The Pliocene-Pleistocene boundary in pelagic oozes off Réunion Island, western Indian Ocean

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ABSTRACT:

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Nannoplankton and foraminifera from the pelagic oozes from a water depth of 3 684 meters, 150 km southeast of Réunion Island, Indian Ocean, prove the NN18 and NN19 nannoplankton zones, indicating the Pliocene–Pleistocene boundary. The Pliocene–Pleistocene boundary was established at 220–230 cm depth. The abundance of *Globorotalia truncatulinoides* increases from about 50 cm below the sea floor. The microfossil assemblages and clay mineral components of the sediments may be correlated with changes of climatic conditions influenced by glaciations.

Key words: Réunion Island, Indian Ocean, Biostratigraphy, Calcareous nannoplankton, Foraminifers, Pelagic ooze.

INTRODUCTION

The Middle Pliocene (ca. 3 Ma) represents a time in geological history when the climate of the Earth was warmer than at present (HAYWOOD & *al*. 2000). The Late Pliocene was a transition epoch from a warmer to a colder climate characterized by glacial-interglacial cycles. A progressive global cooling took place between 3 and 2 Ma (e.g., DAVIES & *al*. 1995; CROWLEY 1996; KAMEO 2002).

The Pliocene–Pleistocene boundary from the Western Indian Ocean was reported from a few places on the basis of nanno- and microfossils (SCHLICH & *al.* 1974), although mixed Pleistocene, Pliocene and older sediments were mostly found. The whole sequence of Cenozoic sediments in the equatorial Indian Ocean is proved biostratigraphically (BACKMAN & DUNCAN 1988).

In this study we document the Pliocene–Pleistocene boundary in the southernmost part of the Mascarene Basin, off Réunion Island. The boundary was determined on the basis of calcareous nannofossils and foraminifers. We combined stratigraphical and mineralogical data to infer the palaeoclimatic conditions. The climatic cooling at the turn of the Pliocene and Pleistocene is well confirmed.

The material studied was taken during the SO87 cruise, financed by the German Ministry of Research and Technology, carried out at the volcanic Réunion Island (STOFFERS & *al.* 1996).

GEOLOGICAL SETTING OF RÉUNION ISLAND

In the western part of the Indian Ocean, there are a few abyssal basins with depths exceeding 5 km. The largest of them are the Somali, Mascarene and Mauritius Basins. Réunion Island is located in the southern part of the Mascarene Basin (Text-fig. 1). The Mascarene Basin is filled with over 1 600 m of mainly carbonate sediments.

Réunion Island (55°32' E and 21°07' S) lies about 700 km east of Madagascar, and about 1 200 km west of the Mid-Indian Ridge. The island is a result of within plate volcanism – a product of the oceanic crust hotspot system (STOFFERS & *al.* 1996). Bathymetric data and the determination of the age of the rocks (LÉNAT & *al.* 1989; FRETZDORFF 1997) confirmed that the formation of the island was initiated by a relatively young volcanism (5 million years).

PREVIOUS WORK

The sediments around the island were investigated first by PHILIPPOT (1984). Around the island occur mainly volcanogenic muds, whereas outward occur pelagic oozes (Text-fig. 1). The volcanogenic mud consists mainly of fragments of basaltic rocks, minerals of volcanic origin (plagioclases, pyroxenes and olivines), volcanic glass shards, zeolites and clay minerals. Moreover, there are different quantities of carbonate bioclasts and small quantities of siliceous ones (DUCZMAL-CZERNIKIEWICZ & *al.* 2003). The pelagic oozes consist mainly of carbonate bioclasts, with minor proportions of other components (*op.cit.*). KOLLA & BISCAYE (1973), KOLLA & *al.* (1976) and PHILIPPOT (1984) described clay minerals in the sediments from the Western Indian Ocean. They distinguished montmorillonite, illite, chlorite and kaolinite minerals at the bottom of the oceanic sediments.

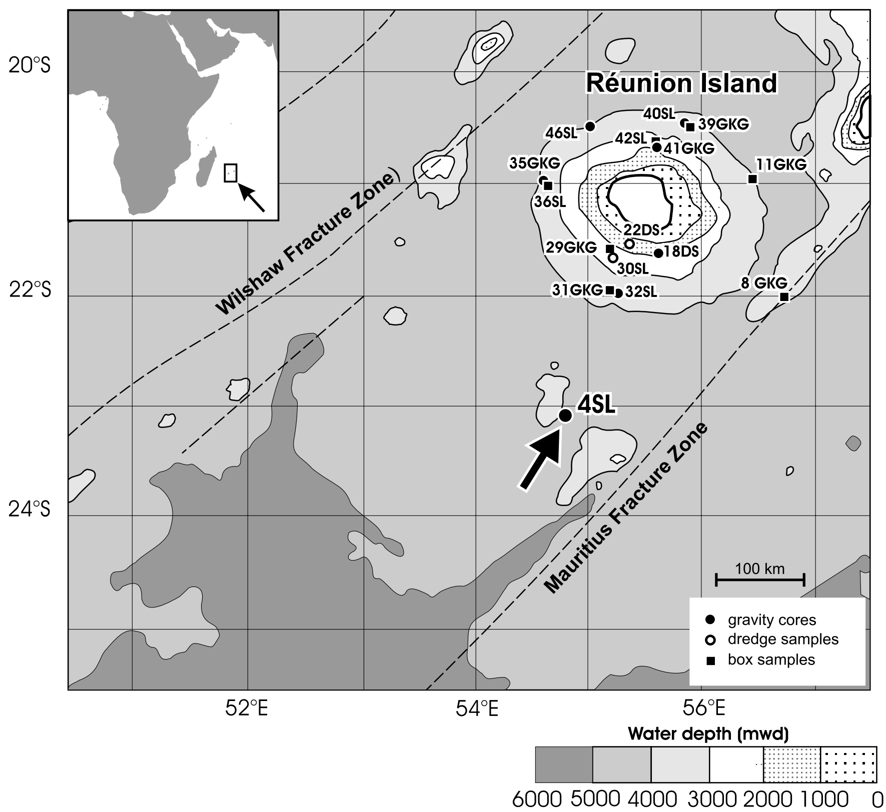

Fig. 1. Bathymetric map of the study area and location of the stations (after STOFFERS & al. 1994).

In the previous available DSDP, Leg 25, Site 239, from the Mascarene Basin, only mixed Pliocene and Pleistocene nannoflora assemblages were found, and thus it has been impossible to determine the Pliocene–Pleistocene boundary (SCHLICH & *al.* 1974). The whole sequence of Cenozoic sediments in the equatorial Indian Ocean (Leg 115) (BACKMAN & *al.* 1988) is well documented biostratigraphically, by both calcareous and siliceous microfossils. However, in sediments investigated in the Atlantis Fracture Zone (DSDP Leg 118), in the South West Indian Ridge, Lower Pleistocene (Site 734 G), Middle Pleistocene (Site 732) and Holocene sediments (Site 734 B, D) were recognized (ROBINSON & VON HERZEN 1989).

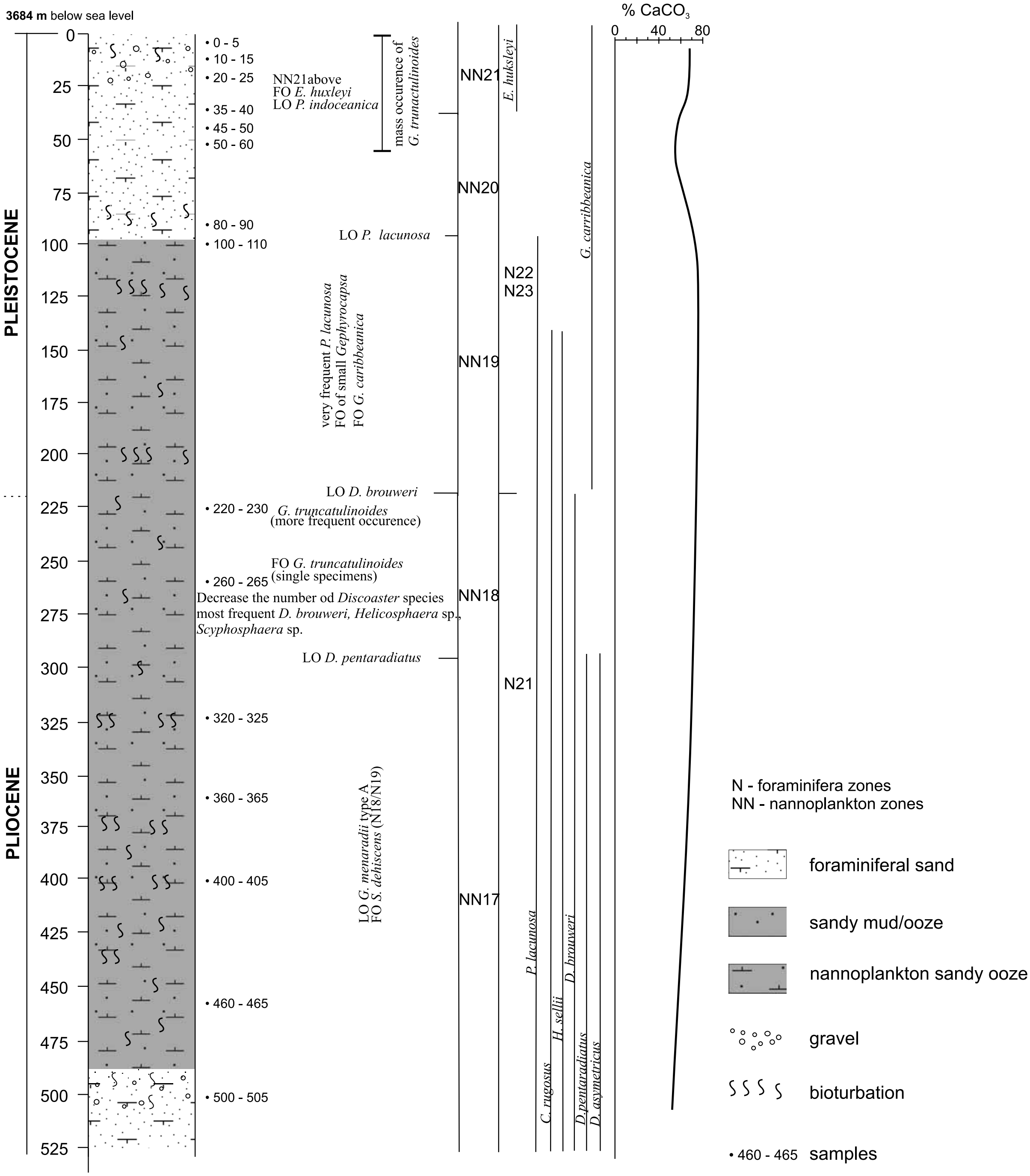

Fig. 2 Lithologic profile of the 4SL core.

OLLIER & *al.* (1998) suggested that the volcaniclastic sediments on the eastern side of Réunion Island were of Pleistocene and Holocene age. PHILIPPOT (1984) reported the NN19, NN20 and NN21 nannoplankton zones in cores from sites closest to the island. According to FRETZDORFF (1997, FRETZDORFF & *al.* 2000) these sediments are not older than 260 000 years.

MATERIALS AND METHODS

In this study, core samples from core 4SL were examined. The gravity core, 5.60 m long, was taken during the SO87 cruise (STOFFERS & *al.* 1996) (Text-fig 2). The mineral components were determined on the basis of petrographic investigations of smear slides prepared by the ROTHWELL method (ROTHWELL 1987), as well as thin sections. The chemical composition of microconcretions was studied under the Scanning Electron Microscope (SEM). Clay fraction components were determined by the X-ray diffraction (XRD) method. According to MOORE & REYNOLDS (1989), two fractions: < 0.2 μm and < 2 μm were investigated.

The micropalaeontological studies included calcareous nannoplankton and foraminifers, selected from washed residues. The 63 μm (100.0–46.5, 35.0–40.0, 20.0–25.0, 0.0–5.0 cm depth intervals) and 50–25 μm fractions (80.0–90.0, 50.0–60.0, 45.0–50.0 cm depth intervals) were used for micropalaeontological analysis. We used the BOLLI & *al.* (1985) Cenozoic biostratigraphical schemes based on low latitude microorganisms, including planktonic foraminifers and calcareous nannoplankton.

RESULTS

Mineralogical composition

Mineral components of marine sediments, especially clay minerals, reflect palaeoclimatic changes (KELLER 1970). The paleoclimatic interpretations of marine clay assemblages yield rather broad palaeoclimatic information although detrital kaolinite and smectite are able to carry a climatic signal to marine sediments (THIRY 2000).

The sediment is dominated by detrital components: bioclasts and lithoclasts, which originated as a result of pelagic sedimentation in the ocean or hemipelagic sedimentation around the island (crystals, lithoclasts). Among the crystals, plagioclases, pyroxenes and less frequent zeolites, quartz, staurolite and apatite were determined. The heavy fraction is dominated by volcanic material from the island. Non-volcanic components (e.g., staurolite) are rare.

Hydrogenic phases (ferric-manganese concretions) originated *in situ* with a growth rate of a few mm per thousand years, determining the sedimentation rate in the 4SL section. Manganese and iron compounds dominate the composition of the microconcretions, and are accompanied by small quantities of Cu, Co and Ni. The morphology and homogeneous chemical composition of the smallest microconcretions confirm the role of bacteria in their formation. Saturation with Mn and Fe compounds occurs through the assimilation and cementation of different sediment components: crystals, nannofossils, zeolites, micrite and clay minerals (Text-fig. 3).

In the 200–400 cm depth interval of the 4SL core kaolinite is the dominant mineral of the clay fraction, accompanied by smectite. In the upper part of the section (45–100 cm depth interval) smectite is the dominant mineral, whereas kaolinite is present only in minor quantities.

Biostratigraphy

Both micro- and nannofossils are useful biostratigraphical tools. They are also excellent tools for revealing environmental aspects of sedimentation processes, e.g. palaeoclimatic fluctuations (e.g., CHAPMAN & CHEPSTOW-LUSTY 1998; SATO & *al*. 2004).

Nannoplankton

The nannoplankton zonation applied follows the standard nannoplankton zonation of MARTINI (1971). Nannoplankton analyses were carried out on the following depths and intervals (in centimetres): 460–465, 430, 400–405, 290, 220–230, 190, 166, 100–110, 80–90, 50–60, 35–40, 20–25, 0–5.

The *Discoaster pentaradiatus* Zone (NN17), which represents the time interval from the last occurrence (LO) of *Discoaster surculus* MARTINI & BRAMLETTE to the LO of *Discoaster pentaradiatus* TAN SIN HOK is difficult to determine. Many older redeposited species: *D. braarudii* (Text-fig. 4.7), *D.*

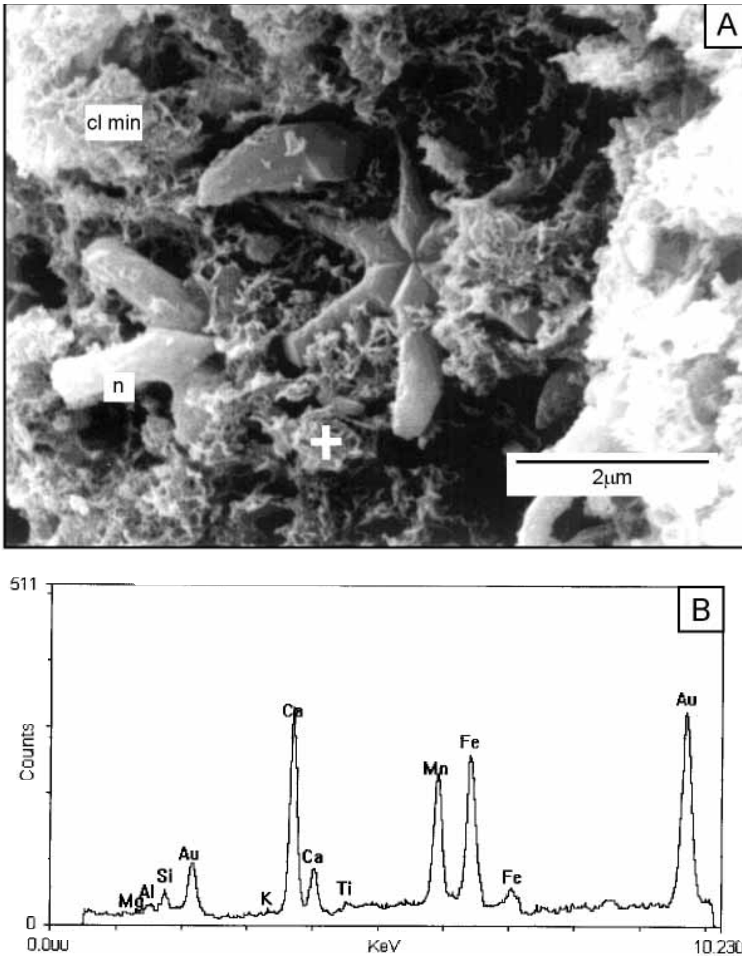

Fig. 3 A – SEM microphotograph of Fe-Mn microconcretion, 4SL, cl-clay minerals, n – nannoplankton, B – Composition of microconcretions obtained by the EDS method.

deflandrei (Text-fig. 4.2), *D. bellus, D. blackstockae* (Text-fig. 4.16), *D. berggrenii* (Text-fig. 4.39), *D. formosus* (Text-fig. 4.9), *D. kugleri* (Text-fig. 4.3), *D. hamatus* (Text-figs 4.13, 4.37), *D. intercalaris* (Text-fig. 4.4), *D. quinqueramus* (Text-figs 4.11, 4.38), *D. variabilis* (Text-fig. 4.14) and *Reticulofenestra pseudoumbilicus* (Text-fig. 4.19) occur in the samples from the intervals and depths 460–465 cm, 430 cm, 400–405 cm, 290 cm. However, the base of the *D. pentaradiatus* Subzone corresponds to the most frequent occurrence of *D. tamalis* (BUKRY 1973). In the samples investigated, *D. tamalis* (Text-fig. 4.12) and *D. triradiatus* (Text-fig. 4.15) appear very often and these are typical Pliocene species of *Discoaster*. In the samples studied, *D. quadramus* (Text-fig. 4.36) also occurs, ranging from zones NN13–NN16 (lower Pliocene), as well as *D. challengeri* (NN7–NN16) (Text-fig. 4.10).

The next Neogene calcareous nannoplankton zone, the *Discoaster brouweri* Zone (NN18), ranges from the LO of *Discoaster pentaradiatus* TAN SIN HOK (Text-fig. 4.41) to the LO of *Discoaster brouweri* TAN, BRAMLETTE & RIEDEL (Text-figs. 4.5, 4.8). Between 220.00 cm and 230.00 cm, a considerable decrease in the number of *Discoaster* species took place, *Discoaster brouweri* remaining the commonest (Text-figs 4.5, 4.8). Other species are very rare. Concurrently, there was a considerable increase in the number of *Helicosphaera* species as well as *Syracosphaera histrica* (Text-fig. 4.33).

The Pleistocene *Pseudoemiliania lacunosa* Zone (NN19) represents an interval from the LO of *Discoaster brouweri* TAN SIN HOK to the LO of *Pseudoemiliania lacunosa* KAMPTNER. Among the species of this zone we determined *D. brouweri, Coccolithus pelagicus, Helicosphaera kamptneri* (Text-

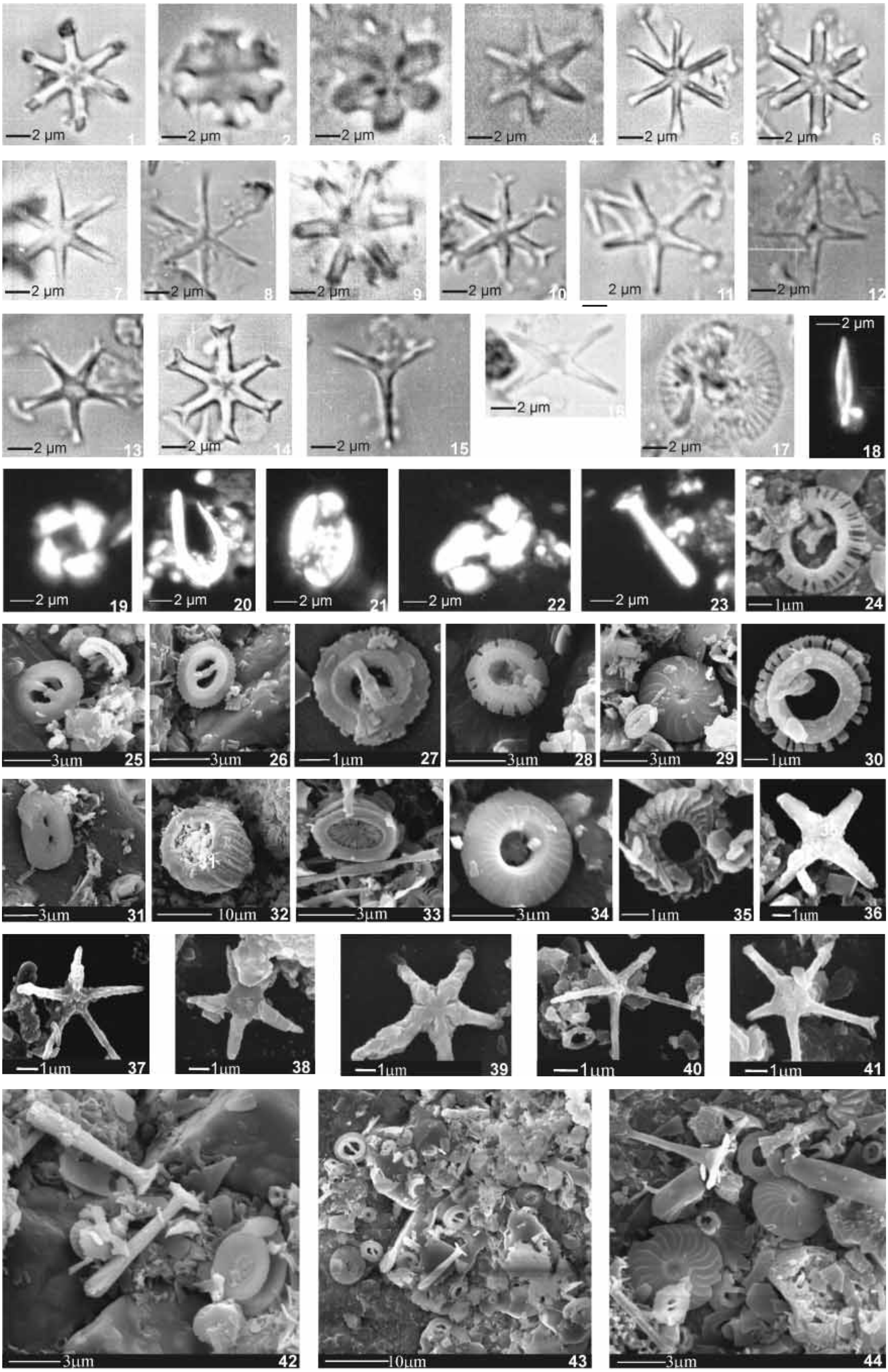
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fig. 4.22), *H. sellii* (Text-fig. 4.31), *Pseudoemiliania lacunosa* (Text-figs 4.24, 4.28, 4.30), *Ceratolithus rugosus* (Text-fig. 4.20), *Calcidiscus macintyrei* (Text-fig. 4.17) and *Scapholithus fossilis* (Text-fig. 4.18). This zone ranges between the depths of 190 cm, 166 cm and 100–110 cm below the sea floor. The first occurrence (FO) of small *Gephyrocapsa* (Text-fig. 4.27) species was observed at a depth of 100–110 cm. *Pseudoemiliania lacunosa* is very common (several specimens in one field of view). In that sample *Discoaster brouweri* has disappeared.

The succeeding Pleistocene nannoplankton zone of *Gephyrocapsa oceanica*, the NN20 Zone, ranges from the LO of *Pseudoemiliania lacunosa* Kamptner to the FO of *Emiliania huxleyi* Lohmann. The latter species is difficult to determine under a polarizing microscope because of its small size; in this case the sample was investigated by SEM. The zone is also characterized by *Gephyrocapsa oceanica* (Text-figs 4.26, 4.43), *G. margerellii* (Text-fig. 4.25), *Calcidiscus leptoporus, C. cristatus, Umbilicosphaera mirabilis, Helicosphaera kamptneri, Thoracosphaera heimii, T. albatrosiana, Scyphosphaera* sp. (Text-fig. 4.32), *Scyphosphaera pulchra, Rhabdosphaera clavigera* (Text-figs 4.23, 4.42), *Pontosphaera japonica* (Text-fig. 4.21) and *P. scutelum.* Samples from the 80–90, 50–60 and 35–40 cm depth intervals below the sea floor represent this zone.

The last interval comprised the *Emiliania huxleyi* Zone (NN21), representing the interval above the FO of *Emiliania huxleyi*. In addition to *E. huxleyi*, this zone contains *Gephyrocapsa oceanica, Calcidiscus leptoporus, Umbilicosphaera maceria* (Text-fig. 4.35), *U. sibogae foliosa* (Text-fig. 4.34), *Helicosphaera kamptneri, Thoracosphaera heimii, T. albatrosiana, S. pulchra, R. clavigera,* and *Ceratolithus cristatus*. The most common are *Helicosphaera kamptneri, Rhabdosphaera clavigera, Scyphosphaera pulchra and Gephyrocapsa oceanica*. As before, we used SEM to identify *Emiliania huxleyi*.

Foraminifera

The planktonic foraminifers are a dominant component of the samples studied. Assemblages were studied from the following depth intervals (in centimetres): 500.0–505.0, 460.0–465.0, 400.0–405.0, 320.0–325.0, 260.0–265.0, 220.0–230.0, 100.0–110.0, 80.0–90.0, 45.0–50.0, 40.0–35.0, 20.0–25.0, 0.0–0.5.

The oldest assemblage (500.0–505.0 cm) includes some forms that first appeared within the Middle Miocene. Most of the long-ranging forms existed till the Pleistocene (*Globorotalia menardii*; *Globigerinoides immaturus*) or to the Recent (*Globigerina falconensis G. scitula*, *Turborotalia quinqueloba*). Some of these forms are known to disappear in the Early Pliocene (*Globorotalia*

Fig. 4 Nannoplankton species, 4SL core. 1. *Discoaster surculus* Martini & Bramlette, 460–465 cm, (Early Pliocene); 2. *Discoaster deflandrei* Bramlette & Riedel, 430 cm, (Miocene); 3. *Discoaster kugleri* Martini & Bramlette, 430 cm, (Miocene); 4. *Discoaster intercalaris* Bukry, 400–405 cm, (Early Pliocene); 5. *Discoaster brouweri* Tan, 220–230 cm, (Pliocene); 6. *Discoaster surculus* Martini & Bramlette, 460–465 cm, (Early Pliocene); 7. *Discoaster braarudii* Bukry, 460–465 cm., (Miocene); 8. *Discoaster brouweri* Tan x 2500, 220–230 cm, (Pleistocene); 9. *Discoaster formosus* Martini & Worsley, 430 cm, (Miocene); 10. *Discoaster challengeri* Bramlette & Riedel, 460–465 cm, (Early Pliocene); 11. *Discoaster quinqueramus* Gartner, 290 cm, (Miocene); 12. *Discoaster tamalis* Kamptneri, 400–405 cm, (Pliocene); 13. *Discoaster hamatus* Martini & Bramlette, 430 cm, (Miocene); 14. *Discoaster variabilis* Martini & Bramlette x 2500, 460–465 cm, (Pliocene); 15. *Discoaster triradiatus* Tan, 400–405 cm, (Pliocene); 16. *Discoaster blackstockae* Bukry, 430 cm, (Early Pliocene); 17. *Calcidiscus macintyrei* (Bukry & Bramlette) Loeblich & Tappan, 166 cm, (Pleistocene); 18. *Scapholithus fossilis* Deflandre, 166 cm, (Pleistocene); 19. *Reticulofenestra pseudoumbilicus* Gartner, 400–405 cm, (Pliocene); 20. *Ceratolithus rugosus* Bukry & Bramlette, 166 cm, (Pleistocene); 21. *Pontosphaera japonica* (Takayama) Nishida, 50–60 cm, (Pleistocene); 22. *Helicosphaera kamptneri* Hay & Mohler, 166 cm, (Pleistocene); 23. *Rhabdosphaera clavigera* Murray & Blackman, 50–60 cm, (Pleistocene); 24. *Pseudoemiliania lacunosa* (Kamptner) Gartner, 100–110 cm, (Pleistocene); 25. *Gephyrocapsa margarellii* Bréhéret, 50–60 cm, (Pleistocene); 26. *Gephyrocapsa oceanica* Kamptner, 50–60 cm, (Pleistocene); 27. *Gephyrocapsa* sp. Kamptner, 100–110 cm, (Pleistocene); 28. *Pseudoemiliania lacunosa* (Kamptner) Gartner, 166 cm, (Pleistocene); 29. *Calcidiscus macintyrei* (Bukry & Bramlette) Loeblich & Tappan, 220–230 cm, (Pliocene); 30. *Pseudoemiliania lacunosa* (Kamptner) Gartner, 166 cm, (Pleistocene); 31. *Helicosphaera sellii* Bukry & Bramlette, 166 cm, (Pleistocene); 32. *Scyphosphaera* sp. Lohmann, 50–60 cm, (Pleistocene); 33. *Syracosphaera histrica* Kamptner, 220–230 cm., (Pliocene); 34. *Umbilicosphaera sibogae foliosa* (Kamptner) Okada & McIntyre, 25 cm, (Pleistocene); 35. *Umbilicosphaera maceria* Okada & McIntyre, 25 cm, (Pleistocene); 36. *Discoaster quadramus* Bukry, 460–465 cm, (Early Pliocene); 37. *Discoaster* cf. *hamatus* Martini & Bramlette, 290 cm, (Miocene); 38. *Discoaster quinqueramus* Gartner, 430 cm, (Miocene); 39. *Discoaster berggrenii* Bukry, 400–405 cm, (Miocene); 40. *Discoaster asymmetricus* Gartner, 430 cm, (Pliocene); 41. *Discoaster pentaradiatus* Tan, 460–465 cm, (Pliocene); *Discoaster pentaradiatus* Tan, 220–230 cm, (Pliocene); 42. *Rhabdosphaera clavigera* Murray & Blackman, 35–40 cm, (Pleistocene); 43. *Gephyrocapsa oceanica* Kamptner, 35–40 cm, (Pleistocene); 44. *Calcidiscus macintyrei* (Bukry & Bramlette) Loeblich & Tappan, 220–230 cm, (Pliocene).

menardii "A") and at the end of the Pliocene (*Globigerinella obesa* - Text-fig. 5.4, *Globoturborotalia decoraperta*- Text-fig. 5.5). Foraminifers are represented by both small-sized, mainly delicate forms and larger, robust forms.

The sample from the 460.0–465.0 cm depth interval is characterized by rare *Sphaeroidinellopsis seminulina* (Text-fig. 5.6), *Sphaeroidinella dehiscens*, *Globigerinoides conglobatus*, *G. elongatus*, and *Globorotalia menardii "A"*. The co-occurrence of the latter species and of *S. dehiscens* (FO) indicates the Early Pliocene age of this assemblage, which is additionally supported by *Globorotalia evoluta*.

The succeeding sample (400.0–405.0 cm depth interval) contains the first *Globorotalia menardii cultura*, *G. crassaformis oceanica*, *G. exilis* (Text-fig. 5.8), *G. scitula scitula*, *Pulleniatina obliquiloculata*, *Dentoglobigerina altispira* Cushman & Jarvis and *Hastigerina siphonifera*.

The assemblage from the 260.0–265.0 cm depth interval comprises *Orbulina suturalis*, *Globorotalia crassaformis*, and robust forms of the *Globorotalia menardii* group (*G tumida* - Text-fig. 5.2, *G. flexuosa*). These forms are accompanied by foraminifers of the genus *Globigerinoides*: *G. conglobatus* (Text-fig 5.9), *G. elongatus*, *G. extremus*, *G. ruber*, *G. sacculifer* and *G. trilobus*. Also present are *Sphaeroidinella dehiscens* and its morphotype, *S. ionica*. In addition, a single specimen of *Globorotalia truncatulinoides* was found for the first time.

A similar assemblage, also with rare *G. truncatulinoides*, was noted in the sample from the 220–230 cm depth interval. The next assemblage (100.0–110.0 cm depth interval) comprises very numerous *S. dehiscens* (Text-fig. 5.7), accompanied by various rare *Globigerinoides*, *Globorotalia tumida flexuosa* (Text-fig. 5.3), *Neogloboquadrina humerosa* (Text-fig. 5.10), *Globorotalia crassaformis* (Text-fig. 5.14) and *G. truncatulinoides* (Text-fig. 5.20).

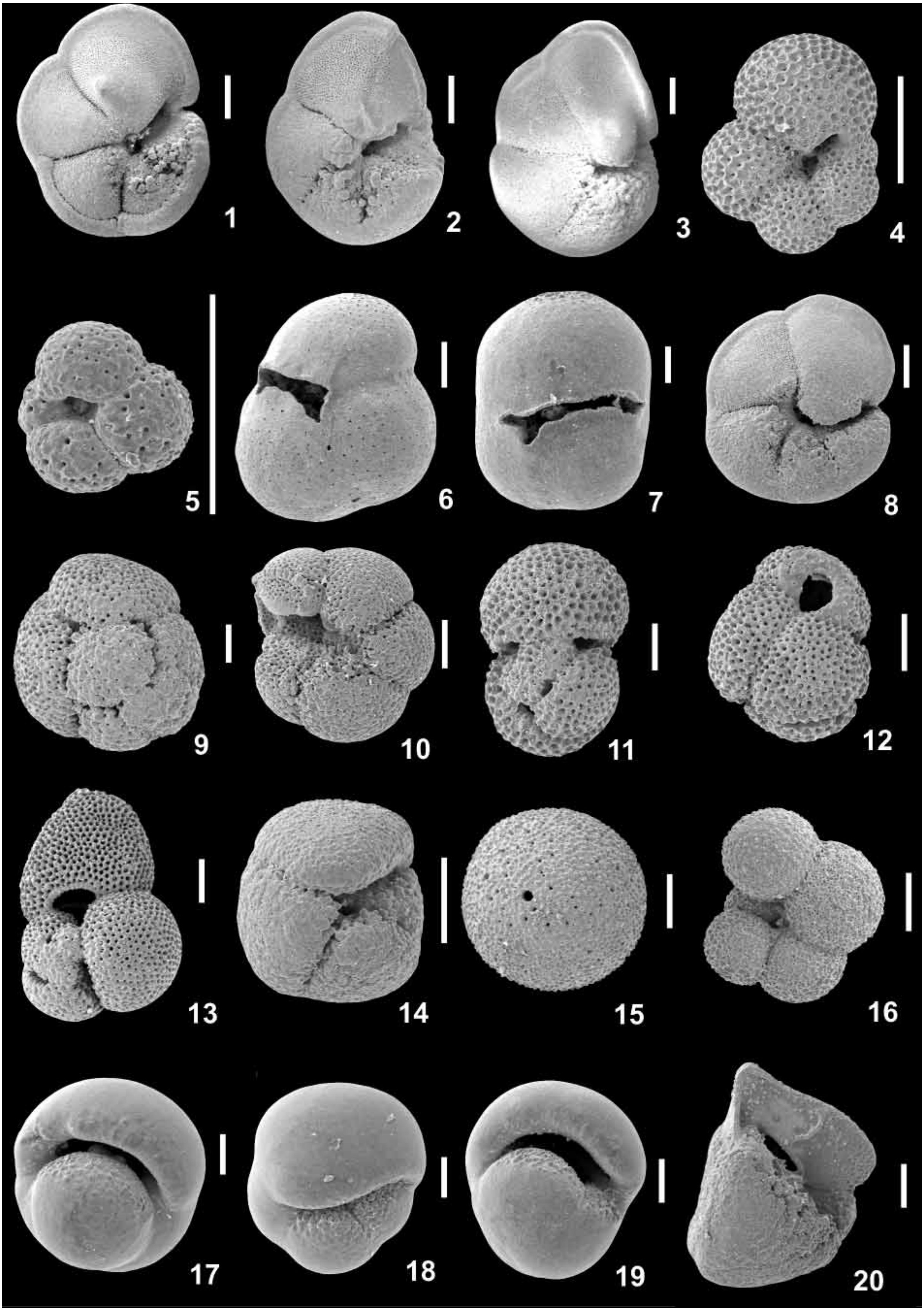
The number of foraminiferal species increases in the samples from the 20–90 cm depth interval. These samples are dominated by *Sphaeroidinella dehiscens*, but *Globigerinoides sacculiferus* (Text-fig. 5.13), *G. immaturus* (Text-fig. 5.11), *G. conglobatus*, *Pulleniatina finalis* (Text-fig. 5.17), as well as *Neogloboquadrina humerosa* and *Globorotalia tumida* are also quite common. The abundance of *Globorotalia truncatulinoides* increases systematically towards the youngest sample.

The sample from the 0.0–0.5 cm depth interval is characterized by a high abundance of *G. truncatulinoides*. This youngest sample also contains *Globorotalia menardii* (Text-fig. 5.1), *Globorotalia tumida*, *Globigerinoides elongatus* (Text-fig. 5.12), *Globigerinoides immaturus*, *Pulleniatina finalis*, *Pulleniatina primalis* (Text-fig. 5.18), *Pulleniatina obliquiloculata* (Text-fig. 5.19), *Neogloboquadrina dutertrei* and *Orbulina universa* (Text-fig. 5.15). There are also numerous transitional forms between *Globigerinella siphonifera* (Text-fig. 5.16) and *Globigerinella aequilateralis*. Concurrently *Sphaeroidinella dehiscens* becomes less numerous, disappearing in the youngest sample. The youngest assemblage (0.0–0.5 cm) also contains *Globorotalia tumida flexuosa*, which became extinct in the Middle Pleistocene, and a form close to *S. dehiscens excavata*, which occurred first in the Middle–Late Pleistocene. The Pleistocene is often characterized by mass occurrences of *Pulleniatina finalis* (Text-figs 5.17) and *P. obliquiloculata* (Text-figs 5.19) (BOLLI & al., 1985), both of which were noted at the top of the section.

DISCUSSION

The sediments from core 4SL are different from sediments adjacent to the island, not only with

Fig. 5 Foraminifera species, core 4SL. 1. *Globorotalia menardii* (PARKER, JONES & BRADY), 100.0–110.0 cm, (Early Pleistocene) 2. *Globorotalia tumida* (BRADY), 260.0–265.0 cm, (Late Pliocene) 3. *Globorotalia flexuosa* (KOCH); 100.0–110.0 cm, (Early Pleistocene) 4. *Globigerinella obesa* (BOLLI), 460.0–465.0 cm, (Early Pliocene) 5. *Globoturborotalia decoraperta* (TAKAYAGI & SAITO), 500.0–505.0 cm, (Early Pliocene) 6. *Sphaeroidinellopsis seminulina* (SCHWAGER), 460.0–465.0 cm, (Early Pliocene) 7. *Sphaeroidinella dehiscens* (PARKER & JONES), 100.0–110.0 cm, (Early Pleistocene) 8. *Globorotalia exilis* BRADY, 400.0–405.0 cm, (Middle Pliocene) 9. *Globigerinoides conglobatus* (BRADY); 260.0–265.0 cm, (Late Pliocene) 10. *Neogloboquadrina humerosa* (TAKAYAGI & SAITO), 100.0–110.0 cm, (Early Pleistocene) 11. *Globigerinoides immaturus* LE ROY, 80.0–90.0 cm, (Early Pleistocene) 12. *Globigerinoides elongatus* (D`ORBIGNY), 0.0–0.5 cm, (Early/Middle Pleistocene) 13. *Globigerinoides sacculifer* (BRADY), 80.0–90.0 cm, (Early Pleistocene) 14. *Globorotalia crassaformis* (GALLOWAY & WISSLER), 100.0–110.0 cm, (Early Pleistocene). 15. *Orbulina universa* D`ORBIGNY, 0.0–5.0 cm, (Early/Middle Pleistocene) 16. *Globigerinella siphonifera* (D`ORBIGNY), 0.0–0.5 cm, (Early/Middle Pleistocene). 17. *Pulleniatina finalis* BANNER & BLOW, 80.0–90.0 cm, (Early Pleistocene) 18. *Pulleniatina primalis* BANNER & BLOW, 0.0–5.0 cm, (Early/Middle Pleistocene) 19. *Pulleniatina obliquiloculata* (PARKER & JONES), 0.0–5.0 cm, (Early/Middle Pleistocene). 20. *Globorotalia truncatulinoides* (D`ORBIGNY), 100–110.0 cm, (Early Pleistocene). Scale bar is 0.25 mm.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respect to the micro- and nannofossils, but also with respect to the occurrence of manganese-ferric concretions. A gradual disappearance of Mn and Fe from the centre to the edges of the concretion and diffused borders with the sediment indicate their *in situ* origin. As suggested by PIPER & BLUEFORD (1982), they formed apparently at a similar rate to the sedimentation rate. These sediments were formed under conditions of pelagic sedimentation, and so the low sedimentation rate facilitated the formation of concretions.

In the western part of the Indian Ocean, smectite constitutes 70% of the clay fraction of bottom sediments (KOLLA & BISCAYE 1977); in the surface sediments adjacent to Réunion Island, smectite comprises 100% of the clay fraction. Both KOLLA & *al.* (1976) and PHILIPPOT (1984) suggested that smectite on the island originated as a result of hydrothermal processes. However, the smectite present in the sediments studied resulted more probably from the alteration of basaltic rocks that form Réunion Island (e.g. ZEVENBERGER & *al.* 1996).

Kaolinite was found only in core 4SL. It is a mineral of detrital origin and can be transported over large distances. In the core, kaolinite accompanies nannoflora and was found in an interval at the Pliocene–Pleistocene boundary. The upper part of core 4SL contains mainly smectite and only a small quantity of kaolinite. Other Pleistocene and Holocene sediments around the island contain only smectite in the clay fraction (DUCZMAL-CZERNIKIEWICZ & *al.* 2003). The kaolinite probably originated from weathered rocks of Western Africa or Australia (KOLLA & *al.* 1976; GRIFFIN & *al.* 1968; GOLDBERG & GRIFFIN 1970) and may indicate warm, humid climatic conditions in the Pliocene of the Southern Ocean. The youngest smectite-rich sediments indicate much cooler conditions than in the Pliocene.

Nannoflora and microfauna are represented by partly redeposited or transported and crushed calcareous skeletons and tests. The sediments investigated contain very abundant calcareous nannoplankton, especially various *Discoaster* species. They are usually well preserved, but some mechanical damage is seen in the form of crushed arms. The other species indicate a small degree of recrystallization or dissolution, with the exception of the *Ceratolithus* species, mainly *C. rugosus*, which underwent recrystallization to a striking extent.

In the Pliocene sediments, a considerable proportion of reworked nannoplankton, mainly from the Miocene, was observed. In the Pleistocene sediments, reworked older forms were not found. Sediments represented by the NN17 and NN18 zones contained a considerable amount of reworked older materials. Although *Discoaster* species normally occur in smaller quantities at the end of the Pliocene, this genus represents about 90% of the nannoplankton association in the sediments investigated. A considerable part of them constitutes the Miocene species *D. variabilis, D. bellus, D. blackstockae, D. berggrenii and D. quinqueramus.*

The Pliocene–Pleistocene boundary is marked by the LO of *D. brouweri* TAN SIN HOK. The LO of *D. brouweri* is often difficult to fix due to redeposition, especially in poorly consolidated sediments. The LO of *Calcidiscus macintyrei* is usually lower than the LO of *D. brouweri*. Small forms of Prinsiaceae and also *Helicosphaera kamptneri, Helicosphaera sellii*, *Pontosphaera japonica* and *Pontosphaera scutellum* dominate the Pleistocene sediments.

The sequence of foraminifers was correlated with the calcareous nannoplankton zonation. The character and preservation of foraminifers and calcareous nanoplankton are similar. Thick-walled, dissolution-resistant types (JENKINS & ORR 1971; 1972) belonging to the genera *Globorotalia*, *Pulleniatina*, *Sphaeroidinellopsis*-*Sphaeridinella* and *Neogloboquadrina* are dominant. However, dissolution-susceptible species of *Globigerinoides* (frequent) and *Orbulina* (rare) were also found. In addition, reworked Miocene and Early Pliocene foraminifers also occur.

Foraminiferal assemblages belonging to the Pliocene, partly Early Pliocene (460.0–505.0 cm depth interval) and Middle–Late Pliocene (400.0–405.0 cm depth interval) were found in the samples studied. The sample from the 260.0–265.0 cm depth interval was dated as Late Pliocene, whereas the sample from the 220.0–230.0 cm depth interval corresponds to the Pliocene–Pleistocene boundary. The assemblages from the 100.0–110.0 cm and 80.0–90.0 cm depth intervals are of Early Pleistocene age. In the 220.0–230.0 cm, 100.0–110.0 cm and 80.0–90.0 cm depth intervals, the assemblages represent an Early Pleistocene age. A mass occurrence of *Globorotalia truncatulinoides* (acme zone) was noted in the 5.0–50.0 cm depth interval. The Early/Middle Pleistocene assemblages occurred in the 0.0–5.0 cm interval below the sea floor.

The transition interval between the *G. margaritae* and *G. evoluta* zones, which corresponds to the LO of *Globorotalia menardii* "A" (BOLLI & *al*. 1985) and the FO of *Sphaeroidinella dehiscens* was found in the 460.0–465.0 cm depth interval. The *Sphaeroidinella* event from the mid-Pliocene (KU_ERA 1998) can be recorded between these two depth intervals.

In foraminiferal terms, the Pliocene–Pleistocene boundary coincides with the FO of *Globorotalia truncatulinoides*. In the nannofossil scheme, this level approximates to the LO of *Discoaster brouweri* (BOLLI & *al.* 1985), which marks the boundary between the NN18 and NN19 zones (MARTINI 1971). It appears, however, that in the Indo-Pacific the FO of *G. truncatulinoides* is diachronous (HILLS & THIERSTEIN, 1989); whereas in the equatorial zone its FO corresponds to the Pliocene–Pleistocene boundary, in the subtropical zone, including the study area, its FO is observed in the Late Pliocene. In the material studied, *G. truncatulinoides* was first noted in the 260.0–265.0 cm depth interval, and the LO of *D. brouweri* in the sample from the 230.0–220.0 cm depth interval.

PALEOGEOGRAPHICAL AND PALEOCLIMATIC REMARKS

The coccolithophorids do not give a clear indication of depth of deposition of the sediments in which they are found, nevertheless some rare cases are worth mentioning. OKADA & HONJO (1975) found *Gephyrocapsa oceanica* dominating the flora in shallow marginal seas and inland seas. Small Prinsiaceae of the genera *Emiliania* and *Gephyrocapsa* generally dominate oceanic assemblages, with the exception of tropical areas, where various other species reach high abundances. Instead, Recent and Pleistocene coccoliths are good palaeotemperature indicators (MCINTYRE & BÉ 1967). The genus *Scyphosphaera* is considered a warm water genus, however, it is not solution resistant. To the "warm water taxa" also belong selected species of the genus *Discoaster* (*D. brouweri*, *D. surculus* and *D. pentaradiatus*).

The Pliocene and Pleistocene foraminiferal assemblages are composed of species that have a worldwide distribution (*Globorotalia plesiotumida-tumida-tumida flexuosa* group) and others (*G. multicamerata*, *G. exilis*, *O. universa*, *O. suturalis*) that remained largely restricted to the Atlantic Province. The genus *Globigerinoides*, represented by a number of species in the samples studied, is of considerable significance both in low and in mid-latitudes.

Other species of the genera *Sphaeroidinellopsis-Sphaeridinella* and *Pulleniatina* have different stratigraphical position in the Atlantic and the Indo-Pacific provinces. *Pulleniatina* is the most temperature sensitive planktonic genus, largely confined to tropical and subtropical waters (BOLLI & al. 1985). Forms belonging to this genus became more important component of the Pleistocene foraminiferal assemblages, dominated by *Globorotalia truncatulinoides*.

CONCLUSIONS

1. The pelagic calcareous oozes investigated in this study consist mostly of biogenic components: nanno- and microfossils. Volcanogenic components are less abundant. The pelitic fraction is dominated by clay minerals such as kaolinite and smectite. The occurrence of kaolinite together with Mn–Fe concretions in the Pliocene sediments from the core 4SL differentiate these sediments from the hemipelagic muds closest to Réunion Island. Pleistocene sediments are rich in smectite, which indicates colder climatic conditions then in the Pliocene.

2. In the lower part of core 4SL, mixed Pliocene and Miocene nannoplankton species were found (at the depth of 465 to 290 cm below sea floor). This interval referred to the NN17 nannoplankton Zone ranges from the LO of *Discoaster surculus* to the LO of *Discoaster pentaradiatus*. This nannoplankton zone corresponds to the Early Pliocene foraminiferal assemblages with *Globorotalia menardii "A"*, found in the 505-460 cm depth interval.

3. Climatic changes within the Pleistocene caused by glacial period are expressed by the occurrence of colder water faunal associations. The Pliocene–Pleistocene boundary is placed in the 220–230 cm depth interval, close to the level of the LO of *Discoaster brouweri*. Microfossils from sediments overlaying these intervals belong to the Pleistocene.

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