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Nannoplankton Assemblage Succession Throughout Cretaceous/ Tertiary Boundary in the "P" Well Section, Santos Basin, Brazil

Runtunan Kumpulan Nanoplankton pada batas Kapur/Tersier dalam Penampang Sumur "P", Cekungan Santos, Brasil

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Abstract

The massive change in calcareous nannoplankton assemblages throughout Cretaceous/Tertiary (K/T) boundary (65.5 M.a.) has been illustrated by several authors. The diverse and abundant assemblage disappears suddenly above the Cretaceous/Tertiary boundary. This event is related to the most dramatic environmental changes in the Earth's history due to the catastrophic events, those are meteorite impact (*Chicxulub*) and supervolcano eruption (*Deccan*) occurring at the end of Cretaceous. The succeeding age was a time of rapid evolution of nannoplankton during Paleocene. A quantitative method analysis of nannoplankton throughout Maastrichtian to Paleocene of "P" well section, Santos Basin, Brazil, indicated that the nannoplankton assemblages abruptly decrease in diversity and abundance and mostly change in species composition. The various complex shapes of species at Maastrichtian also underwent changing to simple plain shapes and small at Paleocene. The sedimentary section ranges from the top of zone CC23 (Coccolith Cretaceous 23) to NP9 (Nannoplankton Paleogen 9). It is bounded by the Last Occurrence (LO) of *Tranolithus pachelosus* at the base and *Fasciculithus tympaniformis* at the top. The biostratigraphic discontinuity characterized by the absence of zone CC26 to NP4 is an indicator for the presence of an unconformity at K/T boundary within analyzed section. The Cretaceous nannoplankton assemblages are dominated by Genera *Watznaueria, Micula, Arkhangelskiella, Cribrosphaerella, Eiffellithus, Predicosphaera*, and *Retecapsa*, whilst the Paleocene assemblages are dominated by Genera *Toweius*, *Ericsonia*, and *Coccolithus.* Survivor Cretaceous species recovered into Tertiary sediments consist of *Braarudosphaera bigelowii, Biscutum melaniae, Neocrepidolithus neocrassus, Placozygus sigmoides, Cyclagelosaphaera reinhardtii, Markalius inversus,* and *Scapolithus fossilis*.

Keywords: biostratigraphy, nannoplankton, Cretaceous/Tertiary (K/T) boundary, Santos Basin, Brazil

Sari

Perubahan secara besar-besaran dalam kumpulan nanoplankton pada batas Kapur/Tersier (K/T) (65,5 jtl.) telah digambarkan oleh beberapa peneliti. Kumpulan yang beragam dan melimpah seketika menghilang pada batas Kapur/Tersier. Kejadian ini berhubungan dengan perubahan lingkungan paling dramatis dalam sejarah bumi yang disebabkan oleh bencana besar, yaitu meliputi tumbukan meteor (Chicxulub) dan letusan supervulkanik (Deccan) yang terjadi pada akhir Kapur. Periode berikutnya merupakan waktu evolusi nanoplankton yang berjalan secara cepat selama interval waktu Paleosen.Analisis dengan metode kuantitatif terhadap nanoplankton di sepanjang umur Maastrichtian sampai Paleosen dari penampang Sumur "P", Cekungan Santos, Brasil menunjukkan bahwa kumpulan nanoplankton seketika berkurang dalam keragaman dan kelimpahan serta mengalami perubahan besar dalam komposisi spesies. Bentuk spesies yang kompleks dan beragam pada Maastrichtian juga berubah menjadi sederhana dan kecil pada Paleosen. Penampang sedimen berumur antara puncak zona CC23 (Coccolith Cretaceous 23) sampai zona NP9 (Nannoplankton Paleogen 9).Umur tersebut diikat oleh kemunculan akhir (LO) Tranolithus pachelosus di bagian dasar dan Fasciculithus tympaniformis di bagian puncak. Ketidakselarasan pada batas Kapur/Tersier dijumpai, yaitu

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ditandai oleh ketidakhadiran zone CC26 sampai zona NP4. Kumpulan nanoplankton Kapur didominasi oleh genera Watznaueria, Micula, Arkhangelskiella, Cribrosphaerella, Eiffellithus, Predicosphaera, dan Retecapsa, sedangkan kumpulan Paleosen didominasi oleh Genera Toweius, Ericsonia, dan Coccolithus. Spesies Kapur yang bertahan dan dijumpai pada umur Tersier meliputi Braardosphaera bigelowii, Biscutum melaniae, Neocrepidolithus neocrassus, Placozygus sigmoides, Cyclagelosaphaera reinhardtii, Markalius inversus, dan Scapolithus fossilis.

Kata kunci: *biostratigrafi, nanoplankton, batas Kapur Tersier (K/T), Cekungan Santos, Brasil*

Introduction

Background

The massive change in calcareous nannoplankton assemblages at Cretaceous/Tertiary (K/T) boundary was first noted and illustrated by Bramlette & Martini (1964) and then described in greater detail by Perch-Nielsen (1969, 1979a-b, 1981), Percival & Fischer, 1977, Romein (1977), and Bown (1999). The diverse and abundant Maastrichtian assemblage disappears suddenly at the K/T boundary. It is then replaced by new species and genera evolving from 15 to 18 genera that survived the K/T boundary event (Perch-Nielsen, 1982). However, some survivors are considered as reworked forms by some authors since their occurrence in Tertiary are always very rare, even in the abundant assemblage. The confirmed data reveal that survivors consist of some 12 species of 11 genera from 10 families. The succeeding age was a time of rapid evolution of nannoplankton. There was evident that about 25 new genera occurred during ±12.5 M.a. of Paleocene time interval (Perch-Nielsen, 1985) that evolved from 10 survivors (Bown, 1999).

In this paper, the kind of nannoplankton succession throughout Cretaceous/Tertiary boundary can be seen on the “P” well section in Santos Basin (Figure 1). This basin is included in the basins having the ideal sedimentary section to identify the succession marine organism during K/T boundary. Identification of the succession done is restricted on the age of Late Maastrichtian to Early Paleocene.

Material and Methods

This study is the result of nannoplankton analysis on the 27 samples from “P” well section comprising ditch cuttings and cores. They are processed mainly using *smearing method* and embedded in entellan. The analyzed interval was determined systematically and the observation was undertaken at a magnification of 1000x using a light microscope (LM) in a quantitative method. Observation techniques comprise *bright field (BF), cross polarized light (XPL), Gypsum plate in XPL,* and *phase contrast*. Taxonomy and terminology in the description of index species refers to Perch-Nielsen (1985). The standard zonation of Sissingh (1977) and Martini (1971) is used as a mainframe for biostratigraphic subdivision, and then the result is used to identify the succession of nannoplankton assemblage throughout Cretaceous/Tertiary boundary. The flow chart of research method can be seen in Figure 2.

Cretaceous/Tertiary Boundary

The K/T boundary that marks the separation between Cretaceous and Tertiary is visible in the geological record by a discontinuity (dramatic change) in the fossil development. This boundary corresponds to one of the greatest mass extinctions in Earth history. At least 75 percent of the species on our planet, both in the seas and on the continents, were extinguished. In the oceans, more than 90 percent of the plankton was extinguished, which inevitably led to the collapse of the oceanic food chain (Figure 3). All ammonites, genuine belemnites, and rudistids are extinct, and most species of foraminifera and nannoplankton, diatoms,dinoflagellates, molluscs, echinoids, fish, and marine reptiles disappeared. Even though some groups, such as squids, octopus, nautilus, and a few species of foraminifera and nannoplankton, diatoms, dinoflagellates, brachiopods, molluscs, and echinoids survived, the genetic pool were relatively very small at the dawn of the Tertiary Period. The recovery of the marine biota after K/T boundary event was fairly rapid after the mid-Paleocene due to overall transgressing seas and ameliorating cli-

Figure 1. Studied area of Santos Basin (Modified from HIS., 2007).

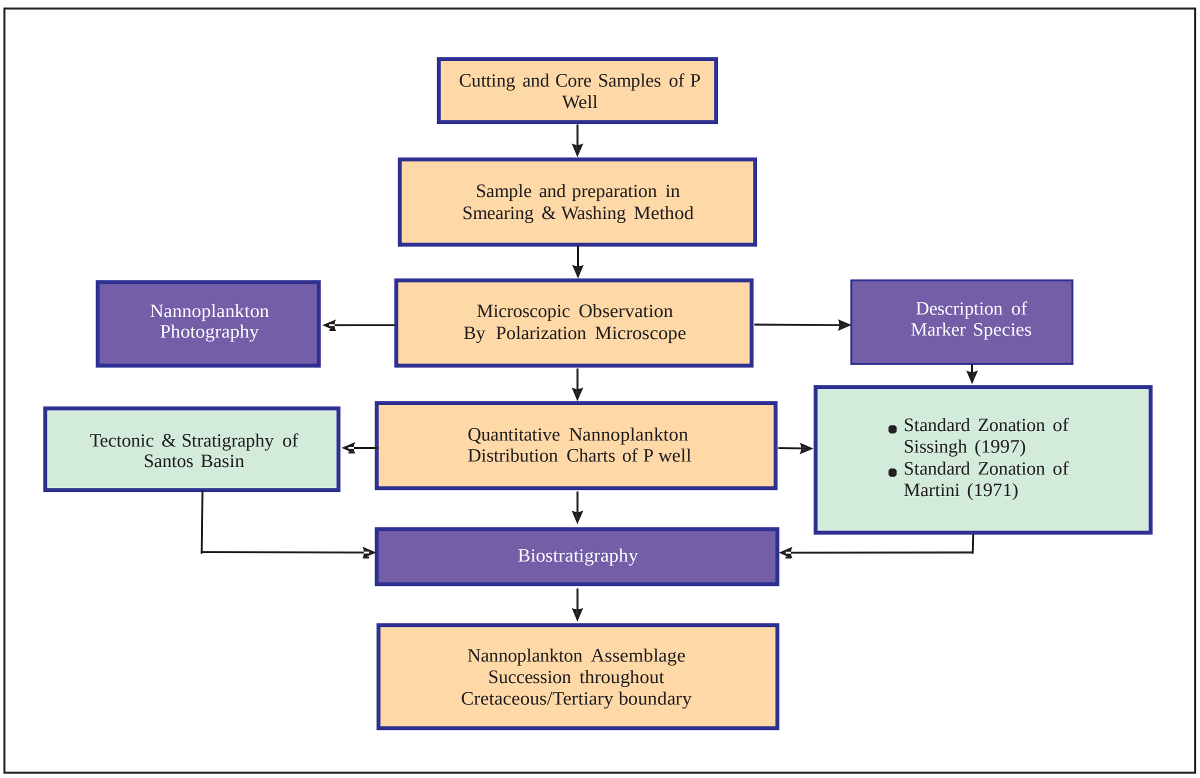

Figure 2. Flow chart of the research method.

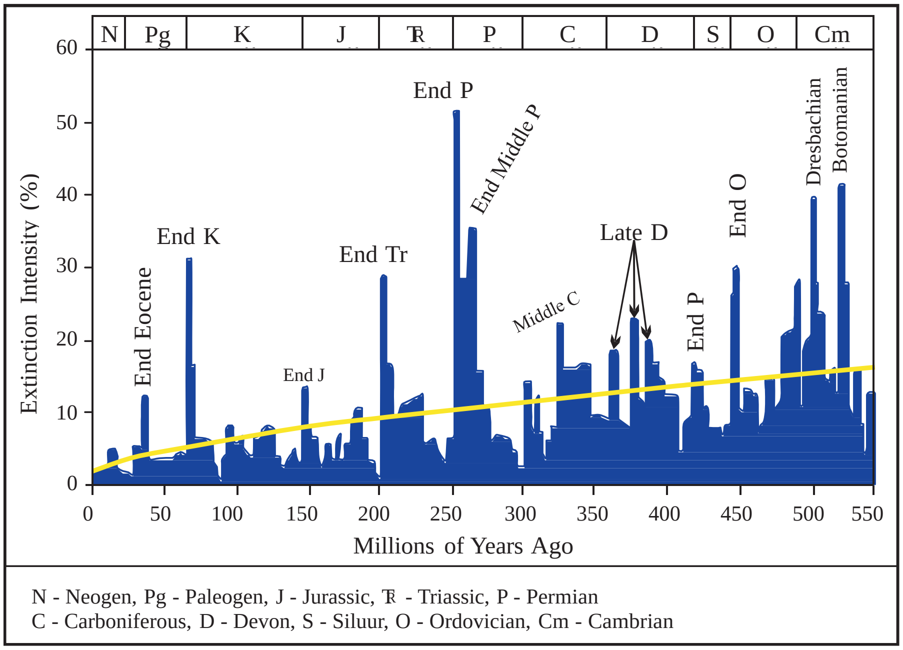

Figure 3. Extinction intensity of marine genus biodiversity (After Raup & Sepkowsky, 1977 *in* Wikipedia, 2007).

mates. On the continent, the large dinosaurs which had been decline for over 20 million years, died out forever. However, most mammals, birds, turtles, crocodiles, lizards, snakes, amphibians, and some land flora were primarily unaffected by the End-Cretaceous mass extinction (Raup & Sapkowsky 1977, *in* Wikipedia, 2007).

There are debates about causes of mass extinction in K/T boundary, and the explanation is present within sedimentary rocks. Rocks deposited during the Cretaceous and Tertiary Periods are separated by thin clay layers that are visible at several sites around the world (Figure 4). A team of scientists led by Alvarez *et al.* (1980) discovered the clay layers contains strikingly high concentration of iridium, an element that is much more common in meteorites (asteroid or comet) than in Earth crustal rocks. Consequently, they suggested that the meteorite impacts

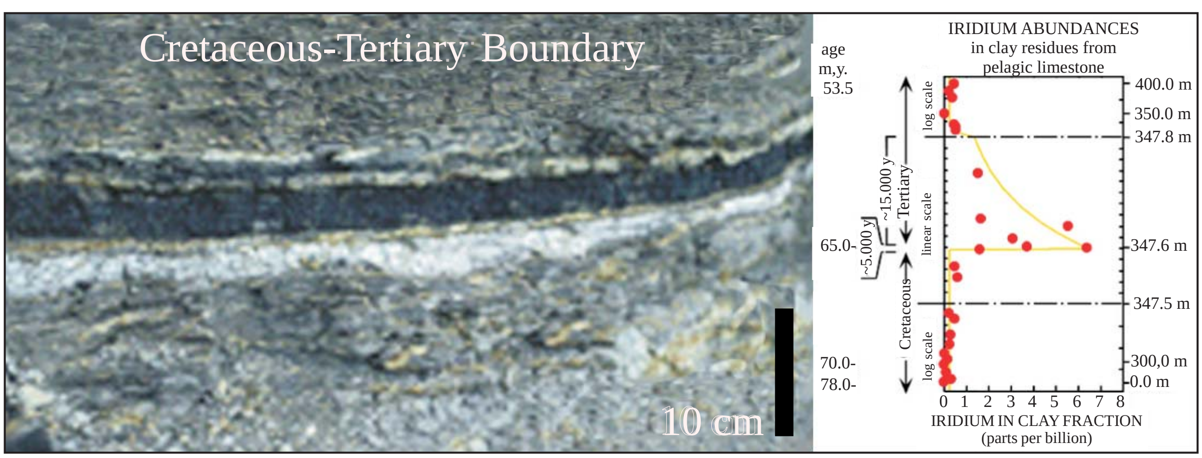

Figure 4. The thin clay layer contains a strikingly high concentration of iridium between K/T boundary (Modification Sharpton *et al.*, 1992).

have generated the iridium anomaly (Sharpton *et al.*, 1992). This argument is supported by the discovery of shocked quartz (Figure 5), microspherules, and mega wave deposits. The high iridium concentrations in the clay layers at several places around the world suggested the impact was a large one. Eventually, most paleontologists began to accept the idea that the mass extinctions at the end of the Cretaceous were largely or at least partly due to a massive meteorite impact (Wikipedia, 2007). The most famous evident for meteorite impact is the 180 km diameter of the buried *Chicxulub Crater*, on the coast of Yucatan, Mexico (Figure 6). Even, some scientists conclude, that the mass extinction event during K/T boundary is not caused by a single impact since multiple impacts appear to be very common

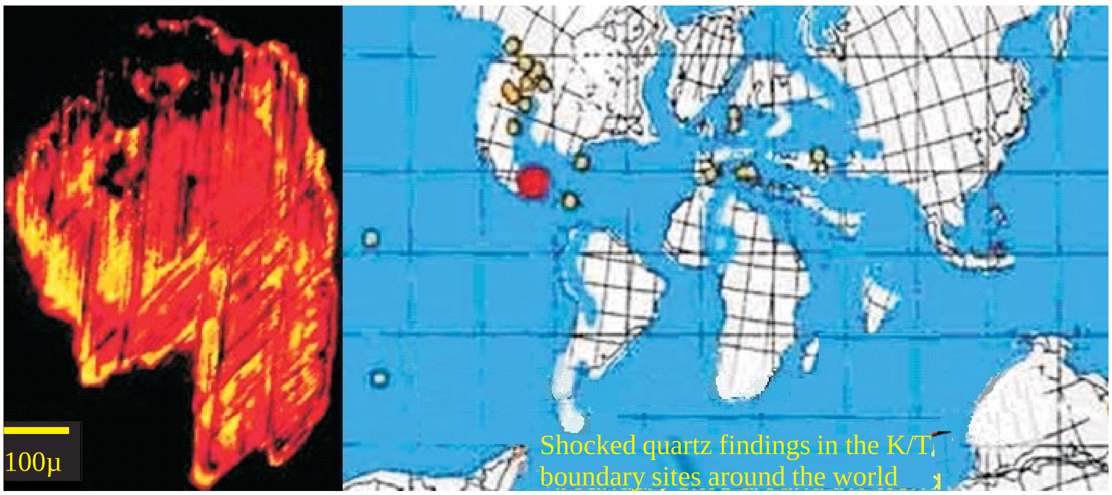

Figure 5. Shocked quartz and its distribution (Modification from Sharpton *et al.*, 1992).

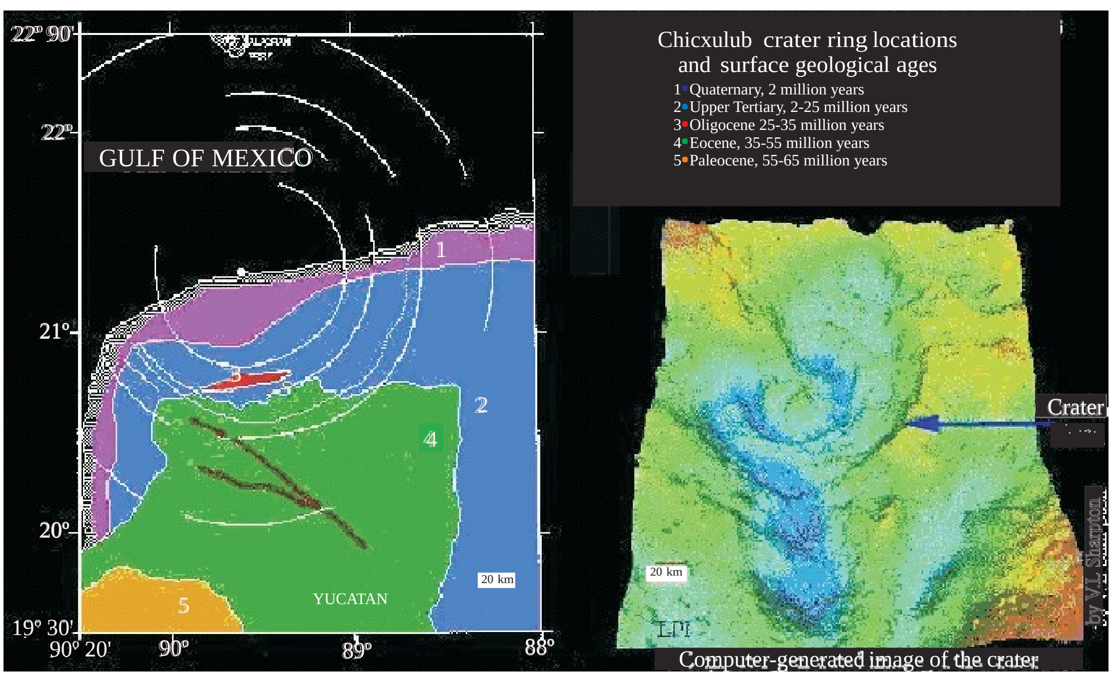

Figure 6. Chicxulub Crater, Yucatan, Mexico (Modification from Sharpton *et al.*, 1992).

throughout the solar system. The Shiva crater is another huge impact crater located under the Arabian Sea off the coast of India near Bombay. This crater also dates from the K/T boundary, 65 M.a., when the Chicxulub crater at the tip of the Yucatán Peninsula also formed. Although it has shifted because of sea floor spreading, when pieced together, it would be about 370 miles (600 km) by 280 miles (450 km) across and 7.5 miles (12 km) deep (and may be just part of a larger crater). It is estimated to have been made by a bolide (an asteroid or meteoroid) 25 miles (40 km) in diameter. This crater was named by the paleontologist Sankar Chatterjee for Shiva, the Hindu god of destruction and renewal. The other craters are Boltysh crater (24 km diameter, 65.17 ± 0.64 M.a.) in Ukraine, Silverpit crater (20 km diameter, 60-65 M.a.) in the North Sea, Eagle Butte crater (10 km diameter, < 65 M.a.) in Alberta, Canada, and Vista Alegre crater (9.5 km diameter, < 65 M.a.) in Paraná State, Brazil (Wikipedia, 2007.). The nemesis hypothesis of Raup and Sepkowsky, 1977 (*in* Wikipedia, 2007) theorizes that there is a periodicity of 26 million years to mass extinctions which is caused by collisions with a comet from the Oor cloud as they are perturbed in their orbits by a dark star (a companion star to the sun) (Geolor's Earth Issues, 2007).

Some scientists considered that there was a link between large impacts and volcanic eruptions. This is evidenced by *Deccan Trap* in India during K/T boundary (the second greatest volcanic eruption after *Siberian Trap* during Permian/Triassic (P/ Ŧr) boundary). By some scientists, The *Deccan Traps* is also assumed as an agent which had been contributed to the extinction in the end of Cretaceous (Wikipedia, 2007).

Santos Basin

The Santos Basin covers an area of 352,260 km2, bordered by Florianopolis High (Pelotas) and Cabo Frio High (Campos). As part of the rifted Atlantic margin of South America, the geological history of the Santos Basin can be divided into pre-Rift (pre-Cretaceous), syn-Rift (Neocomian to Barremian), and post-Rift (Aptian to Recent) stages, as shown on the seismic-based interpretation in Figure 7 (Joshua, 2007).

The lithology and age of pre-Rift rocks in the deepwater Santos Basin are opened to speculation. Reassembly of the African and South American cratons suggests that the Santos' pre-Rift units are a crystalline complex that may contain late stage pre-Rift basaltic flows and intrusions. Field modeling based on interpretation of the Veritas 3D seismic data, plus the fact that this basin is adjacent to the Campos Basin, suggest that the syn-Rift units probably comprise lacustrine, continental, and neritic facies with possible basaltic intrusions and lava flows (Bagni, 2007).

In much of the deepwater area, the basal post-Rift unit is Aptian Salt of more than 2,000 m thick, which forms an excellent seal for the syn-Rift sequence related to the petroleum system. Overlying the salt are Albian deepwater carbonates and marls, which are overlain in turn by Late Cretaceous through Recent turbiditic clastics. The thickness of these clastics varies within basin that floored by salt and/or salt welds, but in general, the clastics thin seaward (Joshua, 2007).

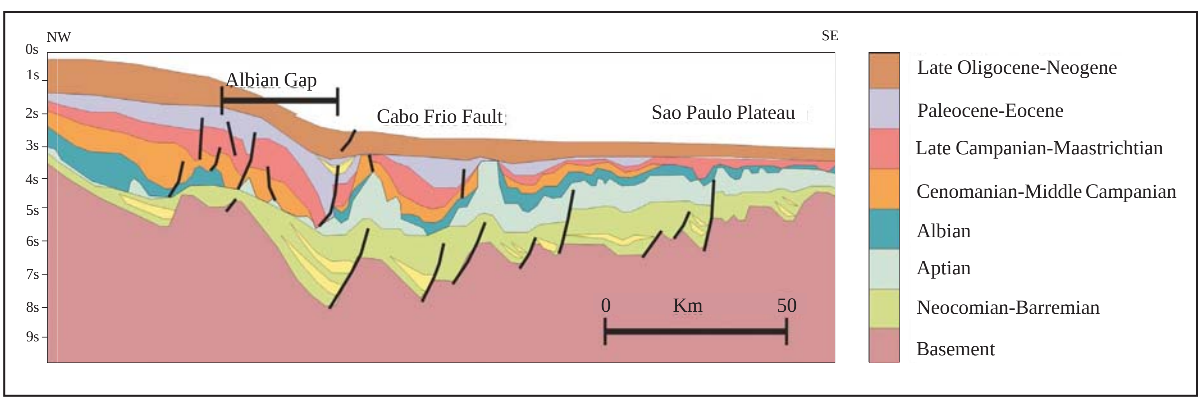

Figure 7. The 2D seismic-based interpretation across the deepwater Santos Basin (Joshua, 2007).

The tectonic-stratigraphic evolution was commenced by Mesozoic pelotas to PE-PB rift followed by the occurrence of Neocomian basalt of the Camboriú Formation. Basin Rifting continued during Barremian/Early Aptian sequence with the result of Guaratiba Formation. The transitional stage is evidenced by the formation of Aptian Evaporites (Ariri Formation). Entering the Albian, the drifting occurred with the result Guaraja Formation (Bagni, 2007).

The further sequences are the results of the Cenomanian-Turonian transgressive phase (Itajai-Açu Formation), the Coniacian to Maastrichtian regressive phase (Juréia Formation) due to Serra do Mar Uplifting, and finally by Tertiary Transgressive phase (Iguape and Marambaia Formations) (Bagni, 2007). Based on a seismic stratigraphic analysis, three major sequences from their internal reflector patterns and external geometry in the southern end of the basin can be identified. The Early Rift Sequence (lower rift on Tupi seismic line) is compounded by volcanic rocks and characterized by parallel to subparallel reflectors, continuous and high dip angles. "The Rift Sequence (upper rift on Tupi seismic line) is characterized by half grabens, possibly filled by coarse sediments. The main internal reflections are divergent and prograding. The final Sag Phase was deposited on an unconformity identified by 3-D data. Reflectors truncate down and onlap above (Joshua, 2007). Regional stratigraphic chart of Santos Basin can be seen in Figure 8.

Analysis Results

Biostratigraphic Subdivision

The standard zonation of Sissingh (1977) for Cretaceous and Martini (1971) for Tertiary are used in the age interpretation and zonal subdivision throughout "P" well section (Table 1). Based on the occurrence of nannoplankton markers, biostratigraphy of the studied section can be subdivided from the base to the top as follows (Figure 9a-f).

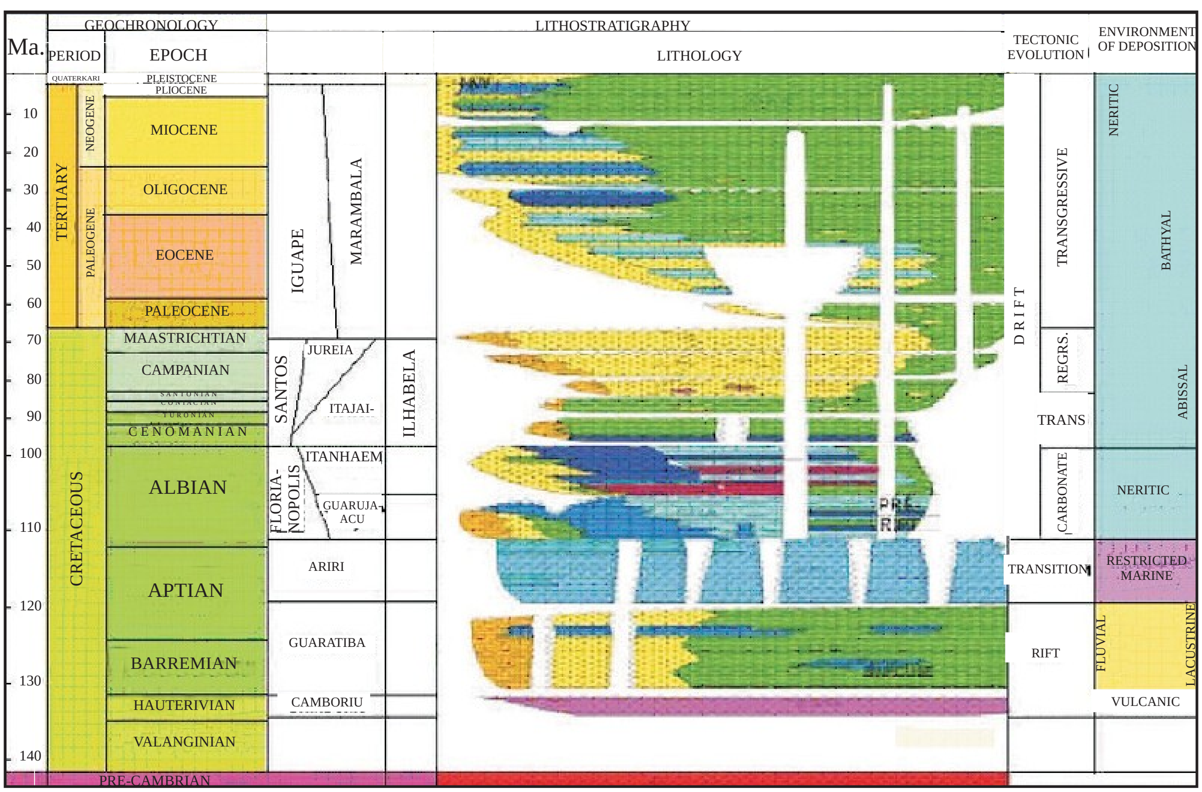

Figure 8. Regional stratigraphy of the Santos Basin (Bagni, 2007).

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Table 1. Biostratigraphy of P Well Section

Sample	Zone	Description
17-27	Zone NP9 (Late Paleocene)	This zone is bounded respectively by the FO of *Discoaster multiradiatus* at the base and the occurrence of *Fasciculithus tympaniformis* at the top. This zone can be subdivided into subzone "a" and "b" by the FO of *Campilosphaera eodela* in sample 21.
8-16	Zone NP8 (Late Paleocene)	This zone is bordered by the FO of *Heliolithus riedelii* at the base and the FO of *Discoaster multiradiatus* at the top.
7	Zone NP7 (Late Paleocene)	The bottom of this zone is revealed by the FO of *Discoaster mohleri*, whilst its top is marked by the FO of *Heliolithus riedelii*.
5-6	Zone NP6 (Middle Paleocene)	The base and the top of this zone are indicated respectively by the FO of *Chiasmolithus bidens* and the FO of *Discoaster mohleri.*
4	Zone NP5 (Middle Paleocene)	The base of this zone is underlain by an unconformity ranges from CC26 to NP4 (uppermost part of Maastrichtian to lower part of Middle Paleocene). This zone is bounded by the occurrence of *Fasciculithus janii* at the bottom and the first occurrence (FO) of *Chiasmolithus bidens* at the top.
3	Zone CC25 (Maastrichtian)	The bottom of this zone is assigned by the LO of *Reinhardtites levis*, whilst its top is indicated by the occurrence of *Calculites obscurus*. This zone is deposited at the top of Cretaceus sedimentary sequence of "P" well section. Zone CC26 is considered to be absent since the LO of *Calculites obscurus* coincided with the highest occurrence of species ranges to CC26. This is supported by the absence of species that restricted within zone CC26 *(Ceratolithoides kamptneri, Nephrolithus frequens, Cribosphaera daniae* and *Micula prinsii)* and the occurrence of Middle Paleocene assemblage within the overlying sample (4).
2	Zone CC24 (Maastrichtian)	This zone is indicated by the LO of *Tranolithus pachelosus* at the base and the LO of *Reinhardtites levis* at the top.
1	Zone CC23 (Maastrichtian)	This sample is the position of the last occurrence (LO) of *Tranolithus pachelosus* that indicates the top of zone CC23.

Nannoplankton Assemblage Succession throughout Cretaceous/Tertiary Boundary in the "P" Well Section

A quantitative method nannoplankton analysis throughout the top of zone CC23 (Maastrichtian) to zone NP9 (Paleocene) of "P" well section, Santos Basin, Brazil has been undertaken to define the succession of nannoplankton assemblage throughout K/T boundary. Unfortunately, the real succession within K/T boundary cannot be seen due to the presence of an unconformity ranges from CC26 to NP4 (Figures 9a-f & 10). However, it was highly evident that the nannoplankton assemblages abruptly decreased in diversity and abundance and mostly changed in species composition (Figure 11). Mass extinction had been occurred in the Cretaceous nannoplankton assemblage during K/T boundary event and only 7 survivors can be recovered (Figure 11a-d). The domination of large various complex shapes of species at the upper part of Maastrichtian

DEPTH (Represented by Number)	AGE (Ma)	PERIODS	EPOCH	STAGE	ZONE: CC (Sissingh, 1977); NP (Martini, 1971)	BIOMARKERS
27	55.8	TERTIARY	PALEOCENE – LATE	THANETIAN	NP9 b	→ Fasciculithus tympaniformis
26					NP9 b	
25					NP9 b	
24					NP9 b	
23					NP9 b	
22					NP9 b	
21					NP9 b	First Occurrence Campilosphaera eodela
20					NP9 a	
19					NP9 a	
18					NP9 a	
17					NP9 a	First Occurrence Discoaster multiradiatus
16					Np8	
15					Np8	
14					Np8	
13					Np8	
12					Np8	
11					Np8	
10					Np8	
9					Np8	
8					Np8	First Occurrence Heliolithus riedelii
7					NP7	First Occurrence Discoaster mohleri
6	58.7				NP6	
5			PALEOCENE – MIDDLE	SELAND.	NP6	First Occurrence Chiasmolithus bidens
4	63.0				NP5	→ Fasciculithus janii
3	66,5	CRETACEOUS	LATE	MAASTRICHTIAN	CC25	→ Calculites obscurus
2					CC24	Last Occurrence Reinhardtites levis
1	70,0				CC23	Last Occurrence Tranolithus pachelosus

PALEOCENE ASSEMBLAGE

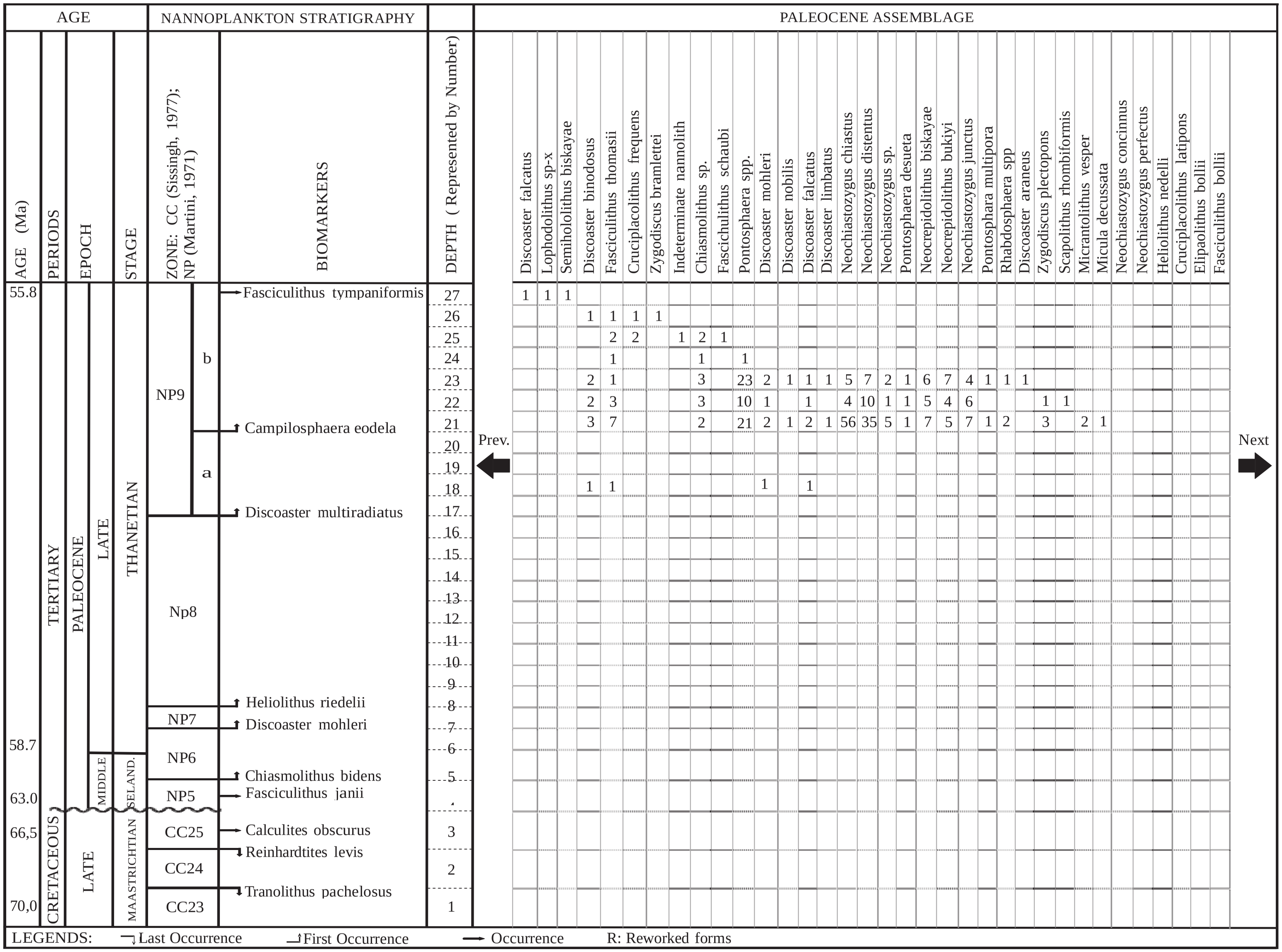
DEPTH	Fasciculithus janii	Coccolithus pelagicus	Chiasmolithus consuetus	Cruciplacolithus tenuis	Ellipsolithus macellus	Ericsonia robusta	Ericsonia subpertusa	Ericsonia spp.	Sphenolithus primus	Prinsius bisulcus	Fasciculithus tympaniformis	Toweius selandianus	Toweius spp	Prinsius sp.	Fasciculithus sp	Toweius pertusus	Chiasmolithus bidens
27		230		2	2	7	5	5	17	2	7	17	35		4	58	1
26		43			1	2	1	2	23		5	5	3		2	9	1
25		40	3	1	1	5	2	8	11	2	4	14	2		2	51	
24		52	2		2	1	2		11		1	2	1		1	7	1
23		315	6	2	7	85	72	118	54	5	3	46	34		1	125	2
22		295	7	3	6	63	43	102	21	10	5	86	43		2	168	2
21		375	7	5	21	69	64	175	23	3	13	17	31		2	142	
20		7				1	2		3	2	2	8	3		1	2	
19		6		1		1	2		3	2	2	6	2			7	1
18		23	1	1	4	2	5	11	27	11	7	125	18		4	17	1
17		265	3	1	3	55	43	75	65	15	13	175	23		7	35	2
16		5							4	1		5	3			12	
15		1			1				2			2	1				
14		2				3	1	3	2								
13		1			1	1		1	2		1	1					
12		1		1				3					1				
11		2		1				2	1	2	1	6	1				
10		2		3				6	2	1		3	2				
9		1	1	1				2		1		1					
8		5	1	1	1	2	2	3	1	2	2	7	1			2	1
7	1	8	1	3	2	8	10	7	7	5	2	21	2		1		
6		1					1		1		1	1					
5	1	2		1			1	1			2				1	1	1
4	2	2	1	2	1	1	2	1	1	1	1	2	2	1			
3																	
2																	
1																	

DEPTH	Discoaster multiradiatus	Fasciculithus alanii	Fasciculithus lilinae	Ellipsolithus distichus	Sphenolithus sp	Semihololithus kerabyii	Fasciculithus clinatus	Heliolithus cantabriae	Fasciculithus involutus	Toweius rotundus	Zygodiscus herlynii	Sphenolithus primus	Sphenolithus anarharhopus	Toweius eminens	Campylosphaera eodela	Lophodolithus nascens	Sphenolithus small	N…
27	2	6	1	2	2	2	2	1	1	175	1	7	4	1	2	2	5	1
26		1			4	1	3			35	2	9	2		1	1	7	1
25		3		1	3		1		1	125		6	5	2	1	1	2	
24		1		1	3					41		3	2		1			
23	1		1	2	11		3			435	2	5	35	3	8	2		4
22	1				5		1			780	1	2	17		4	1		5
21	2		3	3	7		2			1080	1	2	13	5	7	7		3
20		1			2					4			2					
19					1					5		1	1					
18		1	1	1	14		1		2	11		3	11	1				1
17	2	1	1	1	27		2		3	425	1	5	17					2
16					3					2	1							
15					2													
14					2		1											
13					1													
12					3				1									
11				1	2			1										
10					3													
9																		
8				1	1		2											
7				3	8	1												
6																		
5																		
4																		
3																		
2																		
1																		

Next →

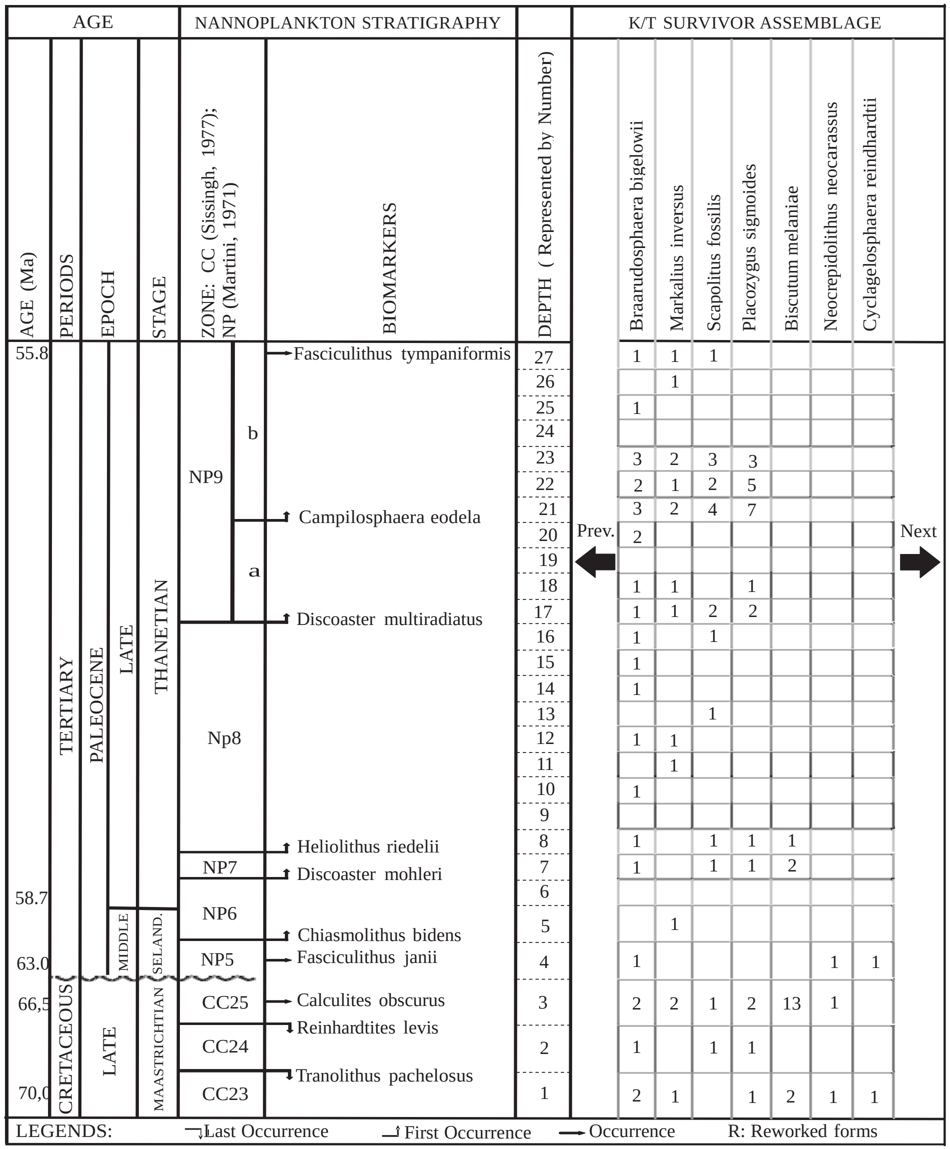
LEGENDS: Last Occurrence; First Occurrence; → Occurrence; R: Reworked forms

Figure 9a. Quantitative Paleocene nannoplankton distribution chart and biostratigraphy of "P" Well Section.



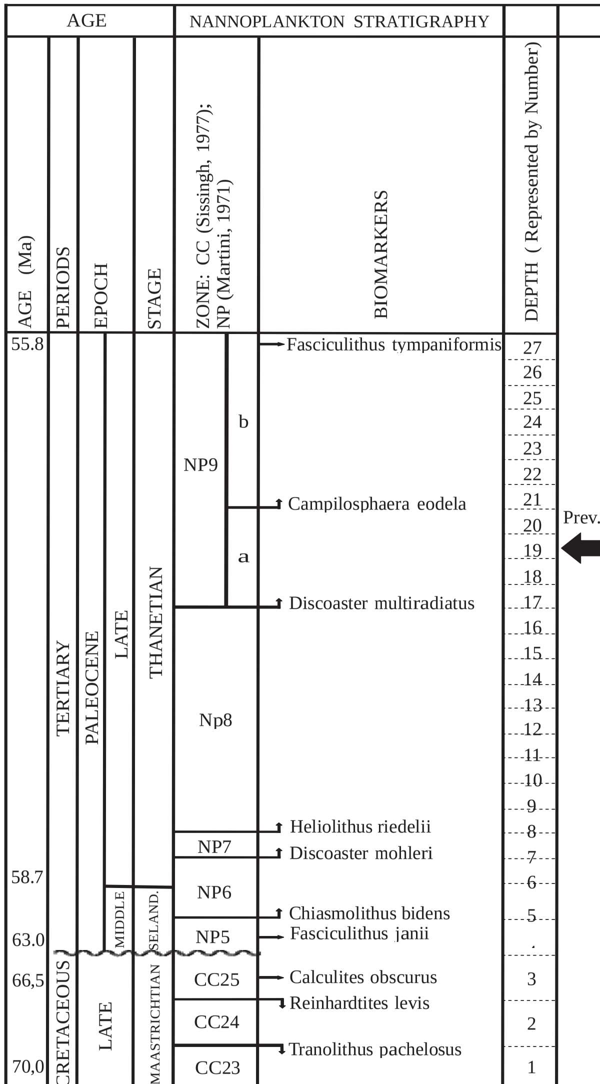
Species	27	26	25	24	23	22	21	20	19	18
Discoaster falcatus	1									
Lophodolithus sp-x	1									
Semihololithus biskayae	1									
Discoaster binodosus		1			2	2	3			1
Fasciculithus thomasii		1	2	1	1	3	7			1
Cruciplacolithus frequens		1	2							
Zygodiscus bramlettei		1								
Indeterminate nannolith			1							
Chiasmolithus sp.			2	1	3	3	2			
Fascichulithus schaubi			1							
Pontosphaera spp.				1	23	10	21			
Discoaster mohleri					2	1	2			1
Discoaster nobilis					1		1			
Discoaster falcatus					1	1	2			1
Discoaster limbatus					1		1			
Neochiastozygus chiastus					5	4	56			
Neochiastozygus distentus					7	10	35			
Neochiastozygus sp.					2	1	5			
Pontosphaera desueta					1	1	1			
Neocrepidolithus biskayae					6	5	7			
Neocrepidolithus bukiyi					7	4	5			
Neochiastozygus junctus					4	6	7			
Pontosphara multipora					1		1			
Rhabdosphaera spp					1		2			
Discoaster araneus					1					
Zygodiscus plectopons						1	3			
Scapolithus rhombiformis						1				
Micrantolithus vesper							2			
Micula decussata							1			
Neochiastozygus concinnus										
Neochiastozygus perfectus										
Heliolithus nedelli										
Cruciplacolithus latipons										
Elipaolithus bollii										
Fasciculithus bollii										

Figure 9b. Quantitative Paleocene nannoplankton distribution chart and biostratigraphy of “P” Well Section.



DEPTH	Braarudosphaera bigelowii	Markalius inversus	Scapolitus fossilis	Placozygus sigmoides	Biscutum melaniae	Neocrepidolithus neocarassus	Cyclagelosphaera reindhardtii
27	1	1	1				
26		1					
25	1						
24							
23	3	2	3	3			
22	2	1	2	5			
21	3	2	4	7			
20	2						
19							
18	1	1		1			
17	1	1	2	2			
16	1		1				
15	1						
14	1						
13			1				
12	1	1					
11		1					
10	1						
9							
8	1		1	1	1		
7	1		1	1	2		
6							
5		1					
4	1					1	1
3	2	2	1	2	13	1	
2	1		1	1			
1	2	1		1	2	1	1

Figure 9c. Quantitative Survivor nannoplankton distribution chart and biostratigraphy of "P" Well Section.



PALEOCENE ASSEMBLAGE

Species	Depth 3	Depth 2	Depth 1
Acuturris acotus	2	1	2
Ahmuellerella octoradiata	8	1	3
Amphizygus broksi	3	1	2
Arkhangelskiella confusa	65	2	17
Arkhangelskiella cymbiformis	135	5	33
Biscutum coronum	7	1	5
Biscutum elipticum	3	1	2
Biscutum spp.	8	2	7
Calculithes sp.	5	2	3
Calculithes obscurus	7	2	5
Calculithes percenis	2	1	2
Ceratolithodes aculeus	53	2	7
Ceratolithodes prominens	5	1	2
Ceratolithodes quasiarcuatus	23	2	6
Ceratolithodes sesquipedals	8	1	2
Chiastozygus sp.	6	2	3
Chiastozygus platyrhethus	2	1	1
Chiastozygus synquadryperforatus	15	2	5
Chiastozygus traballs	5	2	3
Corollithion sp.	5	1	2
Corollithion signum	4	1	2
Chibrospharella ehrenbergii	85	1	5
Cylindralithus sculptus	6	1	2
Eifellithus gorkae	75	7	26
Eifellithus parallelus	17	2	5
Eifellithus turriseifellii	6	2	4
Gartnerago segmentatum	3	1	2
Helicolithus trabeculats	5	2	3
Loxolithus armilla	8	2	5
Micula decussata	510	2	17
Micula awastica	1		2
Mischeomarginatus pleniporus	2	2	1
Petrarhabdus capulatus	2		2
Placozygus fibuliformis	10	2	4
Podorhabdus eikefensis	2	1	2
Prediscospharea arkhangelskyi	2		2
Prediscospharea bukryi	2		1
Prediscospharea cretacea	85	5	23
Prediscospharea grandia	7	1	2

Reworked occurrences: Chiastozygus synquadryperforatus 1R at depth 7; Micula decussata 1R at depth 19 and 1R at depth 24.

LEGENDS: Last Occurrence First Occurrence Occurrence R: Reworked forms

Figure 9d. Quantitative Cretaceous nannoplankton distribution chart and biostratigraphy of “P” Well Section.

AGE (Ma)	PERIODS	EPOCH		STAGE	ZONE: CC (Sissingh, 1977); NP (Martini, 1971)		BIOMARKERS	DEPTH (Represented by Number)
55.8	TERTIARY	PALEOCENE	LATE	THANETIAN	NP9	b	→ Fasciculithus tympaniformis	27
								26
								25
								24
								23
								22
						a	Campilosphaera eodela	21
								20
								19
								18
					Np8		Discoaster multiradiatus	17
								16
								15
								14
								13
								12
								11
								10
								9
					NP7		Heliolithus riedelii	8
					NP6		Discoaster mohleri	7
58.7			MIDDLE	SELAND.				6
					NP5		Chiasmolithus bidens	5
63.0							→ Fasciculithus janii	.
66,5	CRETACEOUS	LATE		MAASTRICHTIAN	CC25		→ Calculites obscurus	3
					CC24		Reinhardtites levis	2
70,0					CC23		Tranolithus pachelosus	1

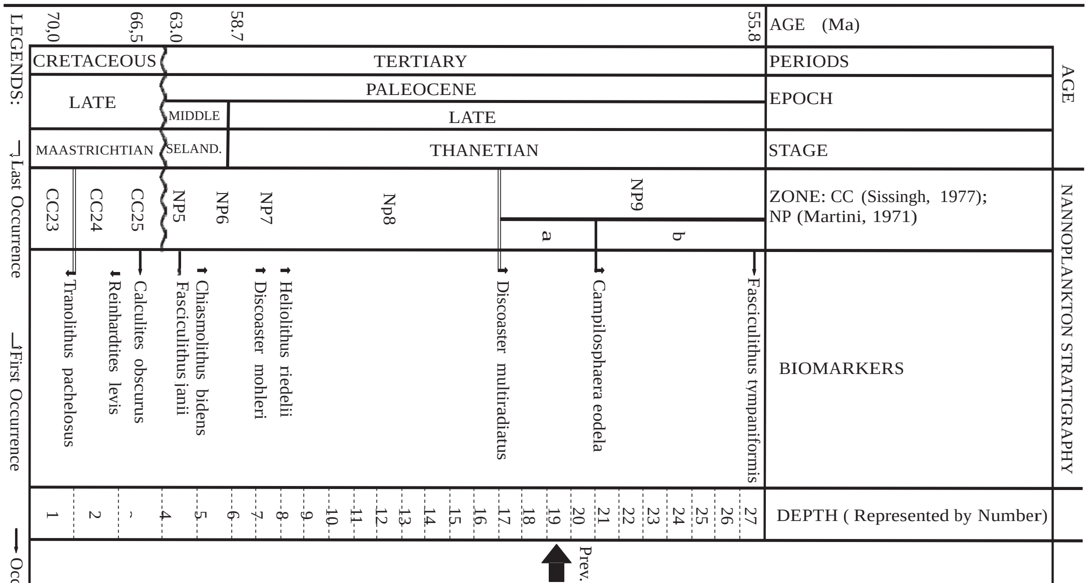
CRETACEOUS ASSEMBLAGE

Species	Depth 1	Depth 2	Depth 3	Depths 4–27
Prediscosphaera spinosa	7	2	17	
Prediscosphaera stoveri	5	2	13	
Repagulum parvidentatum	2	1	3	
Retecapsa angustiforata	3	1	21	
Retecapsa crenulata	6	1	145	
Retecapsa ficule	3	1	17	
Retecapsa schizobrachiata	2	1	3	
Rhagodiscus angustus	3		4	
Rhagodiscus indistinctus	4	2	7	
Rhagodiscus plebeius	6	2	13	
Rhagodiscus reniformia	5	2	11	
Rhagodiscus splendens	13	5	43	
Staurolithites aurolithites bavus	3	1	5	
Staurolithites flavus	2	1	5	
Staurolithites imbricatus	2	1	2	
Staurolithites integer	1		2	
Staurolithites laaffittei	2	1	3	
Staurolithites zooensia	4	2	5	
Tegumentum stradneri	6	3	12	
Tetrapodorhabdus decorus	3	1	5	
Tranolithus gabulus	5	2	10	
Tranolithus minimus	4	3	12	
Uniplanarius staurophora	10	3	23	
Watznaueria barnesae	1230	103	1430	1R (8), 1R (9), 1R (19), 1R (24)
Watznaueria fossacincta	175	27	23	
Watznaueria ovata	17	13	21	
Watznaueria sp.	4	2	3	
Zeugrhabdotus embergeri	2	1	3	
Zeugrhabdotus erectus	13	5	24	
Zeugrhabdotus praesigmoides	2	1	2	
Zeugrhabdotus trivectis	11	3	25	
Helicolithus anceps	2	2	2	
Broinsonia enormis	1	2	3	
Broinsonia signata	1	1	2	
Ahmuellerella regularis	1	1	1	
Kamptnenus magnificus	1	2	2	
Lithraphidites camiolensis	1	2	2	
Cylindralithua serratus	2	1	1	
Biscutum magnum	1	1	2	

← Prev. Next →

LEGENDS: Last Occurrence; First Occurrence; → Occurrence; R: Reworked forms

Figure 9e. Quantitative Cretaceous nannoplankton distribution chart and biostratigraphy of "P" Well Section.



CRETACEOUS ASSEMBLAGE

Species	1 (CC23)	2 (CC24)	~ (CC25)
Ottavianus terrazetus	1	2	2
Ahmuellerella ambiguus	1	1	2
Calculithes additus	1	2	2
Chiastozyqua amphipona	2	1	2
Discorhabdus ignotus	1	1	1
Psyktosphaera fiithii	2	2	3
Staurolithites ellipticus	1	1	2
Tortolithus pagei	1	1	2
Uniplanarius gothicus	1	2	2
Zeugrhabdotus spiralis	2	1	1
Quadrum svabenickae	1	1	2
Quadrum gartneri	2	2	1
Lucianorhabdus caveuxii	2	1	1
Manitivella pemmatoidea	5	6	8
Predicosphaerea incohatus	1	2	3
Microrhabdulus belgicus	1	1	1
Russelia bukiyi	1	1	3
Russelia laswellii	1	1	2
Quadrum bengalensis	1	1	2
Microrhabdulus decoratus	5	6	13
Microrhabdulus undosua	4	3	5
Micula concava	13	10	25
Micula cubiformis	4	3	12
Parhabdolithus elkefensis	1	1	2
Corolithion exiguum	3	2	2
Chiastozygus antiqus	1	2	2
Lithraphidites quadratus		2	4
Octocyclus reindhardtii	2	1	1
Semihololithus priscus			1
Micula murus			1
Semihololithus bicornis			1
Reinhardtites levis	3	2	
Cylindralithus biarcus	2	1	
Placozygus sigmaides	1	2	
Lithraphidites praequadratus	1		
Gaarderella granulifera	1		
Nephrolithua cryatua	1		
Watznaueria biporta	45		
Tranolithus pachelosus	3		
Uniplanarius trifidum	2		
Zeugrhabdotus bicrescenticus	3		
Uniplanarius sissinghi	2		

Next

Figure 9f. Quantitative Cretaceous nannoplankton distribution chart and biostratigraphy of "P" Well Section.

AGE (Ma)	PERIODS	EPOCH	STAGE	ZONE: CC (Sissingh, 1977); NP (Martini, 1971)	BIOMARKERS	DEPTH (Represented by Number)	CRETACEOUS DIVERSITY	CRETACEOUS ABUNDANCE	SURVIVOR DIVERSITY	SURVIVOR ABUNDANCE	PALEOCENE DIVERSITY	PALEOCENE ABUNDANCE	TOTAL DIVERSITY	TOTAL ASSEMBLAGE
55.8	TERTIARY	PALEOCENE LATE	THANETIAN	NP9 b	→ Fasciculithus tympaniformis	27	0	0	3	3	31	611	34	614
						26	0	0	1	1	27	168	28	169
						25	0	0	1	1	30	305	31	306
						24	0	0	0	0	22	138	22	138
						23	0	0	4	11	42	1456	46	1467
						22	0	0	4	10	38	1729	42	1739
				NP9 a	First Occurrence: Campilosphaera eodela	21	0	0	4	16	43	2246	47	2262
						20	0	0	1	2	13	40	14	42
						19	0	0	0	0	15	41	15	41
						18	0	0	3	3	34	326	37	329
					First Occurrence: Discoaster multiradiatus	17	0	0	4	6	35	1294	39	1300
				Np8		16	0	0	2	2	7	36	9	38
						15	0	0	1	1	5	9	6	10
						14	0	0	1	1	7	15	8	16
						13	0	0	1	1	9	11	10	12
						12	0	0	2	2	6	13	8	15
						11	0	0	1	1	14	24	15	25
						10	0	0	1	1	12	34	13	35
						9	0	0	0	0	8	9	8	9
					First Occurrence: Heliolithus riedelii	8	0	0	4	4	17	40	21	44
				NP7	First Occurrence: Discoaster mohleri	7	0	0	4	5	19	97	23	102
58.7				NP6		6	0	0	0	0	5	5	5	5
		MIDDLE	SELAND.		First Occurrence: Chiasmolithus bidens	5	0	0	1	1	10	14	11	15
63.0				NP5	→ Fasciculithus janii	4	0	0	3	3	11	20	14	23
66,5	CRETACEOUS	LATE	MAASTRICHTIAN	CC25	→ Calculites obscurus	3	109	3238	6	21	0	0	115	3259
				CC24	Last Occurrence: Reinhardtites levis	2	77	268	3	3	0	0	80	271
70,0				CC23	Last Occurrence: Tranolithus pachelosus	1	105	1876	6	8	0	0	111	1884

LEGENDS: Last Occurrence; First Occurrence; → Occurrence

Figure 10. Fluctuation of nannoplankton diversity and abundance throughout analyzed section.

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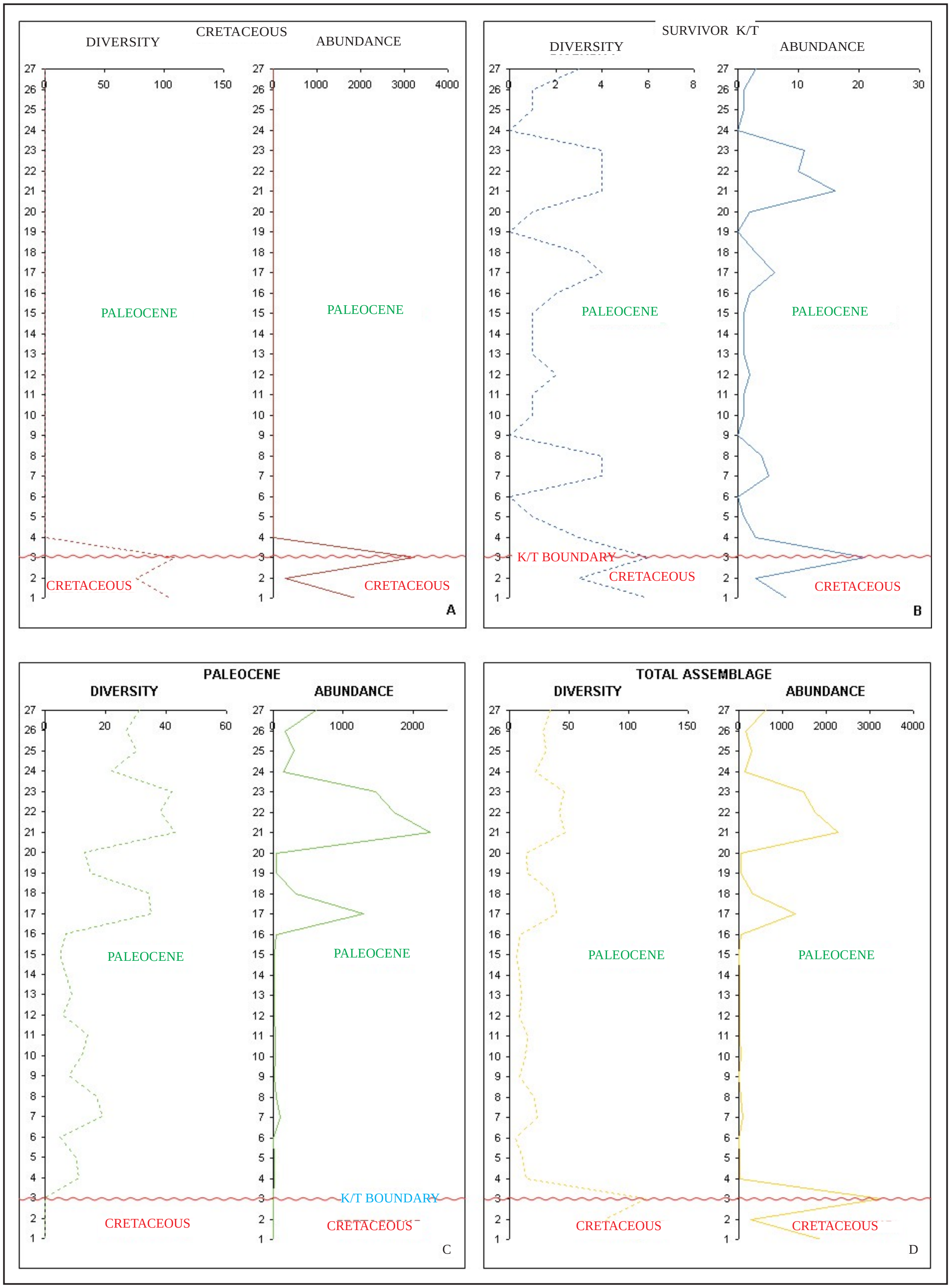

Figure 11. The evolution development graphics, seen in diversity and abundance of Cretaceous, Survivor, and Paleocene nannoplankton assemblages.

(CC25) underwent changing to small and simple plain shapes at the lower part of Paleocene (NP5). In the "P" well section, the Cretaceous nannoplankton assemblages reach 109 species in diversity and 3238 specimens in total assemblage. They are dominated by Genera *Watznaueria, Micula, Arkhangelskiella, Cribrosphaerella, Eiffellithus, Predicosphaera,* and *Retecapsa* (Figure 9D-F). However, none of those dominant species survived in K/T boundary event. A fluctuation in diversity and abundance throughout CC23 to CC25 can be seen clearly.

Survivor Cretaceous species into Tertiary periods consist of 7 species with total assemblage only reach 21 specimen, including *Braarudosphaera bigelowii, Biscutum melaniae, Neocrepidolithus neocrassus, Placozygus sigmoides, Cyclagelosaphaera reinhardtii, Markalius inversus,* and *Scapolithus fossilis* (Figure 9c). They are all minor species within nannoplankton assemblage, but they can survive during K/T boundary event. There is no clearly difference in diversity and abundance fluctuation during Maastrichtian and Paleocene. Their occurrence is always rare to few.

The Paleocene assemblages are characterized by trends of the rising assemblage diversity and abundance of nannoplankton. Generally, the earliest development of new nannoplankton is small and simple coccolith including genera *Praeprinsius Prinsius*, *Neocrepidolithus, Neochiastozygus,* and *Cruciplacolithus,* followed by *Coccolithus, Ericsonia, Toweius, Fasciculithus, Sphenolithus, Ellipsolithus, Chiasmolithus,* and *Zygodiscus* in the Middle, and then closed by *Heliolithus, Discoaster, Helicosphaera, Transversopontis,* and *Lopodolithus.* However, the CC26-NP4 unconformity has removed the small earliest forms. The Paleocene age in this study is initiated by the rare assemblage of genera *Coccolithus, Ericsonia,* medium *Prinsius, Ellipsolithus, Chiasmolithus Toweius, Fasciculithus,* and *Sphenolithus.* The diversity is fluctuated from 5 to 43 species, whilst the abundance from 5 to 2246 specimens is at the upper part of Paleocene. It is dominated by Genera *Toweius, Ericsonia,* and *Coccolithus* (Figure 10).

Rare reworked specimens of Cretaceous nannoplankton are present, including *Micula decussata* and *Watznaueria barnesae* (Figure 9d-e). They can be defined by a different colour (brown) compared with relatively fresh insitu assemblage, etched coccolith, and position in the younger nannoplankton assemblage.

Discussion And Conclusions

The nannoplankton analysis on the "P" well section indicates that 94% of Cretaceous species had been extinguished and remained 6% survivors. A dramatic change in nannoplankton assemblage was found during Paleocene, where the small or simple new species evolved beside the survivors. The peak development of Paleocene nannoplankton evolution was found in the uppermost part of Paleocene.

The nannoplankton succession within "P" well Section is not the real succession within K/T boundary due to the presence of an unconformity ranging from CC26 to NP4. However, it was evident that the nannoplankton assemblages abruptly decreased in diversity and abundance, and mostly changes in species composition.

Fluctuations of diversity and abundance seen in the figure do not completely represent the nannoplankton evolution development (Figure 11). However, that is the final result after the environment of deposition and paleoclimatology are collaborated.

Nannoplankton group dominating at Cretaceous assemblage, are genera *Watznaueria, Micula, Arkhangelskiella, Cribrosphaerella, Eiffellithus, Predicosphaera*, and *Retecapsa* had been extinguished at K/T boundary. It reveals that domination within assemblage is not a guarantee to survive. There is an evidence that they consist of species having restricted tolerance to the environmental change.

Species group consisting of *Braarudosphaera bigelowii*, *Biscutum melaniae*, *Neocrepidolithus neocrassus, Placozygus sigmoides, Cyclagelosaphaera reinhardtii, Markalius inversus,* and *Scapolithus fossilis* is the minority in Cretaceous nannoplankton assemblage. However, they survived into the K/T boundary, even *Braarudosphaera bigelowii* and *Scapolithus fossilis* can be found in the present day ocean due to the wide range tolerance to the extreme environmental change during the K/T boundary.

A trend of the rising diversity and abundance can be seen during Late Paleocene. This is the result of the rising temperature at the Late Paleocene after cooling in the Early Paleocene. The lowest sample contains genera *Coccolithus*, *Ericsonia*, medium *Prinsius*, *Ellipsolithus*, *Chiasmolithus Toweius*, *Fasciculithus*, and *Sphenolithus*, whilst the upper part samples contain much more diverse and abundant.

The presence of Cretaceous reworked forms in Paleocene is the evidence of a relative sea level fall in the studied area during Late Maastrichtian to Early Paleocene, that coincided with the Laramide orogeny event in the most area of the world leading to the formation of the Rocky Mountains and the Himalayas.

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