

# Early Pliocene calcareous and siliceous microfossils of the Sawai Bay Formation, Car Nicobar Island, northern Indian Ocean

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## ABSTRACT:

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The present contribution provides a study of calcareous nannofossils and siliceous microfossils from the Sawai Bay Formation on Car Nicobar Island, northern Indian Ocean. Two stratigraphically short sediment intervals near Sawai Bay have been examined. Qualitative and quantitative microfossil analyses show the Sawai Bay ‘A’ Section to be devoid of siliceous microfossils, while 24 well-preserved calcareous nannofossil taxa are identified. The Sawai Bay ‘B’ Section yields 18 calcareous nannofossil, 33 radiolarian and 25 diatom taxa. The calcareous nannofossil index taxa (*Ceratolithus armatus* Müller, 1974a and *C. cristatus* Kamptner, 1950) indicate both sections to be from zones NN12 (CN10b) and NN13 (CN10c) of early Pliocene (Zanclean) age. The radiolarian taxa, i.e., *Didymocyrtis avita* Riedel, 1953, *Euchitonia* spp., *Siphocampe lineata* (Ehrenberg) Nigrini, 1977, *Stichocorys peregrina* Riedel, 1953, *Semantis* spp. and *Stylochlamydidium* sp. are common in the Sawai Bay ‘B’ Section, which is assigned to Zone RN9. Most of the diatom taxa are represented by representatives of the genera *Actinocyclus* Ehrenberg, 1837, *Azpeitia* Peragallo in Tèmpere and Peragallo, 1912, *Coscinodiscus* Ehrenberg, 1839a, *Grammatophora* Ehrenberg, 1841 and *Triceratium* Ehrenberg, 1839b, with the benthic diatom species *Triceratium favus* Ehrenberg, 1839b being predominant (~35% of the total diatom count). Siliceous microfossils are also represented by silicoflagellates dominated by *Dictyocha* spp. and sponge spicules dominated by astrophorids.

**Key words:** Zanclean; Calcareous nannofossils; Radiolarians; Diatoms; Silicoflagellates; Sponge spicules; Andaman and Nicobar Islands; India.

## INTRODUCTION

The early Pliocene (5.3–3.6 Million years ago; Ma) was a time of relatively warmer climate in comparison to the present (Brierley *et al.* 2009) that cooled during the mid-Pliocene (~3.5 Ma; Matthiessen *et al.* 2009). The warm early Pliocene conditions may

serve as an analogue for present and near-future climate change (Fedorov *et al.* 2013; Haywood *et al.* 2016). The sea surface temperature of all three tropical oceans during this period was stable, with long-term average temperature at ~29°C, more or less similar to present values (Fedorov *et al.* 2013).

The absolute atmospheric CO<sub>2</sub> concentration

during the warmest Pliocene (~5–3 Ma) was about 400 ppmv (Tierney *et al.* 2019; Cui *et al.* 2020), also similar to the present (412 ppmv; Cui *et al.* 2020). Both the Pliocene and present atmospheric CO<sub>2</sub> concentrations are higher than the pre-industrial Holocene levels (Filippelli and Flores 2009; Tierney *et al.* 2019). Thus, studies of Pliocene climate may enrich the understanding of near-future changes caused by modern anthropological activities. For climate models, ocean temperature and primary productivity measurements are crucial in the understanding of any relationship (Versteegh *et al.* 1996).

Calcareous and siliceous microfossils play a pivotal role for correlating the sedimentary rocks and further understanding of the past environment. Most previous Indian Ocean biostratigraphy is based on international ocean drilling samples that are comparatively less detailed than for other geographic regions. The calcareous and siliceous microfossil record from the Indian Ocean marine sediments is sparse. Worth particular mention studies on Neogene calcareous nannofossils are those by Backman and Shackleton (1983), Young (1990), Raffi *et al.* (1995), Dickens and Owen (1999) and Flores *et al.* (2014). Schrader (1974) proposed 21 diatom zones for ~10 to 0.3 Ma from the Deep Sea Drilling Project (DSDP) Site 238, tropical Indian Ocean. Fourtanier (1991) recovered diatom assemblages from the Ocean Drilling Program (ODP) Site 758, equatorial Indian Ocean, to identify major diatom zones from the Upper Campanian (no defined zones), upper Oligocene to lower Miocene (4 zones), and upper Pliocene to Quaternary (3 zones), with some of these assemblages being consistent with those of the equatorial Pacific Ocean (Barron 1985).

This paper covers the biostratigraphy established by calcareous nannofossils and the analysis of siliceous microfossil groups that include diatoms, radiolarians, silicoflagellates and sponge spicules from the Sawai Bay Formation on Car Nicobar Island, northern Indian Ocean.

## PHYSIOGRAPHIC AND OCEANOGRAPHIC OVERVIEW

The Andaman and Nicobar Islands comprise three distinct groups: Andaman, Nicobar and Ritchie's Archipelago. The Andaman group of islands are separated from the Nicobar group by the Ten Degree Channel and form an islandic arc that borders the Bay of Bengal to the west and Andaman Sea to the east. Car Nicobar Island is the northernmost island of the Nicobar group, situated at 09°07'–09°13' N;

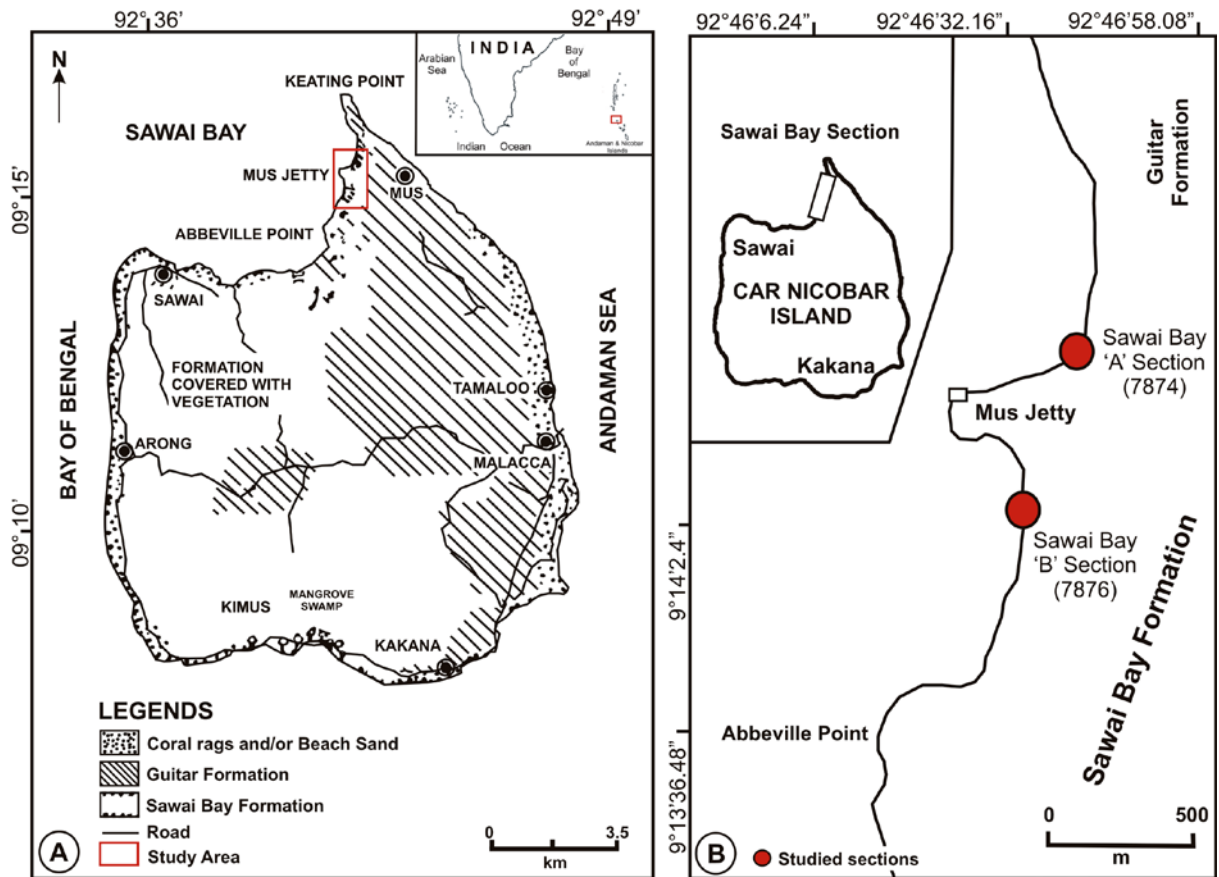
92°43'–92°50' E (Text-fig. 1A) and topographically of low relief (Ghosh and Sarkar 2013). The island's central part is of comparatively higher elevation (~175 m). Field observations show predominant mudstones and limestones. The outcrops lie on Mus Jetty, on the western shore adjacent to Keating Point (Text-fig. 1B).

The original sources of intermediate and deep Indian Ocean water masses differ (Cawthorn *et al.* 2014). Intermediate Indian Ocean (~1200–3800 mbsl) derives from Antarctic Bottom Water and North Atlantic Deep Water, also known as Circumpolar Deep Water (Vincent 1974; Kawagata *et al.* 2006). The Indian Ocean deep water masses derive from northward flowing cold and oxidised Antarctic Bottom Water (Peterson 1984; Kawagata *et al.* 2006). The Indo-Pacific intermixed marine water masses and riverine runoff contribute to the Andaman Sea region (Ibrahim and Yanagi 2006; Amiruddin *et al.* 2011). Seasonal variation and monsoonal activity, tides and heat fluxes strongly affect the surface water circulation with a cyclonic gyre developed during the summer season (Rizal *et al.* 2012).

Furthermore, Pacific Ocean studies suggest that the Andaman Sea productivity was controlled by the Indonesian Throughflow (ITF) (Keller 1985; Kennett *et al.* 1985; Romine and Lombardi 1985). Opening and closing of oceanic gateways also influenced faunal migratory pathways (Srinivasan and Sinha 1998), such as the Indonesian Gateway between the Indian and Pacific regions, although the extent of this closure is debated (Edwards 1975; Berggren 1984; Keller 1985; Romine and Lombardi 1985; Srinivasan and Singh 1991; Ali *et al.* 1994). At about 25 Ma, the ITF developed through major tectonic activities that include the Pliocene formation of islands and mountains (Hill and Hall 2003; Kuhnt *et al.* 2004). Several studies on the plate tectonics in this region (e.g., Raju *et al.* 2004; Cochran 2010) suggest a significant re-organization of the islands at ~4–3 Ma.

## GEOLOGICAL SETTING

The Andaman-Nicobar Basin is a result of a complex tectonic history linked to the Indo–Burmese Plate convergence. This basin originated with the Indian Plate movement towards the north (Curry 2005). The 'soft' (initial) collision of the Indian and Burmese plates took place at ~59 Ma (Klootwijk *et al.* 1992). A 20° anticlockwise rotation of the Indian Plate before 55 Ma closed the suture zone (Basu *et al.* 2012) and slowed seafloor spreading and sub-



Text-fig. 1. Location of the study area. A – Geological map of Car Nicobar Island, and Andaman and Nicobar Islands, India (modified after Sharma and Singh 1993). B – Location of the studied sections near Mus Jetty, Car Nicobar Island.

duction velocity along the Sunda Arc system to reduce seafloor gradient near the volcanic arc. At the terminal Eocene to early Oligocene, the main ridge emerged and initiated major uplift of the Andaman and Nicobar group of islands (Curry *et al.* 1979). However, according to Rodolfo (1969), this basin originated in the late Miocene and was followed by another late Pliocene diastrophism.

Among the different Neogene sequences of India, deep water exposures and shallow marine sediments are well exposed in the Andaman–Nicobar Basin, which has attracted stratigraphers and palaeontologists since the early 20<sup>th</sup> century. Neogene deposits are exposed on Ritchie's Archipelago, Little Andaman and some Nicobar group islands. Three major lithostratigraphic units were distinguished on Car Nicobar Island: the Sawai Bay, Guitar and Neill West Coast Formations (Sharma and Bajpai 2011). The lithostratigraphic type section of the Sawai

Bay Formation (Srinivasan and Sharma 1973) and the Sawain Regional Stage are situated on this island (Sharma and Srinivasan 2007). Based on the latest lithostratigraphic interpretation (Sharma and Srinivasan 2007), the Guitar Formation is equivalent to the 'arenaceous limestone' (Jacob and Sastri 1951), the Sawai Bay Limestone Member (Srinivasan and Sharma 1973) and the Kakana Formation (Chandra and Saxena 1998). For a summary of previous contributions on aspects of Car Nicobar Island lithostratigraphy and biostratigraphy see Sharma and Srinivasan (2007) and Chakraborty and Ghosh (2017).

The Mus Jetty outcrop belongs lithostratigraphically to the Sawai Bay Formation and chronostratigraphically to the uppermost Miocene to lower Pliocene Sawain Regional Stage (Text-fig. 2A, B). In this backdrop, the biostratigraphy in the present study is based on calcareous nannofossils and significant siliceous microfossils.

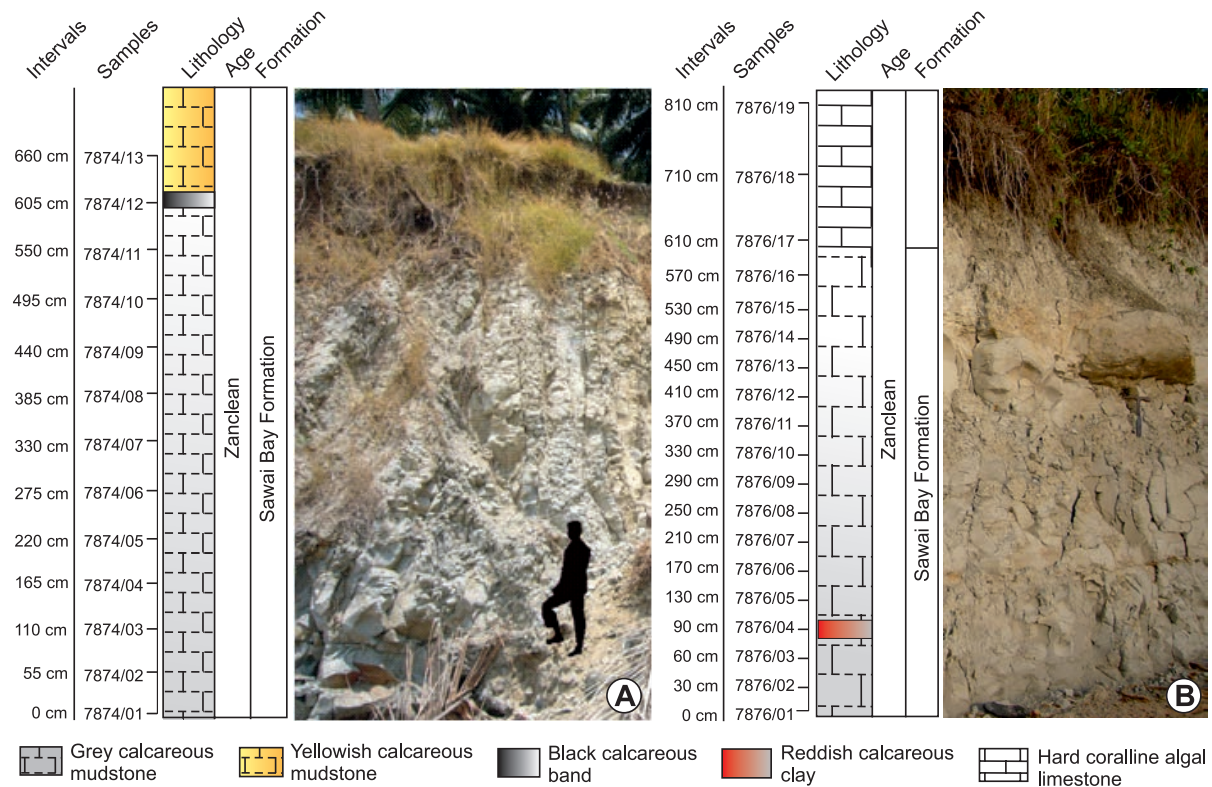
MATERIAL AND METHODS

Samples were collected from the following outcrops of the Mus Jetty locality in Car Nicobar Island:

Sawai Bay ‘A’ Section (09°14’24.4” N, 92°46’40.6” E, Text-fig. 1B) lithologically characterized by more or less homogenous yellowish/grey calcareous mudstone (Text-fig. 2A). The outcrop is located at Sawai Bay, Car Nicobar Island (Text-fig. 1B), regarded as the Sawai Bay Formation type section (Sharma and Srinivasan 2007). The outcrop top is covered by modern coral rags and vegetation. The total outcrop thickness is ~7.5 m. Thirteen samples were collected at a regular interval of 55 cm (Text-fig. 2A).

Sawai Bay ‘B’ Section, located southwest of the ‘A’ Section (09°14’4” N, 92°46’34.1” E; Text-fig. 1B). The section has a thickness of ~8.5 m with the lower part composed of grey calcareous mudstone and the upper part composed of hard coralline algal–foraminiferal limestone. Four samples were collected at 30 cm intervals from the outcrop base. A ~25 cm thick reddish calcareous clay layer occurs about 80 cm above the outcrop base. Thirteen samples were collected at 40 cm intervals from ~1 m above the outcrop base. Two samples were collected from the upper part at 100 cm intervals (Text-fig. 2B).

For the study of calcareous nannofossils, the Bown and Young (1998) smear-slide method was adopted. Norland-61 optical adhesive was used as a mounting medium for the permanent slide preparation with 50×23 mm coverslips and examined under a light microscope (Olympus BX 53 microscope) in cross-polarised (XPL) and phase-contrast (PC) modes. Photographs were taken from the same microscope attached to a digital camera and taxonomically identified according to Young *et al.* (2017). In the present study we have adopted the species names *Ceratolithus armatus* Müller, 1974a and *Ceratolithus cristatus* Kamptner, 1950. *Ceratolithus armatus* is interpreted here to include *C. acutus* Gartner and Bukry, 1974, both described from the early Pliocene of the Indian Ocean (Gartner and Bukry 1974; Müller 1974a). Holotypes and paratypes of the two taxa are quite similar and not easily distinguishable (Young *et al.* 2017). The relative abundance of each taxon and overall nannofossil representation were recorded as: abundant (A) = >10 specimens/field of view (FOV); common (C) = >1–10 specimens/FOV; few (F) = 1 specimen/1–10 FOV; and rare (R) = <1 specimens/10 FOV. The nannofossil biozones of Martini (1971), Okada and Bukry (1980), Young (1998) and Backman *et al.* (2012) were adopted to identify the relative geo-



Text-fig. 2. Sedimentologic logs of the sections on Car Nicobar Island showing the lithology and sampling intervals. A – Sawai Bay ‘A’ Section. B – Sawai Bay ‘B’ Section.

logical ages based on the first and last occurrences (FO and LO), respectively.

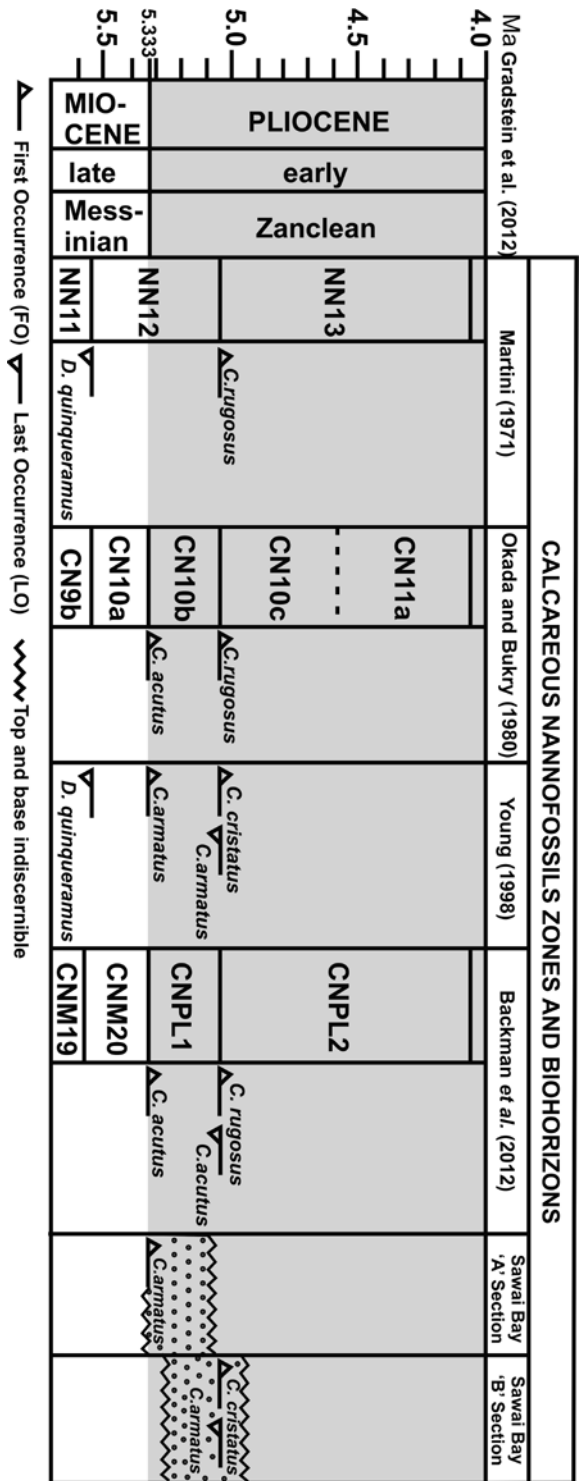
Samples were chemically processed for siliceous microfossils with the methodology of Abrantes *et al.* (2005) used for diatoms, silicoflagellates and sponge spicules, and that of Green (2001) for radiolarians. Microscope slides with 40x20 mm coverslips were prepared for qualitative and quantitative analyses carried out by a light microscope (LM, Olympus BX 50). Since the frequencies of diatoms and other siliceous microfossils are rare, absolute counts are recorded from 20 slides per sample, which often still failed to achieve 300 total counts as per convention. Microphotographs were taken with the DP 26 Olympus Digital Camera (Cell Sens Standard). Ratios of planktic/benthic diatom (Chakraborty and Ghosh 2016; Chakraborty *et al.* 2019) and nassellarian/spumellarian radiolarian taxa (O’Dogherty and Guex 2002) were analysed in all samples for the estimation of sea-level fluctuations (Chakraborty and Ghosh 2016; Chakraborty *et al.* 2019). All figured slides are housed in the Museum of the Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow, India.

Planktic and benthic foraminiferal tests were also observed in the calcareous nannofossil slides but not formally counted in this study. The foraminifera show greater abundance in the Sawai Bay ‘B’ Section.

RESULTS

Sawai Bay ‘A’ Section

Samples from the Sawai Bay ‘A’ Section (BSIP 7874/01–7874/12, Text-fig. 2A) yielded few siliceous microfossils represented by a few sponge spicule and radiolarian fragments. 24 well preserved calcareous nannofossil taxa belonging to 14 genera (Table 1) were identified in 12 samples (BSIP 7874/01–7874/12). Sample BSIP 7874/13 was observed to be devoid of both calcareous and siliceous microfossils. Based on the presence of *C. armatus* and the absence of *C. cristatus*, the section is assignable to the upper portion of the *Ceratolithus tricorniculatus* Interval Zone (Zone NN12; Martini 1971), equivalent to the *Ceratolithus acutus* Range Subzone (Zone CN10b; Okada and Bukry 1980) and the *Ceratolithus acutus* Range Zone (Zone CNPL1; Backman *et al.* 2012) (Text-figs 3 and 4). Thus, the presence of *C. acutus* in all samples clearly indicates a Zanclean age (lower Pliocene). This is further supported by the absence of *Discoaster quinqueramus* Gartner, 1969 at the NN11/ NN12 boundary (Young 1998).



Text-fig. 3. Correlation of Zanclean (lower Pliocene) calcareous nannofossil zones (this study with Martini 1971; Okada and Bukry 1980; Young 1998 and Backman *et al.* 2012).

Calcareous nannofossils	Samples (7874/ )											
	01	02	03	04	05	06	07	08	09	10	11	12
Abundance	++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++
<i>Calcidiscus leptoporus</i> (Murray and Blackman) Loeblich and Tappan, 1978	C	F	F	F	F	C	C	F	F	F	F	C
<i>Ceratolithus armatus</i> Müller, 1974a	R	R	R	R	R	R	R	R	R	R	R	R
<i>Coccolithus pelagicus</i> (Wallich) Schiller, 1930	F	–	R	–	R	R	–	–	–	R	–	–
<i>Cryptococcolithus mediaperforatus</i> (Varol) de Kaenel and Villa, 1996	–	–	–	–	–	–	–	R	–	–	–	–
<i>Cyclicargolithus floridanus</i> (Roth and Hay) Bukry, 1971	–	–	–	–	R	–	–	–	R	–	–	–
<i>Discoaster brouweri</i> Tan Sin Hok emend. Bramlette and Riedel, 1954	F	F	F	F	F	C	F	F	C	R	C	C
<i>Discoaster pentaradiatus</i> Tan Sin Hok, 1927	A	C	C	F	C	C	C	F	F	C	C	F
<i>Discoaster surculus</i> Martini and Bramlette, 1963	F	F	F	F	F	F	R	F	F	F	–	–
<i>Helicosphaera carteri</i> (Wallich) Kamptner, 1954 and <i>Helicosphaera wallichii</i> (Lohmann) Okada and McIntyre, 1977	C	C	C	C	C	C	C	F	C	C	C	C
<i>Helicosphaera sellii</i> (Bukry and Bramlette) Jafar and Martini, 1975	C	R	R	R	F	F	F	F	F	R	C	F
<i>Pontosphaera multipora</i> (Kamptner ex. Deflandre) Roth, 1970	F	F	F	F	F	F	–	R	F	F	F	F
<i>Reticulofenestra pseudumbilicus</i> medium (Gartner) Gartner, 1969	C	C	F	F	F	C	C	C	C	C	C	C
<i>Reticulofenestra haqii</i> Backman, 1978	–	C	A	A	A	C	C	C	C	C	C	F
<i>Reticulofenestra minuta</i> Roth, 1970	A	C	A	A	A	A	A	A	A	A	A	C
<i>Rhabdosphaera clavigera</i> Murray and Blackman, 1898	–	R	–	R	–	–	–	–	–	R	–	–
<i>Scyphosphaera globulata</i> Bukry and Percival, 1971	–	–	–	R	R	–	R	R	R	R	R	–
<i>Scyphosphaera pulcherrima</i> Deflandre, 1942	–	R	–	–	–	–	–	–	–	R	–	–
<i>Sphenolithus abies</i> Deflandre in Deflandre and Fert, 1954	A	A	A	A	A	A	A	C	A	A	C	C
<i>Sphenolithus heteromorphus</i> Deflandre, 1953	–	–	–	–	–	–	–	–	–	–	–	R
<i>Thoracosphaera heimii</i> (Lohmann) Kamptner, 1944	–	–	–	R	–	–	–	–	–	–	–	–
<i>Thoracosphaera albatrosiana</i> Kamptner, 1963	–	R	–	–	–	–	–	–	–	–	–	–
<i>Thoracosphaera tuberosa</i> Kamptner, 1963	–	–	–	–	–	–	–	–	–	–	R	–
<i>Umbilicosphaera jafari</i> Müller, 1974b	R	–	–	–	–	–	–	–	–	–	–	–
<i>Umbilicosphaera rotula</i> (Kamptner) Varol, 1982 and <i>Umbilicosphaera foliosa</i> (Kamptner) Geisen in Sáez <i>et al.</i> , 2003	–	–	F	F	F	–	R	–	R	R	F	F

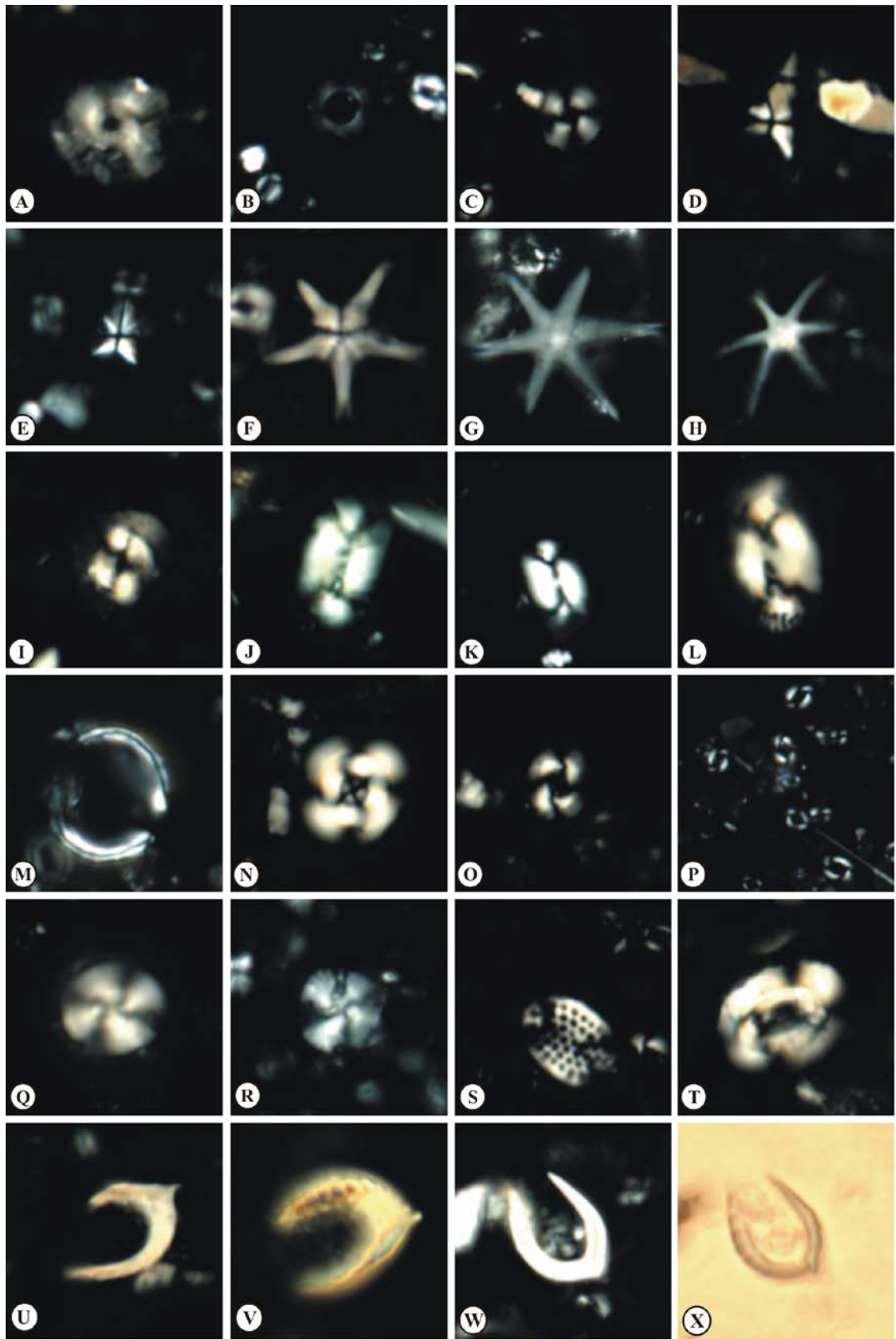
Table 1. Representation of calcareous nannofossils in Sawai Bay 'A' Section, Car Nicobar Island (+ = few, ++ = common, +++ = abundant, – = absent).

## Sawai Bay 'B' Section

The calcareous nannofossil assemblage of Sawai Bay 'B' Section comprises 18 taxa belonging to 11 genera (Table 2). The lower part of the section can be assigned to Zone NN12 of Martini (1971) (~5.33 Ma – equivalent of Zone CN10b based on the presence of *C. armatus* and the absence of *C. cristatus*). The FO of *C. cristatus* in sample BSIP 7874/15 indicates that the upper part of the section belongs to

the *Ceratolithus rugosus* Interval Zone (Zone NN13; Martini 1971), i.e., ~5.08 Ma – equivalent to the *Ceratolithus rugosus* Range Subzone (Zone CN10c; Okada and Bukry 1980) and the *Sphenolithus neobabies* Partial Range Zone (Zone CNPL2; Backman *et al.* 2012) (Text-fig. 3). The presence of *Sphenolithus abies* Deflandre in Deflandre and Fert, 1954 and the medium and large sized *Reticulofenestra pseudumbilicus* (Gartner) Gartner, 1969 also supports assignment to Zone NN13 (Text-fig. 4).

Text-fig. 4. Common calcareous nannofossils from the Sawai Bay sections of Car Nicobar Island. **A** – *Umbilicosphaera foliosa* (Kamptner) Geisen in Sáez *et al.*, 2003 (BSIP 7874/01). **B** – *Umbilicosphaera rotula* (Kamptner) Varol, 1982 (BSIP 7874/01). **C** – *Umbilicosphaera jafari* Müller, 1974b (BSIP 7876/10). **D** – *Sphenolithus heteromorphus* Deflandre, 1953 (BSIP 7874/01). **E** – *Sphenolithus abies* Deflandre in Deflandre and Fert, 1954 (BSIP 7874/07). **F** – *Discoaster pentaradiatus* Tan Sin Hok, 1927 (BSIP 7874/11). **G** – *Discoaster surculus* Martini and Bramlette, 1963 (BSIP 7874/10). **H** – *Discoaster brouweri* Tan Sin Hok emend. Bramlette and Riedel, 1954 (BSIP 7874/01). **I** – *Coccolithus pelagicus* (Wallich) Schiller, 1930 (BSIP 7874/10). **J** – *Helicosphaera carteri* (Wallich) Kamptner, 1954 (BSIP 7876/03). **K** – *Helicosphaera sellii* (Bukry and Bramlette) Jafar and Martini, 1975 (BSIP 7874/02). **L** – *Helicosphaera wallichii* (Lohmann) Okada and McIntyre, 1977 (BSIP 7874/06). **M** – *Scyphosphaera globulata* Bukry and Percival, 1971 (BSIP 7874/05). **N** – *Reticulofenestra pseudumbilicus* large (Gartner) Gartner, 1969 (BSIP 7876/13). **O** – *Reticulofenestra pseudumbilicus* medium (Gartner) Gartner, 1969 (BSIP 7874/01). **P** – *Reticulofenestra haqii* Backman, 1978 (BSIP 7874/05). **Q** – *Cyclicargolithus floridanus* (Roth and Hay) Bukry, 1971 (BSIP 7874/04). **R** – *Calcidiscus leptoporus* (Murray and Blackman) Loeblich and Tappan, 1978 (BSIP 7874/07). **S** – *Pontosphaera multipora* (Kamptner ex. Deflandre) Roth, 1970 (BSIP 7874/08). **T** – *Cryptococcolithus mediaperforatus* (Varol) de Kaenel and Villa, 1996 (BSIP 7874/05). **U–V** – *Ceratolithus armatus* Müller, 1974a (BSIP 7876/14). **W–X** – *Ceratolithus cristatus* Kamptner, 1950 (BSIP 7876/01, 7876/02). →



— 2 µm

Calcareous nannofossils	Samples (7876/ )										11	12	13	14	15	16
	01	02	03	04	05	06	07	08	09	10						
	Abundance										+	+++	+	+++	+++	+
<i>Calcidiscus leptoporus</i> (Murray and Blackman) Loeblich and Tappan, 1978	C	C	C	F	F	F	F	F			R	F	C	C	C	F
<i>Ceratolithus armatus</i> Müller, 1974a	R	R	R	R	–	R	R	–			–	R	–	–	–	–
<i>Ceratolithus cristatus</i> Kamptner, 1950	–	–	–	–	–	–	–	–			–	–	–	–	R	R
<i>Coccolithus pelagicus</i> (Wallich) Schiller, 1930	–	–	F	–	–	R	–	R			–	–	–	–	R	–
<i>Discoaster brouweri</i> Tan Sin Hok emend. Bramlette and Riedel, 1954	F	F	F	C	C	C	F	F			F	F	F	C	F	C
<i>Discoaster pentaradiatus</i> Tan Sin Hok, 1927	F	C	C	C	C	C	F	C			C	F	C	C	F	C
<i>Discoaster variabilis</i> Martini and Bramlette, 1963	F	R	F	F	F	F	C	F			F	F	F	F	C	F
<i>Helicosphaera carteri</i> (Wallich) Kamptner, 1954 and <i>Helicosphaera wallichii</i> (Lohmann) Okada and McIntyre, 1977	C	C	C	C	C	C	–	–		B	C	C	C	C	C	C
<i>Helicosphaera sellii</i> (Bukry and Bramlette) Jafar and Martini, 1975	–	C	F	–	–	–	–	–		A	–	–	F	F	F	–
<i>Pontosphaera multipora</i> (Kamptner ex. Deflandre) Roth, 1970	–	–	–	R	–	–	–	–		R	–	R	R	R	R	R
<i>Reticulofenestra pseudumbilicus</i> large (Gartner) Gartner, 1969	C	C	C	C	C	C	C	C		E	–	–	F	F	F	C
<i>Reticulofenestra pseudumbilicus</i> medium (Gartner) Gartner, 1969	C	C	C	C	C	C	C	C		N	C	C	C	C	C	C
<i>Reticulofenestra haqii</i> Backman, 1978	–	–	F	–	F	–	–	–			C	C	–	–	–	–
<i>Reticulofenestra minuta</i> Roth, 1970	–	–	–	–	–	–	–	–			–	–	C	A	A	–
<i>Rhabdosphaera clavigera</i> Murray and Blackman, 1898	–	–	–	–	–	–	–	–			–	–	R	R	–	–
<i>Scyphosphaera globulata</i> Bukry and Percival, 1971	–	–	–	–	–	–	–	–			–	F	–	–	–	–
<i>Sphenolithus abies</i> Deflandre in Deflandre and Fert, 1954	C	A	C	C	C	F	F	R			C	A	A	C	C	C
<i>Umbilicosphaera rotula</i> (Kamptner) Varol, 1982 and <i>Umbilicosphaera foliosa</i> (Kamptner) Geisen in Sáez <i>et al.</i> , 2003	R	F	F	F	F	F	F	R			F	R	R	–	R	F

Table 2. Representation of calcareous nannofossils in Sawai Bay 'B' Section, Car Nicobar Island (+ = few, ++ = common, +++ = abundant, – = absent).

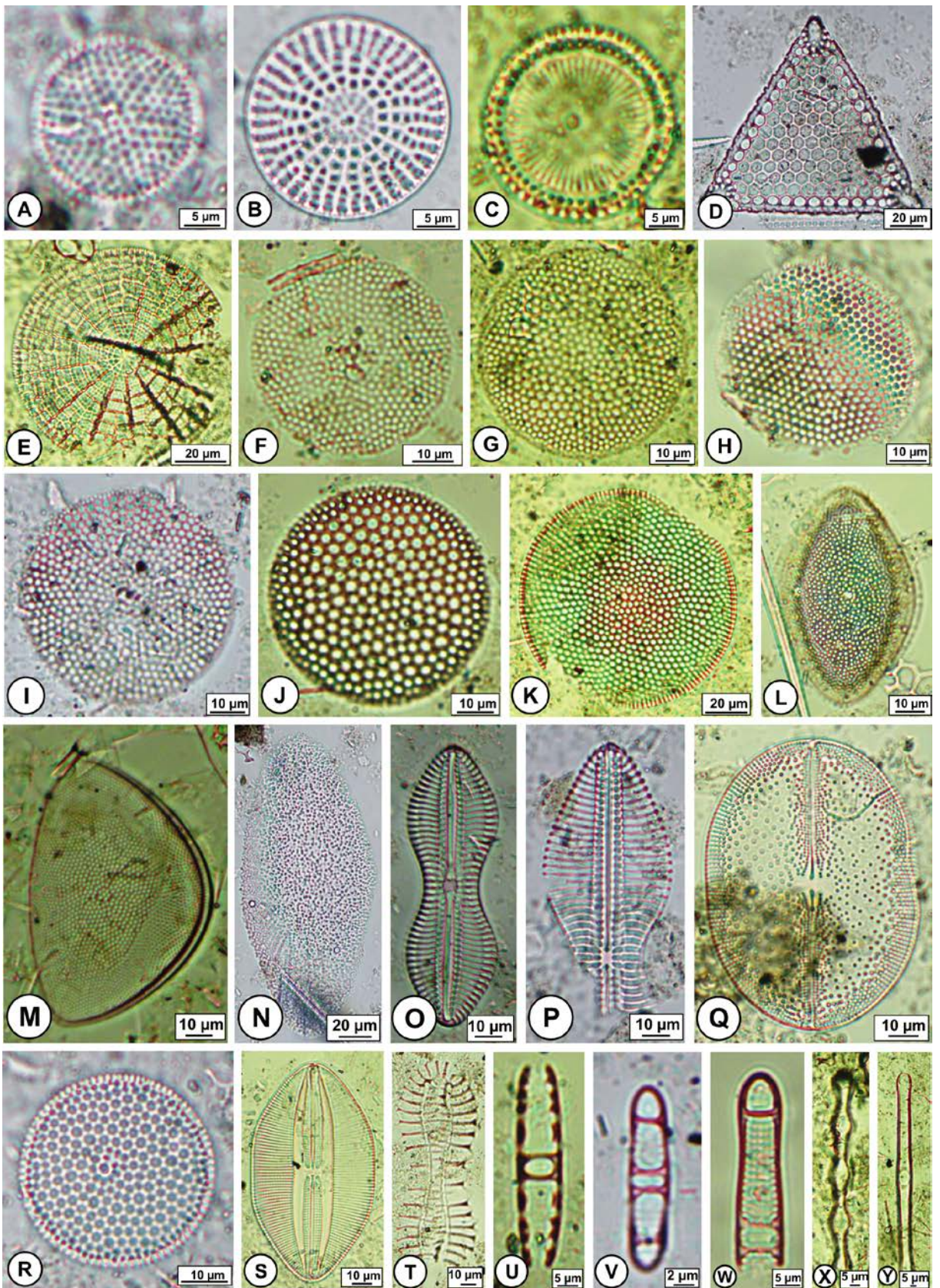
Twenty-five diatom taxa belonging to 16 genera were identified in 16 productive samples (BSIP 7876/01–7876/16; Text-fig. 2B; Table 3). The highest three samples (BSIP 7876/17–7876/19) of this section were barren. The productive samples also yielded silicoflagellates and sponge spicules. Amongst the diatoms, 13 taxa are planktic and 13 benthic, represented mostly by the genera *Actinocyclus* Ehrenberg, 1837, *Azpeitia* Peragallo in Tempère and Peragallo, 1912, *Coscinodiscus* Ehrenberg, 1839a, *Grammatophora* Ehrenberg, 1841 and *Triceratium* Ehrenberg, 1839b (Text-fig. 5A–Y). The benthic diatom *Triceratium favus* Ehrenberg, 1839b is the predominant taxon, contributing to ~35% of the total diatom count. In comparison to the upper Miocene at Cave Point Section, Neil Island (Chakraborty and Ghosh 2016), the preservation potential of diatom valves in the studied section is moderate and their diversity is low. Moreover,

the representation of diatoms is scanty and sporadic, and thus difficult to correlate with standard diatom assemblage zones (*Thalassiosira convexa* and *Nitzschia miocenica* Partial Range Zones; Burckle 1972).

Amongst siliceous microfossils, radiolarians are dominant and comparatively well-preserved in the Sawai Bay 'B' Section. 33 radiolarian taxa belonging to 24 genera were recognised. Common radiolarian taxa include *Didymocyrtis avita* Riedel, 1953, *Euchitonia* spp., *Siphocampe lineata* (Ehrenberg) Nigrini, 1977, *Stichocorys peregrina* Riedel, 1953, *Semantis* spp. and *Stylochlamydidium* sp. (Text-fig. 6A–V). The section can be assigned to the *Stichocorys peregrina* Interval Zone (Zone RN9; Sanfilippo and Nigrini 1998) based on the presence of *S. peregrina* throughout the section. Moreover, the presence of *Didymocyrtis avita* in most of the samples from the section base to the top also confirms the assignment

Text-fig. 5. Common calcareous nannofossils from the Sawai Bay 'B' Section, Car Nicobar Island. **A** – *Azpeitia tabularis* (Grunow) Fryxell and Sims in Fryxell *et al.*, 1986 (BSIP 7876/01). **B** – *Stictodiscus nankooensis* (Grunow) Pantocsek, 1889 (BSIP 7876/02). **C** – *Paralia sulcata* (Ehrenberg) Cleve, 1873 (BSIP 7876/03). **D** – *Triceratium favus* Ehrenberg, 1839b (BSIP 7876/02). **E** – *Arachnoidiscus ornatus* (Ehrenberg) Ehrenberg, 1849 (BSIP 7876/03). **F, I** – *Azpeitia vetustissima* (Pantocsek) Sims in Fryxell *et al.*, 1986 (BSIP 7876/06 and BSIP 7876/02). **G** – *Coscinodiscus* sp. (BSIP 7876/03). **H** – *Thalassiosira leptopus* (Grunow) Hasle and Fryxell, 1977 (BSIP 7876/05). **J** – *Coscinodiscus radiatus* Ehrenberg, 1841 (BSIP 7876/03). **K** – *Coscinodiscus oculus-iridis* (Ehrenberg) Ehrenberg, 1841 (BSIP 7876/03). **L** – *Actinocyclus ellipticus* var. *javanica* Reinhold, 1937 (BSIP 7876/03). **M** – *Hemidiscus cuneiformis* Wallich, 1860 (BSIP 7876/03). **N** – *Actinocyclus ellipticus* f. *lanceolata* Kolbe, 1954 (BSIP 7876/16). **O–P** – *Diploneis crabro* (Ehrenberg) Ehrenberg, 1854 (BSIP 7876/05, 7876/01). **Q** – *Cocconeis* sp. (BSIP 7876/04). **R** – *Coscinodiscus* sp. (BSIP 7876/02). **S** – *Lyrella investigata* (Heiden) Mann in Round *et al.*, 1990 (BSIP 7876/06). **T** – *Surirella* sp. (BSIP 7876/07). **U** – *Grammatophora* sp. (BSIP 7876/06). **V–W** – *Plagiogramma* sp. (BSIP 7876/02, 7876/07). **X** – *Grammatophora undulata* Ehrenberg, 1841 (BSIP 7876/03). **Y** – *Grammatophora stricta* Ehrenberg, 1841 (BSIP 7876/03).





Siliceous microfossils	Samples (7876/)																
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	
<b>Diatoms</b>																	
<i>Actinocyclus ellipticus</i> Grunow in Van Heurck, 1883	–	–	–	–	18	17	–	12			–	–	–	–		–	
<i>Actinocyclus ellipticus</i> var. <i>javanica</i> Reinhold, 1937	–	6	23	–	–	–	–	–			–	–	–	–		–	
<i>Actinocyclus ellipticus</i> forma <i>lanceolata</i> Kolbe, 1954	–	–	–	–	–	–	–	–			–	–	–	6		7	
<i>Arachnoidiscus ornatus</i> (Ehrenberg) Ehrenberg, 1849	–	–	5	–	–	–	–	–			–	–	–	–		–	
<i>Azpeitia nodulifera</i> (Schmidt) Fryxell and Sims in Fryxell et al., 1986	–	7	3	5	–	14	–	–			–	–	–	–		–	
<i>Azpeitia tabularis</i> (Grunow) Fryxell and Sims in Fryxell et al., 1986	6	–	31	–	–	–	–	–			–	–	–	–		–	
<i>Azpeitia vetustissima</i> (Pantocsek) Sims in Fryxell et al., 1986	3	9	–	2	–	4	–	–			–	–	–	–		–	
<i>Cocconeis</i> sp.	–	–	–	2	–	–	–	–			–	–	–	–		–	
<i>Coscinodiscus oculus-iridis</i> (Ehrenberg) Ehrenberg, 1841	–	–	7	–	–	–	–	–			–	–	–	–		–	
<i>Coscinodiscus radiatus</i> Ehrenberg, 1841	–	–	26	–	13	–	17	–			–	–	–	–		–	
<i>Coscinodiscus</i> spp.	–	3	–	–	–	6	–	–			–	–	–	–		–	
<i>Diploneis crabro</i> (Ehrenberg) Ehrenberg, 1854	7	–	–	–	5	–	–	–			–	–	–	–		–	
<i>Grammatophora stricta</i> Ehrenberg, 1841	–	–	5	–	–	16	–	–			–	–	–	–		–	
<i>Grammatophora undulata</i> Ehrenberg, 1841	–	–	6	–	–	–	–	–			–	–	–	–		–	
<i>Grammatophora</i> spp.	–	–	–	–	–	5	–	–			–	–	–	–		–	
<i>Hemidiscus cuneiformis</i> Wallich, 1860	–	–	4	–	–	–	–	–			–	–	–	–		–	
<i>Lyrella investigata</i> (Heiden) Mann in Round et al., 1990	–	–	–	–	6	7	–	–			–	–	–	–		–	
<i>Lyrella</i> sp.	–	–	–	6	–	–	–	–			–	–	–	–		–	
<i>Paralia sulcata</i> (Ehrenberg) Cleve, 1873	–	7	7	–	–	–	–	–			–	–	–	–		–	
<i>Plagiogramma</i> sp.	–	6	–	–	–	6	7	–			6	–	–	–		–	
<i>Rhizosolenia</i> sp.	–	–	–	–	–	–	–	–			7	–	–	–		–	
<i>Stictodiscus nankooensis</i> (Grunow) Pantocsek, 1889	5	5	6	5	11	5	–	–			–	–	–	–		–	
<i>Suirella</i> sp.	–	–	–	–	–	–	6	–			–	–	–	–		–	
<i>Thalassiosira leptopus</i> (Grunow) Hasle and Fryxell, 1977	–	–	–	–	13	–	–	6			–	–	–	–		–	
<i>Triceratium favus</i> Ehrenberg, 1839b	6	71	28	7	76	7	–	12				14	15	–		–	
TOTAL	27	114	151	27	142	87	30	30			13	14	15	6		7	
<b>Radiolarians</b>																	
<i>Acrobotrys disolenia</i> Haeckel, 1887	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Acrosphaera murrayana</i> Haeckel, 1887	–	–	–	–	–	–	–	–	–	–	–	7	–	–	–	–	–
<i>Acrosphaera</i> sp.	–	–	–	–	–	–	–	–	–	–	–	–	–	7	–	–	–
<i>Axoprunum monostylum</i> Caulet, 1986	31	35	–	–	–	–	19	21	–	–	–	–	–	–	–	–	–
<i>Clathrocanium coarctatum</i> Ehrenberg, 1860b	5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Collosphaera</i> sp.	–	–	–	–	–	–	–	–	–	–	–	3	–	–	–	–	–
<i>Cornutella profunda</i> Ehrenberg, 1856	–	–	6	–	12	–	6	–	–	–	6	–	5	–	–	–	–
<i>Dictyocoryne profunda</i> Ehrenberg, 1856	–	–	–	–	–	–	–	–	–	–	13	–	–	–	–	–	–
<i>Didymocyrtis avita</i> Riedel, 1953	36	43	19	27	16	53	31	13	18	16	5	–	7	–	3	1	
<i>Didymocyrtis</i> spp.	–	–	–	–	6	–	–	7	–	–	–	6	7	–	–	–	
<i>Disolenia zanguebarica</i> (Ehrenberg) Nigrini, 1967	–	–	–	–	5	–	6	–	–	–	–	–	6	–	–	–	
<i>Euchitonia</i> spp.	–	61	24	–	–	6	7	5	7	0	70	23	18	17	–	11	
<i>Flustrella</i> sp. A	–	–	–	–	–	4	–	–	–	–	–	–	–	–	–	–	
<i>Flustrella</i> sp. B	–	–	–	–	–	–	2	–	–	–	–	–	–	–	–	–	
<i>Flustrella</i> sp. C	–	–	–	–	–	–	–	–	–	–	13	–	–	–	–	–	
<i>Larospira quadrangula</i> Haeckel, 1887	–	–	–	–	–	–	–	–	–	–	–	35	–	–	–	–	
<i>Lithomelissa</i> sp.	13	–	10	–	–	15	–	–	–	23	–	34	–	–	–	3	
<i>Phormostichoartus doliolum</i> (Riedel and Sanfilippo) Nigrini, 1977	–	6	–	1	–	–	–	–	–	–	–	–	–	1	–	2	
<i>Phormostichoartus fistula</i> Nigrini, 1977	–	–	–	–	–	–	–	–	–	–	–	6	–	–	–	1	
<i>Phormostichoartus</i> sp.	–	–	–	–	–	–	–	–	–	–	7	–	–	–	–	–	
<i>Phortidium pylonium</i> Haeckel, 1887	–	–	–	–	–	–	–	–	–	–	–	54	–	–	–	–	
<i>Rhopalastrum</i> sp.	–	–	–	–	–	–	–	–	–	–	–	25	–	–	–	–	
<i>Semantis</i> spp.	29	54	18	16	–	29	17	17	–	–	41	62	53	52	12	13	

<i>Siphocampe lineata</i> (Ehrenberg) Nigrini, 1977	–	24	81	56	18	17	8	14	–	–	13	11	12	6	–	–
<i>Solenosphaera</i> sp.	–	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–
<i>Sphaeropyle</i> cf. <i>langii</i> Dreyer, 1889	–	–	–	–	–	–	–	–	5	–	–	–	–	–	–	–
<i>Stichocorys peregrina</i> Riedel, 1953	6	–	29	34	–	18	–	36	–	12	72	28	17	6	–	2
<i>Stylodictya validispina</i> Jørgensen, 1905	–	–	–	–	–	–	–	–	–	–	–	7	–	–	–	–
<i>Stylodictya</i> sp.	–	–	36	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Stylochlamyidium asteriscus</i> Haeckel, 1887	–	–	–	–	–	–	–	57	–	–	–	66	12	–	–	–
<i>Stylochlamyidium</i> spp.	–	140	–	–	7	107	–	–	–	–	5	–	–	29	–	–
<i>Tetrapyle circularis</i> Haeckel in Zhang and Suzuki, 2017	–	–	–	–	6	31	–	–	6	–	–	–	–	–	–	–
<i>Tetrapyle octacantha</i> Müller, 1858	–	5	–	–	–	–	–	–	–	–	23	6	17	40	6	7
TOTAL	122	368	223	134	70	280	96	170	36	51	268	373	154	160	21	40
<b>Sponge spicules</b>																
Anatriaena	12	–	–	–	–	6	–	–	–	–	–	–	–	–	–	–
Astrophorida	–	18	30	–	–	–	18	8	–	–	31	–	24	–	23	7
Calthrops	–	–	–	–	–	–	–	–	6	–	–	–	–	–	–	–
Hexactines	13	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Orthodichotriaenes	–	–	6	–	–	–	–	–	7	–	–	–	–	–	–	–
Oxyasters	–	–	–	–	–	–	7	–	–	–	–	–	6	–	–	–
Oxyhexactrines	–	–	–	–	–	–	–	–	–	–	–	–	–	–	7	–
Pinulus	–	12	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Proanatriaena	–	6	–	–	–	–	–	–	–	–	–	–	–	20	–	6
Sigma	–	13	–	–	–	–	–	–	–	–	18	–	–	–	–	–
Triaxonal (Hexactinellid)	–	5	–	–	–	–	–	–	–	12	–	–	5	–	–	–
TOTAL	25	54	36	–	6	25	8	13	12	49	–	–	35	20	30	7
<b>Silicoflagellates</b>																
<i>Bachmannocena elliptica</i> (Ehrenberg) Bukry, 1987	–	–	–	–	–	6	–	–	–	–	–	–	–	–	–	–
<i>Dictyocha extensa</i> (Locker) McCartney <i>et al.</i> , 1995	–	–	–	–	–	–	18	–	–	–	–	–	–	–	–	–
<i>Dictyocha</i> cf. <i>fibula</i> subsp. <i>fibula</i> Ehrenberg, 1838	–	–	–	12	–	–	–	–	–	–	–	–	–	–	–	–
<i>Dictyocha fibula</i> subsp. <i>mutabilis</i> (Deflandre) McCartney <i>et al.</i> , 1995	–	18	–	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Dictyocha varia</i> Locker, 1975	30	–	12	–	–	6	–	–	–	–	–	–	–	–	–	–
TOTAL	30	18	12	12	–	12	18	–	–	–	–	–	–	–	–	–
TOTAL COUNT OF SILICEOUS MICROFOSSILS	204	554	422	173	218	404	152	213	48	100	281	422	189	196	28	53

Table 3. Occurrence (absolute count) of siliceous microfossils in Sawai Bay 'B' Section. The blank columns denote the lack of microfossils.

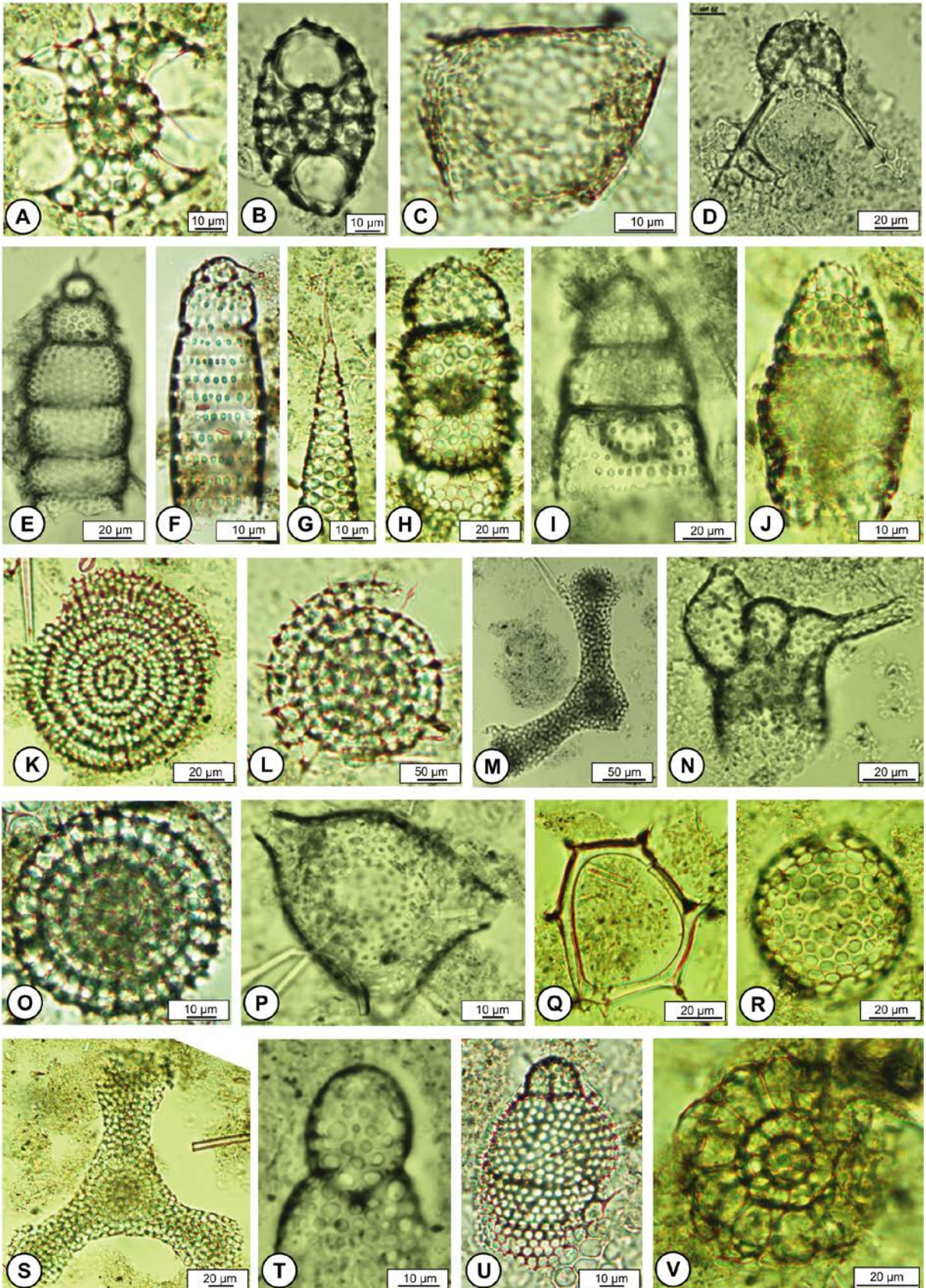
to Zone RN9 (Kamikuri *et al.* 2009). The prevalence of warm water planktic diatoms and radiolarians is characteristic of the overall assemblage (Table 4).

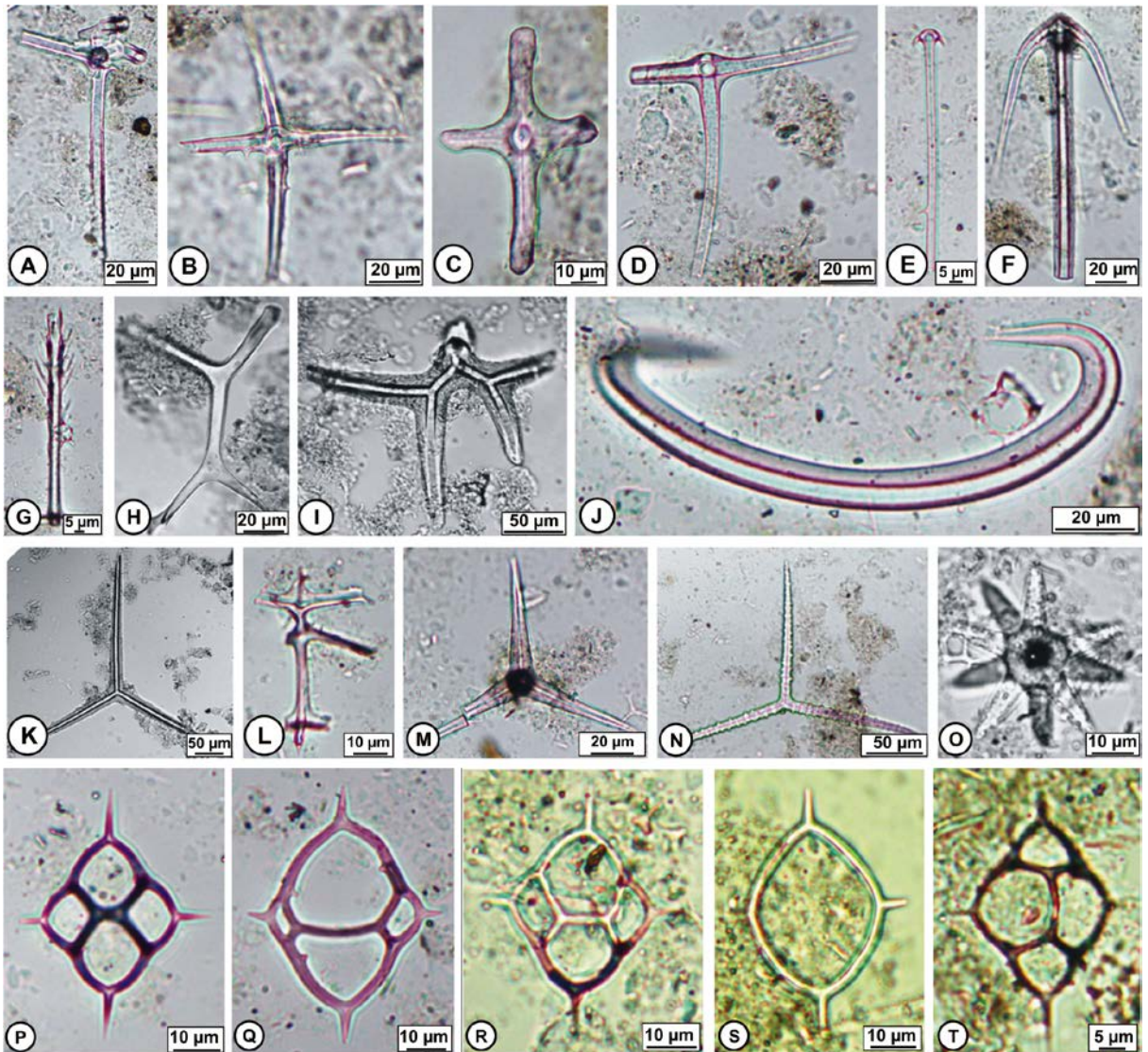
Samples from the Sawai Bay 'B' Section also yield moderately preserved silicoflagellates and sponge spicules. Recovered sponge spicules were abundant and assignable to eleven groups (Text-fig. 7A–O) with the maximum diversity observed in samples BSIP 7876/02 and 7876/12. Astrophorida, oxyasters, proanatriaena, pinulus, sigma and triaxonal sponge spicule groups (e.g., Ivanik 1983; McCartney 1987) were relatively common in most samples, whereas other groups had sporadic occurrences. Absolute sponge spicule counts are shown in Table 3.

Silicoflagellates were represented by 5 taxa belonging to 2 genera (Text-fig. 7P–T), but observed only in samples BSIP 7876/01–7876/07 (Text-fig. 2B). *Dictyocha varia* Locker, 1975 (up to 30 specimens) was the most commonly observed silicofla-

gellate species in the assemblage (Table 3) with other taxa being rare. Apical bridge morphology changes of *Dictyocha varia* to *Dictyocha extensa* (Locker) McCartney *et al.*, 1995 (see McCartney *et al.* 1995) observed in sample BSIP 7876/07, and the occurrence of *Bachmannocena elliptica* (Ehrenberg) Bukry, 1987 in sample BSIP 7876/06 contributes to interpret the palaeoenvironmental changes detected by the aforementioned siliceous microfossils (Table 3). In samples BSIP 7876/02 and 7876/07, *Dictyocha fibula* subsp. *mutabilis* (Deflandre) McCartney *et al.*, 1995 and *D. extensa* are especially abundant. *Dictyocha* cf. *fibula* subsp. *fibula* Ehrenberg, 1838 (see Locker 1974; McCartney *et al.* 1995) and *Bachmannocena elliptica* are present in samples BSIP 7876/04 and 7876/06, respectively, whereas not recognised in the other samples (Table 3).

Quantitative analysis of radiolarian, diatom, silicoflagellate and sponge spicule microfossils were carried





Text-fig. 7A–O. Common sponge spicules from the Sawai Bay 'B' Section, Car Nicobar Island. A–C – Hexactines (BSIP 7876/01). D – Oxyhexactines (BSIP 7876/01). E – Anatriaen (BSIP 7876/01). F – Proanatriaena (BSIP 7876/02). G – Pinulus (BSIP 7876/02). H–I – Orthodichotriaenes (BSIP 7876/03, 7876/08). J – Sigma (BSIP 7876/02). K – Calthrops (BSIP 7876/08). L – Triaxonal (Hexactinellid) (BSIP 7876/02). M–N – Astrophorida (BSIP 7876/02). O – Oxyasters (BSIP 7876/06). P–T – Common silicoflagellates from the Sawai Bay 'B' Section, Car Nicobar Island. P – *Dictyocha varia* Locker, 1975 (BSIP 7876/01). Q – *Dictyocha fibula* subsp. *mutabilis* (Deflandre) McCartney *et al.*, 1995 (BSIP 7876/02). R – *Dictyocha cf. fibula* subsp. *fibula* Ehrenberg, 1838 (BSIP 7876/04). S – *Bachmannocena elliptica* (Ehrenberg) Bukry, 1987 (BSIP 7876/06). T – *Dictyocha extensa* (Locker) McCartney *et al.*, 1995 (BSIP 7876/07).

← Text-fig. 6. Common radiolarians from the Sawai Bay 'B' Section, Car Nicobar Island. A – *Tetrapyle circularis* Haeckel in Zhang and Suzuki, 2017 (BSIP 7876/05). B – *Tetrapyle octacantha* Müller, 1858 (BSIP 7876/02). C – *Disolenia zanguearica* (Ehrenberg) Nigrini, 1967 (BSIP 7876/07). D – *Clathrocanium coarctatum* Ehrenberg, 1860b (BSIP 7876/01). E – *Stichocorys peregrina* Riedel, 1953 (BSIP 7876/08). F – *Siphocampe lineata* (Ehrenberg) Nigrini, 1977 (BSIP 7876/04). G – *Cornutella profunda* Ehrenberg, 1856 (BSIP 7876/07). H – *Didymocyrtis avita* Riedel, 1953 (BSIP 7876/09). I – *Phormostichoartus doliolum* (Riedel and Sanfilippo) Nigrini, 1977 (BSIP 7876/14). J – *Phormostichoartus fistula* Nigrini, 1977 (BSIP 7876/12). K – *Stylocitya validispina* Jørgensen, 1905 (BSIP 7876/12). L – *Flustrella* sp. A (BSIP 7876/06). M – *Euchitonia* sp. (BSIP 7876/03). N – *Acrobotrys disolenia* Haeckel, 1887 (BSIP 7876/01). O – *Flustrella* sp. B (BSIP 7876/07). P – *Solenosphaera* sp. (BSIP 7876/14). Q – *Semantis* sp. (BSIP 7876/08). R – *Collosphaera* sp. (BSIP 7876/12). S – *Dictyocoryne profunda* Ehrenberg, 1860a (BSIP 7876/11). T – *Lithomelissa* sp. (BSIP 7876/10). U – *Phormostichoartus* sp. (BSIP 7876/11). V – *Flustrella* sp. C (BSIP 7876/11).

Diatom taxa	Habitat	Ecological preference
<i>Actinocyclus ellipticus</i> Grunow in Van Heurck, 1883	planktic	Warm water (Koizumi <i>et al.</i> 2004; Barron 1985)
<i>Actinocyclus ellipticus</i> var. <i>javanica</i> Reinhold, 1937	planktic	Warm water (Baldauf 2013)
<i>Actinocyclus ellipticus</i> forma <i>lanceolata</i> Kolbe, 1954	planktic	
<i>Azpeitia nodulifera</i> (Schmidt) Fryxell and Sims in Fryxell <i>et al.</i> , 1986	planktic	Warm water (Koizumi <i>et al.</i> 2004)
<i>Azpeitia tabularis</i> (Grunow) Fryxell and Sims in Fryxell <i>et al.</i> , 1986	planktic	Warm water (Koizumi and Yamamoto 2016)
<i>Azpeitia vetustissima</i> (Pantocsek) Sims in Fryxell <i>et al.</i> , 1986	planktic	Warm water (Frydas and Stefanopoulos 2009)
<i>Coscinodiscus oculus-iridis</i> (Ehrenberg) Ehrenberg, 1841	planktic	Cold water (Koizumi and Yamamoto 2016)
<i>Coscinodiscus radiatus</i> Ehrenberg, 1841	planktic	Warm water (Pushkar <i>et al.</i> 1999)
<i>Hemidiscus cuneiformis</i> Wallich, 1860	planktic	Warm water (Koizumi 1981)
<i>Thalassiosira leptopus</i> (Grunow) Hasle and Fryxell, 1977	planktic	Warm water (Koizumi 1981)
<i>Arachnoidiscus ornatus</i> (Ehrenberg) Ehrenberg, 1849	benthic	
<i>Diploneis crabro</i> (Ehrenberg) Ehrenberg, 1854	benthic	Temperate water (De Wolf 1982)
<i>Grammatophora stricta</i> Ehrenberg, 1841	benthic	
<i>Grammatophora undulata</i> Ehrenberg, 1841	benthic	Warm water (López Fuerte <i>et al.</i> 2010)
<i>Lyrella investigata</i> (Heiden) Mann in Round <i>et al.</i> , 1990	benthic	
<i>Paralia sulcata</i> (Ehrenberg) Cleve, 1873	benthic	Warm to cold water (Chakraborty <i>et al.</i> 2019)
<i>Stictodiscus nankooensis</i> (Grunow) Pantocsek, 1889	benthic	
<i>Triceratium favus</i> Ehrenberg, 1839b	benthic	Temperate water (De Wolf 1982)
<b>Radiolarian taxa</b>		
<i>Acrosphaera murrayana</i> Haeckel, 1887	spumellaria	Warm water (Haeckel 1887)
<i>Acrosphaera</i> sp.	spumellaria	Cold water (Sharma and Bora 2007)
<i>Axoprunum monostylum</i> Caulet, 1986	spumellaria	Warm water (Caulet 1986)
<i>Collosphaera</i> sp.	spumellaria	Warm water (Sandoval <i>et al.</i> 2017)
<i>Dictyocoryne profunda</i> Ehrenberg, 1856	spumellaria	Warm water (Casey 1977)
<i>Didymocyrtis avita</i> Riedel, 1953	spumellaria	Warm water (Caulet 1986)
<i>Didymocyrtis</i> spp.	spumellaria	Warm water (Welling and Pisias 1998)
<i>Euchitonia</i> spp.	spumellaria	Warm water (Petrushevskaya 1971)
<i>Flustrella</i> spp.	spumellaria	
<i>Larcospira quadrangula</i> Haeckel, 1887	spumellaria	Warm water (Haeckel 1887)
<i>Phorticium pylonium</i> Haeckel, 1887	spumellaria	Warm water (Gupta 2020)
<i>Rhopalastrum</i> sp.	spumellaria	Cosmopolitan (Barwicz-Piskorz 1978)
<i>Sphaeropyle</i> cf. <i>langii</i> Dreyer, 1889	spumellaria	Warm water (Gupta <i>et al.</i> 2012)
<i>Stylodictya validispina</i> Jørgensen, 1905	spumellaria	Cosmopolitan to Warm water (Benson 1966)
<i>Stylodictya</i> sp.	spumellaria	Warm water (Boltovskoy 1998)
<i>Stylochlamydidium asteriscus</i> Haeckel, 1887	spumellaria	Warm water (Boltovskoy 1998)
<i>Stylochlamydidium</i> spp.	spumellaria	Warm water (Boltovskoy 1998)
<i>Tetrapyle circularis</i> Haeckel in Zhang and Suzuki, 2017	spumellaria	Cosmopolitan (Chang <i>et al.</i> 2003)
<i>Tetrapyle octacantha</i> Müller, 1858	spumellaria	Warm water (Pisias and Moore 1995)
<i>Acrobotrys disolenia</i> Haeckel, 1887	nassellaria	Warm water (Chakraborty and Ghosh 2015)
<i>Clathrocanium coarctatum</i> Ehrenberg, 1860b	nassellaria	Warm water (Boltovskoy and Vrba 1989)
<i>Cornutella profunda</i> Ehrenberg, 1856	nassellaria	Cold water (Boltovskoy and Vrba 1989)
<i>Disolenia zanguebarica</i> (Ehrenberg) Nigrini, 1967	nassellaria	Warm water (Lombardi and Boden 1985; Matsuzaki <i>et al.</i> 2014)
<i>Lithomelissa</i> sp.	nassellaria	Warm water (Cortese <i>et al.</i> 2003)
<i>Phormostichoartus doliolum</i> (Riedel and Sanfilippo) Nigrini, 1977	nassellaria	Warm water (Oseki and Suzuki 2009)
<i>Phormostichoartus fistula</i> Nigrini, 1977	nassellaria	Cosmopolitan (Oseki and Suzuki 2009)
<i>Phormostichoartus</i> sp.	nassellaria	Cold water (Renaudie 2012)
<i>Semantis</i> spp.	nassellaria	Cold water (Funnell and Reidel 1971)
<i>Siphocampe lineata</i> (Ehrenberg) Nigrini, 1977	nassellaria	Cold water (Boltovskoy 1998)
<i>Solenosphaera</i> sp.	nassellaria	Warm water (Boltovskoy 1998)
<i>Stichocorys peregrina</i> Riedel, 1953	nassellaria	Warm water (Riedel 1953; Casey <i>et al.</i> 1983)

Table 4. Habitat and ecological preference of the recovered species of diatoms (taken into account up to species level) and radiolarian taxa from the early Pliocene of Car Nicobar Island.

out on productive samples (BSIP 7876/01–7876/16, Table 3) exclusive of samples BSIP 7876/09 and 7876/10, in which calcareous nannofossils and diatoms were not observed. Radiolarians dominate the biosiliceous composition with up to 95% in sample BSIP 7876/11 (Text-fig. 8A). The maximum diatom contribution (up to 65%) was observed in sample BSIP 7876/05 (Text-fig. 8A). Siliceous sponges were most abundant (up to 49%) in sample BSIP 7876/10 (Text-fig. 8A). A much lower silicoflagellate percentage (up to 15%) was observed in sample BSIP 7876/01 (Text-fig. 8A).

The planktic/benthic diatom ratio is conventionally used to interpret sea-level fluctuations (Chakraborty and Ghosh 2016) and was analysed here in all samples from the Sawai Bay 'B' Section (Text-fig. 8B). From this analysis, planktic diatoms prevail in samples BSIP 7876/03, 7876/06, 7876/07, 7876/11 and 7876/16 with relative counts that progressively increase from 62%, 65%, 80% to 100%, respectively. Benthic diatoms are more abundant compared to planktic in samples BSIP 7876/02, 7876/04, 7876/11, 7876/12 and 7876/13 (Text-fig. 8B). The radiolarian nassellarian–spumellarian ratio is also used to interpret sea-level fluctuations (O'Dogherty and Guex 2002; Lukeneder and Smrečková 2006). In the Sawai Bay 'B' Section, spumellarians were consistently dominant among radiolarians (Text-fig. 8C).

## DISCUSSION

### Biostratigraphy

The presence of *Ceratolithus armatus* in all samples from the base of the Sawai Bay 'A' Section confirms a Zanclean age, as the FO of *C. armatus* lies at the CN10a/CN10b (Okada and Bukry 1980) and the CNM20/CNPL1 (Backman *et al.* 2012; Raffi *et al.* 2016) boundaries. Since there are no other index forms available in the section top, a maximum upper age limit of ~5.08 Ma (Young 1998) is suggested. The presence of *Ceratolithus cristatus* in sample BSIP 7876/15 of the Sawai Bay 'B' Section indicates that the uppermost samples are of a younger age, i.e., above ~5.08 Ma. The FO of *C. cristatus* lies at the CN10b/CN10c (Okada and Bukry 1980), CNPL1/CNPL2 (Backman *et al.* 2012; Raffi *et al.* 2016) and NN12/NN13 (Martini 1971) boundaries.

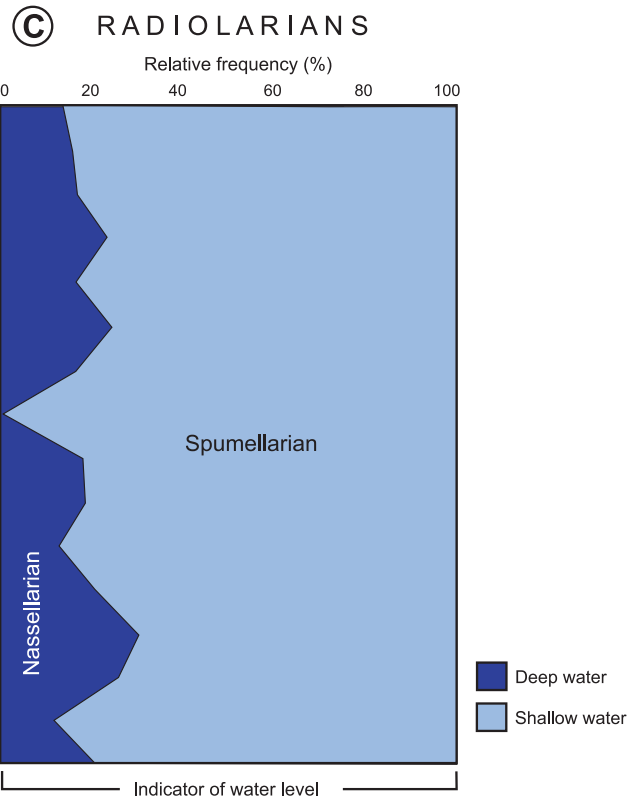
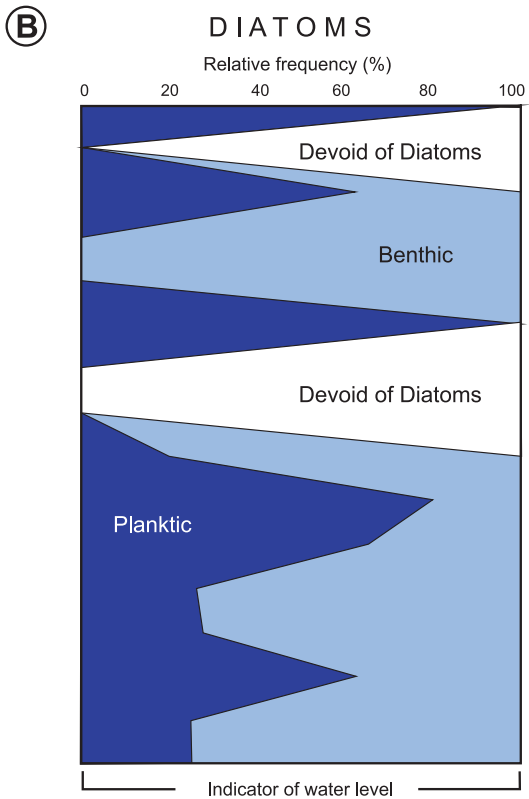
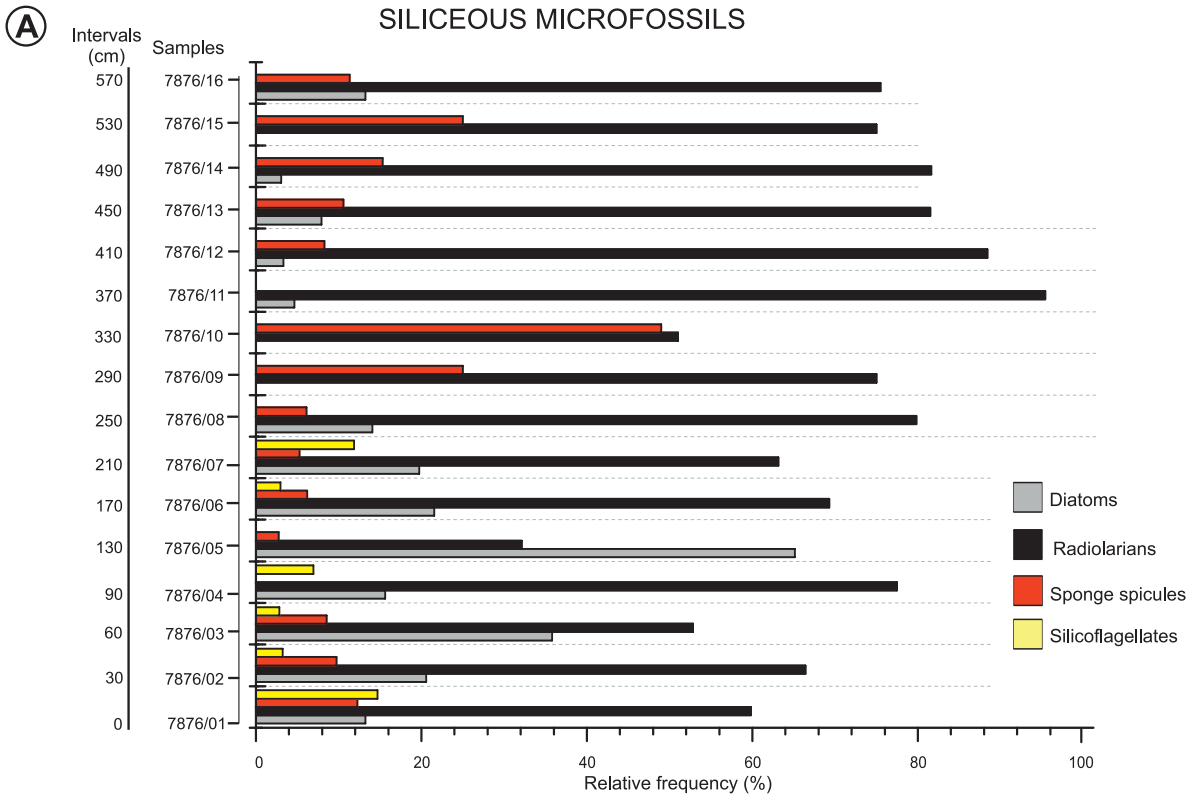
The radiolarian assemblage is represented by the biostratigraphically significant taxa *Stichocorys peregrina* and *Didymocyrtis avita* (Text-fig. 3) that indicate

Zone RN9 (Sanfilippo and Nigrini 1998; Kamikuri *et al.* 2009). In the eastern equatorial Pacific Ocean, the evolutionary transition (ET) from *Stichocorys delmontensis* Campbell and Clark, 1944 to *S. peregrina* took place at 6.89/6.81 Ma (Lazarus *et al.* 1995; Sanfilippo and Nigrini 1998). However, according to Kamikuri *et al.* (2009), the ET took place at ~6.88/7.17 Ma. Zone RN9 includes the ET from *Didymocyrtis penultima* Riedel, 1957 to *D. avita* (Sanfilippo and Nigrini 1998). However, Kamikuri *et al.* (2009) did not recognise this event in ODP Sites 845 and 1241. According to Kamikuri *et al.* (2009), the FO of *D. avita* in the eastern equatorial Pacific Ocean was at ~6.84/6.91 Ma, its LO was at ~0.81/0.88 Ma, and the ET from *D. avita* to *D. tetrathalamus* Haeckel, 1887 was at ~4.23/4.27 Ma. It should be mentioned here that *D. tetrathalamus* is absent in the studied radiolarian assemblage, indicating an age prior to ~4.23/4.27 Ma for the studied sequence (Sawai Bay 'B' Section).

Based on the above mentioned calcareous nannofossil (both Sawai Bay 'A' and 'B' sections) and radiolarian index taxa (Sawai Bay 'B' Section), the age can be defined as Zanclean. However, the absolute age difference between the outcrop bases is indiscernible.

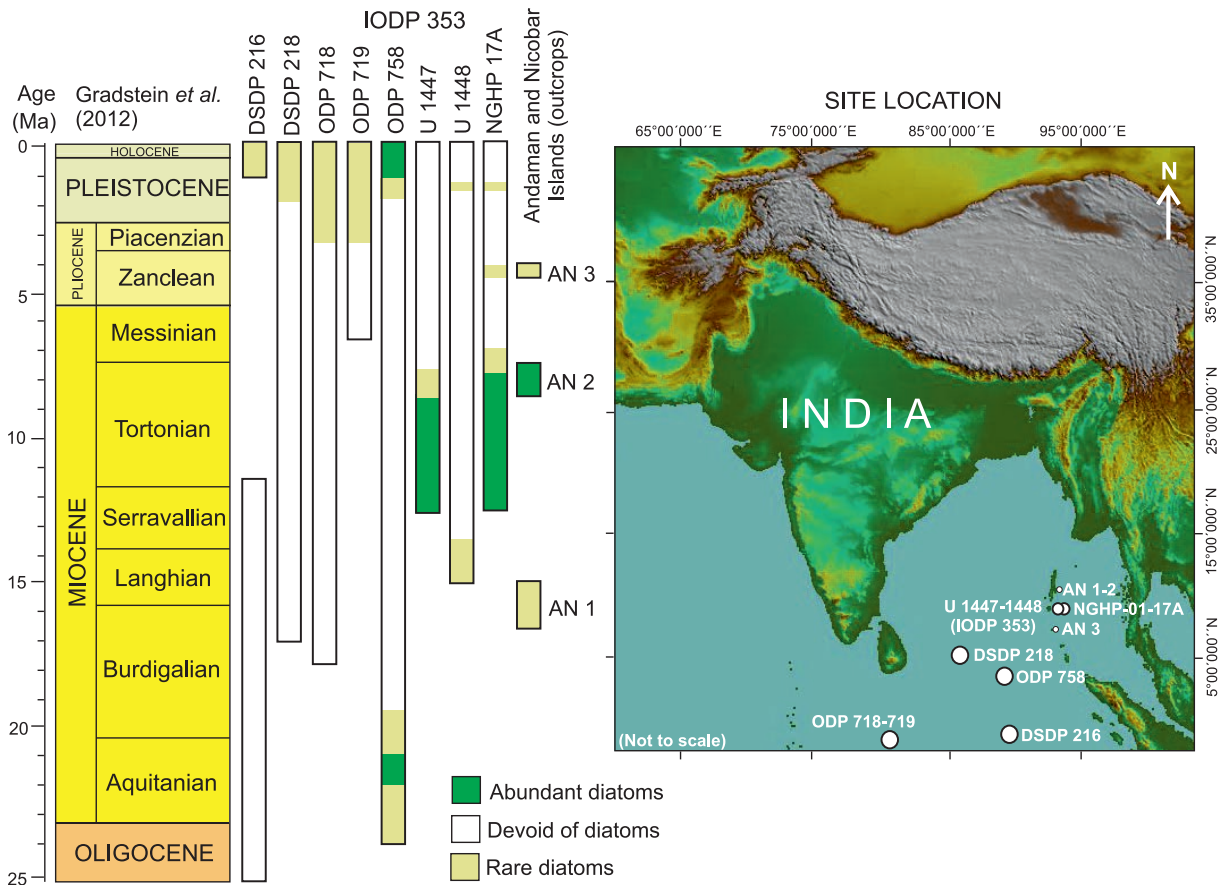
Diatoms recorded from the Zanclean sediments of Car Nicobar Island are more or less similar to the low latitude equatorial assemblage reported from the International Ocean Discovery Program (IODP) Expedition 320/321, Site U1337 (Pälike *et al.* 2010). The assemblage includes *Actinocyclus ellipticus* Grunow in Van Heurck, 1883, *Azpeitia* spp., *Coscinodiscus* spp., *Hemidiscus cuneiformis* Wallich, 1860 and *Thalassiosira leptopus* (Grunow) Hasle and Fryxell, 1977. The present assemblage is devoid of diatoms representing *Thalassionema* Grunow ex. Mereschkowsky, 1902, which is typical for the upper Miocene, but absent in the Zanclean (Mikkelsen 1990). Based on the study of DSDP Leg 69, eastern equatorial Pacific, Sancetta (1983) suggested that the sharp decrease of the *Thalassionema* group after the Miocene–Pliocene boundary coinciding with an overall diatom abundance decrease, is indicative of a major shift in productivity patterns and upwelling.

The dissolution of diatom valves in the outcrops studied can be explained by the absence of smaller taxa belonging to the genera *Thalassiosira* and *Fragilariopsis* Hustedt, 1913 documented from the lower Pliocene of the tropical Indian Ocean and the lower Pliocene diatomaceous deposits of California (Barron and Baldauf 1986). The presence of *Actinocyclus ellipticus* forma *lanceolata* Kolbe, 1954 in the studied diatom assemblage from Sawai Bay 'B' Section is biostratigraphically significant,



Text-fig. 8 – Microfossil content in the Sawai Bay ‘B’ Section. A – graphic representation of relative frequency of siliceous microfossils; B – diatom planktic/benthic ratio; C – radiolarian nassellarian/spumellarian ratio.





Text-fig. 9. Occurrence of diatoms (abundant, rare and devoid) in ODP, DSDP (modified after Baldauf *et al.* 1992), IODP, NGHP sites of northern Indian Ocean and their correlation with onshore sequences of Andaman and Nicobar Islands.

as its LO is at  $\sim 3.4$  Ma (Lazarus *et al.* 2014). On the other hand, the occurrence of *Actinocyclus ellipticus* var. *javanica* Reinhold, 1937 in the same assemblage may be regarded as unusual, as its LO is at  $\sim 7.9$  Ma (late Miocene; Barron 1985). Either this taxon regionally continued into the Zanclean or may be re-worked, as suggested by the presence of the reworked middle Miocene species *Sphenolithus heteromorphus* Deflandre, 1953 in the calcareous nannofossil assemblage.

### Palaeoenvironment

As revealed from the present study, radiolarians are the main contributors to the biogenic opal fraction, followed by diatoms, sponge spicules and silicoflagellates (Text-fig. 8A). This radiolarian dominance may be due to the selective dissolution of particular siliceous microfossil groups. Fluctuation of radiolarian and diatom relative counts is the highest in the middle of the Sawai Bay 'B' Section, which

represents shallower and warmer temperate waters (Text-fig. 8B, C; Tables 3 and 4). Radiolarian abundance is inversely proportional to diatom abundance (Text-fig. 8A), perhaps due to the dissolution of more fragile diatom skeletons or radiolarian predation on diatoms (Swanberg and Anderson 1985).

Warm water radiolarian species are common; however, cold water forms (e.g., *Semantis* spp., *Siphocampe lineata*) dominate in both lower and upper parts of the Sawai Bay 'B' Section (Text-fig. 2B; Tables 3 and 4). Amongst the cold water taxa, *Semantis* spp. is the most dominant taxon recorded from the eastern equatorial Pacific Ocean (Boltovskoy and Jankilevich 1985). Diatom occurrences are rare in the studied section from which no concrete palaeoenvironmental inferences may be made, but the overall radiolarian and diatom representations together synergistically imply water temperature changes induced by monsoons that could have developed periodical gyres and/or local upwelling in the northern Indian Ocean during the early Pliocene.

The diatom abundance is controlled by preservation potential, dependent on a combination of factors that include dissolution and overall low productivity in oligotrophic conditions (Exon and Kennett 2001). There are no readily observed lithological variations in the Sawai Bay 'B' Section; however, the ratios of planktic/benthic diatoms (Text-fig. 8B) and nassellarian/spumellarian radiolarians (Text-fig. 8C) vary. The most likely reason for this variation may be due to severe selective dissolution of siliceous microfossils during the early Zanclean.

Siliceous microfossil abundance and diversity significantly decreased in the Zanclean of the Indian Ocean in comparison to the late Miocene, when a biogenic bloom well developed in the Andaman and Nicobar Basin (Chakraborty and Ghosh 2016, 2017). This corroborates with the studies of Lyle and Baldauf (2015) from the equatorial Pacific.

Based on studies of Miocene and Pliocene sediments from the northern Indian Ocean, from the DSDP, ODP, IODP and National Gas Hydrate Program (NGHP), as well as the Andaman and Nicobar Island outcrops, diatom occurrence varies from abundant to rare, and in some instances may be completely absent (Text-fig. 9). According to most previous studies, diatoms became abundant in the Tortonian; however, diatoms are mostly rare to absent in the Zanclean (Text-fig. 9). Mikkelsen (1990) studied the western equatorial Pacific Ocean (ODP Sites 705–716) to propose a diatom biostratigraphy and commented that decline of diatom abundance was caused by an early Pliocene shift of opal accumulation from the equatorial region to the Antarctic Convergence. In a study of global ocean sediments, Cortese *et al.* (2004) argued that since the Langhian, the main opal sink moved from the North Atlantic to the Pacific (eastern equatorial Pacific, North Pacific and Peru) and finally to the Southern Ocean. This may be a potential reason for the rare occurrence of siliceous microfossils in Zanclean sediments of the Indian Ocean.

## CONCLUSIONS

The age of the Sawai Bay Formation exposed on Car Nicobar Island has been precisely dated as Zanclean based on the index calcareous nannofossils of zones NN12 (CN10b) and NN13 (CN10c). The radiolarian assemblage also denotes the same age according to the presence of characteristic index species of Zone RN9. The overall diversity and abundance of siliceous microfossils viz., radiolarians, diatoms, silicoflagellates and sponge spicules were

low. The diatom abundance gradually became low towards the upper part of the studied sections that yielded other siliceous microfossils. This phenomenon may be correlated with the dissolution of diatom valves. Critical evaluation of siliceous microfossils indicates that Zanclean flora and fauna were dominated by warm shallow water taxa of diatoms and radiolarians. As revealed by the present study, warm water conditions prevailed during the Zanclean.

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