., Pringle, M.S., Johnson, M.R.W., Robertson, A.H.F., and **Wijbrans, J.R.** 1997. Laser Ar-40/Ar-39 dating of single detrital muscovite grains from early foreland-basin sedimentary deposits in India: Implications for early Himalayan evolution, *Geology,* **25**: 535–538.

Patterson, R.T., **Guilbault, J.P. and Thomson, R.E.** 2000. Oxygen level control on foraminiferal distribution in Effingham Inlet, Vancouver island, British Columbia, Canada. *Journal of Foraminifera Research*, **30**: 321-335.

Plint, A.C. 1988. Sharp-based shoreface references and "off bars" in the Cardium Formation of Alberta; their relationship to relative changes in sea level, p. 357-370. In: *Sea Level Changes-An integrated approach* (Eds. Wilgus, C.K., Hastings, B.S., *et al.*). Special Publication, Society of Economic Paleontologists and Mineralogists, Special Publication, **42**.

Posamentier, H.W., Allen, G.P., James, D.P., and **Tesson, M.** 1992. Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration significance. *Bulletin American Association of Petroleum Geologists*, **76**: 1687–1709.

Prasad, V. and Sarkar, S. 2002. Fossil *Scytonema* (Nostocales) from Subathu Formation, Tal Valley, Garhwal Himalaya, India. *Journal of Palaeontological Society of India,* **47**: 145-149

Raiverman, V.D. 1979. Stratigraphy and facies distribution, Subathu sediments, Simla Hills, Northwestern Himalaya. *Miscellaneous Publication Geological Survey of India*, **41**:111–125.

Raiverman, V.D. 2002. *Foreland sedimentation in Himalayan tectonic regime: a re-look at the orogenic process*. Bishen Singh Mahendra Pal Singh, Dehradun.

Raiverman, V. 2006. Himalayan elevation— somnolence to hyperactivity. *Journal of Geological Society of India,* **67**: 21-26.

Raiverman, V. 2007. Geothermic revolution, mountain elevation, tectonic pulsation and foreland sedimentation in the Himalayan system. *Himalayan Geology*, **28**(2): 33-44.

Raiverman, V.D. and **Raman, K.S**. 1971, Facies relations in the Subathu sediments, Simla Hills, northwestern Himalaya, India: *Geological Magazine*, **108**: 329–341.

Ranga Rao, A.R, 1986. North-west Himalayan foothills: its stratigraphical record and tectonic phases. *Bulletin of the Oil and Natural Gas Commission,* **23**: 109–128.

Sahni, A., and **Kumar, K.** 1980. Lower Eocene Sirenia, *Ishatherium subathuensis* gen. et sp. nov. from the type area, Subathu Formation, Subathu, Simla Himalaya, H.P. *Journal of Palaeontological Society of India,* **23-24**: 132-135.

Schaub, H. 1981. Nummulites et Assilina de la T'thys Paleogene: taxonomie, phylogenese et biostratigraphie. *Me´moires suisses de la Paleontologie* **1981**: 104–106.

Serra-Kiel, J., Ottiger, L., Caus, E., Drobne, K., Ferrendez, C., Jauhri, A.K., Less, G., Pavlovec, R., Pignatti, J., Samso, J.M., Schaub, H., Sirel, E., Strougo, A., Tambareau, Y., Tosquella, J. and **Zakrevskaya, E.** 1998. Larger foraminiferal biostratigraphy of the Tethyan Paleocene and the Eocene. *Bulletin of the Geological Society of France*, **169** (2): 281–299.

Siddaiah, N.S., and **Kumar, K**. 2007. Discovery of volcanic ash bed from the basal Subathu Formation (Late Paleocene–Middle Eocene) near Kalka, Solan District (Himachal Pradesh), Northwest Sub-Himalaya, India. *Current Science*, **92**(1): 118-125.

Siddaiah, N.S. and Kumar, K. 2008. Tonstein (altered volcanic ash) from Late Paleocene (~ 58.7-55.8 Ma) sediments of the Northwest Himalaya and their significance for timing of initiation of India-Asia collision, p. 145-164. In: *Collision Zone Geodynamics (Golden Jubilee Volume)* (Eds. Arora, B.R. and Sharma, R.). Memoir Geological Society of India, **72**.

Siddaiah, N.S and Shukla, M.K. 2012. Occurrence of rhyolite in Jangalgali Formation, Jammu and Kashmir, Northwest Himalaya, India. *Current Science*, **103** (7): 817-821.

Siddiqui, N. K. 2009. Sedimentary Basin architecture of Pakistan, p. 401-474. In: *Proterozoic and Phanerozoic integrated stratigraphy (South-East Asia) India, Pakistan, Bangladesh and Sri Lanka* (Eds. Raju, D.S.N. and Misra, R.). Oil and Natural Gas Corporation Bulletin, **44** (2).

Singh, B.P. 2000. Sediment dispersal pattern in the Murree Group of the Jammu area, N.W. Himalaya, India. *Himalayan Geology,* **21**: 189–200.

Singh, B.P. 2003. Evidence of growth fault and forebulge in the Late Paleocene (57.9–54.7 Ma), western Himalayan foreland basin, India. *Earth Planetary Science Letters*, **216**: 717–724.

Singh, B.P. 2010. Marine to continental transition in Himalayan foreland: discussion. *Bulletin Geological Society of America*, **122**: 954–955.

Singh, B.P. 2012. How deep was the early Himalayan foredeep? *Journal of Asian Earth Sciences,* **56**: 24–32.

Singh, B.P. 2013. Evolution of the Paleogene succession of the western Himalayan foreland basin. *Geoscience Frontiers*, **4**: 199-212.

Singh, B.P., and **Andotra, D.S**. 2000. Barrier lagoon and tidal cycles in Paleocene to middle Eocene Subathu Formation, NW Himalaya, India. *Tertiary Research*, **20**: 65–78.

Singh, B.P., and **Singh, H.** 1995. Evidence of tidal influence in the Murree Group of rocks of the Jammu Himalaya, India, p. 343-351. In: *Tidal Signatures in Modern and Ancient Sediments* (Eds. Fleming, B.W., Bartholoma, A.) International Association of Sedimentologists, Special Publication, **24**.

Singh, B.P., Pawar, J.S., Raghumani Singh, Y., Singh, G.P. and **Srivastava, A.K.** 2010. Marine to continental transition and Sequence Stratigraphy in a Paleogene Succession of the Western Himalayan Foreland Basin, India. *Gondwana Geological Magazine,* **25**(2): 195-211.

Singh, B.P., and **Srivastava, A.K.** 2011. Storm activities during the Sedimentation of Late Paleocene-Middle Eocene Subathu Formation, Western Himalayan Foreland Basin. *Journal of Geological Society of India*, **77**: 130-136.

Singh, I.B. 1978. On some sedimentological and paleoecological aspects of Subathu-Dagshai-Kasauli successions of Simla Hills: *Journal of Paleontological Society of India*, **21–22**: 19–28.

Srikantia, S.V., and **Bhargava, O.N.** 1967. Kakara Series—a new Palaeocene formation in Simla Hills. *Bulletin of the Geological Society of India*, **4**: 114–116.

Srikantia, S.V., and **Sharma, R.P**. 1970. The occurrence of Kakara (Paleocene) affinity in the Bakhalag Bugher belt, Himachal Pradesh. *Journal of Geological Society of India*, **11**(2): 185-188.

Srivastava, V.K. and **Casshyap, S.M**. 1983, Evolution of the pre-Siwalik Tertiary basins of Himachal Himalaya. *Journal of Geological Society of India*, **24**: 134–147.

Tahirkhelli, R.A.K., **Mattauer, M., Proust, F., and Tapponnier, P**. 1979. The India-Eurasia suture zone in northern Pakistan: some new data for interpretation at plate scale, p. 125-130. In: *Geodynamics of Pakistan* (Eds. Farah, A., and DeJong, K.A.). Geological Survey of Pakistan.

Tucker, **M.E**. 1985. Shallow-marine carbonate facies and facies models. In Brenchley, P.J. and Williams, B.P.J.(Eds) *Sedimentology; Recent developments and applied aspects*. Blackwell Scientific Publications, Oxford. 147-169.

Wilson, J.L. 1975. *Carbonate facies in geological time*. Springer.

Manuscript accepted March 2013