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APECTODINIUM ACME AND PALYNOFACIES CHARACTERISTICS IN THE LATEST PALAEOCENE-EARLIEST EOCENE OF NORTHEASTERN INDIA: BIOTIC RESPONSE TO THE PALAEOCENE-EOCENE THERMAL MAXIMA (PETM) IN LOW LATITUDE

VANDANA PRASAD*,[1], RAHUL GARG#,[1], KHOWAJA-ATEEQUZZAMAN[1], INDRA BIR SINGH[2] and MICHAEL M. JOACHIMSKI[3]

[1]BIRBAL SAHNI INSTITUTE OF PALAEOBOTANY, 53 UNIVERSITY ROAD, LUCKNOW – 226007
[2]DEPARTMENT OF GEOLOGY, LUCKNOW UNIVERSITY, LUCKNOW – 226007
[3]INSTITUT FUR GEOLOGIE UND MINERALOGIE, SCHLOSSGARTEN, 91054 - ERLANGEN, GERMANY

ABSTRACT

Ubiquitous predominance of *Apectodinium*, a presumably heterotrophic, warm water dinoflagellate, is one of the most prominant biotic response in the marginal marine realm to the warming event known as the Palaeocene-Eocene Thermal Maxima (PETM). Global records of *Apectodinium* dominated assemblages associated with PETM Event are known mainly from the mid-high latitudes. The low latitude records of the *Apectodinium* acme coinciding with a negative carbon isotope excursion (CIE) and combined with palynofacies data from the coastal marine succession in the Khasi Hills, northeastern India (occupying equatorial palaeolatitudes) are discussed in relation to the PETM. The association of *Apectodinium* acme with rich and varied terrestrial organic matter indicates lowered salinity and enhanced coastal runoff in response to high precipitation leading to increased river discharge. High input of organic detritus raised surface water productivity in the stressed marginal coastal sea, conducive to proliferation of *Apectodinium* and other related early wetzelielloids. It is presumed that the environmental impact of PETM in the equatorial region was in the form of intense warm and humid climate with enhanced precipitation.

Key words: Palaeocene-Eocene Thermal Maxima (PETM), *Apectodinium*, Palynofacies, Palaeoenvironment, Northeastern India

INTRODUCTION

The Palaeocene-Eocene boundary interval shows one of the most prominent climate changes in the earth's history at a time when large continental ice sheets were absent (Miller *et al.*, 1987; Zachos *et al.*, 1993; Sloan and Rea, 1995; Bains *et al.*, 1999). The Palaeocene-Eocene Thermal Maximum or PETM [earlier known as Late Palaeocene Thermal maxima (LPTM) or Initial Eocene Thermal Maxima (IETM)] was a short-lived abrupt warming event that lasted ~220 kyr (Zachos *et al.*, 1993; Thomas and Shackleton, 1996; Norris and Röhl, 1999; Röhl *et al.*, 2000; Schmitz *et al.*, 2001). During this interval, deep water at the high latitudinal regions rapidly warmed up to 6-8° C, with considerable warming (~1-6° C) of oceanic surface waters in the equatorial region (Kennett and Stott, 1991).

The cause of PETM is supposed to rest with the introduction of ~1,050-2100 Gt of isotopically depleted carbon from marine gas hydrate and its subsequent oxidation to carbon dioxide in the atmosphere (Dickens *et al.*, 1995; Matsumoto, 1995; Dickens, 2000; Bains *et al.*, 1999). The base of PETM corresponds to a prominent negative shift of 2.5‰ or more in $\delta^{13}C$ of marine carbonate (Kennett and Stott, 1991; Thomas and Shackleton, 1996) and of >5‰ in terrestrial records (Koch *et al.*, 1992). The biotic response to this warming event was remarkably widespread and reflected globally, showing matching geochemical signatures in several marine and terrestrial records (see Aubry *et al.*, 1998 and Schmitz *et al.*, 2000). The event seems to be most dramatically reflected in the deep-sea microfossil records by massive extinction of benthic foraminifera (BEE) (Miller *et al.*, 1987; Thomas, 1990; Kennett and Stott, 1991; Schmitz *et al.*, 1996). Surface dwelling phytoplanktons and terrestrial mammals are considered to have undergone significant turnover and diversification (Kelly *et al.*, 1996; Aubry, 1998; Clyde and Gingerich, 1998).

Amongst the prominent biotic signatures of the PETM event, sudden proliferation of presumably heterotrophic, organic walled warm water dinoflagellate *Apectodinium* in marine realm on a global scale is extremely significant (Bujak and Brinkhuis, 1998; Crouch *et al.*, 2001; Crouch *et al.*, 2003a,b). The presence of such a synchronous acme of *Apectodinium* dinoflagellate cysts in a very short time span (almost irrespective of latitudinal position) is unique within the entire dinoflagellate cyst fossil record (Crouch *et al.*, 2001). It indicates prevalence of more or less similar palaeoenvironmental conditions in marginal seas spread over far and wide areas in both southern and northern hemispheres. While *Apectodinium* dominated assemblages of high and mid-(palaeo) latitudinal regions from deeper water and its association with the PETM event (backed by geochemical, calcareous plankton and other palaeoenvironmental signatures) has been studied and assessed extensively, data from marginal marine setting and low equatorial (palaeo) latitudes is severely limited. Though widespread occurrences of *Apectodinium*-rich assemblages are reported from shallow marine setup of India (Jain and Garg, 1986; Garg *et al.*, 1995; Garg and Khowaja-Ateequazzaman, 2000; Mehrotra and Sarjeant, 1999), their relationship with the PETM event is yet to be assessed.

The present study deals with the evaluation of *Apectodinium*-rich assemblages, occurring in a coal-bearing succession (Lakadong Sandstone) in the northeastern India (Cherrapunji and Jathang sections of the Khasi Hills, South Shillong Plateau, Meghalaya) for their possible relationship with the global PETM event. The *Apectodinium*-acme in this region has been assigned to the Aau biozone of Powell (1992) and calibrated with larger foraminifer zones SBZ5, bracketing it by inference within the planktic foraminifer zone P5 (Garg and Khowaja-Ateequazzaman, 2000), representing Sparnacian stage (probable PETM age). In the absence of any calcareous microfossil signatures of PETM besides the *Apectodinium*-

*E-mail: prasad.van@gmail.com
#E-mail: rahul_bsip@yahoo.com; rahulbsip@gmail.com

acme that coincides with a ~2‰ negative excursion in $\delta^{13}C$, association with rich and varied terrestrial organic matter in a progradational coastal setup is analyzed to interpret the palaeoenvironmental conditions prevailing during this short term aberrant warming event in the (palaeo) equatorial regions. Clastic-dominated unfavourable facies of Lakadong Sandstone does not permit plankton-based zonation and correlation as calcareous microfossils (foraminifera and nannofossils) are completely missing. Moreover, marginal marine setting with shifting influence of freshwater, sediment supply and local sea-level changes at certain levels further hampered formulation of detailed dinoflagellate cyst zonation schemes as the organic-walled phytoplanktons are confined to select levels only. Hence palynofacies studies have been applied for correlating different intervals as well as for deciphering the palaeoenvironmental set up in the Cherrapunji and Jathang sections of the South Shillong Plateau.

GEOLOGICAL SETTING

The Shillong Plateau lies on the southwestern edge of the Assam Shelf, which is considered to be the northeastern extension of the Indian Peninsular Shield (Murty, 1983). The southern fringes of the Shillong Plateau (known as the South Shillong Plateau in the geological literature) comprise the Garo-Khasi-Jaintia hilly tract in Meghalaya (Figs. 1A, 1B). The marine Upper Cretaceous-Palaeogene succession exposed on the plateau region and on its southern slopes,

Table. 1: Lithostratigraphic setup of the Palaeogene succession, Khasi hills [after Raja Rao, 1981 and Garg and Khowaja-Ateequazaman, 2000].

EPOCH	AGE	FORMATION/ MEMBER		LITHOLOGY
EOCENE	YPRESIAN	SYLHET LIMESTONE FORMATION	UMLATDOH Lst	Grey to pinkish grey foraminiferal limestone with calcareous sandstone partings
EOCENE / PALAEOCENE	SPARNACIAN / THANETIAN	SYLHET LIMESTONE FORMATION	LAKADONG Sst	Predominantly buff to whitish, soft friable, medium to coarse grained arkosic sandstone, often pyriteous frequently burrowed, carbonaceous shales and siltstones and thin coal seams.
PALAEOCENE	THANETIAN	SYLHET LIMESTONE FORMATION	LAKADONG Lst	Grey to brownish grey foraminiferal-algal limestone, dolomitic at the base with thin grey shale, silty shale partings.
PALAEOCENE	SELANDIAN	THERRIA FORMATION		Hard buff to brownish, medium to coarse, ferrugenous sandstone with thin bands of pyriteous siltstone and carbonaceous shale.

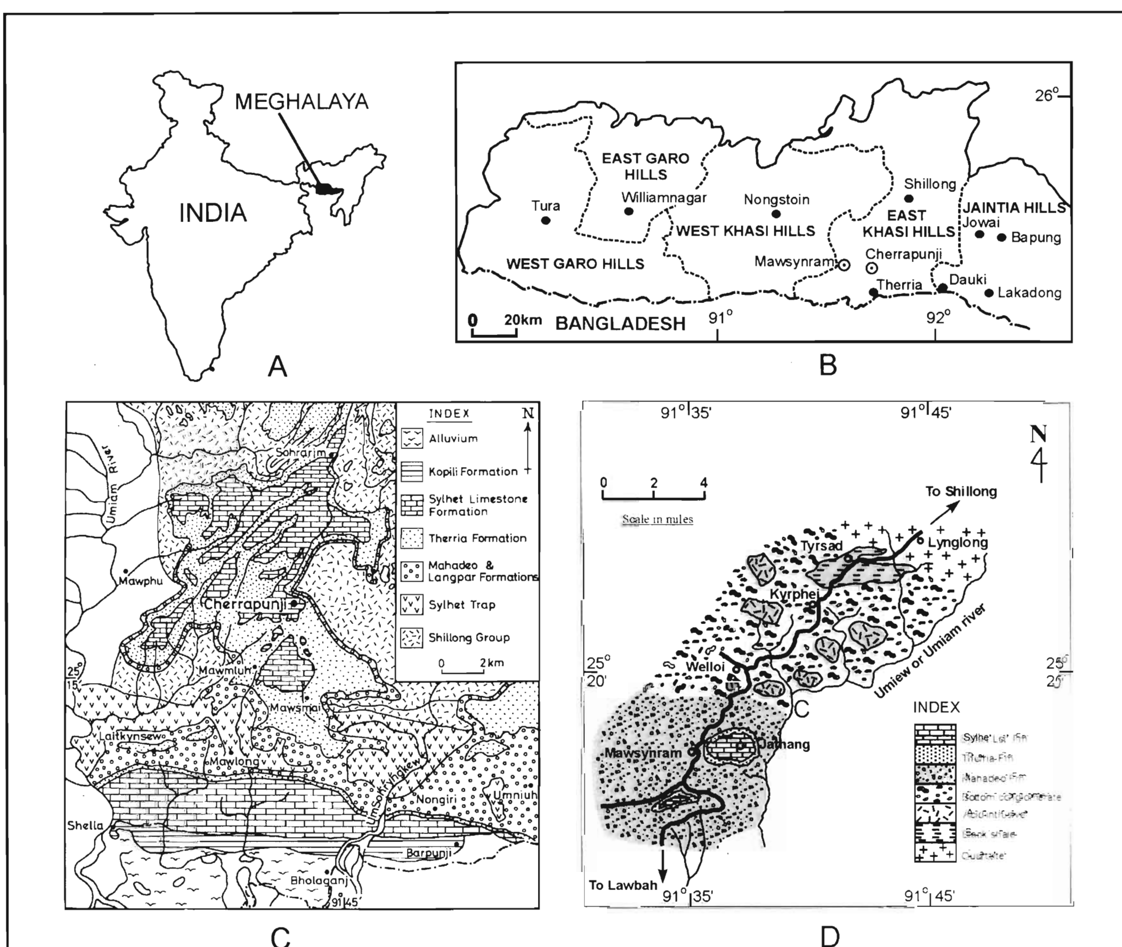


Fig. 1. Location (A,B) and geological map of the study areas in Cherrapunji C (after Ghosh, 1940, and Garg and Khowaja-Ateequzzaman, 2000) and Mawsynram D (after U. K. Misra and S. Sen, unpublished), Khasi Hills, Meghalaya, India.

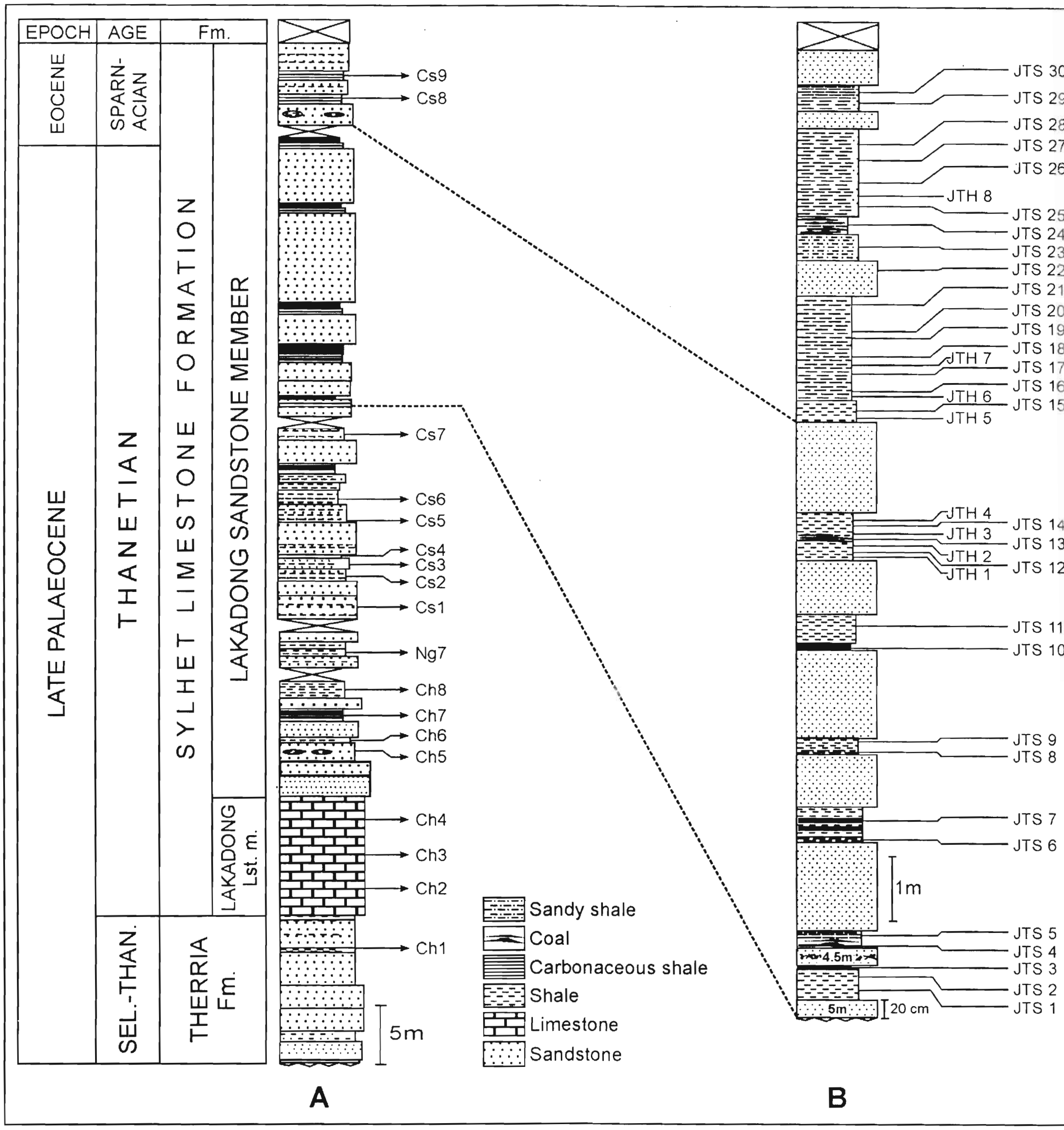


Fig. 2. Litholog of studied sections exposed in (A) Cherrapunji and (B) Jathang. Position of samples in both the lithologs are given.

bordering the plains of Bangladesh, is characterized by the extensive development of carbonate alternating with sandstone. The major part of this succession ranges in age from late Paleocene to middle Eocene (Table 1).

The Palaeogene carbonate succession exposed in the Khasi Hills, South Shillong Plateau belongs to the Sylhet Limestone Formation, which includes three prominent foraminifera rich limestone units, interbedded with thick sandstone-shale units (Wilson and Metre, 1953; Nagappa, 1959; Raja Rao, 1981). The Sylhet Limestone Formation ranges in age from late Palaeocene to middle Eocene (Thanetian – Bartonian). All the three limestone units contain characteristic and datable larger benthic foraminiferal assemblages. The Lakadong Sandstone Member contains thin, impersistent but workable coal seams in parts of the Khasi and the Jaintia Hills. The present study is confined to the Lakadong Sandstone Member of the Sylhet Limestone Formation exposed around Cherrapunji (Cherrapunji area) and Jathang (Mawsynram area) in the East Khasi Hills (Figs. 1C, 1D). Incidentally, today this area receives the maximum annual rainfall in the world due to the orographic rising of the clouds almost throughout the year.

The foram-algal rich Lakadong Limestone and the coal-bearing Lakadong Sandstone (Sylhet Limestone Formation) conformably overlie the sandy Therria Formation. The Lakadong Limestone and Lakadong Sandstone are exposed over wide areas around the Cherrapunji and the Mawsynram regions.

MATERIAL AND METHODS

Samples for the present study were collected from sections exposed north of Cherrapunji and at Jathang, near Mawsynram in the East Khasi Hills (Figs. 2A,B). For the recovery of dinoflagellate cysts, the samples were processed using standard palynological techniques. After HCl and HF treatment, the macerate was treated for few minutes with dilute HNO_3 and washed using 15μm sieve. Precise quantitative estimation of organic matter (debris) was done for palynofacies analysis by the method of Sittler and Schuler (1991). For palynofacies analysis samples were treated with HCl and HF and thoroughly washed with distilled water. Use of oxidizing regents was restricted to minimum to provide consistency in the organic matter characteristics. The water-free residue was mixed with polyvinyl alcohol and spread evenly on the glass cover slides. Permanent slides were prepared by fixing the oven-dried cover slides using Canada Balsam as the mounting medium. Study and photography was carried out on Olympus Vanox-AH2 microscope with Nomarski Interference Contrast and automatic photo attachments. The illustrated specimens are provided with the England Finder positions on the respective slides. The slides have been registered and deposited in the repository of the Museum, Birbal Sahni Institute of Palaeobotany, Lucknow.

In the present study, the organic carbon isotopic analysis was performed on the *Apectodinium* dominated samples of Lakadong Sandstone of Jathang section. Fifteen samples (JTS15-JTS30) were used for the organic carbon isotopic study. 10 mg were taken for the extraction of organic carbon. Samples were washed with deionized water and then treated with 30% HCl to dissolve any carbonate. The residues were washed thoroughly with deionized water, dried and homogenized in a mortar. Analyses were performed with elemental analyzer (CE 1110) connected on-line to a Thermo Finnigan Delta Plus mass spectrometer (at the University of Erlangen-Nuremberg, Germany). All values are reported in the standard δ notation in permil relative to V-PDB. Accuracy and reproducibility was monitored by replicate analysis of the graphite standard USGS 24. Reproducibility was better than ± 0.1 ‰ (1 std.dev.)

DINOFLAGELLATE CYST ASSEMBLAGES FROM THE KHASI HILLS

The dinoflagellate cysts recovered from Cherrapunji and Jathang sections are well preserved and show moderate species richness. However, they are absent at few specific levels as a result of change in the facies from shallow marine to near shore coastal depositional setting with greater freshwater influence. The assemblages contain 30 species of dinoflagellate cysts and three species of acritarchs. Peridinioid dinoflagellate cysts (*Apectodinium*, *Rhombodinium*?, *Wilsonidium*?) strikingly dominate over all the other species. The assemblages contain several species of *Apectodinium* including *A. homomorphum*, *A. hyperacanthum*, *A. parvum*, *A. paniculatum*, *A. quinquelatum*, *A. augustum* and *Apectodinium* sp. A. Amongst these, *A. homomorphum* is the most dominant form, followed by *A. paniculatum*. In addition to *Apectodinium*, the Cherrapunji assemblages show common *Wilsonidium*?, while those from the Jathang section contain a rich suite of *Rhombodinium*? species. Some of the characteristic forms of dinoflagellate assemblage are illustrated (Plate I).

Other dinocyst species apart from wetzelielloids are represented by *Polysphaeridium subtile*, *Cordosphaeridium inodes*, *C. exilimurum*, *Achmosphaera sp.*, *Spiniferites spp*, *Thallasiphora pelagica*, *Adnatosphaeridium multispinosum*, *Operculodinium spp.*, *Amphorosphaeridium multispinosum*; with rare occurrence of *Ifecysta pachyderma*, *Muratodinium fimbriatum and Lanternosphaeridium lanosum*. A unique feature of the assemblages from the South Shillong Plateau is that the horizon showing *Apectodinium* acme is represented by domination of *A. homomorphum* species in the basal most part of Eocene. This horizon also exhibits a prominent negative shift with value of -27 ‰ δC^{13} and is considered as a Maximum Flooding Surface (mfs) in the sequence of peak transgression of the area. In the Cherrapunji section, initial increase in the number of wetzelielloid taxa (*Apectodinium* and *Wilsonidicy*) is noted much below the actual *Apectodinium* acme. However in the Jathang section a unique assemblage of wetzelielloid dinoflagellate cysts is recorded above the *Apectodinium* acme showing abundance of forms exhibiting characteristic morphological features transitional between *Apectodinium* and *Rhombodinium*. Both *Wilsonidium* and *Rhombodinium* are globally known from the early Eocene strata only. Hence presence of these taxa from the late Thanetian-Sparnacian stage is thought to represent the earliest evolutionary stock of the wetzelielloid lineage that subsequently gave rise to *Rhombodinium* and *Wilsonidium* in Eocene. The taxonomic and morphologic aspects of these early wetzelielloids are under study and will be dealt with in detail elsewhere. The previous record of *Wilsonidium* is from the late Thanetian of the Turgay Strait, Kazakhstan (Iakovleva *et al.*, 2001). Based on these findings, first appearance of representatives of the Wetzelielloid group has been suggested in the late Palaeocene, just below the PETM (Iakovleva *et al.*, 2001). Common occurrence of Wetzelielloid group across the PETM interval in northeastern India is noteworthy. There is a close morphological similarity of the forms from the two regions.

PALAEOECOLOGY OF *APECTODINIUM*

Apectodinium is supposed to be a warm water taxon; motile stage closely resembles the modern day protoperidinioid dinoflagellate cysts (Bujak and Brinkhuis, 1998). It is belived to be a heterotrophic peridinioid that fed on organic detritus or other micro biota e.g. prasinophyte algae, diatoms (Jacobson and Anderson, 1986; Crouch *et al.*, 2001). *Apectodinium* is thought to be a taxon that prefers low salinity, and its motile stages, therefore, might have been

EXPLANATION OF PLATE I

(All photographs magnefied x 500)

Apectodinium and related taxa from the Cherrapunji section:

1. ***A. paniculatum***, BSIP slide nos. 12482, W44/2.
2. ***Apectodinium*** sp cf. ***A. paniculatum***, BSIP slide nos. 12490, U54.
3. ***Wilsonidium*** ? sp. A, BSIP slide nos. 12485, J43/1.
4. ***A. homomorphum***, BSIP slide nos. 12487, G60.

5,6. ***Apectodinium*** sp., BSIP slide nos. 12483, F64, 12481, W39/4.

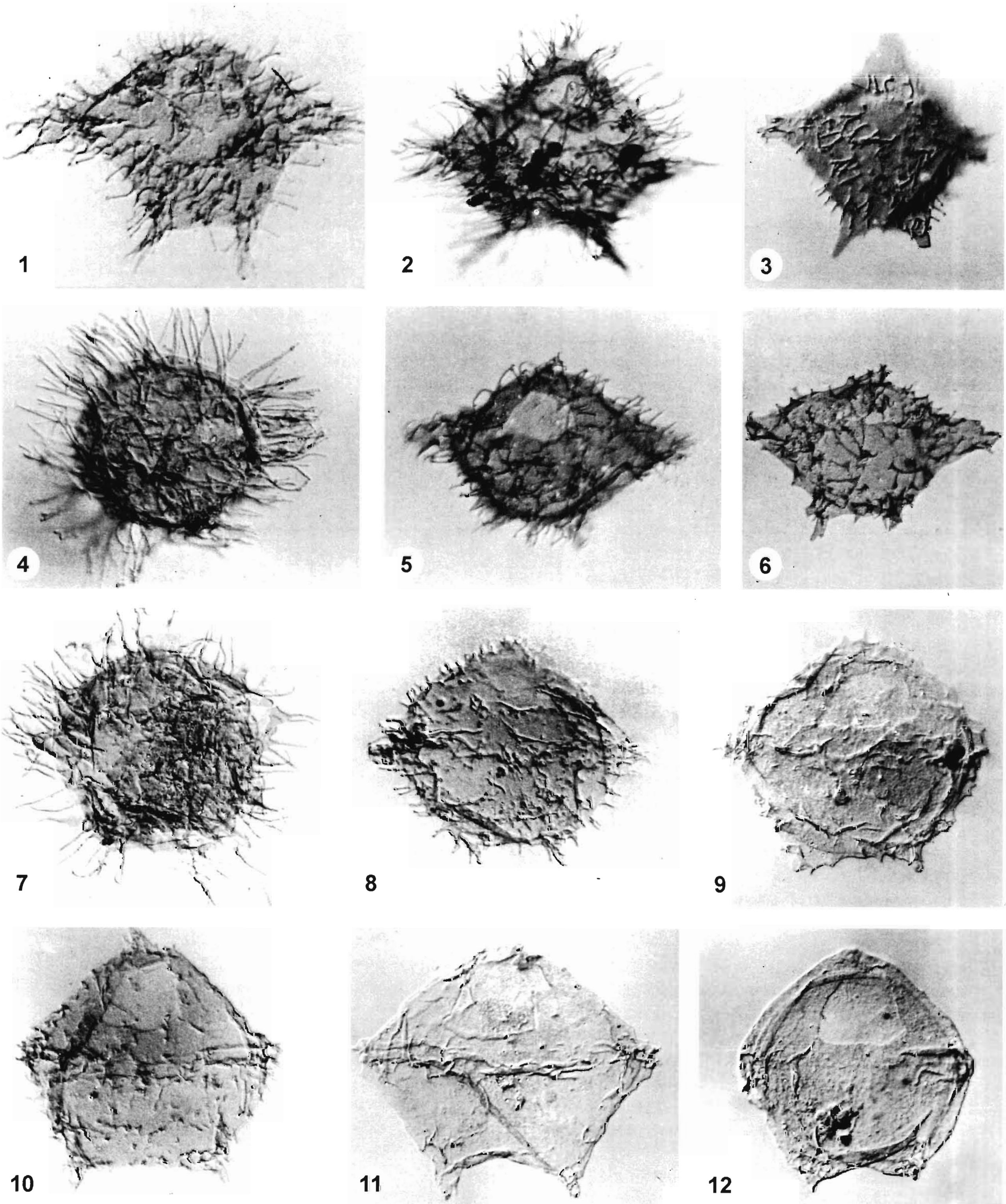
Apectodinium and related early wetzelielloid taxa from the Jathang section:

7. ***A. homomorphum***, BSIP slide nos. 12726, K62/4.

8,10. ***Apectodinium*** spp., BSIP Slide nos. 12726, P58; 12727, V42/4.

11,12 ***Rhombodinium***? spp., BSIP slide nos. 12729, H54/2, 12728, J45/4.

Plate I



PRASAD, GARG, ATEEQUZZAMAN, SINGH AND JOACHIMSKI highly tolerant towards fluctuating salinity and reducing conditions of water column in stressed marine environments. Hence, under such specific environmental conditions, it tends to dominate the assemblages completely when present (Powell *et al.*, 1996). Further, high frequency of heterotrophic peridinioids is due to high primary productivity related to increased nutrient availability in upwelling areas and river mouths (Powell *et al.*, 1992).

In the above context, occurrence of a rich suite of desmids (fresh water algae) in the thin impersistent coal-coaly shale below the *Apectodinium*-rich levels, abounding with transported terrestrial organic matter, in the Jathang section is quite significant (Prasad *et al.*, 2003). The large proportion of fresh water desmids (as primary producers) forming the base of the food chain and high amount of organic detritus could have been the source of nutrient for *Apectodinium* (Prasad *et al.*, 2003). It is proposed that the non mixing of less dense, warm fresh water with more saline sea water during high runoff periods created stratification in the marine water column of the coastal region. Based on modern environmental analogues, it is further surmised that algal blooms in the freshwater plumes over the marine saltwater belonging to cyanophyceae and chlorophyceae might have proliferated in the stratified water column to provide abundant food material to the *Apectodinium* community. These plumes existed in front of estuarine river mouths of palaeodelta complex. Gavrilov *et al.* (1997) argued that during PETM event, interaction between the transgressive sea and coastal topography induced the supply of biophile elements, which would have served as nutrient for the bioproductivity in the basin. Miller *et al.* (1987) have stated that the equable climate of PETM event is related to decrease in thermohaline circulatory system of the ocean, a reduction in decreased wind stress, leading to decrease in upwelling that corresponds to greatly suppressed primary productivity in the marine systems. However, this is applicable to relatively deep marine sequences. In shallow marine coastal regions, the increased precipitation and high continental runoff associated with warm climate greatly enhanced the primary productivity (Malone, 1991). In the present study, *Apectodinium* abundances have invariably been found associated with high influx of terrestrial organic debris in the progradational deposits laid down during early Transgressive Systems Tract and Maximum Flooding Surface. Runoff related high input of organic detritus, nutrient availability and low salinity possibly led to a significant increase in the surface water productivity of the marginal marine setup for the organisms. Significantly, this has been inferred as one of the causative factors, besides exceptionally

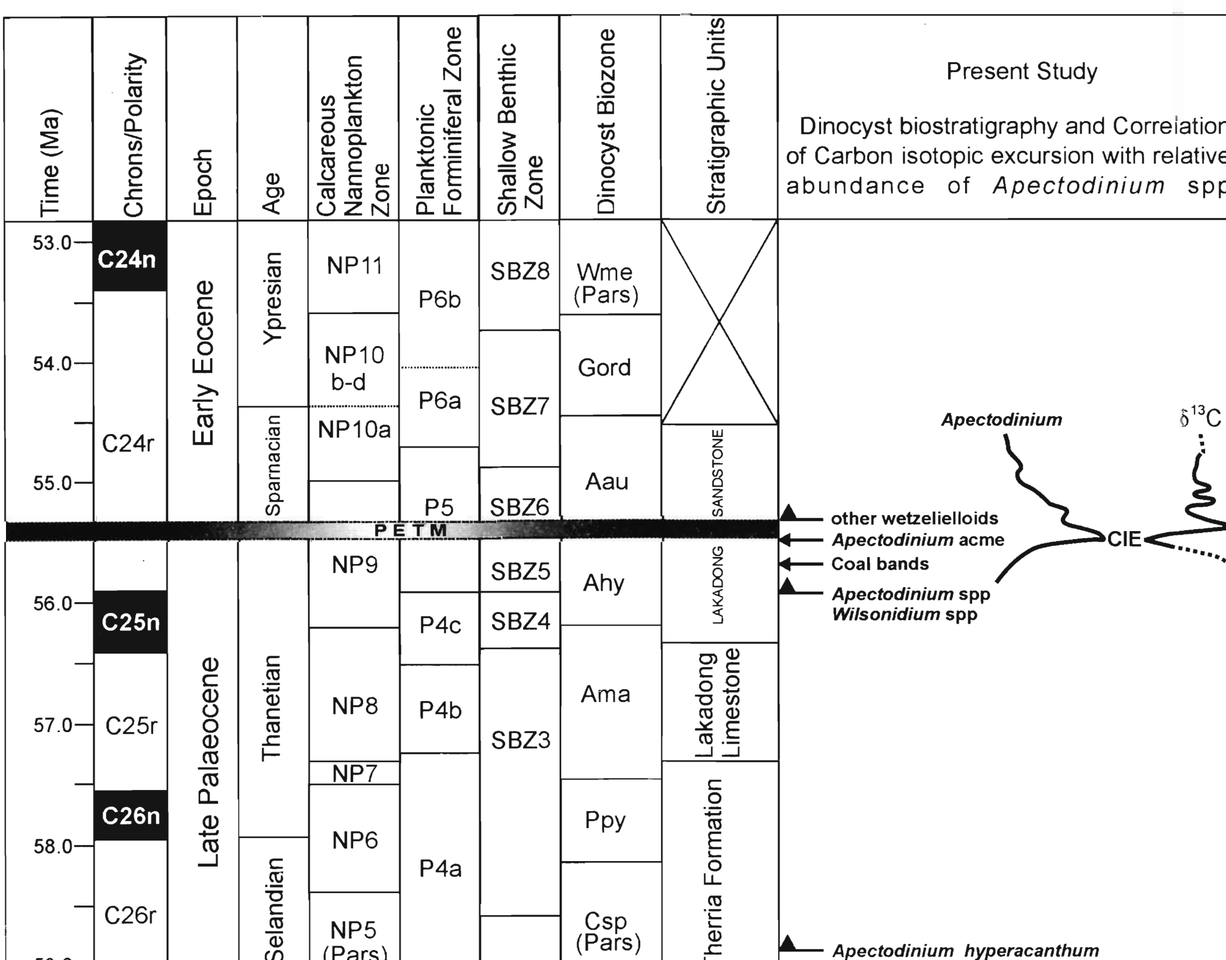


Fig. 3. Relationship of *Apectodinium* Acme, CIE, PETM event and global zonal stratigraphic scheme (after Berggren *et al.*, 1995, 2000; Aubry *et al.*, 2000 and Aubry *et al.*, 2003) in the Khasi hills, South Shillong Plateau, northeastern India. (Integration of Dinocyst zones and SBZ with standard planktic foraminifera/nannofossil zones is by implication).

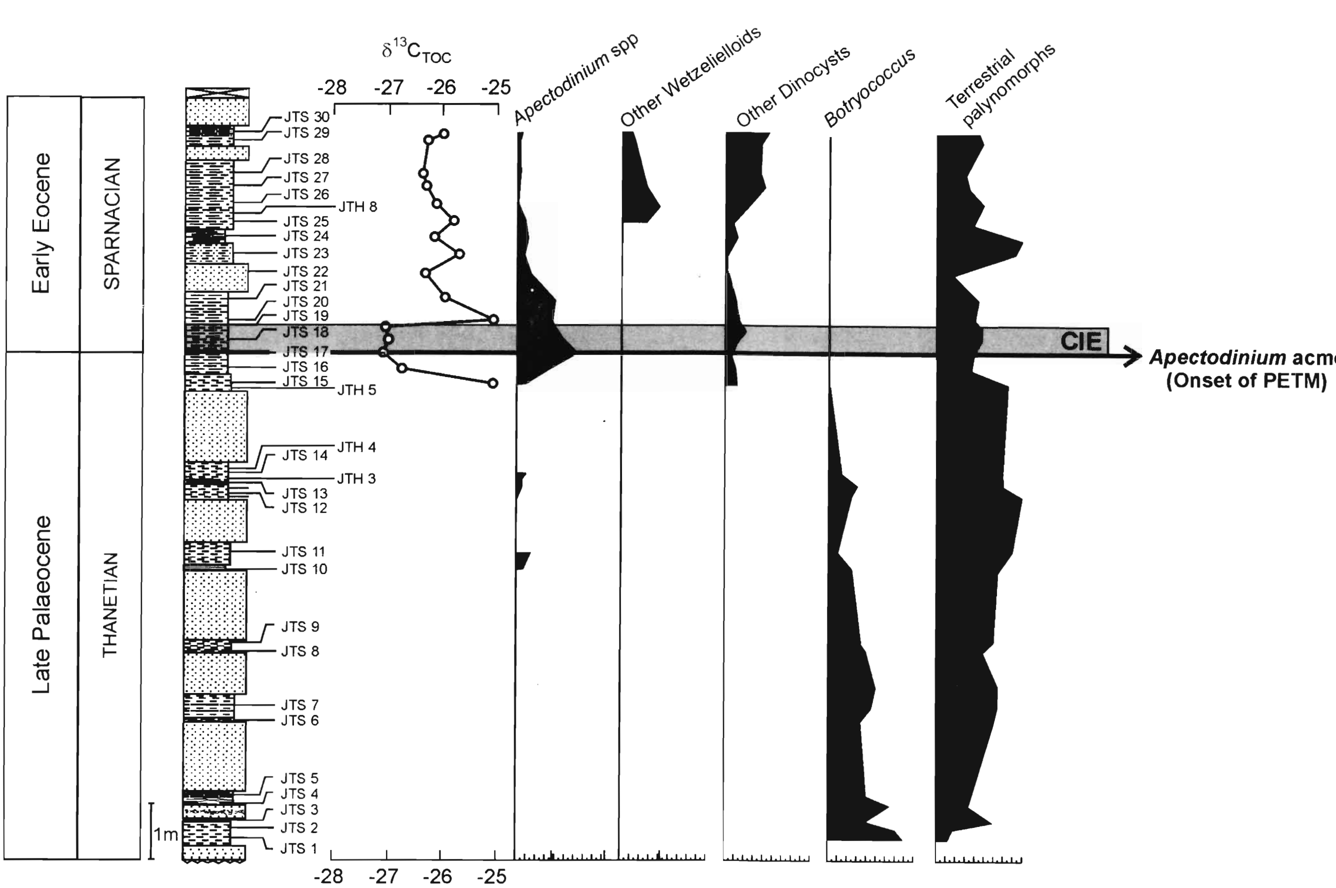


Fig. 4. Organic carbon isotopic curve, *Apectodinium* Acme and relative abundance of other palynomorphs across Palaeocene-Eocene, boundary, Jathang Section.

high global sea surface temperatures, for the *Apectodinium* acme event elsewhere (Crouch *et al.*, 2001; Crouch *et al.*, 2003a,b).

AGE AND CORRELATION

Apectodinium is one of the most characteristic and stratigraphically important genera in the Palaeogene dinoflagellate cyst assemblages worldwide. Standard biozonation schemes based on its species have been proposed and precisely calibrated with standard planktonic foraminifera and calcareous nannofossil biozonation schemes (Powel, 1992; Bujak and Hudge, 1994; Bujak and Brinkhuis, 1998). The succession under study is from near shore, inner neritic area, and does not contain any nannofossils or planktic forams. Thus it is not possible to directly assign the standard calcareous planktic microfossil zones. In the present study, the *Apectodinium*-rich assemblages show a first order correlation with the Shallow Benthic Zones of larger foraminifera recorded from the underlying Lakadong Limestone and the overlying Umlatdoh Limestone. The dinoflagellate cyst Aau biozone Powell, 1992 is characterized by the presence of *Apectodinium augustum*, *A. hyperacanthum*, *A. paniculatum*, *A. parvum*, *A. quinquelatum* and *A. summisum*, and also the long ranging *A. homomorphum*. It has been calibrated with calcareous nannofossil Zone NP9 (pars) of (Martini, 1971) and planktonic foraminiferal Zone P5 (pars) (Fig. 5).

The present dinoflagellate cyst assemblages, assigned to the Ahy/Aau biozones of Powell (1992), are found to directly overlie the *Glomalveolina primaeva* Assemblage zone (SBZ3=Late P4) and the lower part of the *Ranikothalia nuttalli-Miscellanea miscella* Assemblage zone (SBZ5 =P5), recorded from the underlying Lakadong Limestone (Jauhri, 1994, 1996, 1997, 1998). The basal part of the overlying Umlatdoh Limestone has been assigned to the base of the zone SBZ7, in view of the occurrence of *Daviesiana ruida* in association with *R. nuttalli* (Jauhri, 1994, 1997). This first order calibration has prompted the suggestion that the *Apectodinium* acme in Meghalaya shows a close stratigraphic correspondence with the SBZ 5-SBZ 6 zones of the larger foraminifera, which have been equated with the planktic foraminiferal mid P5 Zone (Garg and Khowaja-Ateequzzaman, 2000) and hence corresponds to the newly introduced stage Sparnacian at the base of Eocene (Aubry *et al.*, 2003) (Fig. 3). The presence of rich and diverse *Apectodinium* assemblages with marker species in the Lakadong Sandstone exposed in the Cherrapunji and Jathang sections suggests its placement in the Aau biozone. The CIE interval associated with the *Apectodinium* acme at the base of Aau biozone is assigned to base of Sparnacian or Palaeocene-Eocene boundary interval (Fig. 8).

Comparable assemblages dominated by *Apectodinium* are widely recorded from other regions in India (see Fig. 7) e.g. Vriddhachalam (Jain and Garg, 1986) and subsurface of Karaikal (Jain and Garg, unpublished data) in the Cauvery Basin, Tamilnadu; subsurface of the Krishna-Godavari Basin, Andhra Pradesh (Garg *et al.*, 1995; Mehrotra and Sarjeant, 1999); and subsurface of the Kutch Basin and the Upper

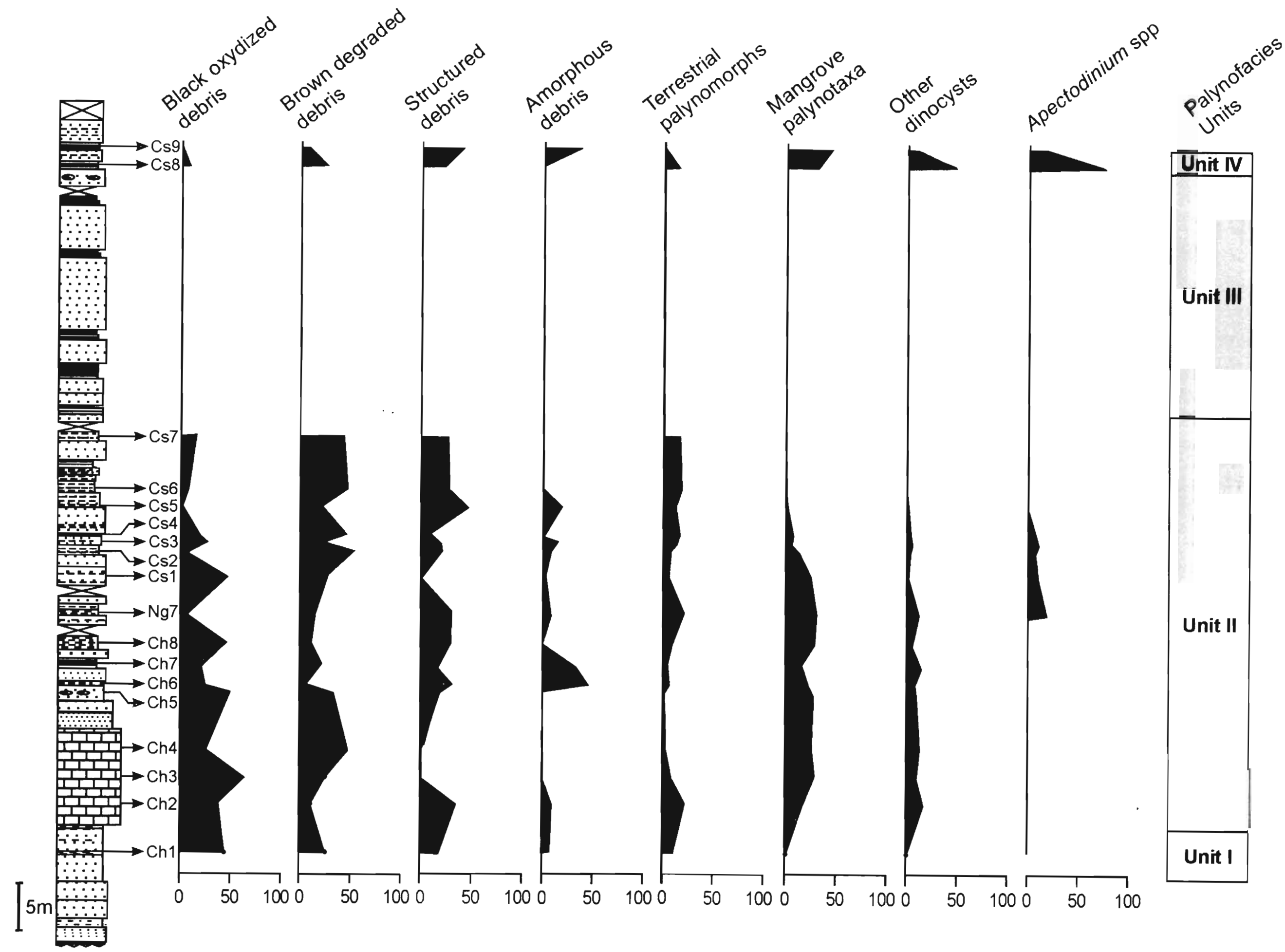


Fig. 5. Palynofacies distribution and relative abundance of *Apectodinium* in the Cherrapunji Section.

Assam Valley (Garg and Khowaja-Ateequzzaman, unpublished data). Direct calibration of *Apectodinium*-rich dinoflagellate assemblages with the late Palaeocene nannofossil zone NP9 has been established in the Cauvery Basin (Jain *et al.*, 1983; Jain and Garg, 1986).

THE ORGANIC CARBON ISOTOPIC STUDY

A prominent negative shift of -2 ‰ in $\delta^{13}C$ values from -25.3 ‰ to about -27.3 ‰ (Fig. 4) is noted in the upper part of Lakadong Sandstone, within the palynofacies Unit IV from Sample nos. JTS15 - JTS-17. A strong acme of *Apectodinium* spp (exceeding 65% of the total palynomorphs) coincides with the prominent negative shift in $\delta^{13}C$ which is interpreted to represent carbon isotope excursion (CIE) in the Jathang section (Fig. 9).

PALYNOFACIES STUDY

On the basis of palynofacies and lithological characteristics the Palaeocene-Eocene succession of Cherrapunji and Jathang sections have been divided in to four Units (I, II, III and IV). In the Cherrapunji section all the four units are present. In the Jathang section, the upper most part of Unit II, Unit III and Unit IV are present; while Unit I is missing (Figs. 5,6). In Jathang section, Unit III and IV were sampled at close interval in order to identify PETM interval, location of CIE, and to document paleoevironmental changes immediately before and after the PETM event.

i. Unit I

Lithofacies: Hard, buff to brownish, medium to coarse, ferruginous sandstone that is gradually replaced by fine sandstone with thin bands of pyriteous siltstone and carbonaceous shale upward. Regionally spread *Thalassinoides* ichno horizon above the coarse sandstone is the characteristic feature of this litho unit (Fig. 3).

Palynofacies: Dominated by black oxidized and brown degraded organic matter debris that gradually decreases upward to be replaced by large proportion of well-preserved structured debris above the ichno horizon. Amorphous organic matter is absent throughout the unit while palynomorphs, representing brackish swamp conditions, show moderately increasing trend upwards. This unit shows upward decreasing trend in the dinocyst diversity. The size of the land derived debris increases but its sorting decreases (Fig. 5).

Depositional environment: The palynofacies study indicates depositional environment ranging from open marine, inner neritic to more proximal coastal setting. The dominance of black and brown, degraded debris in the lower part indicates high energy and oxidizing conditions at the time of deposition, that is replaced by low energy and reducing environment of deposition in upper part, indicated by the influx of well preserved terrestrial debris.

ii. Unit II

Lithofacies: Grey to brownish grey bivalve rich, foaminiferal–algal limestone with thin grey shale and carbonaceous shale parting in the upper part (Figs. 5,6).

Palynofacies: Increase in black oxidized debris and degraded brown debris, absence of amorphous debris and presence of poorly preserved dinoflagellate cysts in the lower part of this unit are indicative of oxidizing conditions. An increasing trend in terrestrial palynodebris and dinocyst abundance is noted. However, dinocyst diversity decreases considerably in the upper part of this unit. Amongst palynomorphs, representatives of brackish swamp conditions (*Spinizonocolpites* spp, *Proxapertites* spp, and pteridophytic spores) show increasing trend upward. Dominance of well preserved cuticular debris and amorphous organic matter is confined to the upper part of this unit. Predominance of monotypic assemblages of *Apectodinium* dinoflagellate cysts is observed at specific levels particularly in the grey shales in the upper most part of this unit (Figs. 5,6). Jellified organic matter dominates in the carbonaceous/coaly band. A unique feature is the occurrence of large proportions of freshwater desmids below the carbonaceous/coal band in the Jathang section.

Depositional environment: Deposition took place in more proximal environment than Unit I. The bivalve rich limestone facies with high proportion of black oxidized debris and degraded brown debris indicates shallowing of the basin, low water depth, low terrigenons clastic supply and well oxygenated conditions at the sediment water interface. Gradual increase in the terrestrial plant debris in the upper part of this unit indicates further progadation and deposition in a more proximal coastal setting. Based on palynofacies studies, the most likely environment of upper part of this unit is estuarine. It is considered that high input of freshwater from the adjacent land would have created brackish water conditions, favourable for the growth and proliferartion of the *Apectodinium* dinoflagellate cysts. The dominance of amorphous organic matter content, associated with fine translucent debris, indicates low energy stagnant condition of the water column and anoxic conditions at the sediment water interface leading to the deposition of laminated, organic rich shale in the upper part of this unit. An increase in pteridophytic spores and other land derived debris indicate fresh water swamp with warm and humid climatic conditions during deposition of the upper part of this unit. Occurrence of freshwater desmid in association with land derived organic matter in the upper most part of this unit indicates mild acidic peat bog type of environment.

iii. Unit III

Lithofacies: Intercalations of 40-60 cm thick buff to whitish, soft, friable, medium to coarse grained sandstone and 20-30 cm thick chocolate shales containing thin lignitic, carbonaceous and coaly shales at the base (Fig. 5,6).

Palynofacies: The palynofacies of chocolate shales and the associated carbonaceous/lignitic/coaly sequence is characterized by abundant unsorted terrestrial organic matter debris, low numbers of pollen and spores and large proportion of *Botryococcus* algae. There is complete absence of

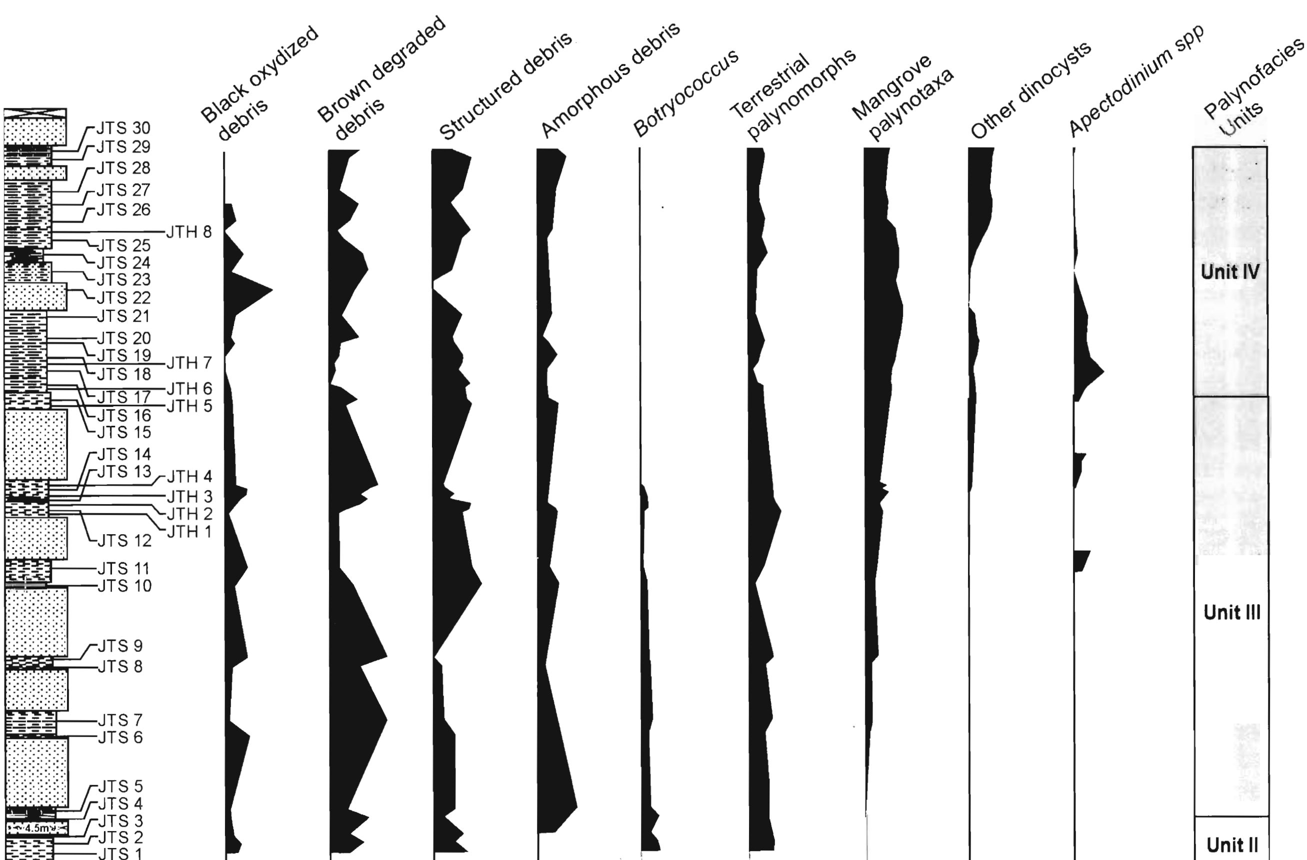


Fig. 6. Palynofacies distribution and relative abundance of *Apectodinium* in the Jathang Section.

dinoflagellate cysts in the lower part of this unit. However, brackish mangrove and coastal elements increase in the upper part of the unit. Samples from upper part show occasional poorly preserved dinoflagellate cysts (Figs. 5,6).

Depositional environment: The palynofacies of the carbonaceous shale and thin coal bands indicate supratidal to freshwater swamp conditions and water logged anoxic environment of deposition. Occurrence of large proportion of *Botryococcus* colonies in the lower part of this unit indicates prevalence of freshwater swamp conditions. Low occurrence of pollen and spore is due to dilution by high input of terrestrial clastic material. Occurrence of jellified organic matter debris at specific intervals in this facies indicates process of coal formation. The increasing trend in the brackish mangrove and dinocyst content in the upper part of this unit indicates lagoonal environment of deposition with increasing marine influence.

iv. Unit IV

Lithofacies: 30-80 cm thick grey fissile laminated shales with small pyritic nodules, interbeded with 20-30 cm thick coarse sugary sandstone (Fig. 6).

Palynofacies: Palynofacies of this unit is characterized by gradual upward increase in the dinoflagellate cyst diversity and abundance. The lower part of the unit is dominated by palynomorphs representing brackish swamp environment with monotypic blooms of *Apectodinium* dinoflagellate cysts. The frequency of land-derived palynomorphs gradually decreases upward and is replaced by more diverse dinoflagellate cyst assemblages dominated by *Apectodinium* spp, *Rhombodinium*? spp and *Wilsonidium*? spp. Amongst the terrestrial organic matter, the size and frequency of black and brown degraded debris decreases and is replaced by fine well preserved structured debris and amorphous debris in the upper part of this unit.

Depositional Environment: Enhanced frequency of dinoflagellate cysts in this unit as compared to the underlying unit, indicates inundation of coastal swamp by the sea water. The abundance of terrestrial clastic debris is indicative of its constant supply from the adjacent land. Increased dinoflagellate cyst diversity in the upper part is indicative of further landward inundation of the sea and prevalence of normal marine conditions in the upper part of this unit.

INTERPRETATIONS OF PALYNNOFACIES DATA IN A SEQUENCE STRATIGRAPHIC FRAMEWORK

In a marginal marine setting, palynofacies parameters largely depend on sea level fluctuations. Vertical changes in the palynofacies have been used in the interpretation of the depositional environment and relative sea level changes in the Late Palaeocene-Early Eocene sequence of Cherrapunji and Jathang sections (Figs. 5,6).

The lower part in Cherrapunji section, representing the basal most part of palynofacies of Unit I, is marked by a high percentage of oxidized and degraded organic debris. Abundance of oxidized debris is probably because of its highly buoyant and resistant nature to biodegradation, hence, it can survive reworking and transportation during Transgrssive Systems Tract (TST) towards more distal environment, away from the fluvio-deltaic source. This feature corresponds to the retrogradational sequence of the Transgressive System Tract (Steffen and Gorin, 1993). The shelf sheet sand of Cherrapunji section was deposited in the accommodation space made available by the landward shift of the shore face (shoreface retreat). In Cherrapunji section a distinct bioturbated horizon is present within Unit I. This bioturbation horizon is considered as shelf sheet sand deposit and is interpreted as Maximum Flooding Surface (mfs) or maximum starvation surface (Garg and Khowaja-Ateequazzaman, 2000). It represents low sedimentation rate. and makes a marker bed within the Therria Formation (Fig. 7).

In the Cherrapunji section, the upper part of Unit II corresponds to the foraminifer-algal rich limestone. It shows upward decreasing trend in dinocyst assemblages (Fig. 5). The oxidized and degraded terrestrial organic matter content indicates shallowing of the basin, low water depth and well-oxygenated environment of deposition. It represents aggradational phase and initial stage of early Highstand Systems Tract (HST) (Fig. 7) in the Cherrapunji section. However, in the Jathang section only the lower part of Unit II i.e., sandstone and carbonaceous shale is exposed (Fig. 2). The lower part of Unit II (Figs. 5,6)) in the Cherrapunji and Jathang sections shows marked increase in terrestrial organic matter suggesting a rapid progradation of the shoreline and establishment of lagoonal environment of deposition (Fig.7). The high freshwater influx due to proximity of fluviodeltaic systems caused low salinity milieu, ideal for the proliferation of *Apectodinium* assemblages. The carbonaceous shale in the upper part of the sequence was deposited in coastal peat bog type of environment formed in low-lying coastal areas during late Highstand Systems Tract (Fig. 7). Thus the Unit II was deposited during Highstand Systems Tract with slowly falling sea-level.

The high siliciclastic influx, predominance of terrestrial organic matter and gradual increase in marine components represents deposits of early Transgressive Systems Tract for Unit III (Fig. 7). During this phase, organic rich sediments and coal were laid down in highly restricted coastal environments, such as fresh water swamp and closed lagoons. In the Jathang section, this unit is represented by alternation of sandstone and shales along with bands of carbonaceous shale (Fig. 7). There is no record of deposits of Lowstand Systems Tract (LST) between Unit II and Unit III. Such deposits are probably absent in the study area. The sharp increase in marine biotic component of Unit IV as compared to Unit III indicates deposition in more distal setting. The high content of terrestrial component in theses deposits indicates high fresh water influx and low salinity conditions suitable for the luxuriant growth of *Apectodinium*. The *Apectodinium* dominated shale layer probably represents Maximum Flooding Surface (mfs) or peak transgression (Fig. 7). The presence of large proportion of amorphous organic matter, well preserved structured organic debris and high dinocyst diversity and abundance further points towards increased water depth and low level of oxygen in water column (Fig. 6). These features during deposits of Unit IV further suggest sea-level rise and peak transgression in the area (Fig.7).

DISCUSSION

i. Relationship with PETM event

Apectodinium is the earliest representative of the wetzelielloid group of peridiniacean dinoflagellates, which

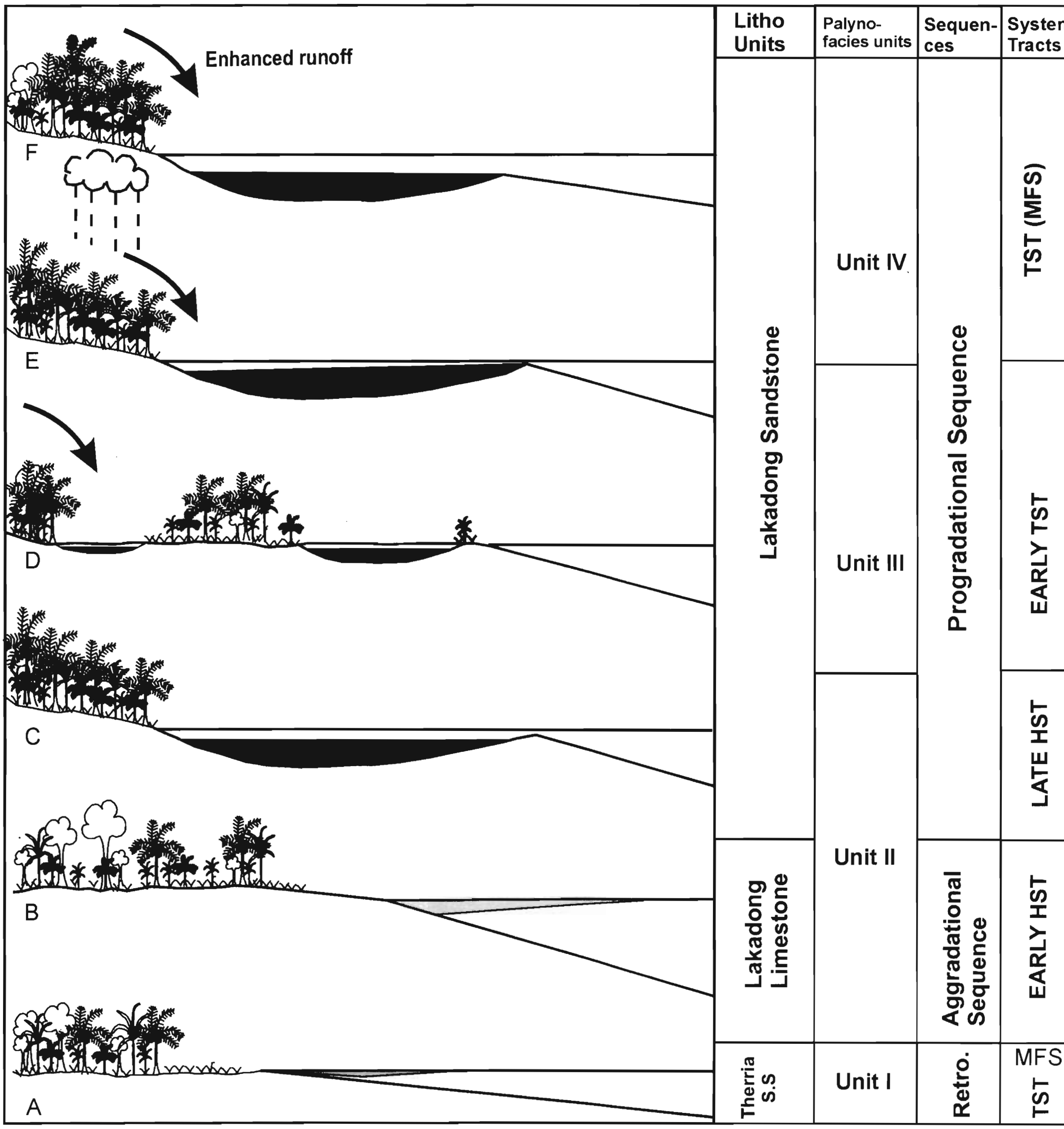


Fig. 7. Schematic drawing showing successive stages of depositional environments and its relationship with the Palynofacies units and System Tracts during latest Palaeocene -earliest Eocene in South Shillong Plateau, Meghalaya; Tst- Transgressive Systems Tract, Hst- High stand Systems Tract

A. Deposition of Transgressive shelf sheet sand B. Deposition of foraminifera-algal rich limestone. C. Deposition of organic rich sediments in estuarine environment D. Deposition in carbonaceous shale/coal in a coastal freshwater swamp environment E. Deposition of organic rich shales in caostal lagoon F. Deposition of organic rich sediments in a shallow marine setting.

was long believed to have originated and rapidly diversified during late Thanetian times. Evidences from Tunisia (Brinkhuis *et al.*, 1994) and India (Garg and Khowaja-Ateequzzaman, 2000; Garg *et al.*, 2006) now suggest that *Apectodinium* first appeared much earlier (close to the Danian-Selandian boundary), in the low latitudes. Based on the studies carried out in northwest Europe and other parts of the world, it has been observed that dinoflagellate cyst assemblages became dominated by *Apectodinium* within the nannoplankton zone NP9 and the planktic foraminiferal zone P5, within late Thanetian – Sparnacian, leading to the suggestion that the *Apectodinium* acme at the base of Sparnacian corresponds to the PETM (earlier considered LPTM) (Bujak and Brinkhuis, 1998) (Fig. 3). Subsequent calibration with the BEE and CIE has led to the conclusion that *Apectodinium* acme was indeed a globally synchronous phenomenon associated with the Palaeocene Eocene Thermal Maxima (PETM), and that the onset of the acme of *Apectodinium* coincided with the CIE and beginning of the PETM and its decline occurred near the end of the PETM (Crouch *et al.*, 2001; Crouch *et al.*, 2003a,b).

The Indian occurrences of the *Apectodinium* acme from

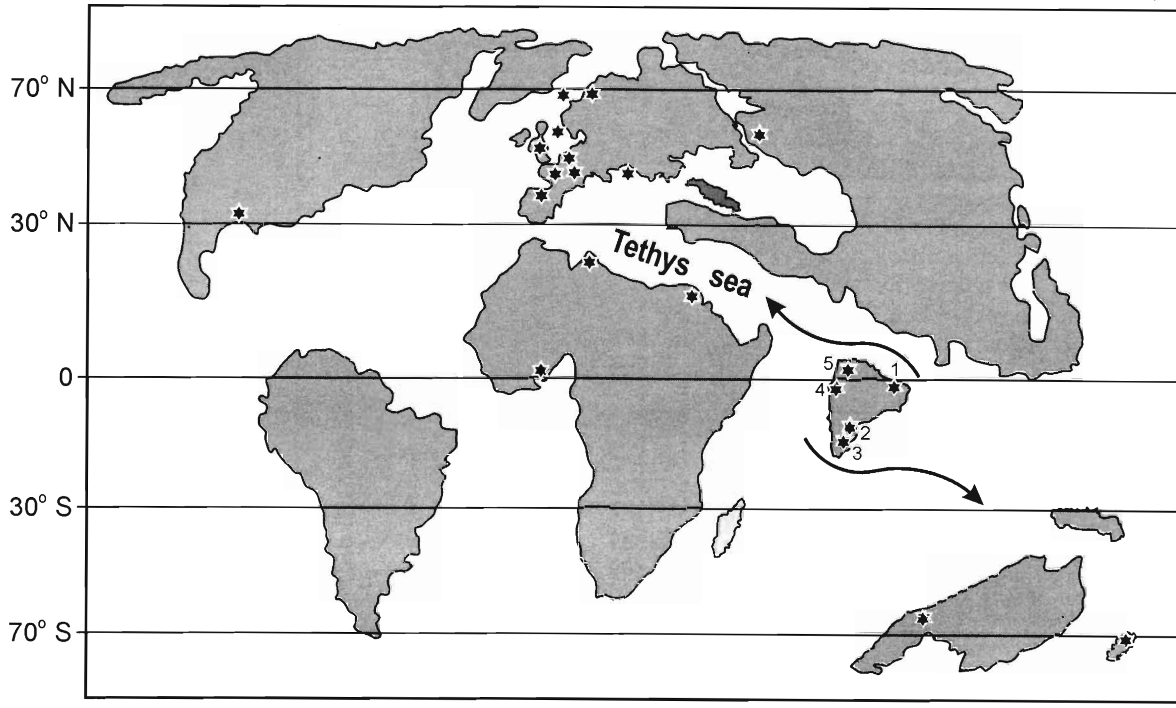


Fig. 8. Global distribution of *Apectodinium* dominated dinoflagellate cyst assemblages (marked by stars) and probable migratory routes (arrows) [Palaeogeographic reconstruction of late Palaeocene after Scotese and Golanka, 1992 in Crouch *et al.* 2001; 1-Meghalaya and Upper Assam Valley 2-Krishna-Godavari basin, 3-Cauvery Basin, 4-Kutch Basin, 5-Surghar Salt range, Pakistan].

low latitude (palaeo) significantly conform to PETM and show similar distribution pattern. *Apectodinium* dominated assemblages from India have been plotted on a palaeogeographic map of the late Palaeocene-early Eocene along with known global records (Fig. 8). It clearly brings out the fact that the only other records of *Apectodinium*-dominated assemblages from palaeoequatorial region are from Nigeria (Jan du Chene and Aderidan, 1984) and Pakistan (Köthe, 1988, 1990). However, late Paleocene records of *Apectodinium* from mid and high latitudes of Northern and Southern Hemispheres are numerous e.g. Austria (Heilmann-Clausen and Egger, 2000), Belgium and France (Dupis *et al.*, 1990; De Coninck, 1999a, 1999b), Denmark (Heilmann–Clausen, 1985, 1998), England (Costa and Downie, 1976; Harland, 1979; Powell *et al.*, 1996), Germany (Heilmann-Clausen and Costa 1989; Köthe, 1990), Spain (Caro, 1973; Núñez-Betelu *et al.*, 2000), North Sea (Heilmann–Clausen, 1994; Powell *et al.*, 1996; Thomas, 1996), Alabama (Harrington and Kemp, 2001), Turgay Strait, Kazakhstan (Iakovleva *et al.*, 2001), western Siberia (Iakovleva, 2000), Australia (Cookson and Eisenack, 1965) and New Zealand (Wilson, 1967,1988; Crouch *et al.*, 2000, 2001, 2003a,b) (Fig. 8).

It is considered that impact of the sudden warming during PETM might have varied considerably from low to high latitudes. A rapid warming of deep water in high latitudes and considerable rise in temperature in surface waters in the equatorial region is interpreted (Kennett and Stott, 1991). Temperature related changes during PETM seem to be more pronounced in mid and high latitudinal regions. It is envisaged that in the low latitudes these changes were reflected by intense warm and humid climate with enhanced rate of precipitation (Crouch *et al.*, 2003a). Pittet *et al.* (1995) interpreted that the distribution of coal and high influx of siliciclastic sediments through time is mainly controlled by climatic cycles associated with the 400,000-year orbital eccentricity cycles. Influx of siliciclastics and the occurrences of coal seem to be linked with warm and humid periods (Pittet and Gorin, 1997). Occurrence of the laminated carbonaceous shale during that interval and coeval occurrence of thin impersistent coal beds in the entire South Shillong Plateau (Garo, Khasi and Jaintia hills) were deposited during late Highstand and early Transgressive phases in the late Palaeocene, prior to the PETM event. The palynological evidences during PETM interval indicate domination of brackish mangrove, coastal vegetation and tropical rainforest elements (e.g. *Spinozonocolpites*, *Proxapertites* etc.) (Fig.6). The megafloral evidences from Lakadong Sandstone postulate warm and humid climate with much higher rainfall, leading to swampy conditions (Mehrotra, 2000, 2003).

In northwestern Belgium, deposition of lignite during PETM event indicates development of marshes and swamp due to climate warming (Steurbaut *et al*, 2000). Development of organic rich sapropelic sediments has been recorded from several regions in the world (Gavrilov *et al.*, 1997; Muzylev *et al.*, 1989; Oberhänsli and Beniamovskii, 2000; Speizer *et al.*, 2000). Speizer and Wagner (2002) described suboxic-anoxic conditions and deposition of TOC rich sapropelic sediments in the epicontinental basins bordering the Tethys.

In the present study, the palynofacies trend of Unit IV (Figs. 5,6) in Cherrapunji and Jathang sections indicates sea level rise in low land coastal region. It was a short-lived transgression close to the Paleocene-Eocene boundary, which resulted in flooding of low land coastal swamp by the sea. Globally, the transgression at the base of Eocene corresponds to the PETM event (Steurbaut *et al.*, 2000). In the present study, it is discussed that the PETM event close to the Paleocene-Eocene boundary has resulted in renewed transgression and formation of brackish lagoons with increasing marine influence (Fig. 7). The *Apectodinium* acme may correspond to the maximum flooding event. During this transgression, inner shelf conditions were established and the sea inundated coastal areas to form lagoons and estuarine complexes in the more proximal setting.

Sequence stratigraphic analysis in various stratigraphic sections of late Paleocene-early Eocene was done globally for the identification of third order sea level fluctuations and depositional set up in different basins (Powell *et al.*, 1996). The dinocyst record provides an excellent means of identifying the proximal and distal deposits of a marginal sea; hence dinocyst sequence biostratigraphy was applied on the late Palaeocene-early Eocene sequences exposed in southeast England (Powell *et al.*, 1996), and later on in the Turgay Strait, Kazakhstan (Iakovleva *et al.*, 2001). Five Thanetian sequences Th1, 2, 3, 4, 5 have been identified on the basis of dinoflagellate cyst palaeoecology and sedimentological evidences (Powell *et al.*, 1996). In the present study from northeast India, such sequences cannot be identified due to the lack of continuity in the dinocyst data, absence of characteristic unconformity surfaces, difficulty in identification of maximum flooding surfaces in near coast deposits, and nonavailability of equivalent deep marine sediments in the area. However, based on the available dinocyst evidences, it is considered that the Units I, II, III in Cherrapunji and part of Unit II and Unit III in Jathang can be tentatively equated with Th- 4 and part of the Th-5 sequences while Unit IV corresponds to Th-5 sequence of Powell *et al.* (1996). The PETM event is supposed to have occurred during Th-5 (Iakovleva *et al.*, 2001). Deposits of the Lowstand Systems Tract of Th- 4 sequence are absent in the present area of study.

The onset of *Apectodinium* Acme in Unit IV of the Meghalaya in the present study has been considered to represent PETM event in India. Possible relationship of the *Apectodinium* acme in India with the global PETM event is depicted in figure 8. *Apectodinium* dominance in Indian sections may thus correspond to the global biotic response linked to PETM event. Another significant expression of PETM event in the low equatorial latitudes from India is the increased rate of precipitation (a somewhat monsoon like climate), which resulted in the high river discharge, and enhanced terrigenous input in marginal seas, and development of coastal marshes and lagoon. This led to the deposition of thick siliciclastic sediments with organic matter rich shale and coal deposits in the coastal regions of shallow marine areas. The studies from the late Palaeocene-early Eocene of northeast India strongly support the above contention. *Apectodinium*-bearing deposits from other localities of India need to be worked out for facies analysis, precise chronostratigraphy and sequence stratigraphy to provide a more regional perspective of PETM event. However, a major constraint in the Indian sections is due to near coast deposits with high terrigenous clastic input, poor and sporadic presence of calcareous planktons and dinoflagellate cysts, and nonavailability of equivalent deep water deposits.

ii. Evolution and migration of *Apectodinium*

Brinkhuis *et al.* (1994) noted that the first appearance of *A. hyperacanthum* from the northern low latitude in El Kef section of NW Tunisia lies close to the Danian-Selandian boundary, corresponding to the planktic foraminifera zone P3a and nannoplankton Zone NP5. Garg and Khowaja-Ateequzzaman (2000) and Garg *et al.* (2006) discussed that the first appearance of *A. hyperacanthum* in Meghalaya, India, correlated with planktic foraminiferal zone P3 (Fig. 3). Hence, first appearance of *Apectodinium* from the southern low latitudes during early Selandian from India further strengthens the hypothesis of Bujak and Brinkhuis (1998) that the evolution of *Apectodinium* took place in low latitudes much earlier during Middle Paleocene time in the Tethyan realm. During late Palaeocene, it migrated into mid and high latitudinal regions worldwide, associated with the relative sea level High Stand/transgression under the influence of enhanced warming of PETM event (Powell *et al.*, 1996; Bujak and Brinkhuis, 1998). Occurrence of morphotypes, similar to *Apectodinium* and *Wilsonidium* reported from the Turgay Strait, Kazakhstan in the present study from the Unit IV of Jathang section is very striking (Fig. 4). These forms are considered to have Tethyan affinity (Iakovleva *et al.*, 2001). The coeval occurrence of these *Apectodinium*, *Wilsonidium*? forms in these far and wide areas proves existence of connection between the eastern Tethys (India) and the Turgay Strait and may further suggest their rapid migration to northern mid latitudes as a result of the relative sea level rise under the influence of PETM through the Tethys Sea Corridor (Fig. 8). The widespread occurrences of similar *Apectodinium* rich assemblages during the same time interval around the margins of the Indian subcontinent also indicate their rapid dispersal. It is presumed that circulation around the Indian Subcontinent and that the westerly flowing equatorial currents through the Tethys Sea Corridor might have provided a rapid migratory mechanism of *Apectodinium*. However, this migratory mechanism for dinoflagellate cysts is highly speculative and there is need to study more sections in low to mid latitudes for better understanding of the regional migratory routes.

Co-occurrence of several new morphotypes supposed to represent the earliest wetzelielloid stock, with the *Apectodinium* acme is a unique feature, related with their rapid evolution and radiation within a short span of time. Although further records of similar forms from equable palaeolatitudes are still awaited, but it can be argued that PETM related climatic perturbations induced a rapid evolutionary turnover in the earliest wetzelielloid stock. The marginal seas in the (palaeo) equatorial latitudes during earliest Eocene probably provided suitable niches for rapid proliferation of *Apectodinium* and related early wetzelielloids with great morphological diversity within a brief time span characterized by profound global warming and associated environmental perturbations.

CONCLUSIONS

1. *Apectodinium* acme recorded from a marginal coastal marine setting in low equatorial (palaeo) latitudes from northeastern India corresponds to the synchronous global biotic response of dinoflagellates to the CIE and the PETM event at Palaeocene-Eocene boundary.
2. The environmental impact of PETM related events in the highly stressed coastal marine setting of the (palaeo) equatorial region is characterized by intensely warm and humid climate resulting in the enhanced rate of precipitation, a monsoon like climate, massive river discharge and reduced salinity in the coastal waters.

3. Runoff-related high input of terrestrial organic debris led to a significant rise in the surface water productivity of the coastal marine waters that was advantageously exploited by these presumably heterotrophic dinoflagellates. The large proportion of fresh water desmids and high amount of organic detritus could have been the source of nutrient for motile stages of *Apectodinium* and related dinoflagellates.
4. Sudden appearance of several new morphotypes at the base of Sparnacian, CIE and *Apectodinium* acme suggests rapid evolution of the early wetzelielloid stock with great morphological diversity under the influence of the extreme warming event and highly stressed coastal environment. These early wetzelielloids probably flourished in palaeoecological conditions similar to those favoured by *Apectodinium*.
5. The present investigations from northeastern India strengthen the hypothesis that *Apectodinium* originated in the low latitudes and migrated contemporaneously and rapidly during the extreme climatic warming event of PETM.

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