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# LARGER FORAMINIFERAL AND CALCAREOUS ALGAL FACIES IN THE LAKADONG FORMATION OF THE SOUTH SHILLONG PLATEAU, NE INDIA

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## ABSTRACT

The Lakadong Limestone of the East Khasi Hills of the South Shillong Plateau, N.E. India is a major carbonate unit of the Lakadong Formation of the late Palaeocene to early Eocene age, which is the lowermost constituent formation of the Sylhet Limestone Group. The carbonates of the Lakadong Formation represent the larger foraminiferal-algal build-ups deposited in the progradational cycles of the carbonate platform related to sea-level fluctuations during the Thanetian and the Ilerdian. The foraminifera, calcareous algae and microfacies characters allow to distinguish two facies associations in the carbonate sequence: (i) Facies A characterising the lower 50m part and (ii) Facies B characterising the upper 50m part. The Facies A corresponds to the Thanetian sedimentation cycle in which deposition occurred in a relatively low-energy environment on a shallow subtidal ramp (protected lagoon). The Facies B correlates with the Ilerdian sedimentation cycle during which deposition occurred under low to moderate energy conditions on a relatively deeper mid-uppermost outer ramp, which allowed development of sediment-binding coralline algae and foraminifera such as discocyclinids and *Ranikothalia*.

**Keywords:** Sylhet Limestone Group (Palaeocene-Eocene), Lakadong Formation, South Shillong Plateau, NE India, larger foraminiferal-algal facies, depositional environment

## INTRODUCTION

This paper deals with the calcareous algal and foraminiferal facies developed in the Lakadong Formation in the South Shillong Plateau, NE India. This formation is considered to range from Thanetian to early Ilerdian (Jauhri, 1996; Jauhri and Agarwal, 2001) and is the lower unit of the Sythet Limestone Group. The investigation covers outcrops exposed in the Um Sohryngkew River section near the village Therria, which is located in the southern corner of the South Shillong Plateau of NE India and borders the plains of the Bangladesh (Fig. 1). The south-western part of this plateau shows extensive development of carbonate outcrops of this group which ranges in age from the late Palaeocene to the middle Eocene. These carbonate deposits contain rich assemblages of calcareous algae besides the shallow, neritic larger foraminifera. The Sylhet Limestone Group includes three carbonate units intercalated between two sandstone beds (Table 1) and is overlain by shale/ sandstone alternations of the Kopili Formation which is of late Eocene age. The constituent formations of the sylhet Limestone in the Khasi and the Jaintia Hills were deposited during the marine transgressions of the late Palaeocene, early Eocene and middle Eocene (Nagappa, 1959; Murty, 1983; Jauhri and Agarwal, 2001).

**Table 1: Stratigraphy of the Sylhet Limestome Group in the South Shillong Plateau (after Dasgupta, 1977).**

| | | | |
|---|---|---|---|
| | KOPILI FORMATION | | Late Eocene |
| Sylhet Limestone Group | PRANG FORMATION (200 m) | | Middle Eocene |
| | Umlatdoh Formation | Narpuh Sandstone (20 m) | Early Eocene |
| | | Umlatdoh Limestone (55 m) | |
| | Lakadong Formation | Lakadong Sandstone (25 m) | Late Palaeo-cene |
| | | Lakadong Limestone (200 m) | |
| | THERRIA FORMATION | | |

The rich assemblages of calcareous algae and larger foraminifera present in the carbonates of the lowermost formation (Lakadong Formation) are potentially useful in dating the succession and interpreting its depositional environment (Jauhri; 1988, 1966, 1997, 1998). The purpose of this paper is to describe the algal-foraminiferal facies in the carbonate succession of the Lakadong Formation and to discuss significance of these facies in interpreting the depositional environment of the carbonates of the Lakadong Formation.

## STRATIGRAPHIC SETTING

Geologically, the area is the north-eastern extension of the Indian Peninsular shield (Murty, 1983). As a result of tectonics in the Himalayan and in the adjoining Arakan-Yoma region, the Shillong Plateau occurs as an uplifted part of the basement bounded by nearly east-west aligned normal faults towards the northern and southern boundaries of the plateau. Cenozoic transgression in the Shillong Plateau began in the Danian (early Palaeocene, Nagappa, 1959; Garg and Jain, 1995) which was followed by a very large transgression during the late Palaeocene when an arm of sea from the Eastern Tethys covered extensively the Shillong Plateau via the Middle East, Pakistan and Tibet. Subsequently, two more transgressive events occurred during early Eocene and middle Eocene (Nagappa, 1959; Sander, 1962; Hottinger, 1971; Sahni and Kumar, 1974; Rahaghi, 1983; Wan, 1991; Jauhri and Agarwal, 2001). Shallow, neritic sediments characterized the deposition and carbonates accumulated extensively during these epochs. These carbonates are represented mainly by three formations of the Sylhet Limestone which are well exposed in the Um Sohringkew River section of the East Khasi Hills.

The geological and stratigraphical setting of the South Shillong Plateau has been described in Medlicott (1871), Evans

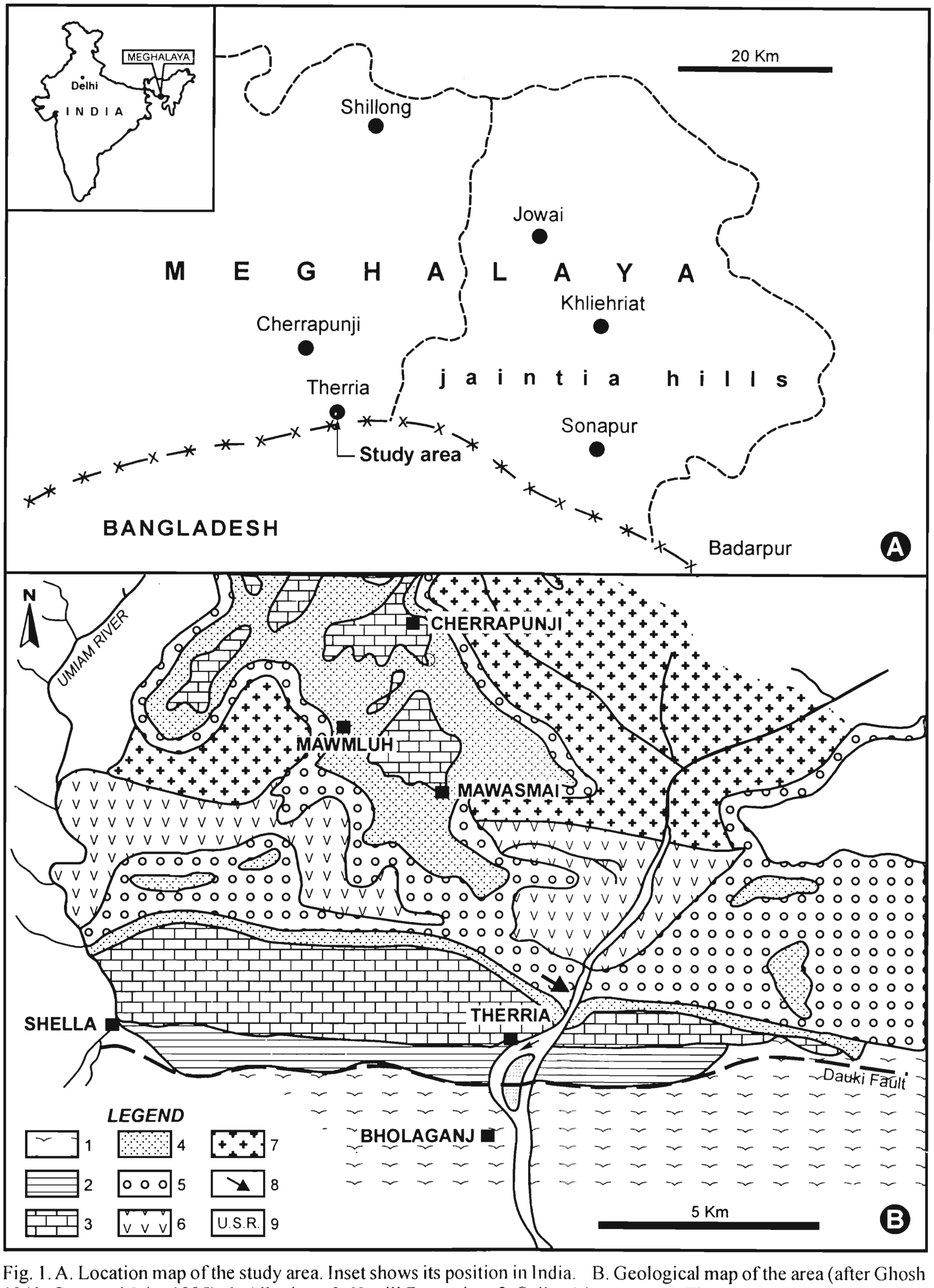



Fig. 1. A. Location map of the study area. Inset shows its position in India. B. Geological map of the area (after Ghosh 1940; Garg and Jain, 1995). 1. Alluvium; 2. Kopili Formation; 3. Sylhet Limestone; 4. Therria Formation; 5. Langpar Formation & Um Sohryngkew Formation; 6. Sylhet trap; 7. Archaean; 8. K/T section; 9. Um Sohryngkew River.

(1932), Ghosh (1940), Wilson and Metre (1953), Nagappa (1959), Biswas (1962), Murty *et al.* (1976), Dasgupta (1977), Samanta and Raychoudhary (1983), Murty (1983), Garg and Khowaja-Ateequzzaman (2000), Jauhri and Agarwal (2001). The constituent formations of the Sylhet Limestone Group, in ascending order, are the Lakadong Formation (the lowermost unit), the Umlatdoh Formation (the middle unit), and the Prang Formation (the upper unit). These units are constituted mainly by carbonate facies and are separated by two sandstone interbeds; one (Lakadong sandstone) is intercalated between the lower and the middle units, and the other (Narpuh Sandstone) separates the middle unit from the upper unit.

The carbonate member of Lakadong Formation known as the Lakadong Limestone records the late Palaeocene-early Eocene marine transgression in the area. It outcrops extensively in the Khasi and the Jaintia Hlls of Meghalaya. The Lakadong Limestone is made up of thick, massive, algal-foraminiferal carbonates characterised by the assemblages of these groups. The first appearance of larger foraminifera in the Lakadong Limestone dates the beginning of the late Palaeocene marine transgression, which is indicated by the presence of *Glomalveolina primaeva* as Thanetian

(Jauhri, 1994, 1997).

## BIOSTRATIGRAPHIC FRAMEWORK

The samples from the lower part of the Lakadong Limestone (86/Lkd/DR1-5 and 91/Lkd/DR1'-DR6', Fig. 2) have yielded biostratigraphic markers such as *Glomalveolina primaeva, G. levis, Miscellanea juliettae, M. yvettae,* etc. (Jauhri, 1988, 1998) which suggest that the lower part can be regarded as representing the interval equivalent to the SBZ 3 and SBZ 4 (Serra-Kiel *et al.,* 1998). Though direct correlation with planktic foraminifera zones is not feasible because of the absence of microfossils of this group in the studied section, these shallow benthic zones (SBZ 3 and SBZ 4) have been shown to be equivalent of the late *Planorotalites pseudomenardii* zone (late P4), i.e. Thanetian (Serra-Kiel *et al.,*1998). The samples (86/Lkd/DR6-10 and 91/Lkd/DR 7'-10') from the upper part of the succession show presence of *Ranikothalia nuttalli, Miscellanea miscella,* etc. which characterise the post-Thanetian formations in many areas of the Tethyan region (Jauhri, 1997). While *R. nuttalli* ranges from SBZ 5 to SBZ 6 in the Tethyan lower Palaeogene, *M. miscella* occurs in this region in the strata equivalent of SBZ 4 and SBZ 5 (Serra-Kiel *et al.,* 1998). These forms indicate that the upper part corresponds to Serra-Kiel *et al.*'s (1998) SBZ 5 and SBZ 6, which are referable to the late *Morozovella velascoensis* zone (P5), i.e. early Ilerdian. Thus, based on the foraminiferal association, it is suggested that the Lakadong carbonates span the interval from the late early Thanetian to early Ilerdian (Jauhri, 1994, 1996, 1998; Misra *et al.,* 2002).

## FACIES DEVELOPMENT

The Lakadong Formation consists of two major lithologies: the lower Lakadong Limestone and the upper Lakadong Sandstone. The lithofacies characters of the Lakadong Limestone were studied by Jauhri (1994). The Lakadong Limestone was deposited in the shallower to deeper ramp environment usually with low-water energy. The succession of carbonate deposition ended with the onset of lagoonal-coastal swampy conditions in which the overlying Lakadong Sandstone with coal and carbonaceous matter accumulated.

Lithologic examination of the section of the Lakadong Limestone in the study area shows a 100 m sequence of wackestones, grainstones, packstones and boundstones of larger foraminifera and calcareous algae. The foraminifera, calcareous algae and microfacies characters allow to subdivide the studied succession broadly into two distinct facies in the section (Fig. 2).

### Facies A (Lower 50m sequence)

It corresponds to the sedimentation cycle dated as the Thanetian (Jauhri, 1998; Jauhri and Agarwal, 2001). This facies is represented by wackestones to grainstones near the base (0-10m) and contains pellets and scarce bioclasts (Pl. I, fig. 1). Presence of endobenthics (e.g. spatangoids (echnoids) and

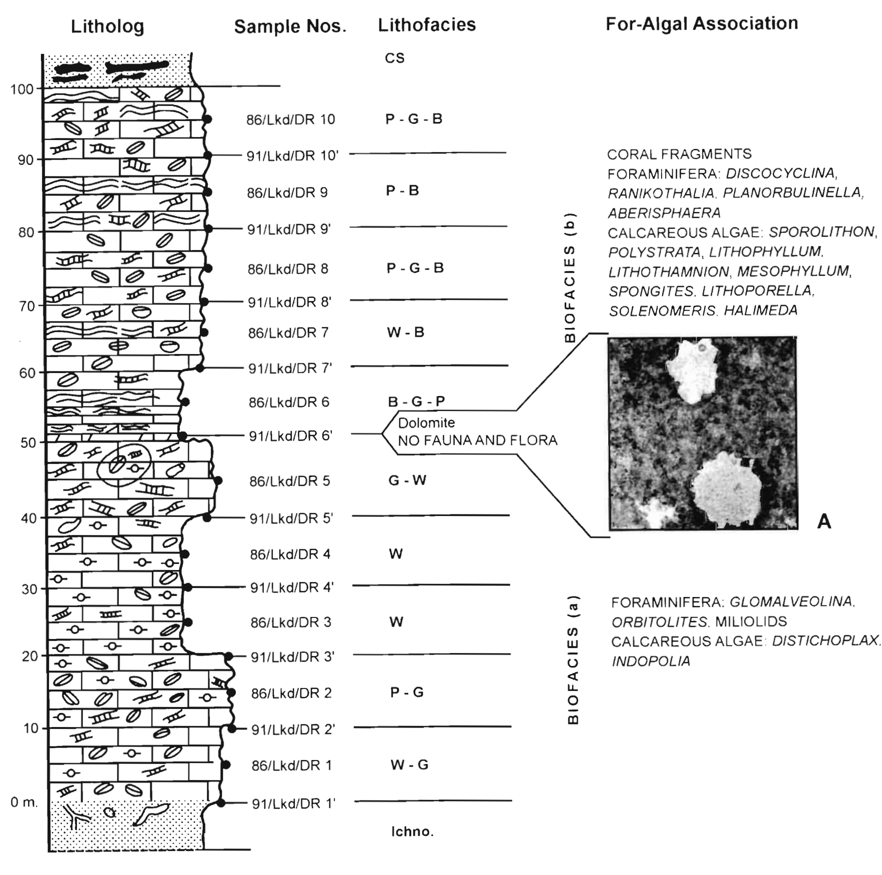



Fig. 2. Lithofacies and foraminiferal and algal associations (biofacies) of the Lakadong Limestone in the Therria section, Shillong. W = wackestone, G = grainstone, P = packstone,-B = boundstone, CS = coal-bearing sandstone, Ichno. = Ichno-horizon in the Therria Sandstone. A. Microfacies showing dolomite with a mosaic of large replacement calcite crystals, x12.

*Turritella*-like gastropods) is also noticed. These grade into packstones and wackestones in the 10-40m interval showing increase in the bioclasts of larger foraminifera, dasyclads and *Distichoplax biserialis* (Pl. I, figs. 3-6). In the 40-50 m interval, the grainstones also occur and contain intraclasts of skeletal wackestones. The larger foraminifera belong mainly to glomalveolines, orbitolitids, rotaliids, miliolids and a few complex agglutinated types. Skeletal grains are poorly to moderately sorted and present in the matrix of carbonate mud and skeletal debris. The uppermost sample (91/Lkd/DR6') from the lower part, in close contact with the basal interval of the upper part, is characterised by the absence of microfossils and presence of dolomite with patches of secondary calcite (Fig. 2).

The foraminiferal assemblage in this facies is dominated by *Glomalveolina* (Pl. I, figs. 3-4) which is accompanied with *Orbitolites*, miliolids, some agglutinated forms and a few smaller benthics (Jauhri, 1994). The algal content is relatively poor and is characterised by predominant *Distichoplax biserialis*, *Indopolia satyavantii* (Pl. I, fig. 5), and rare representatives of disarticulated intergenicula of geniculate coralline algae, e.g. *Corallina* (Pl. I, fig. 2), *Jania*, *Neogoniolithon*, ? *Lithophyllum* (Pl. I, fig. 1), *Sporolithon aschersoni* (Pl. II, fig. 6), *Ovulites*, and fragments referable to Melobesioideae (Misra *et al.*, 2002). Coralline algal growth-forms are commonly represented by encrusting types and fruticose protuberances (Table 2). At some levels, only algal fragments occur (e.g. 86/Lkd/DR2).

### Interpretations

Abundant glomalveolinids with miliolids, orbitolitids and predominant *Distichoplax biserialis* along with common *Indopolia satyavantii* are characteristic of protected lagoonal facies (shallow subtidal ramp, Buxton and Pedley, 1989), (see Fig. 3). Hottinger (1983, 1997) and Reiss and Hottinger (1983) interpreted alveolinids, orbitolitids and miliolids as the characteristic foraminiferal assemblage of upper photic zone marked by relatively low-water energy and depths less than 40m. These foraminifers are also comparable with the back-bank associations of Aigner (1983) and Rácz (1979).

Though *D. biserialis* is believed to range from littoral to fore-reef environment (Scheibner, 1968), it occurs predominantly in the reef and reef-margin facing the back-reef environment, e.g. Palaeocene carbonate, Shillong Plateau, India (Ghose, 1977) and Palaeocene carbonate, Ras Al Hamra, Oman (Rácz, 1979). *Indopolia* is known to characterise shallow shelf facies (back-reef) in Iraq (Elliott, 1968), Ras Al Hamra, Oman (Rácz, 1979), Greece (Deloffre *et al.*, 1991), and Trichinopolly, south India (Misra *et al.*, 2000).

Presence of large amounts of mud as matrix, encrusting to fruticose coralline algal growth-forms and poorly sorted grains indicate deposition on soft bottom usually with quiet-water conditions. Nebelsick *et al.* (2000) and Nebelsick and Bassi (2000) interpret low-water turbulence for the foraminiferal-coralline algal facies of the Gornji Grad Beds (lower Oligocene, Slovenia) from the comparable facies characters, e.g. large amounts of muddy matrix, presence of fruticose protuberances, low-diversity corallines and benthic foraminifera such as alveolinids, miliolids, etc. However, in the basal interval (e.g. 86/Lkd/DR2) grainstone matrix, the moderate degree of sorting of the skeletal grains, fragmented algal components and *Corallina* and *Jania* point to a relatively higher energy environment. Near the top (86/Lkd/DR5), moderately high water turbulence and shallowing conditions of deposition are suggested by mud-poor sediments characterized by intraclasts and fruticose protuberances of *Neogoniolithon*. The uppermost dolomitic interval of the lower sequence is interpreted as an evidence of the surface of emergence marking a break in sedimentation.

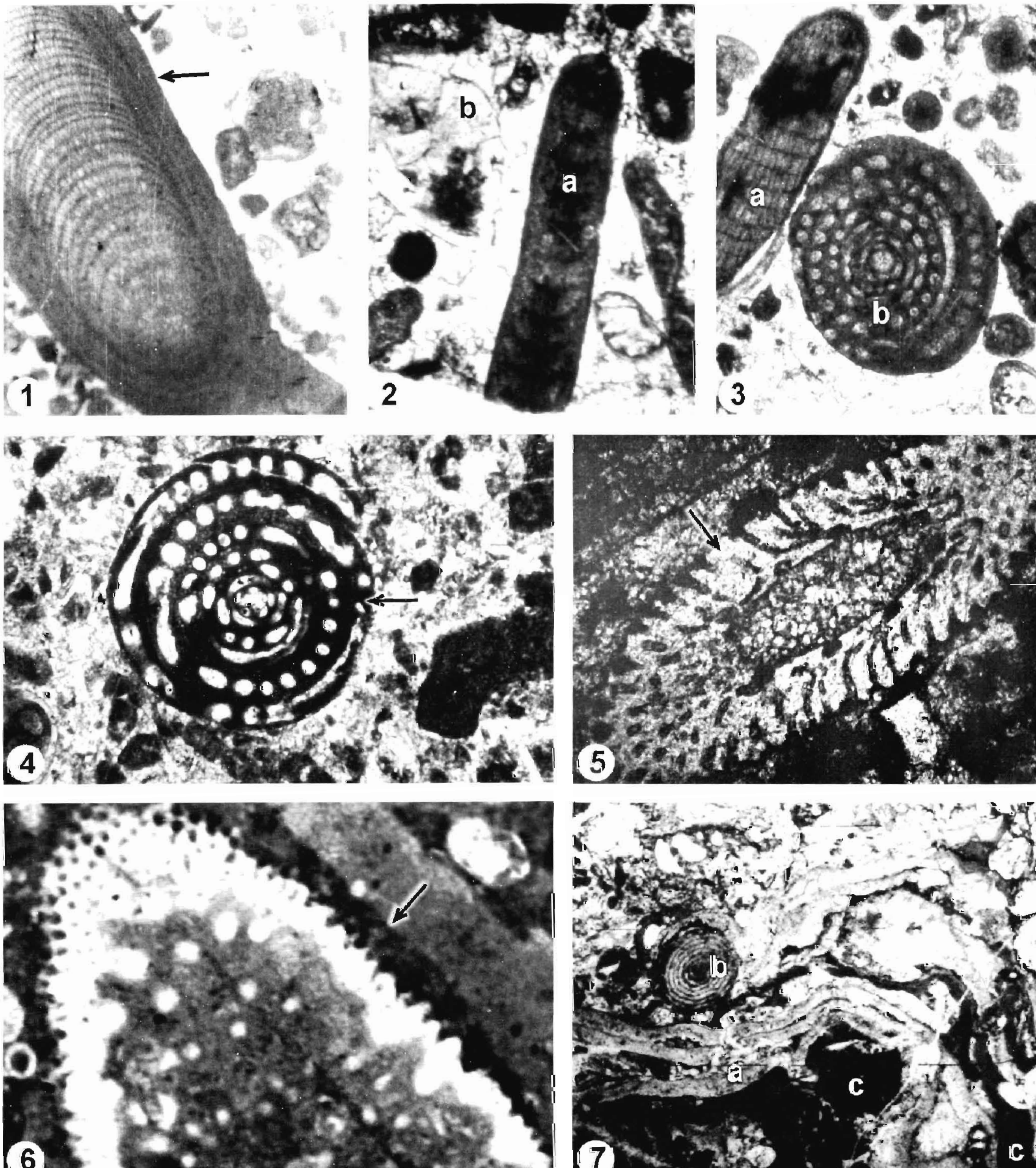
### Facies B (Upper 50m sequence)

It corresponds to the sedimentation cycle dated as the Ilerdian (Jauhri, 1998; Jauhri and Agarwal, 2001). The upper part, 50-100 m, consists of algal boundstones in abundance along with less common coral boundstone with packstone, wackestone and occasional grainstone matrix (86/Lkd/DR6, 8, 10) and shows poor to moderate degree of sorting. The sediment is mainly the carbonate mud, and the skeletal particles include larger foraminifera with larger dimensions than those in the lower part represented mainly by *Ranikothalia* (Pl. II, fig. 2), *Discocyclina* (Pl. II, figs. 2-3) in abundance, *Miscellanea miscella*, rare *Alveolina* (Pl. I, fig. 7) - restricted to sample Nos. 86/Lkd/DR6, 91/Lkd/DR8)], corals (86/Lkd/DR6, Jauhri, 1994, Pl. 2, fig. 4) and sediment-binding algae. The algal bioclasts are occasionally encrusted by foraminifera, i.e. *Aberisphaera* is seen encrusting on the coralline algae (Pl. II, fig. 1). Near the top of the sequence, *D. biserialis* becomes dominant and foraminifera rare in a silty matrix and the bioclasts show a moderate degree of sorting (Fig. 2).

The basal portion is characterised by coral-algal boundstones with some packstones and grainstones of foraminifera, e.g. *Miscellanea miscella* (86/LKD/DR6). In the overlying intervals, the boundstones are associated with packstones, rare wackestone and grainstone with abundant *Discocyclina* and *Ranikothalia* (Fig. 2), few rotaliaceans (e.g. *Miscellanea miscella*,) subordinate alveolinids (confined to

## EXPLANATION OF PLATE I

1. Coralline algal fragment (? ***Lithophyllum*** marked by arrow) surrounded by broken skeletal fragments of foraminifers, echinoids, etc (Thin-section No. Geol./L.U./DR1/202/b; sample no. 86/Lkd/DR1), x 60.
2. Coralline alga (***Corallina*** - a) and foraminiferal (rotaliid - b) grainstone facies (Thin-section No. Geol./L.U./DR2/203b1; sample no. 86/Lkd/DR2), x 50.
3. Grainstone facies with an articulated coralline form (a) and ***Glomalveolina*** (b) and other skeletal fragments (Thin-section No. Geol./L.U./DR2/203b1; sample no. 86/Lkd/DR2), x 50.
4. Wackestone facies with ***Glomalveolina*** (shown by arrow) and broken fragments of smaller benthics and algae (Thin-section No. Geol./L.U./DR3/204b; sample no. 86/Lkd/DR3), x 60.
5. A dasyclad (***Indopolia satyavantii*** -shown by arrow) in a wackestone facies (Thin-section No. Geol./L.U./DR4/205a; sample no. 86/Lkd/DR4), x 60.
6. A large dasyclad fragment (indicated by arrow) in wackestone facies (Thin-section No. Geol./L.U./DR5/bii; sample no. 86/Lkd/DR5), x 100.
7. Boundstone facies with ***Polystrata alba*** (a), trapped sedimentary particles, ***alveolinid*** (b) and coralline algae (c) (Thin-section No. Geol./L.U./DR6/211; sample no. 86/Lkd/DR6), x 10.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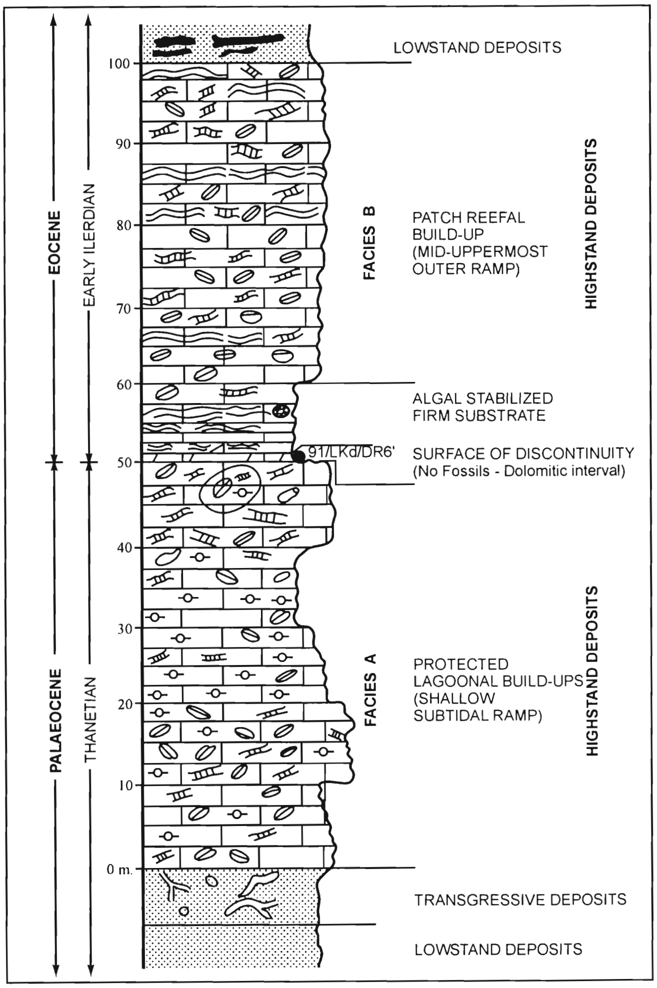


Fig. 3. Depositional environment of the sequences identified in the Lakadong Formation in the study area. A surface of discontinuity which is indicated by absence of fossils and dolomitic layer, separates the lower and upper sequences of the Lakadong Limestone.

86/Lkd/DR6 and 91/Lkd/DR8) and encrusting foraminifera, e.g. *Planorbulinella* (86/Lkd/DR7) and *Aberisphaera* (86/Lkd/DR8). See Jauhri, 1994.

The algal assemblage is diversified and contains corallines in abundance. The lower intervals of this facies are characterised by *Lithophyllum*, *Jania*, *Halimeda* (Pl. II, fig. 4), *Solenomeris* and *Polystrata* (Pl. I, fig. 7) in low percentage, whereas the upper intervals show occurrence in high percentage of *Lithothamnion* (Pl. II, fig. 5), *Mesophyllum*, *Lithoporella*, *Sporolithon* (Pl. II, fig. 6) and *Spongites* Misra et al., 2002, Pl. II, figs. 3,4); see Fig. 2. *D. biserialis* continues throughout in reduced frequency of occurrence, but in the topmost interval (Lkd/DR10) it becomes abundant with other corallines becoming rare (Jauhri, 1994). A variety of growth-forms is noticed in this facies; the dominant being the encrusting, lamellate (layered), warty, lumpy and fruticose types (Woelkerling *et al.*, 1993; Nebelsick and Bassi, 2000) (Table 2).

The poor degree of sorting of allochems is a conspicuous feature of the upper sequence. However, in some intervals, especially in the uppermost interval, of this sequence the algal-foraminiferal packstones, grainstones and boundstones show moderately sorted skeletal grains and abundance of *Distichoplax biserialis* in a silty matrix.

**Interpretations**

The presence of foraminifera, abundant algal boundstones and some corals at the base marks the return of marine environment. Encrusting foraminifera (e.g. *Planorbulinella* and *Aberisphaera*), algal boundstone and some corals (Jauhri, 1994) indicate the formation of algal-stablized, firm substrate and reduced water turbulence that may have resulted from slower rates of sedimentation (Fig. 3). The algal association in the lower intervals of the upper sequence shows common occurrence of *Polystrata* and *Solenomeris*. Both have been considered to be characteristic of reef and reef-margin facies in the Sirte Basin, Libya (Wray, 1977) and Ras Al Hamra, Oman (Rácz, 1979). Bassi (1998) reports that *Polystrata* colonises the mid and uppermost outer ramp environment of the Lessini shelf characterised by "...low-energy conditions and encrustations on hard or soft substrate either alone or in consortium of the non-geniculate corallines and encrusting foraminifera". *Solenomeris*, too, is an encrusting form and is known to have formed extensive carbonate encrustations during the Ilerdian in the Pyrnean region (Perrin, 1987).

*Sporolithon*, *Lithoporella, Spongites, Lithothamnion* and *Mesophyllum* which are the common genera in the upper intervals (Misra *et al.*, 2002) are characteristic of 70 m water depth in the Hawaiian Islands and the Carribbean Sea and 30-80m water depth on the shelves of the Indo-Pacific region (Adey, 1979). This algal assemblage is also comparable with that occurring in the Flower Garden Banks (north-eastern Gulf of Mexico) well below the normal-wave base at 70-100 m (Minnery, 1990). Broadly similar assemblage has been interpreted as characterising the middle ramp setting during the Upper Eocene in eastern Colli Berici, northeastern Italy (Bassi, 2005), though the Colli Berici deposits appear to be storm-influenced. The predominant foraminifera associated with the algal assemblage are *Ranikothalia* and *Discocyclina*,

## EXPLANATION OF PLATE II

1. Boundstone facies with encrusting foraminifer ***Aberisphaera*** (a) axial section) encrusting on coralline algae (b) (Thin-section No. Geol./L.U./DR7/c; sample no. 86/Lkd/DR7), x 60.
2. Poorly sorted packstone facies with ***Ranikothalia nuttalli*** (Davies) (a), ***Discocyclina*** (b), smaller benthics and fragments of algal boundstone (Thin-section No. Geol./L.U./DR7/c; sample no. 86/Lkd/DR7), x 25.
3. Poorly sorted packstone facies with ***Nummulites*** (a), ***Discocyclina*** (b), **rotaliid** (c), a few fragments of ***D. biserialis*** (marked by arrow) and skeletal debris (Thin-section No. Geol./L.U./DR8/209; sample no. 86/Lkd/DR8), x 15.
4. Grainstone facies with ***Halimeda*** (a), ***D. biserialis*** (b) and skeletal fragments (Thin-section No. Geol./L.U./DR9/210b; sample no. 86 Lkd/DR9), x 25.
5. Coralline algal facies with ***Lithothamnion*** present as an encrusting form (Thin-section No. Geol./L.U./DR9/210c; sample no. 86 Lkd/DR9), x 100.
6. Algal boundstone showing ***Sporolithon*** (Thin-section No. Geol./L.U./DR9/210a; sample no. 86/Lkd/DR9), x 15.

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**Plate II**

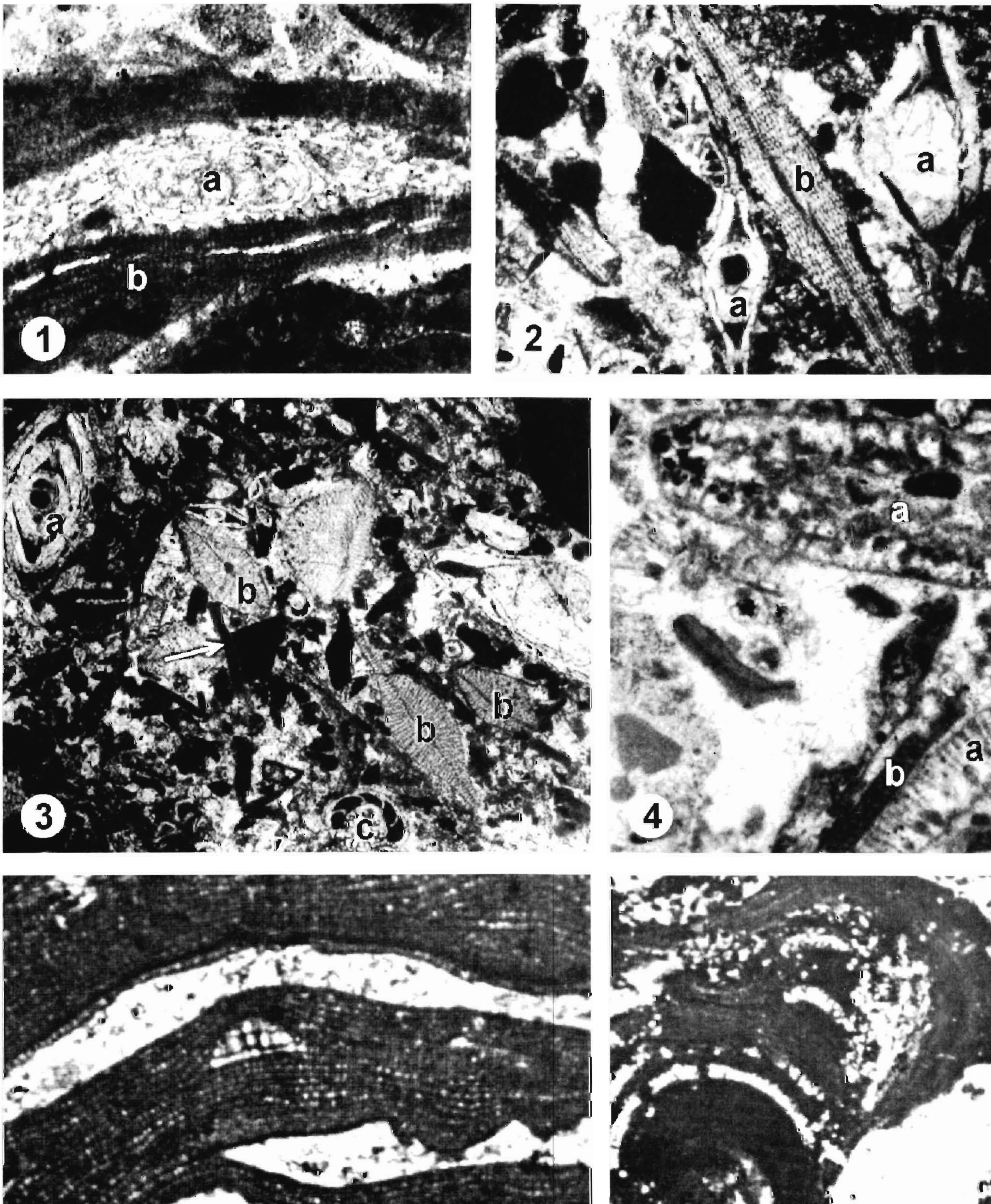


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**Table 2: Distribution of calcareous algae and growth forms in the carbonate facies of the Lakadong Formation in the study area.**

| Taxonomic Composition | Facies (A) (Lower 50m unit) | Facies (B) (Upper 50m unit) |
|---|---|---|
| **Sporolithaceae** | | |
| *Sporolithon aschersonii* | ⊙ | ⊙ |
| *Sporolithon* sp. | | ⊙ |
| **Mastophoroideae** | | |
| *Lithoporella* sp. | | ⊙ |
| ? *Neogoniolithon* sp. | ⊙ | |
| *Spongites* sp. | | ⊙ |
| **Melobesioideae** | | |
| *Lithothamnion* sp. | | ⊙ |
| *Mesophyllum* cf. *pfenderae* | | ⊙ |
| Melobesioideae indet. | ⊙ | |
| *Distichoplax biserialis* | ⊙ | ⊙ |
| **Lithophylloideae** | | |
| *Lithophyllum dentatum* | | ⊙ |
| ? *Lithophyllum* sp. | ⊙ | |
| **Corallinoideae** | | |
| *Corallina prisca* | ⊙ | |
| *Jania occidentalis* | ⊙ | ⊙ |
| **Peyssonneliaceae** | | |
| *Polystrata alba* | | ⊙ |
| **Solenoporaceae** | | |
| *Solenomeris* sp. | | ⊙ |
| **Halimedaceae** | | |
| *Halimeda* sp. | | ⊙ |
| *Ovulites* sp. | ⊙ | |
| **Accetabulariaceae** | | |
| *Indopolia satyavanti* | ⊙ | |
| **Growth-Forms** | | |
| Encrusting | ⊙ | ⊙ |
| Layered | | ⊙ |
| Protuberances | | |
| Warty | | ⊙ |
| Lumpy | | ⊙ |
| Fruticose | ⊙ | ⊙ |
| Fragments | ⊙ | |

together with *Miscellanea* and rotaliids (Jauhri, 1994, 1996). Buxton and Pedley (1989) indicate that these forms, particularly discocyclinids, constitute a typical "orbitoid" facies in a deeper ramp environment. Bassi (1998) also interprets such foraminiferal-algal facies as characteristic of low-energy deposits which possibly are known to have accumulated below normal-wave base in the mid-uppermost outer ramp environment (Fig. 3).

The common occurrence of taxa, such as *Miscellanea* in some intervals of this facies, with grainstone matrix, can be accounted for by the episodes of storms which occasionally affect such environment and temporarily result in high-energy

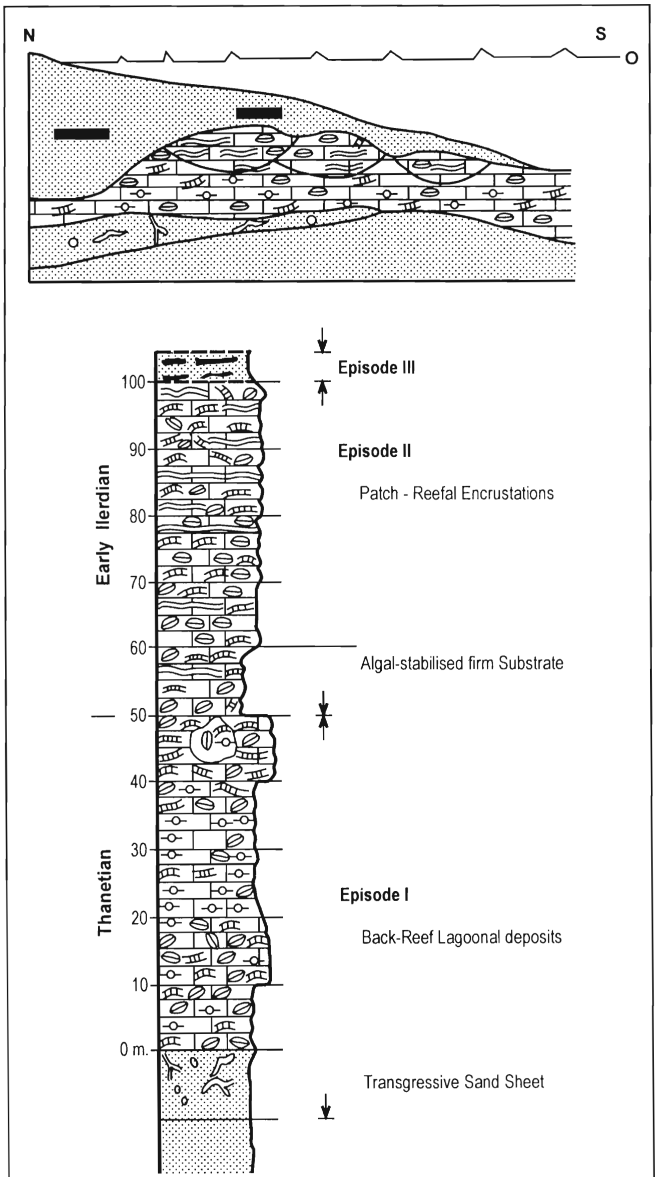


Fig. 4. Schematic model of facies and sequence development on the Thanetian-early Ilerdian carbonate platform in the Shillong area (not to scale).

conditions. However the carbonate muddy matrix, poorly sorted grains and dominance of encrusting, layered growth-forms and warty to lumpy protuberances in general support low to moderate energy environment, possibly below normal wave base, during deposition of the upper sequence. The microfacies characters of the uppermost interval of the upper sequence (86/Lkd/DR10), however, show moderate degree of sorting and influx of silty clastic material, indicating increasing influence of physical processes which had destructive effect on the carbonate-precipitating organisms and their patch-reefal build-ups (Ghose, 1977; Jauhri, 1994). This type of environment must have preceded the deposition of the overlying Lakadong sandstone which accumulated during regressive phase of sea in the area.

## DEPOSITIONAL MODEL

The carbonate build-ups of the Lakadong Formation are characterised by poorly sorted, bioclastic lime-mud with modest representation of organic boundstones in the upper part. They consist mainly of progradational highstand deposits, related to two events of sea-level rise: first, Thanetian which began with deposition of the bioturbated, sandy horizon of the underlying Therria Sandstone, and second, Ilerdian which flooded the emergent carbonate build-up accumulated during the Thanetian (Jauhri, 1994; Jauhri and Agarwal, 2001). Three episodes may be distinguished in the succession (Fig. 4):

### Episode I

The basal part of the lower sequence of the Lakadong Limestone and the underlying bioturbated sandy horizon represent transgressive deposits of the Thanetian depositional cycle. As progradation set in, the foraminiferal-algal build-ups accumulated mainly in a low-energy environment possibly of a protected lagoon, at depths, of 20-40m, on a shallow subtidal ramp (Fig. 3). Large amounts of lime-mud of the original environment and poorly sorted grains indicate deposition on soft grounds with calm-water conditions. With continued progradation, the carbonate build-up maintained its steady growth and showed a tendency of shallowing up to wave base and of emergence towards the top of the lower sequence. This is indicated by moderately sorted skeletal grains and presence of intraclasts in this part of the sequence and appearance of dolomite marked by patches of secondary calcite and absence of fossils in the dolomitic interval of the lower sequence.

### Episode II

The upper sequence is initially transgressive and then regressive and was laid down during the Ilerdian depositional cycle. The basal part of this sequence is characterised by algal-stablised, firm ground interpreted to have been deposited during a rapid rise in sea level. It promoted the growth of coralline algae-corals-encrusting foraminifera in low-energy conditions (below normal-wave base) on relatively deeper mid-uppermost outer ramp (Fig. 3). The bathymetric changes possibly related to the second event of sea-level rise introduced a new foraminiferal-algal association mainly comprising *Ranikothalia*, *Discocyclina*, and rich coralline algae. This association continues above in varying proportions and is accompanied at few intervals higher in the sequence by an increase in organisms such as corals, echinoids and encrusting foraminifera (e.g. *Planorbulinella*, *Abesisphaera*). It seems that the skeletal parts of foraminifera and sediment-binding algae may have provided attachment surfaces to encrusting foraminifers and corals (occasional) and promoted development of patch-reefal build-ups (Jauhri, 1994; 1996). The deposits near the top exihibit influx of silty clastic material and absence of corallines and associated fauna. This change is interpreted as indicative of increasing influence of physical processes pointing to shallowing and regressive conditions of sea.

### Episode III

The terrigenous carbonaceous deposits of the Lakadong Sandstone document regression and seem to have been deposited in an environment of lagoonal-coastal swampy conditions.

## DISCUSSION AND CONCLUSION

The carbonates of this formation mainly represent progradational highstand deposits which can be broadly organised into two sequences corresponding to two major episodes of deposition (Fig. 4) correlative, on the basis of foraminiferal assemblages (Jauhri, 1996; 1998; Jauhri and Agarwal, 2001), with the Thanetian and the Ilerdian Stages of the South Pyrenean region (Robador, 1991; Serra-Kiel *et al.*, 1998). Episode I is represented by the lower sequence of the Lakadong Limestone which is dominated by glomalveolinids, *D. biserialis* and *Indopolia* and dated by *Glomalveolina primaeva* and related species as the Thanetian. It is followed by another important transgression of episode II represented by the upper sequence which has been dated here as the early Ilerdian by *Ranikothalia nuttalli* and *Miscellanea miscella*. Besides these elements, discocyclinids, encrusting foraminifera and coralline algae occur commonly in this part.

A distinct surface of discontinuity (sedimentary unconformity) evidenced by a dolomitic interval is noticed in the topmost interval of the lower sequence of the Lakadong Limestone; it separates the Thanetian succession from that of the Ilerdian in the studied section. The faunal and floral changes noticed in the upper sequence of this limestone are related to the change in depositional environment associated with early Ilerdian transgression (Jauhri, 1996). The latter marks the arrival of *Ranikothalia*, *Miscellanea miscella* and a rich algal flora represented by coralline algae.

The upper sequence of carbonates grades upwards into the terrigenous coastal-sandy deposits of swampy facies of the Lakadong Sandstone. These deposits are carbonaceous in nature and also contain coal in some sections. They possibly represent lowstand deposits laid down during third episode of the regressive phase of sea in the studied section.

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