Journal of the Palaeontological Society of India
Volume 62(2), December 31, 2017: 225-236
ISSN 0552-9360

CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY AND ITS PALAEOENVIRONMENTAL IMPLICATIONS FROM MANNAR BASIN, SRI LANKA

ABHA SINGH[1], SIYUMINI PERERA[2*], K. DAHANAYAKE[3] and J. GUNATILAKE[3]

[1]BIRBAL SAHNI INSTITUTE OF PALAEOSCIENCES, 53-UNIVERSITY ROAD, LUCKNOW-226007, INDIA
[2]POST GRADUATE INSTITUTE OF SCIENCE, UNIVERSITY OF PERADENIYA, SRI LANKA
[3]DEPARTMENT OF GEOLOGY, FACULTY OF SCIENCE, UNIVERSITY OF PERADENIYA, SRI LANKA
E-mail: *siyuminiperera@gmail.com; abha.maurya@gmail.com

ABSTRACT

Present study evaluates the record of calcareous nannofossils from the deep ocean calcareous sediments recovered as drill cuttings from CLPL-Barracuda G1/1 Petroleum Exploration Well drilled at Mannar Basin. The well site is 68 km away from the North Western coastline of Sri Lanka at a latitude of 08° 20' 34.460" N and a longitude of 79° 09' 39.378" E. Randomly selected 20 samples were studied covering the depth from 2,145 m – 3,405 m. Each sediment sample represented a depth of 10 m.

The recorded assemblage of nannofossils was comprised of 75 species belonging to 30 genera and 20 families. In terms of both diversity and abundance of species the recorded nannofossil assemblage was well preserved and extremely productive. The presence of zonal marker taxa and other age-diagnostic species envisaged Middle Paleocene to Late Oligocene age of the 1,260 m thick well section. The absence of pentaliths indicates the existence of open marine depositional setting in the Mannar Basin during this time. The upliftment of Himalayas during the Eocene period, caused by the collision between Indian and Eurasian lithospheric plates lead to a series of episodic intra-plate deformations which caused multiple episodes of erosion followed up by rapid deposition of terrigenous sediments in to the Bay of Bengal. Depocenteres like Cauvery and Mannar Basins, which are in close proximity to the Indian landmass, was simultaneously affected by the unexpected influx of the terrigenous sediment flow generated by those depositional events. This could have been the reason for the substantial reduction in the diversity of nannofossils recorded for the depth interval of 2,795 m – 3,405 m.

Keywords: Nannofossils, Mannar Basin, Biostratigraphy, Depositional setting, Sri Lanka.

INTRODUCTION

Calcareous nannofossils are considered as one of the most outstanding tool to determine the stratigraphy together with the evolution of species upon the temporal and spatial deposition in a marine sedimentary basin. Gulf of Mannar, which is considered as a sub-Basin of South-eastern offshore part of Cauvery Basin, is the southernmost extension of the Mesozoic rift basins along the east coast of India (Rao *et al*., 2010). The area of this basin under the Sri Lankan jurisdiction is approximately 45,000 km^2. In 2011, Cairn Lanka Private Limited (CLPL) explored three exploration wells at Mannar Basin out of which only two were successful with evidence for hydrocarbon deposits. Cairn's first exploration well, referred to as CLPL-Dorado-91H/1z (Dorado), was drilled to a water depth of 1,354 m, which penetrated a gross 25 m hydrocarbon column in a sandstone between the depth of 3,044 m - 3,069 m, measured depth (MD). The column is inter-bedded with an igneous formation suggesting several episodes of volcanism in the Mannar Basin. Total depth of the well is 3,288 m, MD. The second exploration well, CLPL-Barracuda-1G/1 (Barracuda) is located 68 km off the western coastline of Sri Lanka and 38 km west of the Dorado well, drilled to a depth of 4,741 m, MD in 1,509 m water depth. It penetrated 24 m of three hydrocarbon bearing sandstones between the depths of 4,067 m - 4,206 m, MD. Both discoveries were predominantly natural gas. Third and the final well, drilled 2.5 km north of the Dorado well, was plugged and abandoned as a dry hole (Premarathne *et al*., 2011). In this study, drill cutting samples recovered during the commercial drilling programme conducted by CLPL for Barracuda oil exploratory well, were analyzed for nannofossils using standard nannofossil extraction protocols. In the present paper, a systematic study of nannofossil assemblage (under light microscope) is presented along with their application in age determination, biozonation and palaeoenvironmental interpretation of the Mannar Basin.

GEOLOGICAL SETTING

Both geologically and physically the island of Sri Lanka is a southern extension of the Precambrian terrain of South India (Fig. 1). The island had recently detached from the mainland by the shallow sea covering the Palk Straits and the Gulf of Mannar (Vitanage, 1970). The Precambrian high grade metamorphic basement of Sri Lanka accounts for approximately 90% of the total land area, had been subdivided into four litho-tectonic units namely Highland Complex, Wanni Complex, Vijayan Complex and Kadugannawa Complex (Cooray, 1994). They comprised of chemically different rock assemblages as described by Kehelpannala (1997), Dahanayake and Jayasena (1983). According to Kehelpannala (2003), these litho-tectonic units had evolved individually juxtaposed by two collision events occurred during Pan-African assembly of Gondwana fragment. As noted by Vitanage (1972), rest of the island other than the Precambrian metamorphic terrain, underlain by Jurassic sandstones and arkose sediments, Miocene limestones, Pleistocene Red-earths with laterites and Quaternary alluvium deposits.

The Mannar Basin had formed during a multiphase rifting event that accompanied continental separation prior to the Mesozoic break-up of the Gondwanaland. In brief, the

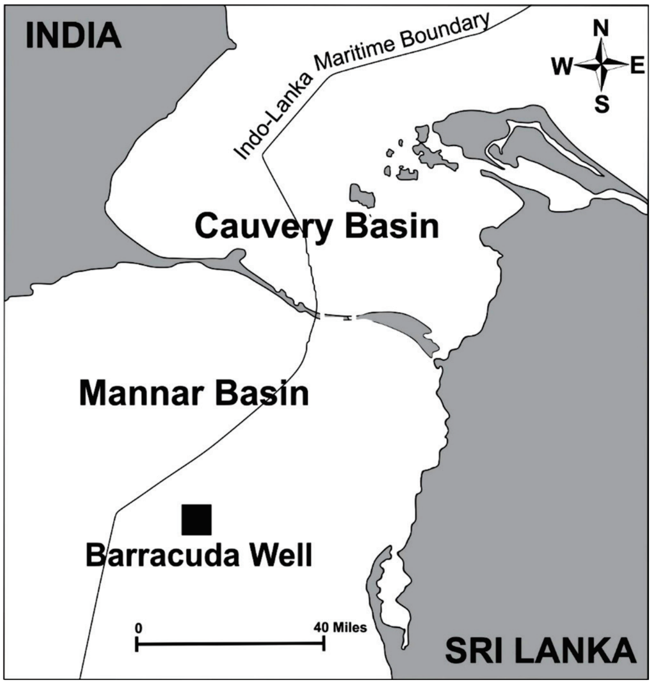


Fig. 1. Map showing location of the study area (after Premarathne, 2013).

first phase of this Mesozoic event inside the Mannar Basin had initiated around 160 Ma, followed by the parting of West and East Gondwanaland. This phase had occurred along a major rift system developed around the present Horn of Africa and extending southwards to the present Falkland Islands. East Gondwanaland had begun to break apart during the Early Cretaceous around 125 Ma. This process had perhaps commenced during India-Seychelles-Madagascar separation from Australia-Antarctica block. This event would have been the precursor to the initiation of the seafloor spreading in the oceanic Bay of Bengal. India-Seychelles block had separated from Madagascar around 100 Ma, followed by dispersion of India and Seychelles around 65 Ma (Uchupi and Emery, 1991; Metcalfe, 1996; Gnos *et al*., 1997). Subsequently, Sri Lankan margins had experienced a phase of subsidence facilitated by a phase of thermal contraction (Baillie *et al*., 2002). Cauvery Basin had remained as a passive margin from 70-1 Ma, which is the late Cretaceous to Tertiary (Shaw *et al*., 2002).

MATERIAL AND METHODS

Washed and dried drill cutting samples were provided by Cairn Lanka Private Limited from off-shore petroleum exploration operations. The authority of the samples used for the present study belongs to the Petroleum Resources Development Secretariat, Sri Lanka. Twenty samples were selected at 50 m intervals representing the well depths from 2,145-3,405 m (MD) for nannopalaeontological analyses. As suggested by Premarathne (2013), the Barracuda well is generally comprised

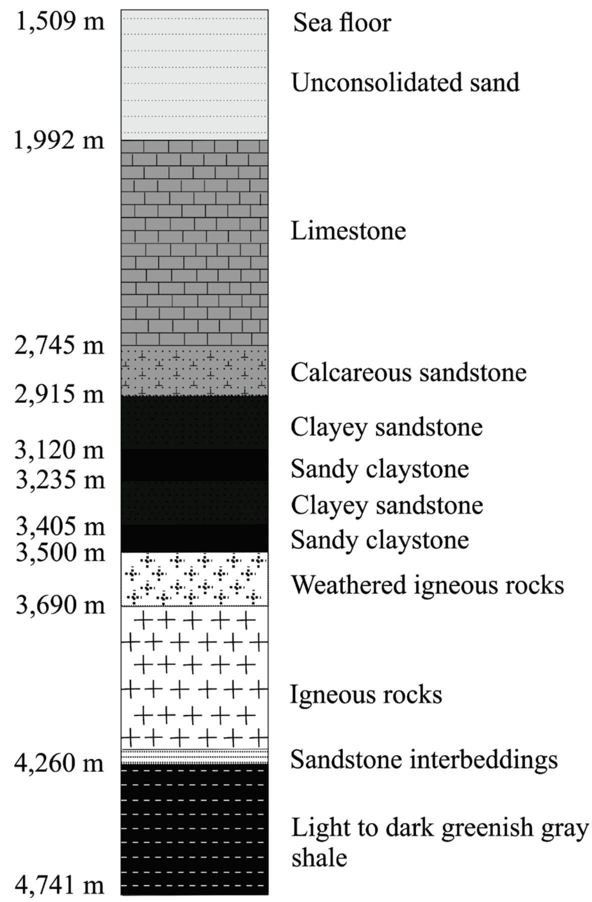


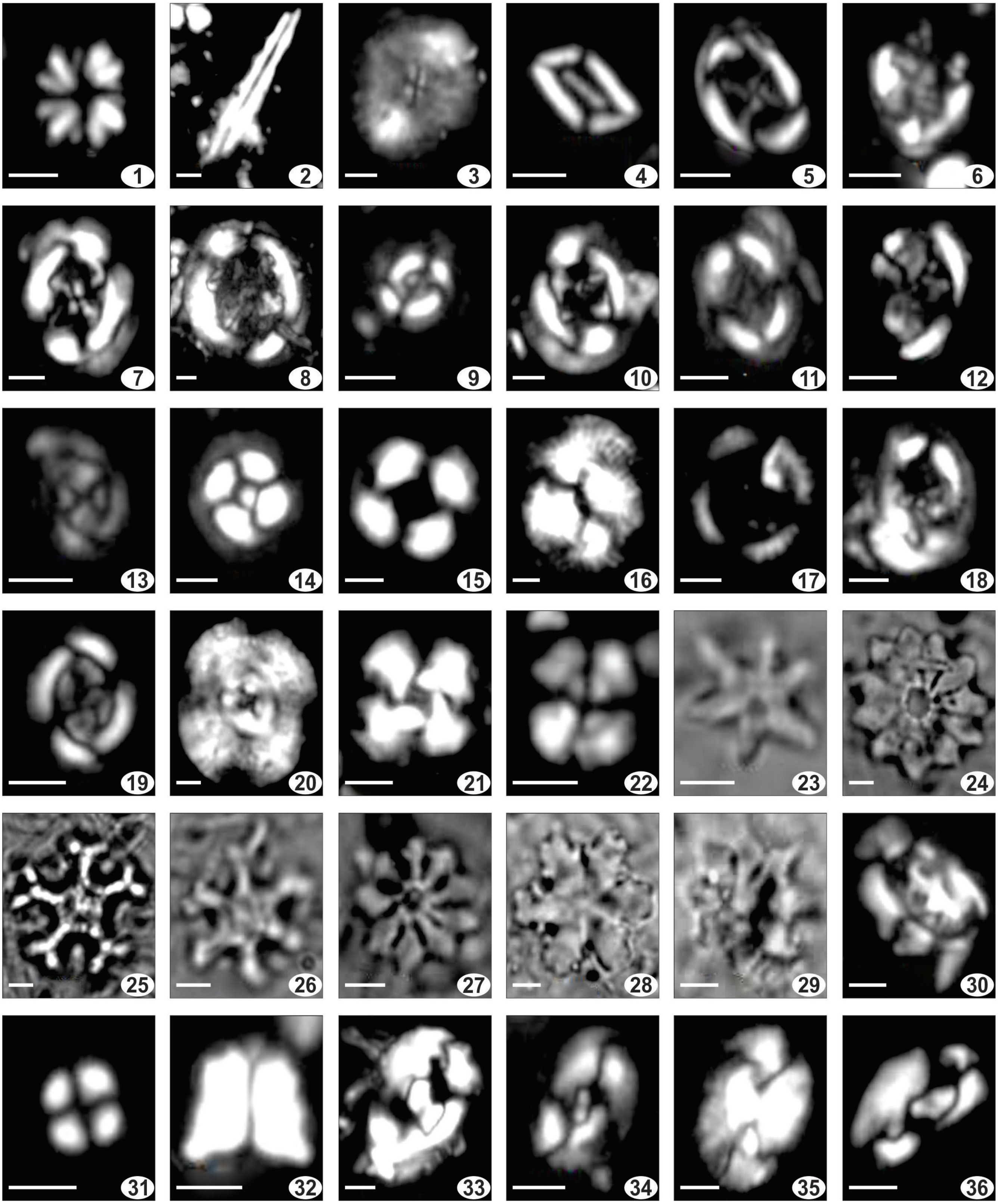
Fig. 2. Litholog of the CLPL-Barracuda-1G/1 well.

EXPLANATION OF PLATE I

1. ***Biantholithus flosculus*** Bown, 2005; 2. ***Blackites spinosus*** (Deflandre and Fert) Hay and Towe, 1962; 3. ***Calcidiscus bicircus*** Bown, 2005; 4. ***Calciosolenia aperta*** (Hay and Mohler) Bown, 2005; 5. ***Campylosphaera dela*** (Bramlette and Sullivan) Hay and Mohler, 1967; 6. ***Chiasmolithus bidens*** (Bramlette and Sullivan) Hay and Mohler, 1967; 7. ***Chiasmolithus consuetus*** (Bramlette and Sullivan) Hay and Mohler, 1967; 8. ***Chiasmolithus expansus*** (Bramlette and Sullivan) Gartner, 1970; 9. ***Chiasmolithus nitidus*** Perch-Nielsen; 10. ***Chiasmolithus titus*** Gartner, 1970; 11, 12. ***Clausicoccus fenestratus*** (Deflandre and Fert) Prins, 1979; 13. ***Clausicoccus subdistichus*** (Roth and Hay) Prins, 1979; 14. ***Coccolithus cachaoi*** Bown, 2005; 15. ***Coccolithus formosus*** (Kamptner) Wise, 1973; 16. ***Coccolithus pelagicus*** (Wallich) Schiller, 1930; 17. ***Coronocyclus nitescens*** (Kamptner) Bramlette and Wilcoxon, 1967; 18. ***Cruciplacolithus asymmetricus*** Van Heck and Prins, 1987; 19. ***Cruciplacolithus latipons*** Romein, 1979; 20. ***Cyclicargolithus abisectus*** (Muller) Wise, 1973; 21. ***Cyclicargolithus floridanus*** (Roth and Hay) Bukry, 1971; 22. ***Cyclicargolithus luminis*** (Sullivan) Bukry, 1971; 23. ***Discoaster acutus*** Bown, 2005; 24. ***Discoaster barbadiensis*** Tan, 1927; 25. ***Discoaster deflandrei*** Bramlette and Riedel, 1954; 26. ***Discoaster distinctus*** Martini, 1958; 27. ***Discoaster kuepperi*** Stradner, 1959; 28. ***Discoaster nodifer*** (Bramlette and Riedel) Bukry, 1973; 29. ***Discoaster saipanensis*** Bown and Jones, 2006; 30. ***Ellipsolithus bollii*** Perch-Nielsen, 1977; 31. ***Ericsonia subpertusa*** Hay and Mohler, 1967; 32. ***Fasciculithus tympaniformis*** Hay and Mohler, 1967; 33. ***Helicosphaera bramlettei*** (Müller) Jafar and Martini, 1975; 34. ***Helicosphaera clarissima*** Bown, 2005; 35. ***Helicosphaera ethologa*** Bown, 2005; 36. ***Helicosphaera euphratis*** Haq, 1966. (Scale bar represents 2 µm)

Journal of the Palaeontological Society of India
Volume 62 (2), December 31, 2017

Plate I



of alternative layers of sandstone, clay stone, and limestone together with a thick basaltic layer (Fig. 2). The bottom is underlain by a light greenish grey colour shale which is suspected to possess the potential to behave as the source rock for the hydrocarbon discovered from that well. The selected samples represented the following lithologies which were proposed by Premarathne (2013).

- BSI4-1 - BSI4-10 → Limestone
- BSI4-11 - BSI4-12 → Calcareous sandstone
- BSI4-13 - BSI4-15 → Clayey sandstone
- BSI4-16 - BSI4-17 → Sandy claystone
- BSI4-18 - BSI4-20 → Clayey sandstone

Light Microscopy (LM)

Smear-slides were prepared for nannofossil studies according to standard nannofossil extraction procedure suggested by Bown (1998). Nannofossils were observed with a Leitz make polarizing Microscope with X10 or X12.5 occulars and X100 objective, the latter requiring oil immersion. Gypsum plate was used together with the crossed nicols to identify the morphology of some problematic forms. The nannofossil assemblage recorded in the present study is shown in plate 1 and 2.

RESULTS AND DISCUSSION

Stratigraphic distribution

The distribution of nannofossil assemblage within the section of 2,145m – 3,405m in the CLPL-Barracuda-1G/1 well is summarized in figure 3. To indicate the abundance of individual species, the following criteria were used.

A →Abundant (>5 specimen/field of view)
C →Common (1 specimen/3-10field of view)
F → Few (1 specimen/11-20 field of view)
R →Rare (1 specimen/21-100 field of view)

In the samples BSI4-1 to BSI4-8 none of the nannofossil species were recorded as "Abundant". In the sample BSI4-10, *Sphenolithus obtusus* and *Discoaster barbadiensis* were recorded as "Abundant", while *Cylcicargolithus floridanus* was "Abundant" in BSI4-9 and BSI4-11. *Coccolithus pelagicus* was significantly distributed entirely throughout the well section while reporting the maximum abundance at BSI4-16, BSI4-17 and BSI4-18. *Calcidiscus* sp., *Chiasmolithus titus, Coccolithus formosus, Reticulofenestra minuta* and *Sphenolithus moriformis* were also present in substantial counts. The abundance of the individual species recorded from BSI4-19 and BSI4-20 was considerably less, while BSI4-12 and BSI4-13 had no species preserved at all.

Preservation

The principal governing processes of preservation of nannofossils are dissolution and overgrowth, both of which may occur in varying degrees in a single sample. The state of preservation showed for the nannofossil assemblages in the present study, can be categorized as follows.

VG →Very Good G → Good M → Moderate P → Poor

Out of the 20 samples, 55% demonstrated a "Good" preservation state (BSI4-2 to BSI4-5, BSI4-7, BSI4-8, BSI4-10, BSI4-11, BSI4-16, BSI4-18, BSI4-20), showing very little evidence of dissolution and overgrowth. All the primary morphological characteristics had been slightly altered leaving space for identify up to the species level. 35% of the samples revealed to be having a "Moderate" preservation state (BSI4-1, BSI4-6, BSI4-9, BSI4-14, BSI4-15, BSI4-17, BSI4-19), suggesting that specimens exhibits some etching and/or overgrowth features. Although the primary morphological features had been altered to a substantial extent, still specimens could be identifiable to the species level. The remaining 10% of the samples represented by BSI4-12 and BSI4-13 were barren.

Diversity

The total nannofossil assemblage from studied samples represents, 75 species belonging to 30 genera and 20 families including coccoliths, placoliths, nannoliths and helicoliths. Overall, the diversity is good to moderate. Samples BSI4-7 and BSI4-10 are found to be highly diversified. They contained more than 30 species in a 50 field of views of an individual sample. In other samples diversity is moderate. They contained 20-25 species in each sample. Some samples which contained 5-10 species in 50 field of views were identified as less diversified samples. Perhaps, this less diversity must be due to poor preservation conditions.

Sample Productivity

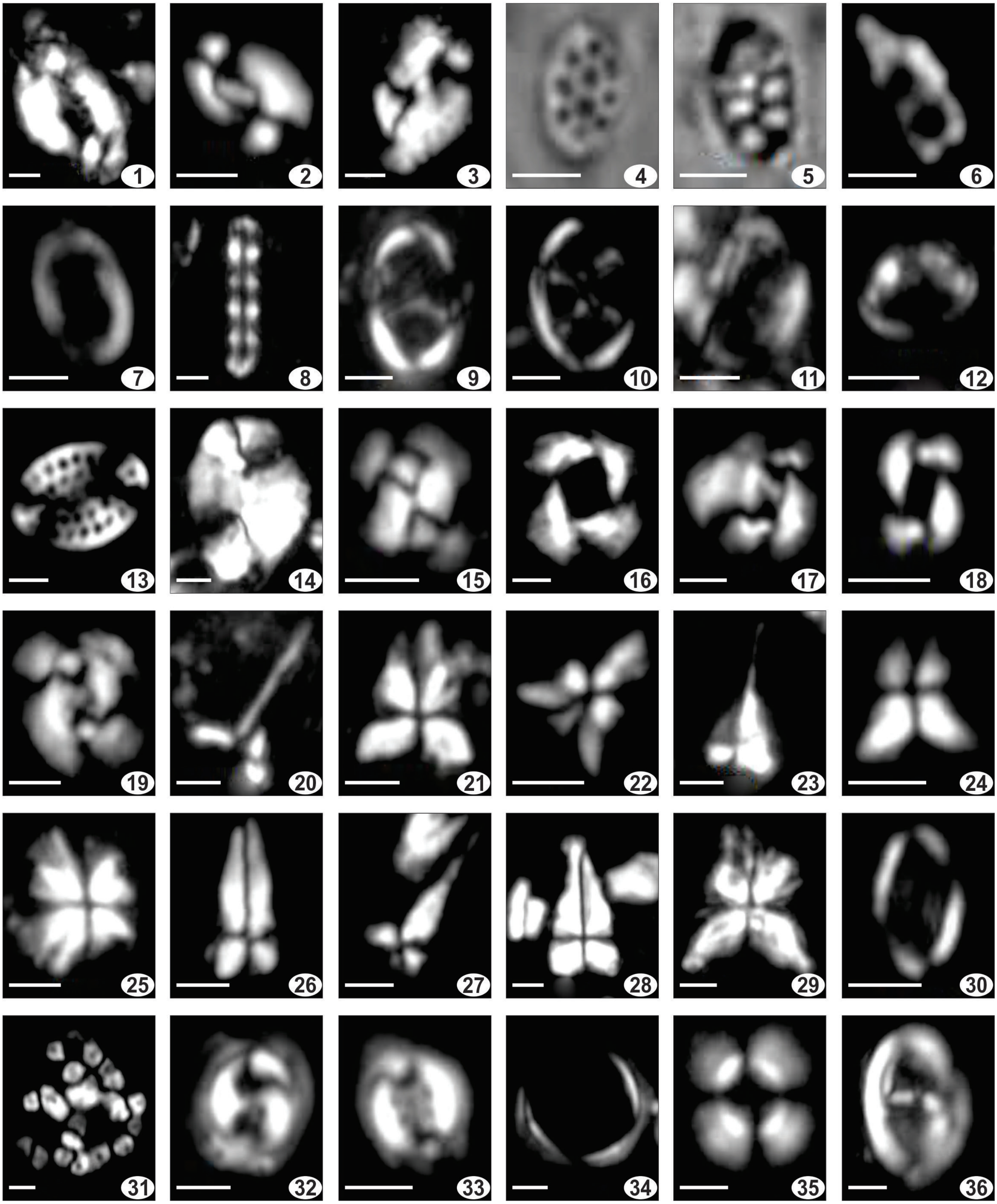
Productivity depends on the overall nannofossil assemblage recorded from each sample. The independent state of preservation of nannofossil assemblage is documented here-in. To record the productivity in samples, following criteria were used.

V → Very good (>10 specimen/field of view)
G → Good (2-10 specimen/field of view)
M → Moderate (1 specimen/field of view)
P → Poor (1 specimen/10 field of view)

EXPLANATION OF PLATE II

1. ***Helicosphaera granulata*** (Bukry and Percival) Jafar and Martini, 1975; 2. ***Helicosphaera intermedia*** Martini, 1965; 3. ***Helicosphaera obliqua*** Bramlette and Wilcoxon, 1967; 4. ***Holodiscolithus macroporus*** (Deflandre in Deflandre and Fert, 1954) Roth, 1970; 5. ***Holodiscolithus solidus*** (Deflandre in Deflandre and Fert, 1954) Roth, 1970; 6. ***Isthmolithus recurvus*** Deflandre in Deflandre and Fert, 1954; 7. ***Jakubowskia leoniae*** Varol, 1989; 8. ***Microrhabdulus undosus*** Perch-Nielsen, 1973; 9. ***Neochiastozygus junctus*** (Bramlette and Sullivan) Perch-Nielsen, 1971; 10. ***Neococcolithes protenus*** (Bramlette and Sullivan) Black, 1967; 11. ***Nephrolithus frequens*** Górka, 1957; 12. ***Orthozygus arcus*** Jones *et al*., 2009; 13. ***Pontosphaera multipora*** (Kamptner, 1948 ex Deflandre *in* Deflandre and Fert, 1954) Roth, 1970; 14. ***Pontosphaera plana*** (Bramlette and Sullivan, 1961) Haq, 1971; 15. ***Reticulofenestra bisecta*** (Hay) Roth, 1970; 16. ***Reticulofenestra dictyoda*** (Deflandre in Deflandre and Fert, 1954) Stradner in Stradner and Edwards, 1968; 17. ***Reticulofenestra lockeri*** Müller, 1970; 18. ***Reticulofenestra minuta*** Roth, 1970; 19. ***Reticulofenestra reticulata*** (Gartner and Smith) Roth and Thierstein, 1972; 20. ***Rhabdosphaera vitrea*** (Deflandre *in* Deflandre and Fert, 1954) Bramlette and Sullivan, 1961; 21. ***Sphenolithus anarrhopus*** Bukry and Bramlette, 1969; 22. ***Sphenolithus delphix*** Bukry 1973; 23. ***Sphenolithus distentus*** (Martini) Bramlette and Wilcoxon, 1967; 24. ***Sphenolithus editus*** Perch-Nielsen in Perch-Nielsen et al., 1978; 25. ***Sphenolithus moriformis*** (Bronnimann and Stradner) Bramlette and Wilcoxon, 1967; 26. ***Sphenolithus obtusus*** Bukry, 1971; 27. ***Sphenolithus pseudoradians*** Bramlette and Wilcoxon, 1967; 28. ***Sphenolithus radians*** Deflandre, 1952; 29. ***Sphenolithus spiniger*** Bukry, 1971; 30. ***Tetralithoides symeonidesii*** Theodoridis, 1984; 31. ***Thoracosphaera heimii*** (Lohmann, 1920) Kamptner, 1944; 32. ***Toweius eminens*** (Bramlette and Sullivan) Perch-Nielsen, 1971; 33. ***Toweius serotinus*** Bybell and Self-Trail, 1995; 34. ***Umbilicosphaera bramlettei*** (Hay and Towe) Bown *et al*., 2007; 35. ***Umbilicosphaera jordanii*** Bown, 2005; 36. ***Zeugrhabdotus sigmoides*** (Bramlette and Martini) Bown and Young, 1997. (Scalebar represents 2 µm)

Plate II


1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36

Samples	BSI4-1	BSI4-2	BSI4-3	BSI4-4	BSI4-5	BSI4-6	BSI4-7	BSI4-8	BSI4-9	BSI4-10	BSI4-11	BSI4-12	BSI4-13	BSI4-14	BSI4-15	BSI4-16	BSI4-17	BSI4-18	BSI4-19	BSI4-20
Productivity	G	M	M	G	M	G	VG	G	G	VG	G	Nannofossils not recorded	Nannofossils not recorded	P	P	G	G	M	P	G
Preservation	M	G	G	G	G	M	G	G	M	G	G			M	M	G	M	G	M	G
Biantholithus flosculus						R														
Blackites spinosus											R									
Blackites spp.			R							R										
Calcidiscus bicircus										R										
Calcidiscus spp.		F	C	F	F															
Calciosolenia aperta																R	F			
Campylosphaera dela																R				
Campylosphaera spp.			R	R																
Chiasmolithus bidens														R						
Chiasmolithus consuetus											F									
Chiasmolithus expansus										F										
Chiasmolithus nitidus						F	F													
Chiasmolithus titus											C									
Chiasmolithus spp.						R	R				R									
Clausicoccus fenestratus						F	F	F												
Clausicoccus subdistichus	R		R			F	F	F	F											
Coccolithus cachaoi	R									R					R	R				
Coccolithus formosus										F	C					R				F
Coccolithus pelagicus	F	C	F	F		F	F	F	C	C	F			C	C	A	A	A	F	F
Coccolithus spp.		R	R	F																
Coronocyclus nitescens		R	R																	
Cruciplacolithus asymmetricus										F						F	R			
Cruciplacolithus latipons						F	F										R			
Cyclicargolithus abisectus	R	R	F	F																
Cyclicargolithus floridanus	C	C		C	F	C	C	C	A	C	A						C	F		
Cyclicargolithus luminis														R			R			
Cyclicargolithus spp.				R				F	R											
Discoaster acutus			R																	
Discoaster barbadiensis										A	C									
Discoaster deflandrei		F		C						F										
Discoaster distinctus			F			F	F													
Discoaster kuepperi										F	R									
Discoaster nodifer				F						F										
Discoaster spinescens										R										
Discoaster spp.	R	F	F	F		F	F													R
Ellipsolithus bollii																	F	F		
Ericsonia subpertusa																F				
Ericsonia spp.			F	F				R	F											
Fasciculithus tympaniformis																R		R		
Fasciculithus spp.			F	F																
Helicosphaera bramlettei										R										
Helicosphaera clarissima			F	F		F	F													
Helicosphaera ethologa		F	F	C	F	F	F													
Helicosphaera euphratis	R	F																		
Helicosphaera granulata		R																		
Helicosphaera intermedia					R						R									
Helicosphaera obliqua									F	R										
Helicosphaera spp.			R	F				F												
Holodiscolithus macroporus		R																		
Holodiscolithus solidus					R															
Isthmolithus recurvus				R																
Jakubowskia leoniae																	R			
Neochiastozygus junctus															F					
Neococcolithes protenus																C	F	F		F
Orthozygus arcus					R															
Pontosphaera multipora		F	F	F	F	F	F	F	F	F										
Pontosphaera plana										R	F									
Reticulofenestra bisecta			F																	
Reticulofenestra dictyoda		C	C		C			C		R										
Reticulofenestra lockeri	R																			
Reticulofenestra minuta	C	F	C	C	C	F	C			C										
Reticulofenestra reticulata									F	F										
Reticulofenestra spp.	F			F																
Rhabdosphaera vitrea						R	R													
Sphenolithus anarrhopus																R				
Sphenolithus delphix			R																	
Sphenolithus distentus	F																			
Sphenolithus editus			R			F	F													
Sphenolithus moriformis	F	F	F	F	F	C	C		C	F	A			F		F	F	F		F
Sphenolithus obtusus				R						A	F									
Sphenolithus pseudoradians		F						F												
Sphenolithus radians		F			F						F									
Sphenolithus spiniger						F	F			F										
Sphenolithus spp.	C	C				F	F													
Tetralithoides symeonidesii		R																		
Thoracosphaera heimii		R		R																
Toweius eminens																	C			F
Toweius serotinus																R				
Toweius spp.	F		F														C	C	R	C
Umbilicosphaera bramlettei										R					R			F		
Umbilicosphaera jordanii		C	F			F	F	R	R	F	R									
Zeugrhabdotus sigmoides																		R		
Zygrhablithus bijugatus bijugatus											F									

Reworked Leaked

Fig. 3. Distribution of calcareous nannofossils recorded from CLPL-Barracuda-1G/1 well.

In general, the productivity of CLPL-Barracuda-1G/1 well samples ranges between Very good to Poor. Out of the 20 samples studied, 10% of the samples were highly productive having more than 10 specimen in a single field of view. 45% of the samples recorded a "Good" productivity while 20% demonstrated a "Moderate" productivity having a single specimen in single FOV. 15% of the samples were reported as "Poor" in terms of productivity.

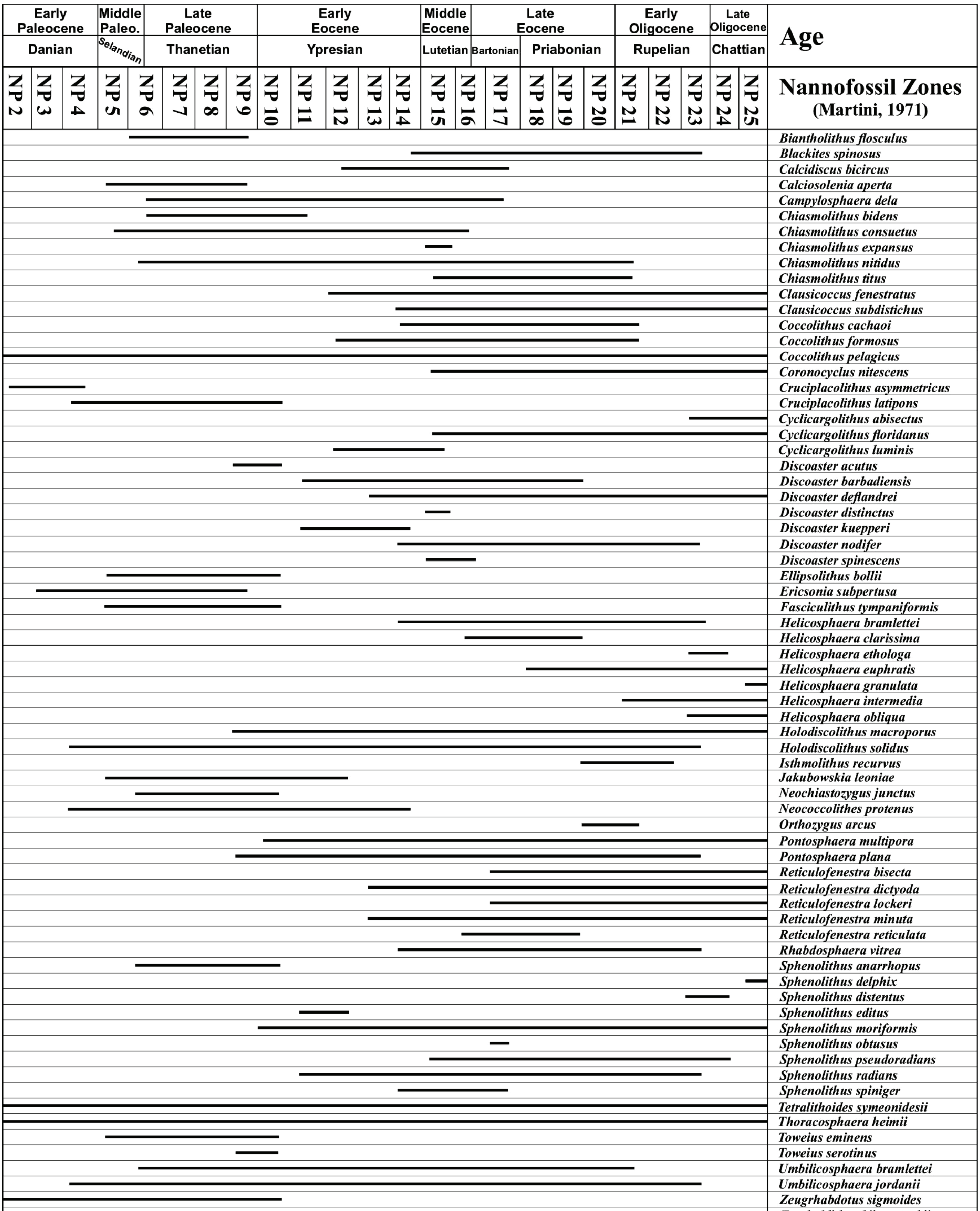


Fig. 4. Chart showing stratigraphic ranges of significant taxa recorded from CLPL-Barracuda-1G/1 well.

Biostratigraphy

Assignments of preliminary ages were carried out based on the biostratigraphic analyses of calcareous nannofossils. The result shows well diversified and good to moderately preserved nannofossil assemblage from 2,145 m to 3,405 m depth. The selected 20 samples from this depth interval, contains nannofossils ranges from Middle Paleocene to Late Oligocene in age (Fig. 4). The NP (Nannofossils Paleogene) zones of Martini (1971) was used for the biostratigraphy of the nannofossils reported in the study and age assignment (Fig. 5).

The distribution pattern of the biostratigraphically significant nannofossil markers within the selected depth interval had been studied using the first occurrence (FO) and last occurrence (LO) of marker species and assemblage characteristics (Fig. 4). At some levels due to the absence of global markers additional events and ranges of some significant taxa were used to date the sediments (stratigraphic ranges were taken from Nannotax3 website). Since these are the drill cutting sediments, samples were highly disturbed despite they were washed and dried on the well site itself. Therefore the accurate dating of these sediments is bit difficult and needs much precision. The difficulty to attain a high level of precision is due to the reworking of older age sediments into younger sediments and leaking of younger sediments into older sediments (Fig. 3). Based on the distribution and the occurrences of marker species and the stratigraphic ranges of other important species, samples were dated into four major age categories.

- BSI4-20 to BSI4-16 → Middle Paleocene to Late Paleocene

Based on the Last appearance datum (LAD) of *Calciosolenia aperta*, BSI4-16 can be assigned to NP9 belonging to Late Paleocene. The presence of *Ellipsolithus bollii, Fasciculithus tympaniformis, Sphenolithus anarrhopus, Toweius eminens, Toweius serotinus,* and *Zeugrhabdotus sigmoides*, together with the presence of *Neococcolithus protenus* in BSI4-20 suggests that it belongs to a zone above or equals to NP4 of Middle Paleocene. Therefore, BSI4-20 to BSI4-16 can be dated as Middle Paleocene to Late Paleocene (NP4 to NP9 Zones of Martini, 1971).

- BSI4-15 to BSI4-9 → Early Eocene to Late Eocene

Based on the LAD of *Reticulofenestra reticulata,* BSI4-9 can be assigned to NP19 Zone of Late Eocene. The LAD of *Neochiatozygus junctus* suggests BSI4-15 can be allocated to NP10 zone of Early Eocene. Therefore, based on the recorded nannofossil assemblage, BSI4-15 to BSI4-9 can be dated as Early Eocene to Late Eocene (NP10 to NP19 Zones of Martini, 1971).

- BSI4-8 to BSI4-5 → Late Eocene to Early Oligocene

LAD of *Holodiscolithus solidus* together with the absence of *Cyclicargolithus abisectus* in BSI4-5 suggests it belongs to the NP22 zone of Early Oligocene. The LAD of *Reticulofenestra*

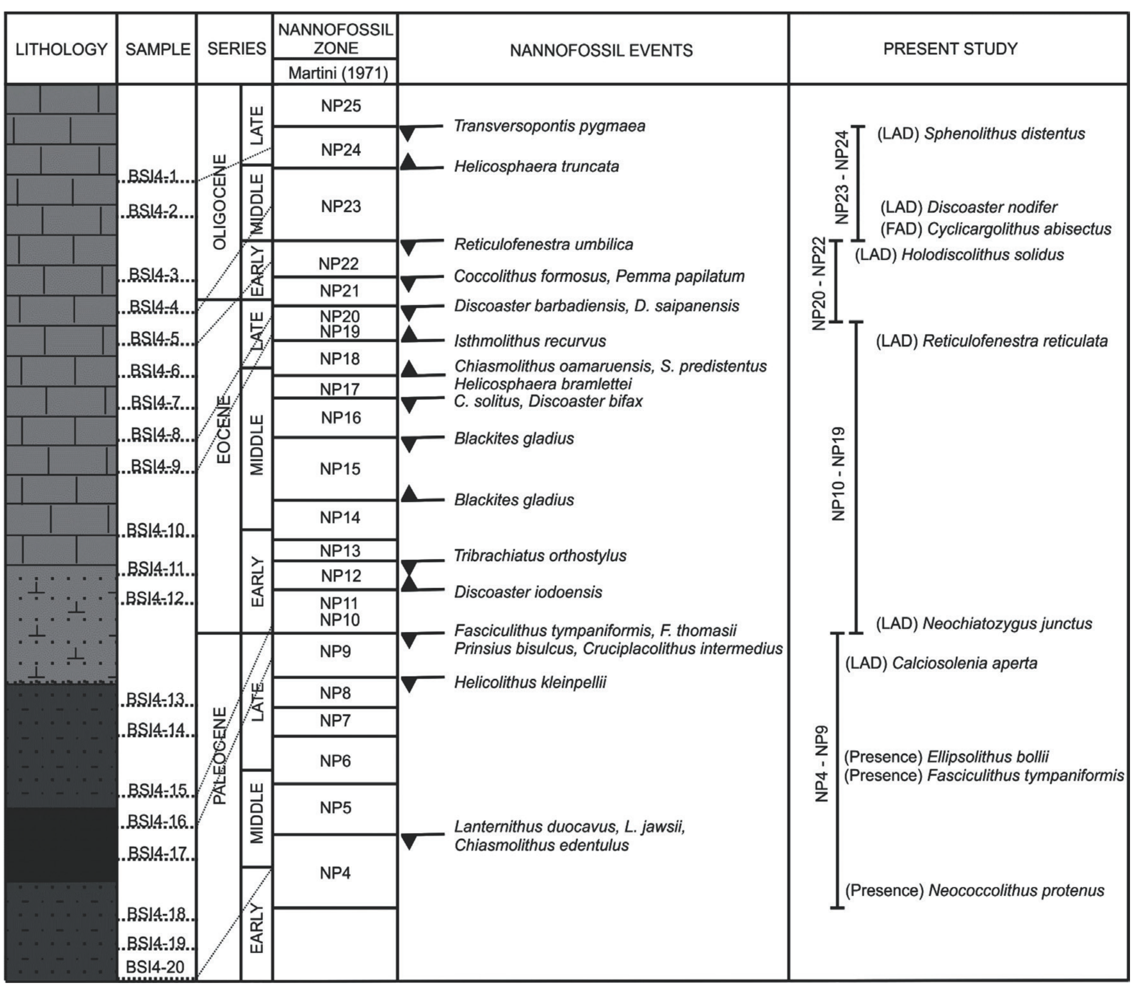


Fig. 5. Composite figure showing nannofossil events in present study and its comparison with nannofossil Zones of Martini (1971) along with age and litholog.

reticulata positioned in BSI4-9 and it belongs to NP19 zone of Early Oligocene. Therefore, the absence of *Reticulofenestra reticulata* restricts BSI4-8 to NP20 of Late Eocene. Therefore, the samples BSI4-8 to BSI4-5 can be dated as Late Eocene to Early Oligocene (NP20 to NP22 Zones of Martini, 1971).

- BSI4-4 to BSI4-1 → Middle Oligocene to Late Oligocene

Based on the recorded nannofossil assemblage and first appearance datum (FAD) of *Cyclicargolithus abisectus* and LAD of *Discoaster nodifer*, BSI4-4 can be assigned to NP23 Zone of Middle Oligocene while LAD of *Sphenolithus distentus* restricts BSI4-1 to NP24 Zone of Late Oligocene. Therefore, BSI4-4 to BSI4-1 samples can be dated as Middle Oligocene to Late Oligocene (NP23 to NP24 Zones of Martini, 1971).

LOW PRODUCTIVITY ZONE IN NANNOFOSSIL ASSEMBLAGE.

In the period around 60 Ma, without accompanying a continental - continental collision, the oceanic lithosphere to the North of the Indian plate commenced to subduct beneath the Eurasian plate at a rate of 10 cm/yr. The oceanic lithosphere to the North of the Indian plate, was gradually subducted completely leading to the continental-continental collision between Late Eocene to Early Oligocene. This period is generally considered as around 34 Ma (Wan, 2010). However, according to Baillie *et al*. (2004), around 50 Ma (Lower Eocene), a collision between continental block of India and Eurasia had occurred. This event had been accompanied by a phase of uplift and erosion in the Himalayas causing speedy deposition of sediments in the Bay of Bengal. This deposition had resulted in an unexpected influx of terrigenous sediments into other depocentres close to the Indian landmass, including Cauvery and Mannar Basins. The uplift had resulted in episodic intra-plate deformation. It had interrupted the overall subsidence history characterized by separate episodes of erosion and rapid deposition of terrigenous sediments. This terrigenous influx might have covered the nannofossil beds affecting the productivity of nannofossil.

The samples BSI4-12 and BSI4-13 did not contain even a single species of nannofossils, and showed an overall dark field of view. These samples represent the depth interval between 2,795 m – 2,955 m. Slides were covered with densely compacted, fine to medium size mineral grains. This result perhaps indicates the sudden influx of terrigenous sediments deposited due to the uplift and erosion of Himalayas. Even the diversity of nannofossils recorded in the subsequent samples (BSI4-14 to BSI4-20) are considerably less, relative to the diversity observed for samples before BSI4-12. This less abundance and poor diversity of nannofossils in subsequent samples can be considered as an indicator of the recovery phase of nannofossils after the sudden interruption with terrigenous influx triggered by tectonic events associated with Indo - Eurasia plate margins.

CONCLUSIONS

1. The nannofossil assemblage from CLPL-Barracuda-1G/1 well sediments include 75 species belonging to 30 genera and 20 families including coccoliths, placoliths, nannoliths and helicoliths.
2. Overall nannofossil species diversity is good and productivity is good to moderate in the entire studied well succession.
3. Based on the occurrence of zonal marker taxa and presence of other age diagnostic species, the 1,260 m thick well section has been dated from Middle Paleocene to Late Oligocene.
4. The absence of pentaliths (*Pemma*, *Micrantholithus* and *Braarudosphaera*) indicates that the sediments had been deposited in an open marine setting.

LIST OF TAXA

1. *Ascidian spicule*
2. *Biantholithus flosculus* Bown, 2005
3. *Blackites spinosus* (Deflandre and Fert) Hay and Towe, 1962
4. *Blackites* sp. 1
5. *Blackites* sp. 2
6. *Blackites* sp. 3
7. *Calcidiscus bicircus* Bown, 2005
8. *Calcidiscus* sp. 1
9. *Calcidiscus* sp. 2
10. *Calcidiscus* sp. 3
11. *Calcidiscus* sp. 4
12. *Calciosolenia aperta* (Hay and Mohler) Bown, 2005
13. Calcisphere
14. *Campylosphaera dela* (Bramlette and Sullivan) Hay and Mohler, 1967
15. *Campylosphaera* sp. 1
16. *Campylosphaera* sp. 2
17. *Chiasmolithus bidens* (Bramlette and Sullivan) Hay and Mohler, 1967
18. *Chiasmolithus consuetus* (Bramlette and Sullivan) Hay and Mohler, 1967
19. *Chiasmolithus expansus* (Bramlette and Sullivan) Gartner, 1970
20. *Chiasmolithus nitidus* Perch-Nielsen, 1971
21. *Chiasmolithus titus* Gartner, 1970
22. *Chiasmolithus* sp. 1
23. *Chiasmolithus* sp. 2
24. *Clausicoccus fenestratus* (Deflandre and Fert) Prins, 1979
25. *Clausicoccus subdistichus* (Roth and Hay) Prins, 1979
26. *Coccolithus cachaoi* Bown, 2005
27. *Coccolithus formosus* (Kamptner) Wise, 1973
28. *Coccolithus pelagicus* (Wallich) Schiller, 1930
29. *Coccolithus* sp. 1
30. *Coccolithus* sp. 2
31. *Coccolithus* sp. 3
32. Coccosphere 1
33. Coccosphere 2
34. *Coronocyclus nitescens* (Kamptner) Bramlette and Wilcoxon, 1967
35. *Cruciplacolithus asymmetricus* Van Heck and Prins, 1987
36. *Cruciplacolithus latipons* Romein, 1979
37. *Cyclicargolithus abisectus* (Muller) Wise, 1973
38. *Cyclicargolithus floridanus* (Roth and Hay) Bukry, 1971
39. *Cyclicargolithus luminis* (Sullivan) Bukry, 1971
40. *Cyclicargolithus* sp. 1
41. *Cyclicargolithus* sp. 2
42. *Discoaster acutus* Bown, 2005
43. *Discoaster barbadiensis* Tan, 1927
44. *Discoaster deflandrei* Bramlette and Riedel, 1954
45. *Discoaster distinctus* Martini, 1958
46. *Discoaster kuepperi* Stradner, 1959

47. *Discoaster nodifer* (Bramlette and Riedel) Bukry, 1973
48. *Discoaster spinescens* Bown and Jones, 2006
49. *Discoaster* sp. 1
50. *Discoaster* sp. 2
51. *Discoaster* sp. 3
52. *Discoaster* sp. 4
53. *Discoaster* sp. 5
54. *Discoaster* sp. 6
55. *Discoaster* sp. 7
56. *Discoaster* sp. 8
57. *Discoaster* sp. 9
58. *Ellipsolithus bollii* Perch-Nielsen, 1977
59. *Ellipsolithus* sp. 1
60. *Ericsonia subpertusa* Hay and Mohler, 1967
61. *Ericsonia* sp. 1
62. *Ericsonia* sp. 2
63. *Fasciculithus tympaniformis* Hay and Mohler, 1967
64. *Fasciculithus* sp. 1
65. *Fasciculithus* sp. 2
66. *Fasciculithus* sp. 3
67. *Fasciculithus* sp. 4
68. *Fasciculithus* sp. 5
69. *Fasciculithus* sp. 6
70. *Helicosphaera bramlettei* (Müller) Jafar and Martini, 1975
71. *Helicosphaera clarissima* Bown, 2005
72. *Helicosphaera ethologa* Bown, 2005
73. *Helicosphaera euphratis* Haq, 1966
74. *Helicosphaera granulata* (Bukry and Percival) Jafar and Martini, 1975
75. *Helicosphaera intermedia* Martini, 1965
76. *Helicosphaera obliqua* Bramlette and Wilcoxon, 1967
77. *Helicosphaera* sp. 1
78. *Helicosphaera* sp. 2
79. *Helicosphaera* sp. 3
80. *Holodiscolithus macroporus* (Deflandre) Roth, 1970
81. *Holodiscolithus solidus* (Deflandre) Roth, 1970
82. *Isthmolithus recurvus* Deflandre, 1954
83. *Jakubowskia leoniae* Varol, 1989
84. *Neochiastozygus junctus* (Bramlette and Sullivan) Perch-Nielsen, 1971
85. *Neococcolithes protenus* (Bramlette and Sullivan) Black, 1967
86. *Orthozygus arcus* Jones *et al*., 2009
87. *Pedinocyclus* sp. 1
88. *Pontosphaera multipora* (Kamptner) Roth, 1970
89. *Pontosphaera plana* (Bramlette and Sullivan) Haq, 1971
90. *Pontosphaera* sp. 1
91. *Reticulofenestra bisecta* (Hay *et al*.) Roth, 1970
92. *Reticulofenestra dictyoda* (Deflandre) Stradner *in* Stradner and Edwards, 1968
93. *Reticulofenestra lockeri* Müller, 1970
94. *Reticulofenestra minuta* Roth, 1970
95. *Reticulofenestra reticulata* (Gartner and Smith) Roth and Thierstein, 1972
96. *Reticulofenestra* sp. 1
97. *Reticulofenestra* sp. 2
98. *Reticulofenestra* sp. 3
99. *Rhabdosphaera vitrea* (Deflandre) Bramlette and Sullivan, 1961
100. *Semihololithus* sp. 1
101. *Semihololithus* sp. 2
102. *Sphenolithus anarrhopus* Bukry and Bramlette, 1969
103. *Sphenolithus delphix* Bukry, 1973
104. *Sphenolithus distentus* (Martini) Bramlette and Wilcoxon, 1967
105. *Sphenolithus editus* Perch-Nielsen, 1978
106. *Sphenolithus moriformis* (Bronnimann and Stradner) Bramlette and Wilcoxon, 1967
107. *Sphenolithus obtusus* Bukry, 1971
108. *Sphenolithus pseudoradians* Bramlette and Wilcoxon, 1967
109. *Sphenolithus radians* Deflandre, 1952
110. *Sphenolithus spiniger* Bukry, 1971
111. *Sphenolithus* sp. 1
112. *Sphenolithus* sp. 2
113. *Sphenolithus* sp. 3
114. *Syracosphaera* sp. 1
115. *Tetralithoides symeonidesii* Theodoridis, 1984
116. *Thoracosphaera heimii* (Lohmann) Kamptner, 1944
117. *Thoracosphaera* sp. 1
118. *Toweius eminens* (Bramlette and Sullivan) Perch-Nielsen, 1971
119. *Toweius serotinus* Bybell and Self-Trail, 1995
120. *Toweius* sp. 1
121. *Toweius* sp. 2
122. *Umbilicosphaera bramlettei* (Hay and Towe, 1962) Bown *et al*., 2007
123. *Umbilicosphaera jordanii* Bown, 2005
124. *Umbilicosphaera* sp. 1
125. *Zeugrhabdotus sigmoides* (Bramlette and Martini) Bown and Young, 1997
126. *Zygrhablithus bijugatus bijugatus* (Deflandre) Deflandre, 1959
127. *Zygrhablithus* sp. 1

Reworked Cretaceous taxa

1. *Eprolithus floralis* (Stradner) Stover, 1966
2. *Microrhabdulus undosus* Perch-Nielsen, 1973
3. *Nephrolithus frequens* Górka, 1957
4. *Watznaueria britannica* (Stradner) Reinhardt, 1964

ACKNOWLEDGEMENTS

The authors are thankful to Prof. Sunil Bajpai, Director, Birbal Sahni Institute of Palaeosciences, Lucknow for the cooperation and providing the laboratory facilities to process the samples (Permission no. BSIP/RDCC/Publication no. 71/2016-17). Also, the authors express their gratitude to the Petroleum Resource Development Secretariat, Sri Lanka for allowing to access the data repositories and for supplying of samples. Dr. R.K. Saxena, is duly thanked for the critical review of the manuscript.

REFERENCES

Baillie, P. W., Shaw, R. D., Liyanaarachchi, D. T. P. and Jayaratne, M. G. 2002. A New Mesozoic Sedimentary Basin, Offshore Sri Lanka, p. 27. In: *EAGA 64th Conference & Exhibition,* Florence, Italy.

Bown, P. R. and Young, J. R. 1998. Techniques, p. 16-28. In: *Calcareous Nannofossil Biostratigraphy* (Ed. Bown, P. R.), British Micropalaeontological Society Series, Chapman and Hall, London.

Cooray, P. G. 1994. The Precambrian of Sri Lanka: a historical review. *Precambrian Research*, **66**: 3-18.

Dahanayake, K. and Jayasena, H. A. H. 1983. General geology and petrology of some Precambrian crystalline rocks from the Vijayan Complex of Sri Lanka. *Precambrian Research*, **19**: 301-315.

Gnos, E., Immenhauser, A. and Peters, T. 1997. Late Cretaceous/early Tertiary convergence between the Indian and Arabian plates recorded in ophiolites and related sediments. *Tectonophysics*, **271**: 1-19.

Kehelpannala, K. V. W. 1997. Deformation of a High-Grade Gondwana Fragment, Sri Lanka. *Gondwana Research*, **1**: 47-68.

Kehelpannala, K. V. W. 2003. Structural evolution of the Middle to Lower crust in Sri Lanka. *Journal of Geological Society of Sri Lanka*, **11**(61): 45-85.

Martini, E. 1971. Standard Tertiary and Quaternary Calcareous Nannoplankton Zonation, p. 739-785. In: *Proceedings of the II Planktonic Conference Roma, 1970* (Ed. Farinacci, A.), Edzioni Tecnoscienza, Rome, 2.

Metcalfe, I. 1996. Gondwanaland dispersion, Asian accretion and evolution of Eastern Tethys, breakup of Rodinia and Gondwanaland and assembly of Asia. *Australian Journal of Earth Sciences,* **43**: 605-623.

Young, J. R., Bown, P. R. and Lees, J. A. 2013. Nannotax 3, http: //ina.tmsoc.org / Nannotax 3 / index.php ? dir = Coccolitho-phores.

Premarathne, D. M. U. A. K. 2011. Oil exploration in Sri Lanka and sustainability of a petroleum system in the Gulf of Mannar Basin. *Journal of the Geological Society of Sri Lanka*, **27**: 23.

Premarathne, D. M. U. A. K., Suzuki, N., Rathnayake, N. P. and Kularathnne, E. K. C. W. 2013. A Petroleum System in the Gulf of Mannar Basin, Offshore Sri Lanka. *Journal of the Geological Society of Sri Lanka***, 29**: 9-12.

Rao, M. V., Chidambaram, L., Bharktya, D. and Janardhanan, M. 2010. Integrated analysis of Late Albian to Middle Miocene sediments in Gulf of Mannar shallow waters of the Cauvery Basin, India: A Sequence Stratigraphic Approach, p. 1-9. In: *8th Biennial international conference and exposition on petroleum geophysics*, Hyderabad.

Roth, P. H. and Berger, W. H. 1975. Distribution and dissolution of coccoliths in the South and central Pacific, p. 87-113. In: *Dissolution of Deep-Sea Carbonates* (Eds. Sliter, W. V., Bé, A. W. H., and Berger, W. H.), Cushman Foundation for Foraminiferal Research Special Publication, 13.

Roth, P. H. and Krumbach, K. R. 1986. Middle Cretaceous calcareous nannofossil biogeography and preservation in the Atlantic and Indian Oceans: implications for palaeoceanography. *Marine Micropaleontology*, **10:** 235-266.

Roth, P. H. and Thierstein, H. R. 1972. Calcareous nannoplankton: Leg 14 of the Deep Sea Drilling Project. *Initial Reports of the Deep Sea Drilling Project*, **14:** 421-485.

Scotese, C. R. 2004. PALEOMAP Project, http://w ww.scotese.com/earth.html

Shaw, R. D. 2002. TGS-NOPEC SL01–Phase 1 Offshore Sri Lanka Seismic Survey Interpretation Report. Prepared for TGS-NOPEC by New South Global Pvt. Limited.

Thierstein, H. R. 1980. Selective dissolution of Late Cretaceous and earliest Tertiary calcareous nannofossils: experimental evidence. *Cretaceous Research*, **2:** 165-176.

Uchupi, E. and Emery, K. O. 1991. Pangean divergent margin: historical perspective. *Marine Geology*, **102**: 1-28.

Vitanage, P. W. 1970. A study of the geomorphology and the morphotectonics of Ceylon p. 391-406. In: *Proceedings to the seminar on geochemical prospecting methods and techniques,* Peradeniya.

Vitanage, P. W. 1972. Post-Precambrian uplifts and regional neotectonic movements in Ceylon, p. 642-654. In: *24th International Geological Congress, Montreal,* 3.

Wan, T. 2010. Formation of Western Pacific Subducion Zone and Yarlung Zangbo Collision Zone, p. 230-233. In: *The Tectonics of China: Data, Maps and Evolution*. Higher Education Press, Beijing.

Manuscript received December 2016

Revised Manuscript accepted April 2017