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The Maastrichtian and early Tertiary record of the Great Australian Bight Basin and its onshore equivalents on the Australian southern margin: a nannofossil study

Samir Shafik[1]

Samples dredged during BMR Survey 66 by R.V. *Rig Seismic* in the central Great Australian Bight Basin are examined and their calcareous nannofossils are recorded. The Maastrichtian, Eocene and Oligocene assemblages are compared with those known from the onshore southern Australian sequence, allowing a better understanding of the history of the southern margin of Australia. The Maastrichtian assemblages, the first found in southern Australia, probably represent a marine ingression encompassing three discernible phases. The Eocene record includes assemblages older than any from onshore and is also older than the base of the Eocene section on the Naturaliste Plateau. An offset parallelism with the onshore record is evident: in the offshore (Great Australian Bight) sequence, early Eocene ingressions preceded a middle Eocene transgression, while in the onshore Otway Basin (to the east) middle Eocene ingressions preceded a late Eocene transgression. In both sequences there are earlier Tertiary ingressions which were suited for calcareous foraminiferids but apparently not coccolith-forming nannoplankton. The previously reported excursion of the low-latitude *Sphenolithus ciperoensis* into southern Australia in the Oligocene is confirmed, being a result of a 'short' warm episode. Surface waters along the southern margin of Australia were warmer in the west than in the east during much of the Eocene and Oligocene. This is attributed to a warm intermittent 'proto-Leeuwin Current', beginning in the middle Eocene, which brought warm surface waters from northwestern Australia into southern Australia. Dilution of the current's effects on the surface waters of southern Australia would be expected in an easterly direction. Nannofossil evidence, supported by palynological and lithological data, suggests that the seafloor in the Great Australian Bight Basin has subsided considerably since the Late Cretaceous. The onset of the increase in rate of subsidence in the middle Eocene (as reflected by the nannofossil assemblages) marked the end of a stage of very slow subsidence initiated at about 90 Ma ago. The assemblages provide strong evidence for a marked fall in sea level during the latest late Eocene, at a rate considerably higher than that of subsidence, resulting in shoaling well into the Oligocene.

Introduction

Optical microscopic examination of calcareous nannofossils extracted from samples dredged during BMR Survey 66 by R.V. *Rig Seismic* in the central Great Australian Bight Basin (Fig. 1) was carried out primarily for dating (Shafik, 1988a,b). Only the better preserved and less reworked assemblages are considered here. These are Maastrichtian, Eocene and Oligocene, and include assemblages previously unknown from southern Australia. These assemblages, arranged in a chronological order, together with a hitherto unknown Eocene assemblage from Potoroo No.1 well (Fig. 1), help reveal the history of marine sedimentation during the Eocene in the Great Australian Bight Basin. Previously, the temporal distribution of calcareous nannofossil assemblages in the Eocene of the onshore southern margin (Eucla and Otway Basins) was used by Shafik (1973, 1983, 1985) to indicate patterns of marine sedimentation which could be translated in terms of marine ingressions and transgressions. The term 'ingression' is used to denote a short-lived marine invasion, with either good or restricted access to the open sea. Isolated calcareous microplanktic assemblages (nannofossils and/or foraminiferids) bracketed by barren intervals in the middle Eocene of the Otway Basin are used to indicate such marine ingressions.

The distribution of modern nannoplankton seems to be primarily controlled by temperature (see, for example, McIntyre & Bé, 1967; Okada & Honjo, 1973; Ruddiman & McIntyre, 1976), although the supply of nutrients is an equally important factor. Thus, indications of palaeotemperatures of surface waters during earlier times (e.g. Late Cretaceous and Tertiary) could be based on the presence of certain key taxa whose known geographic distribution suggests narrow latitudinal preference. The presence of a species whose geographic distribution is largely limited to the tropics, for example, would indicate warm surface waters or location within the tropical belt.

Lithologically, the samples studied reflect conditions transitional from non-marine or marginal marine terrigenous sedimentation during most of the Maastrichtian–mid-Eocene interval, to marine carbonate accumulation during the middle Eocene and onward.

During BMR Survey 66, several submarine canyons were identified cutting into the continental slope of the Great Australian Bight. Because most of these have not been named, letters of the alphabet have been used to differentiate them. Sampling sites in the canyons are indicated in Figure 1, which also shows the seafloor morphology of the Great Australian Bight Basin as a wide continental shelf with gently sloping terraces extending from the shelf edge.

Documentation of dredged assemblages

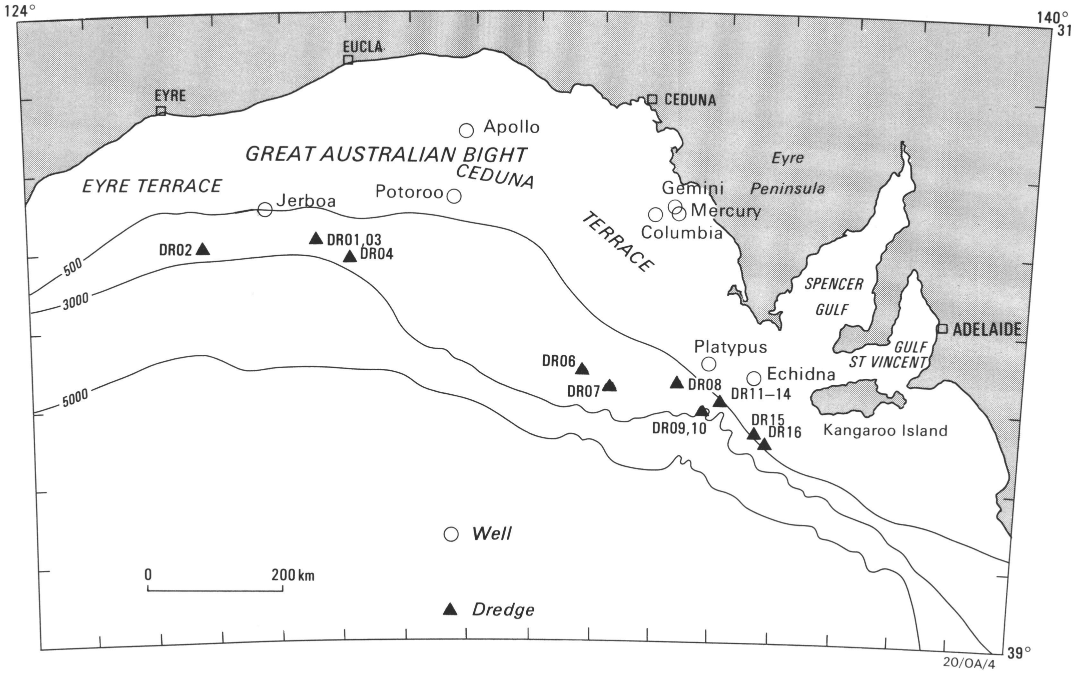
Most of the species identified in this study are illustrated in Figures 2–7. Their negatives are deposited in the Commonwealth Palaeontological Collection (CPC), Bureau of Mineral Resources, Canberra. The Eocene assemblages examined are placed against a set of nannofossil biostratigraphic events (Fig. 8), rather than against a particular formal nannofossil zonal scheme. This permits the use of nannofossil biostratigraphic events not restricted to one zonation. Thus the practice of describing a 'suitable' zonation based on more than one published zonation is not favoured here. Correlation with the low-latitude planktic foraminiferal P zones of Berggren (1969) and Blow (1969, 1979) is attempted wherever possible, in common with established local foraminiferal practice (see, for example, McGowran, 1978, 1988a,b).

Figure 8 also summarises sequences on the Naturaliste Plateau and on the onshore southern margin of Australia (the Eucla and Otway Basins) as based on the work of Shafik (1983, 1985).

Maastrichtian

Siliciclastic sediments of this age were dredged from two stations, 66DR01 and 66DR03, at the northwestern wall of Canyon B which is located at the junction of the Eyre and Ceduna Terraces (Fig. 1). Three assemblages (A, B and C, below) were recognised.

[1] Marine Geoscience & Petroleum Geology Program, Bureau of Mineral Resources, GPO Box 378, Canberra ACT 2601



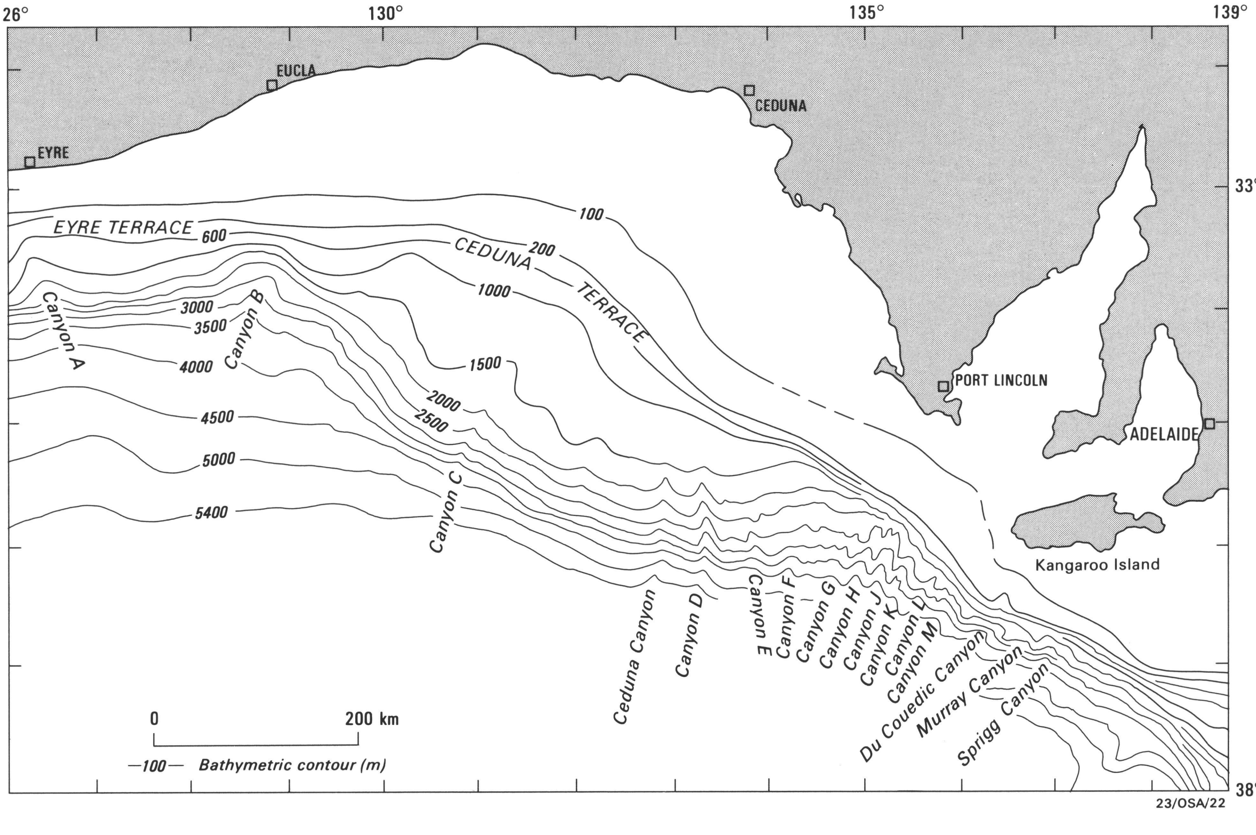


Figure 1. Location map, showing the canyons dredged during R.V. *Rig Seismic* BMR Survey 66.

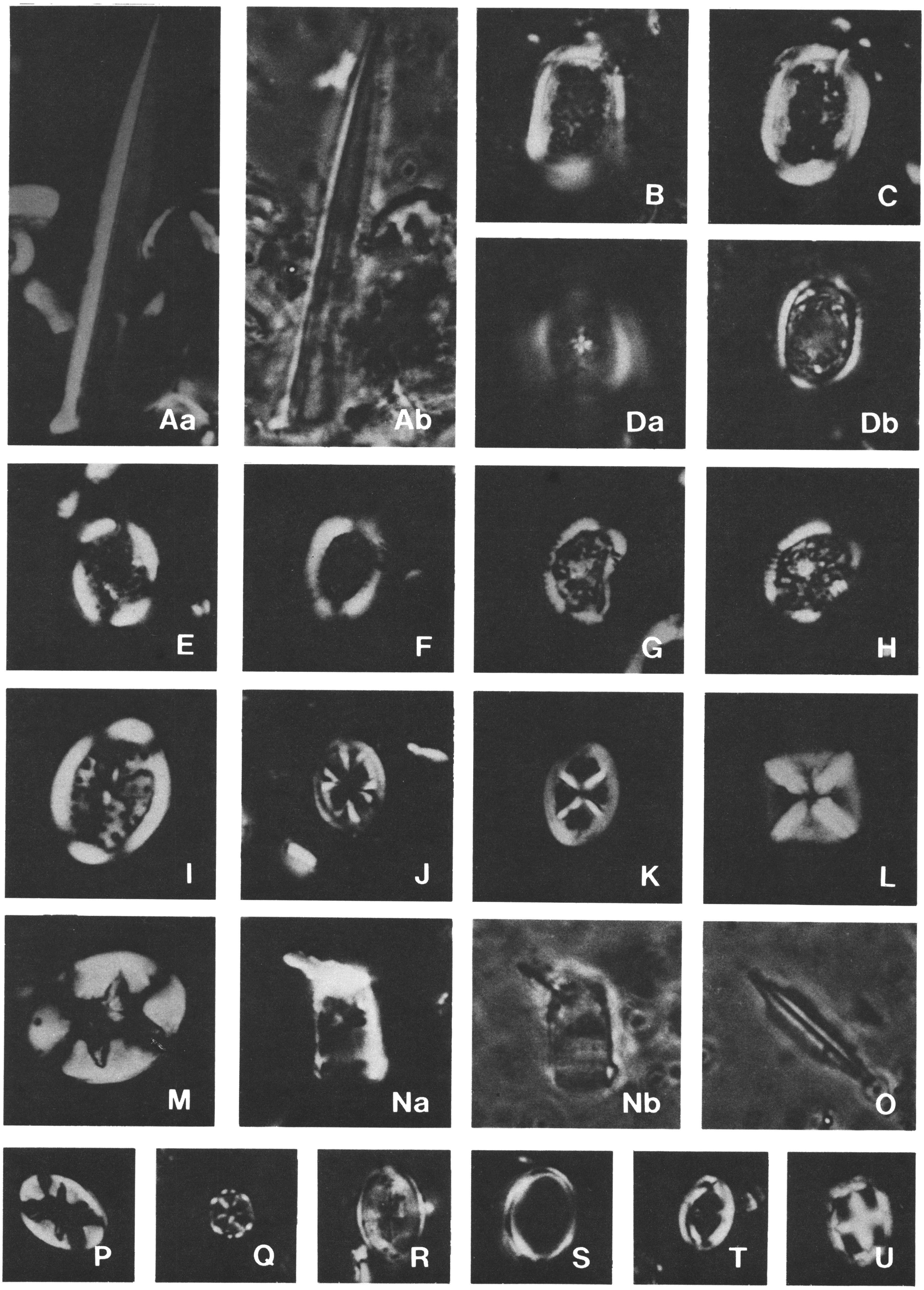


Figure 2. Optical microscopic micrographs of Maastrichtian nannofossils from Canyon B in the central Great Australian Bight Basin. Except for specimen I, which is from 66DR01F, all specimens are from 66DR03A.

Aa, Ab, *Lucianorhabdus* sp. cf. *L. cayeuxii* Deflandre, CPC 28615; **B, C**, *Cribrosphaerella daniae* Perch-Nielsen, B, CPC 28616, C, CPC 28617; **Da, Db**, *Nephrolithus corystus* Wise with two parallel sides, CPC 28618; **E**, *Teichorhabdus ethmos* Wind & Wise, CPC 28619; **F**, *Grantarhabdus camaratus* (Bukry), CPC 28732; **G, H**, *Nephrolithus corystus* Wise (kidney-shaped), G, CPC 28620, H, CPC 28621; **I**, *Arkhangelskiella speciallata* Vekshina, CPC 28634; **J**, *Ahmuellerella octoradiata* (Gorka), CPC 28622; **K**, *Chiastozygus litterarius* (Gorka), CPC 28623; **L**, *Micula staurophora* (Gardet), CPC 28624; **M, P**, *Eiffellithus turriseiffeli* (Deflandre), M, CPC 28625, P, CPC 28626; **Na, Nb**, *Lapideacassis cornuta* (Forchheimer & Stradner), CPC 28627; **O**, *Lithraphidites praequadratus* Roth, CPC 28628; **Q**, *Corollithion exiguum* Stradner, CPC 28629; **R**, *Gartnerago* sp., CPC 28630; **S**, *Kamptnerius magnificus* Deflandre with its asymmetric rim flange preserved but not its central cover, CPC 28631; **T**, *Placozygus fibuliformis* (Reinhardt), CPC 28632; **U**, *Prediscosphaera spinosa* (Bramlette & Martini), CPC 28633. All specimens ×2000.

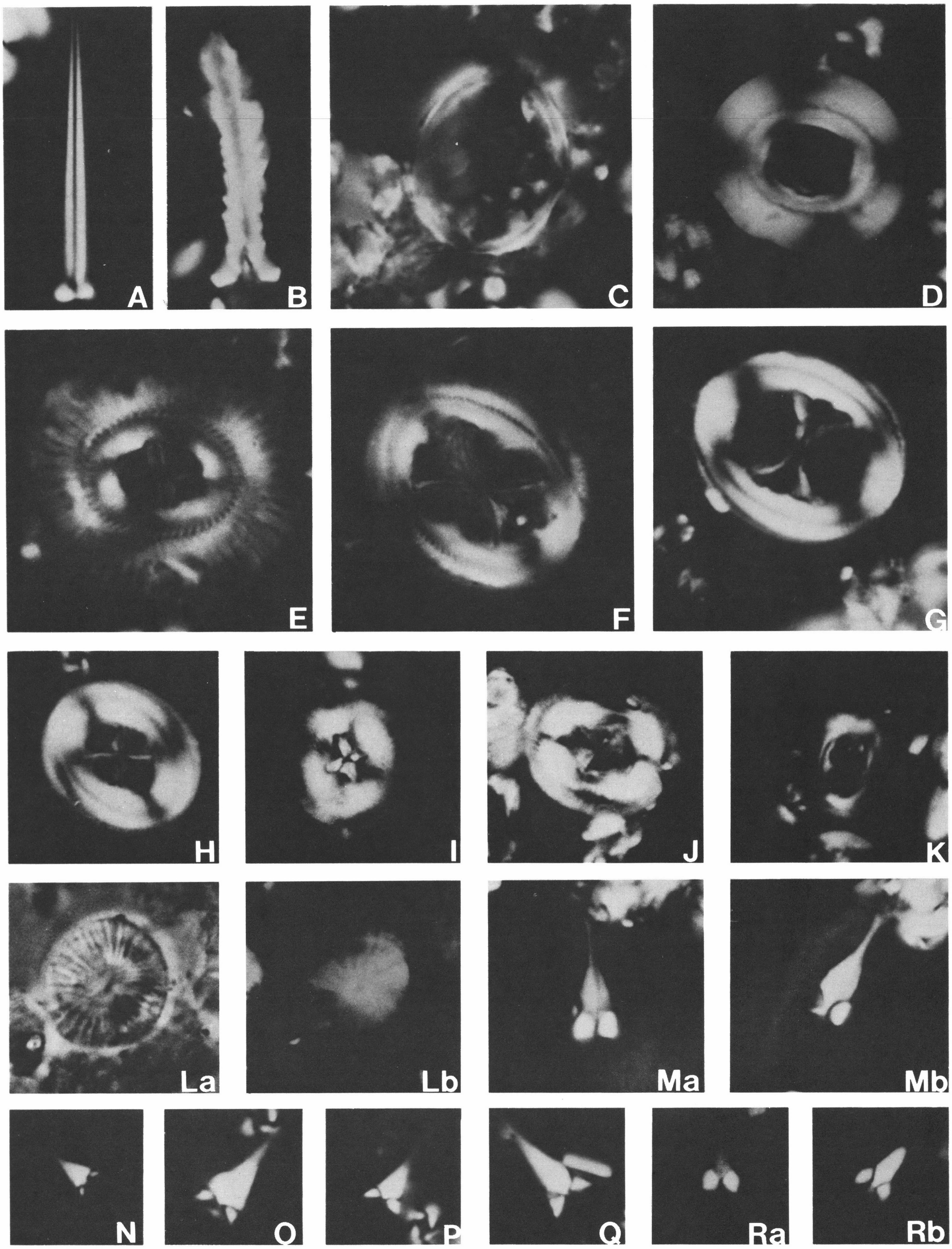


Figure 3. Optical microscopic micrographs of nannofossil taxa from the Eocene of Potoroo No.1 well and Eocene–Oligocene dredges in the central Great Australian Bight Basin.

A, *Blackites tenuis* (Bramlette & Sullivan), CPC 28641 from 66DR14B; **B**, *Zygrhablithus bijugatus bijugatus* (Deflandre), CPC 28642 from 66DR14B; **C**, *Reticulofenestra oamaruensis* (Deflandre), CPC 28643 from 66DR14B; **D**, *Reticulofenestra umbilica* (Levin), CPC 2864 from 66DR14A(5); **E**, *Chiasmolithus gigas* (Bramlette & Sullivan), CPC 28645 from 66DR01D; **F**, *Chiasmolithus grandis* (Bramlette & Riedel), CPC 28646 from 66DR01D; **G**, *Chiasmolithus oamaruensis* (Deflandre), CPC 28647 from 66DR01A; **H**, *Chiasmolithus altus* Bukry & Percival, CPC 28648 from 66DR06B; **I**, *Chiasmolithus consuetus* (Bramlette & Sullivan), CPC 28649 from 66DR08A; **J**, *Chiasmolithus solitus* (Bramlette & Sullivan), CPC 28650 from 66DR08A; **K**, *Campylosphaera dela* (Bramlette & Sullivan), CPC 28651 from 66DR08A; **La, Lb**, *Striatococcolithus pacificanus* Bukry & Percival, CPC 28652 from Potoroo No.1 at 945.5 m; **Ma, Mb, Ra, Rb**, *Sphenolithus ciperoensis* Bramlette & Wilcoxon, M, CPC 28635, R, CPC 28636, both from 66DR06B; **N, O**, *Sphenolithus predistentus* Bramlette & Wilcoxon, N, CPC 28637, O, CPC 28638, both from 66DR12B; **P, Q**, *Sphenolithus distentus* Bramlette & Wilcoxon, P, CPC 28639, Q, CPC 28640, both from 66DR12B. All specimens ×2000.

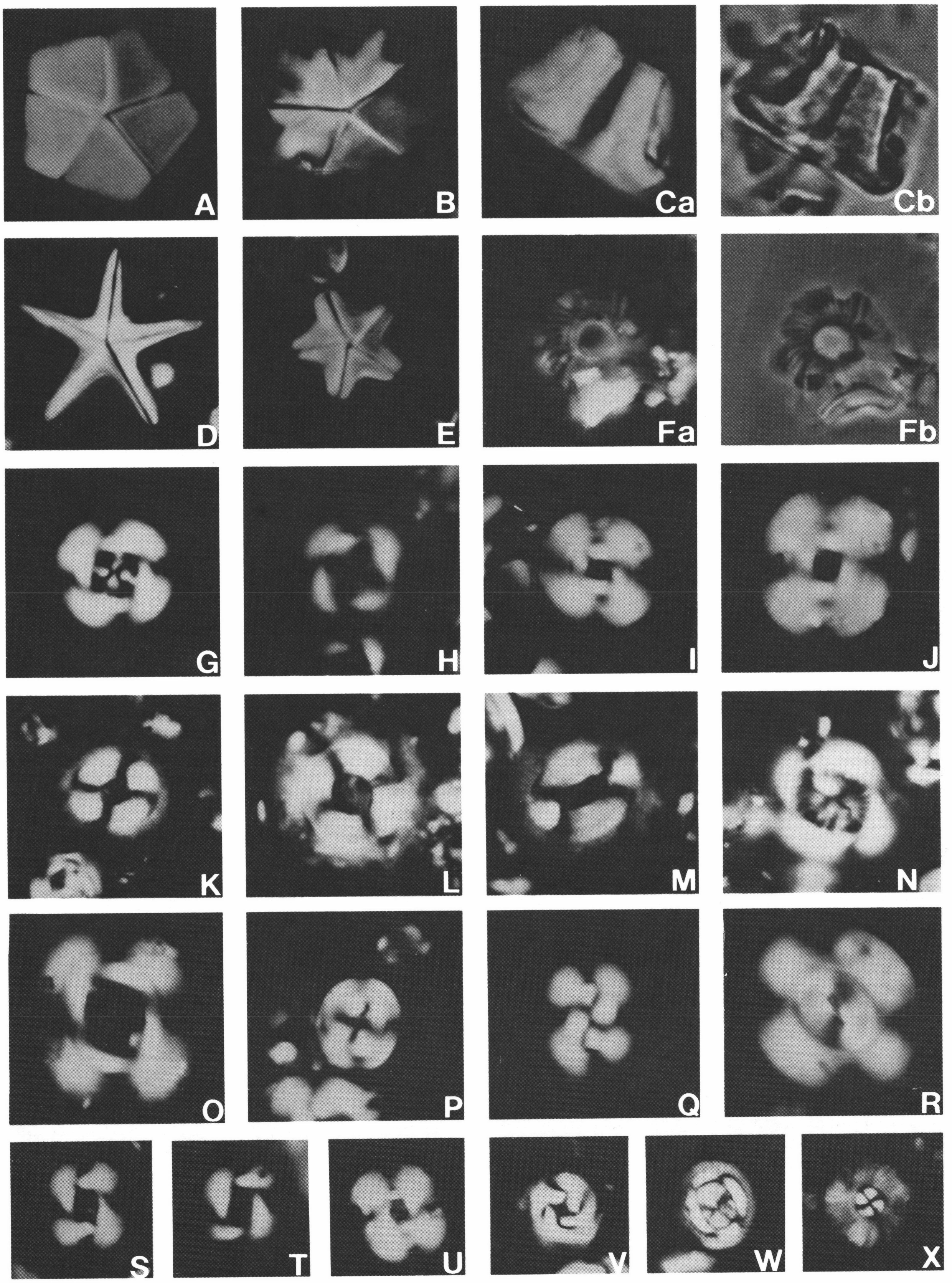


Figure 4. Optical microscopic micrographs of nannofossil taxa from the Eocene of Potoroo No.1 well, and Eocene–Oligocene dredges in the central Great Australian Bight Basin.

A, *Braarudosphaera bigelowii* (Gran & Braarud), CPC 28653 from Potoroo No.1 at 945.5 m; **B**, *Micrantholithus bramlettei* Deflandre, CPC 28654 from Potoroo No.1 at 945.5 m; **Ca, Cb**, *Micrantholithus altus* Bybell & Gartner, CPC 28655 from Potoroo No.1 at 945.5 m; **D**, *Micrantholithus attenuatus* Bramlette & Sullivan, CPC 28656 from Potoroo No.1 at 945.5; **E**, *Micrantholithus pinguis* Bramlette & Sullivan, CPC 28657 from Potoroo No.1 at 945.5 m; **Fa, Fb**, *Pedinocyclus larvalis* (Bukry & Bramlette), CPC 28658 from 66DR14B; **G, H**, *Cyclicargolithus reticulatus* (Gartner & Smith), G, CPC 28659 from 66DR01A, H, CPC 28660 from 66DR14A(5); **I, J**, *Cyclicargolithus abisectus* (Müller), I, CPC 28661, J, CPC 28662, both from 66DR06B; **K, L**, *Coccolithus formosus* (Kamptner), K, CPC 28663, L, CPC 28664, both from 66DR14B; **M**, *Coccolithus eopelagicus* (Bramlette & Riedel), CPC 28665 from 66DR01A; **N**, *Reticulofenestra hampdenensis* Edwards, CPC 28666 from 66DR14D; **O**, *Reticulofenestra umbilica* (Levin), CPC 28667 from 66DR14B; **P**, *Reticulofenestra orangensis* (Bukry) n. comb., CPC 28668 from 66DR01A; **Q**, *Reticulofenestra scrippsae* (Bukry & Percival), CPC 28669 from 66DR01A; **R**, *Reticulofenestra scissura* Hay & others, CPC 28670 from 66DR12B; **S, T**, *Reticulofenestra dictyoda* (Deflandre & Fert), S, CPC 28671, T, CPC 28672, both from Potoroo No.1 at 945.5 m; **U**, *Cyclicargolithus floridanus* (Roth & Hay), CPC 28673 from 66DR06B; **V**, *Cyclicargolithus gammation* (Bramlette & Sullivan), CPC 28675 from 66DR08A; **W**, *Clausicoccus cribellum* (Bramlette & Sullivan), CPC 28674 from 66DR06B; **X**, *Markalius* sp. transitional between *M. astroporus* (Stradner) and *M. inversus* (Deflandre), CPC 28676 from 66DR08A. All specimens ×2000.

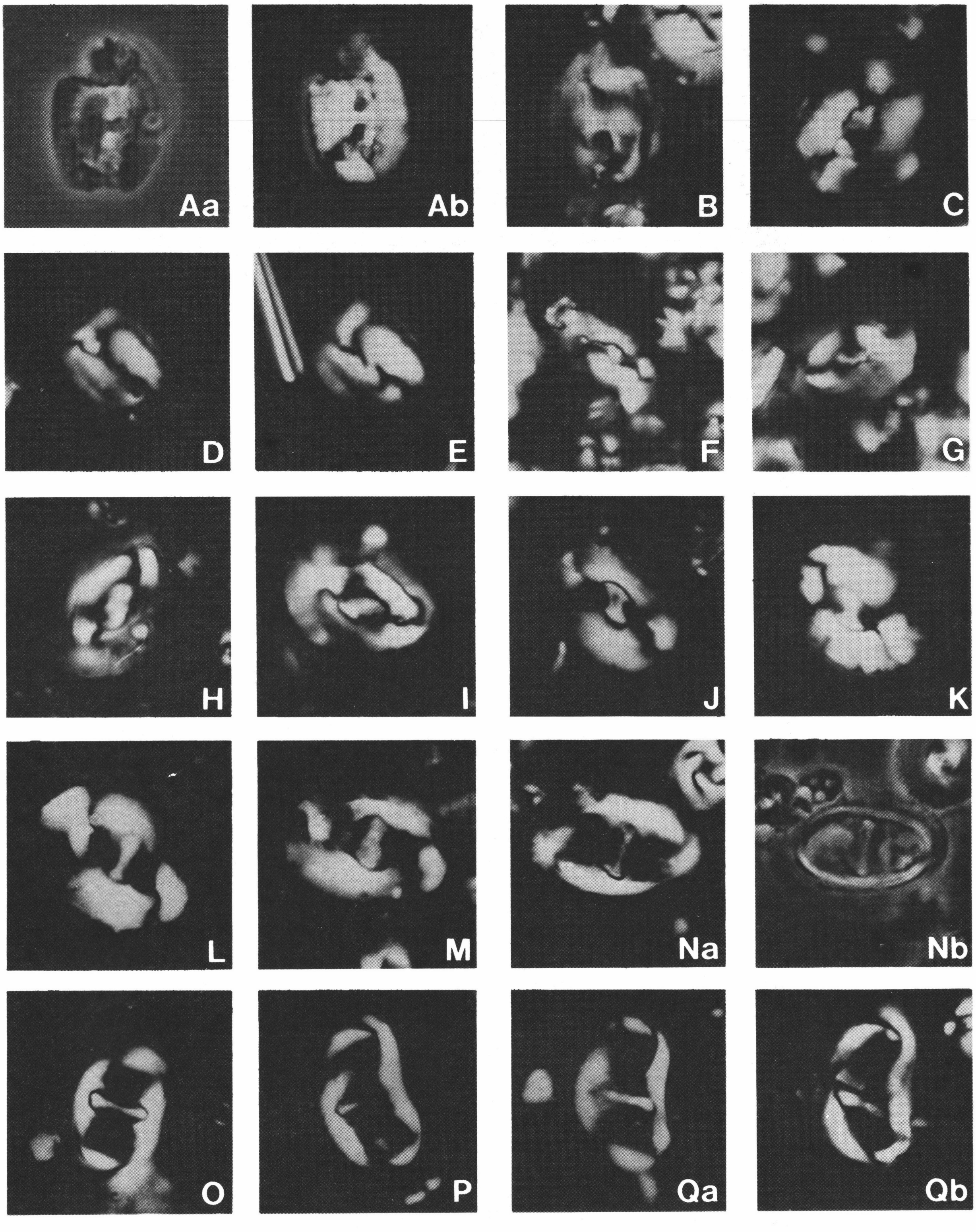


Figure 5. Optical microscopic micrographs of nannofossil taxa from the Eocene of Potoroo No.1 well and Eocene-Oligocene dredges in the central Great Australian Bight Basin.

Aa-B, *Helicosphaera recta* (Haq), A, CPC 28677, B, CPC 28678, both from 66DR06B; **C**, *Helicosphaera euphratis* Haq, CPC 28679 from 66DR06B; **D, E**, *Helicosphaera obliqua* Bramlette & Wilcoxon, D, CPC 28680, E, CPC 28681, both from 66DR12B; **F**, *Helicosphaera* sp., CPC 28682 from 66DR12B; **G**, *Helicosphaera heezenii* (Bukry), CPC 28683 from 66DR14A(5); **H, I**, *Helicosphaera* sp. aff. *H. reticulata* Bramlette & Wilcoxon, H, CPC 28684, I, CPC 28685, both from 66DR14A(5); **J, K**, *Helicosphaera* sp. cf. *H. bramlettei* (Müller) Jafar & Perch-Nielsen, J, CPC 28686 from 66DR10A, K, CPC 28687 from 66DR14B; **L, M**, *Helicosphaera seminulum* Bramlette & Sullivan, L, CPC 28688, M, CPC 28689, both from Potoroo No.1 at 945.5 m; **Na-O**, *Lophodolithus nascens* Bramlette & Sullivan, N, CPC 28690 from 66DR08A, O, CPC 28691 from Potoroo No.1 at 945.5 m; **P-Qb**, *Lophodolithus mochlophorus* Deflandre, P, CPC 28692 from Potoroo No.1 at 945.5 m, Q, CPC 28693 from 66DR08A. All specimens ×2000.

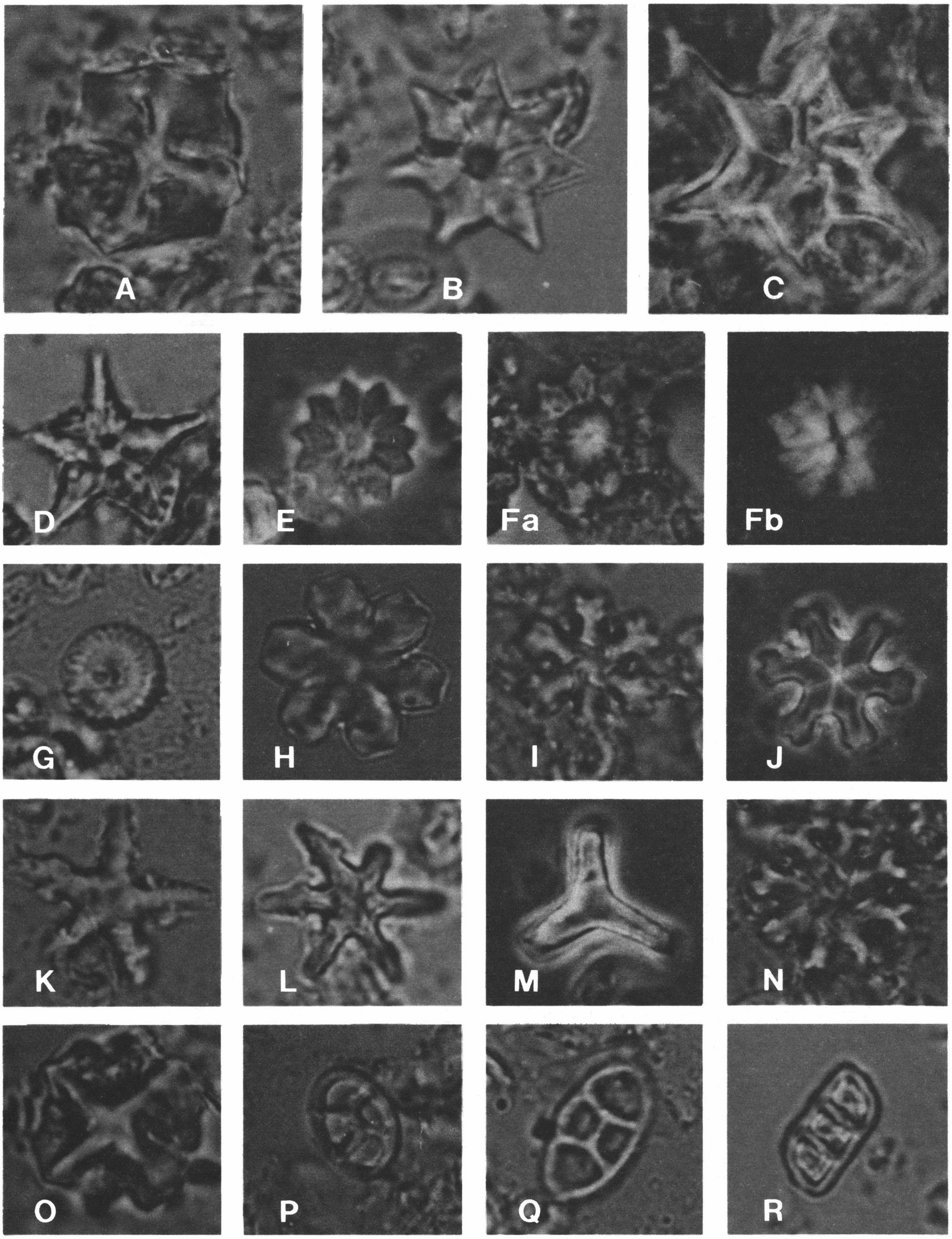


Figure 6. Optical microscopic micrographs of nannofossil taxa from the Eocene of Potoroo No.1 well and Eocene–Oligocene dredges in the central Great Australian Bight Basin.

A, O, *Nannotetrina pappi* (Stradner), A, CPC 28694, O, CPC 28695, both from 66DR01D; **B**, *Discoaster saipanensis* Bramlette & Riedel, CPC 28696 from 66DR01A; **C**, *Discoaster lodoensis* Bramlette & Riedel, CPC 28697 from Potoroo No.1 at 945.5 m; **D**, *Discoaster sublodoensis* Bramlette & Sullivan, CPC 28698 from Potoroo No.1 at 945.5 m; **E**, *Discoaster barbadiensis* Tan Sin Hok, CPC 28699 from 66DR01D; **Fa, Fb**, *Discoasteroides kuepperi* (Stradner), CPC 28700 from Potoroo No.1 at 945.5 m; **G**, *Discoaster delicatus* Bramlette & Sullivan, CPC 28701 from 66DR01D; **H–J**, *Discoaster deflandrei* Bramlette & Riedel 'group', H, CPC 28704 from 66DR06B, I, CPC 28702, J, CPC 28703, both from 66DR01D; **K, L**, *Discoaster tanii nodifer* Bramlette & Riedel, K, CPC 28705, L, CPC 28706, both from 66DR14D; **M**, *Tribrachiatus orthostylus* Shamarai, CPC 28707 from 66DR08A; **N**, *Discoaster gemmifer* Stradner, CPC 28709 from 66DR01D; **P, Q**, *Neococcolithes dubius* (Deflandre), P, CPC 28708 from 66DR08A, Q, CPC 28710 from 66DR01D; **R**, *Isthmolithus recurvus* Deflandre, CPC 28711 from 66DR14D. All specimens ×2000.

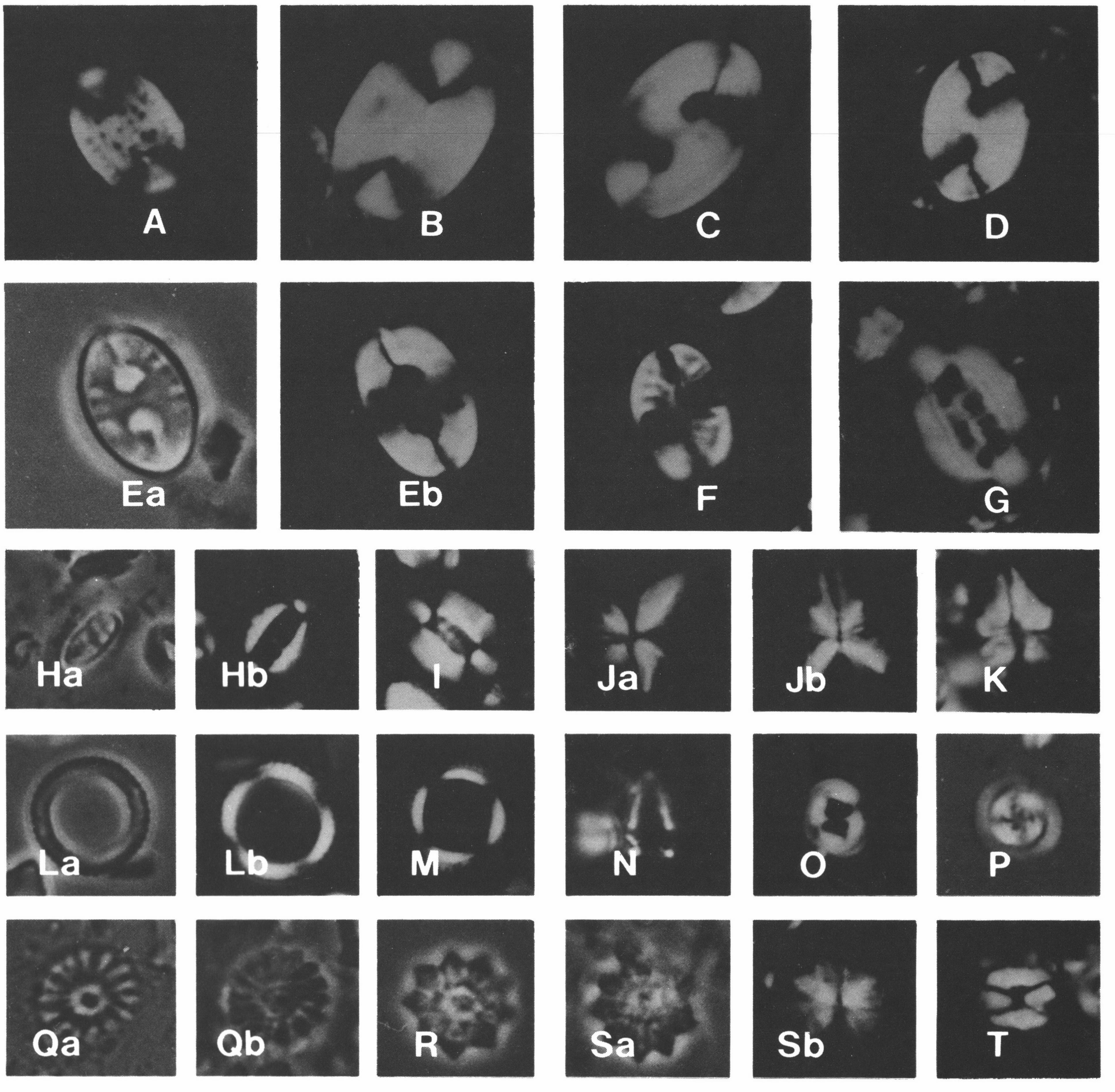


Figure 7. Optical microscopic micrographs of nannofossil taxa from the Eocene of Potoroo No.1 well and Eocene–Oligocene dredges in the central Great Australian Bight Basin.

A, *Pontosphaera multipora* (Kamptner) CPC 28712 from 66DR12B; **B**, *Pontosphaera plana* (Bramlette & Sullivan), CPC 28714 from 66DR08A; **C, D**, *Pontosphaera ocellata* (Bramlette & Sullivan), C, CPC 28713 from Potorooo No.1 at 945.5 m, D, CPC 28715 from 66DR08A; **Ea, Eb**, *Transversopontis pulcher* (Deflandre) CPC 28716 from 66DR08A; **F**, *Pontosphaera pectinata* (Bramlette & Sullivan), CPC 28717 from 66DR08A; **G–Hb**, *Ellipsolithus distichus* Bramlette & Sullivan, G, CPC 28718, H, CPC 28719 from 66DR08A; **I**, *Ellipsolithus lajollaensis* Bukry & Percival, CPC 28720 from 66DR08A; **Ja, Jb**, *Sphenolithus radians* Deflandre, CPC 28721 from Potoroo No.1 at 945.5 m; **K**, *Sphenolithus* sp., CPC 28722 from 66DR12B; **La, Lb**, *Coronocyclus nitescens* (Kamptner), CPC 28723 from 66DR06B; **M**, *Calcidiscus protoannulus* (Gartner), CPC 28724 from Potoroo No.1 at 945.5 m; **N**, *Amitha prolata* Shafik, CPC 28725 from 66DR12B; **O**, *Toweius callosus* Perch-Nielsen, CPC 28726 from Potoroo No.1 at 945.5 m; **P**, *Blackites spinulus* (Levin), CPC 28727 from 66DR12B; **Qa, Qb**, *Discoaster bifax* Bukry, CPC 28728 from 66DR01D; **R–Sb**, *Discoasteroides kuepperi* (Stradner), R, CPC 28729, S, CPC 28730, both from 66DR08A; **T**, *Lanternithus minutus* Stradner, CPC 28731 from 66DR08A. All specimens ×2000.

Assemblage A. Sample 66DR01H, a dark brown-black, highly organic silty mudstone, contained moderately preserved rare nannofossils representing a small number of taxa. This sample was collected from the same station as the highly fossiliferous sample 66DR01F (see below); at this station water depth today is 3280–2950 m. The assemblage is dominated by three species: *Arkhangelskiella speciallata, Micula staurophora* and *M. concava*. Other species represented are *Prediscosphaera cretacea* (frequent), *Markalius astroporus* (rare), *Cribrosphaerella daniae* (extremely rare), and *?Kamtpnerius magnificus* (fragment). The age is considered Maastrichtian on account of the age of the associated, and lithologically similar, sample 66DR01F (discussed below); the presence of *Cribrosphaerella daniae* supports this age assignment. This is confirmed by the co-occurring foraminiferids which are Maastrichtian in age (see McGowran, 1988).

Assemblage B. Sample 66DR03A, a glauconitic, petoidal, dark brown, organic rich silty mudstone, yielded a moderately preserved and highly diversified calcareous nannofossil

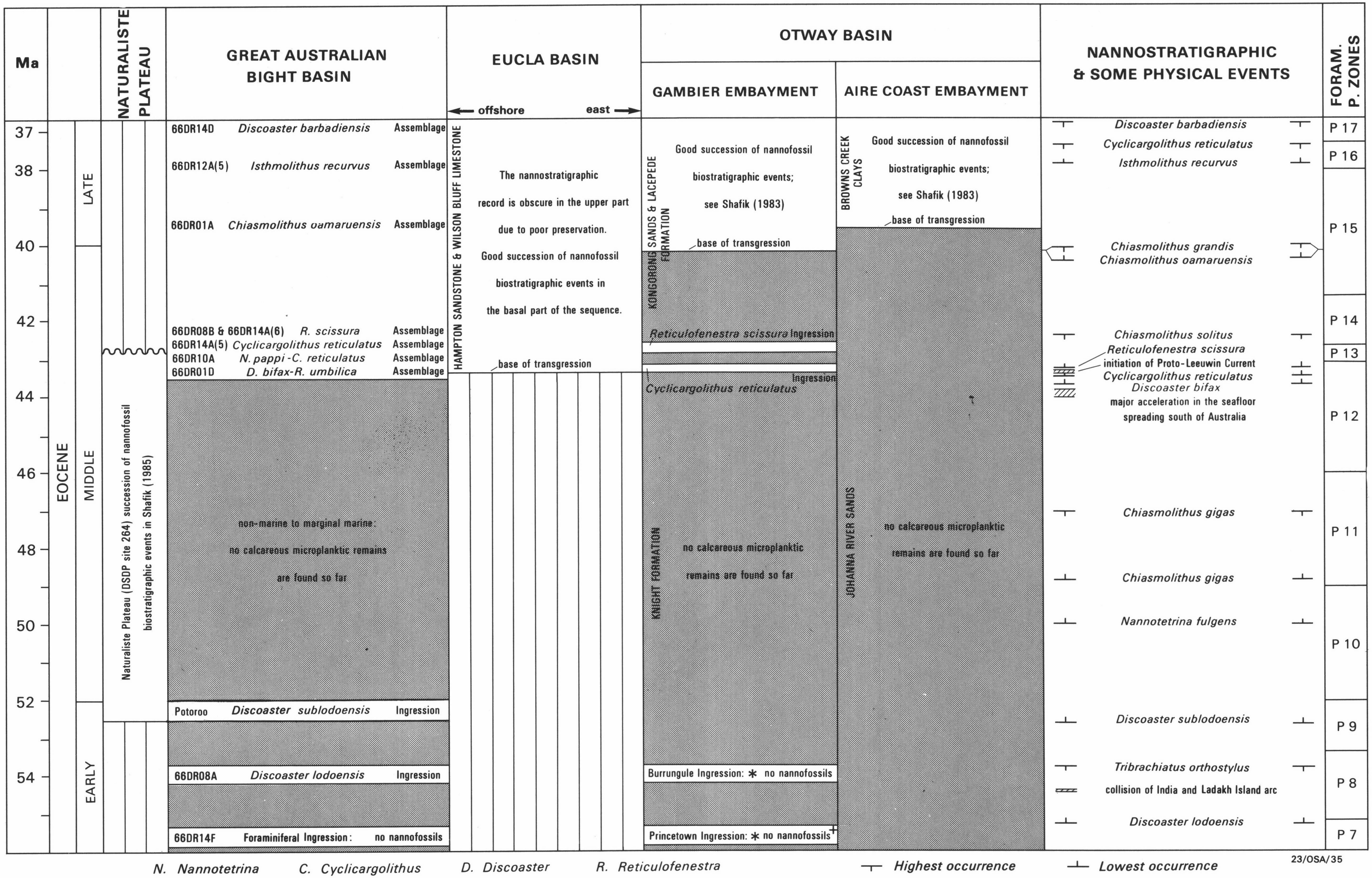


Figure 8. Eocene calcareous nannofossil biostratigraphic events and some physical events pertinent to the stratigraphic evolution of the southern margin of Australia.
Correlation of nannofossil events with the foraminiferal P zones and the time scale follows that suggested by Berggren & others (1985) where possible.
* Placement relative to the P zones is based on correlations by McGowran (1988b, in press).

assemblage. This sample was dredged from water depths of 3535–3390 m. The assemblage included:

- *Acuturris scotus* (Risatti) Wind & Wise *in* Wise & Wind, 1977
- *Ahmuellerella octoradiata* (Gorka) Reinhardt, 1967
- *Arkhangelskiella cymbiformis* Vekshina, 1959
- *Arkhangelskiella speciallata* Vekshina, 1959 (rare)
- *Biscutum notaculum* Wind & Wise *in* Wise & Wind, 1977
- *Boletuvulum* sp.
- *Chiastozygus litterarius* (Gorka) Manivit, 1971
- *Corollithion exiguum* Stradner, 1961
- *Corollithion rhombicum* (Stradner & Adamiker) Bukry, 1969
- *Cretarhabdus conicus* Bramlette & Martini, 1964
- *Cretarhabdus surirellus* (Deflandre & Fert) Reinhardt, 1970
- *Cribrosphaerella daniae* Perch-Nielsen, 1973
- *Cribrosphaerella ehrenbergii* (Arkhangelsky) Deflandre, 1952
- *Eiffellithus turriseiffeli* (Deflandre) Reinhardt, 1965
- *Gartnerago* sp.
- *Grantarhabdus camaratus* (Bukry) Wise, 1983
- *Kamptnerius magnificus* Deflandre, 1959
- *Lapideacassis cornuta* (Forchheimer & Stradner) Wind & Wise *in* Wise & Wind, 1977
- *Lithraphidites carniolensis* Deflandre, 1963
- *Lithraphidites praequadratus* Roth, 1978
- *Lithraphidites quadratus* Bramlette & Martini, 1964
- *Lucianorhabdus* sp. cf. *L. cayeuxii* Deflandre, 1959
- *Markalius astroporus* (Stradner) Mohler & Hay *in* Hay & others, 1967
- *Microrhabdulus belgicus* Hay & Towe, 1963
- *Micula concava* (Stradner) Bukry, 1969
- *Micula staurophora* (Gardet) Stradner, 1963
- *Nephrolithus corystus* Wind, 1983
- *Nephrolithus* sp. aff. *N. frequens* Gorka, 1957
- *Placozygus fibuliformis* (Reinhardt) Hoffmann, 1970
- *Prediscosphaera cretacea* (Arkhangelsky) Gartner, 1968
- *Prediscosphaera grandis* Perch-Nielsen, 1979 (very rare)
- *Prediscosphaera spinosa* (Bramlette & Martini) Gartner, 1968
- *Prediscosphaera stoveri* (Perch-Nielsen) Shafik & Stradner, 1971
- *Rhagodiscus angustus* (Stradner) Stradner *in* Stradner, Adamiker & Maresch, 1968
- *Rhagodiscus reniformis* Perch-Nielsen, 1973
- *Scapholithus fossilis* Deflandre *in* Deflandre & Fert, 1954
- *Stephanolithion laffittie* Noel, 1957
- *Teichorhabdus ethmos* Wind & Wise *in* Wise & Wind, 1977
- *Tetrapodorhabdus decorus* Wind & Wise, 1983
- *Vekshinella elliptica* Gartner, 1968
- *Watznaueria barnesae* (Black) Perch-Neilsen, 1968

The key species *Nephrolithus corystus, Cribrosphaerella daniae* and *Arkhangelskiella cymbiformis* are particularly abundant, but *Lithraphidites quadratus* is rare. These species indicate a mid to late Maastrichtian age.

The overall aspect of the assemblage suggests high-latitude position and deposition in a neritic environment: *Watznaueria barnesae* is extremely rare, whereas *Nephrolithus corystus, Cribrosphaerella daniae, Micula concava, Ahmuellerella octoradiata* and *Kamptnerius magnificus* are particularly abundant. The high-latitude position is reinforced by the total lack of distinctly low-latitude species such as *Cribrocorona gallica* (Stradner) Perch-Nielsen, 1973.

Assemblage C. Sample 66DR01F, a pale green-beige silty sandstone including dark brown organic shale, contained another moderately preserved but less diverse nannofossil assemblage. This included:

- *Arkhangelskiella cymbiformis* Vekshina, 1959
- *Arkhangelskiella speciallata* Vekshina, 1959
- *Biscutum* spp.
- *Chiastozygus litterarius* (Gorka) Manivit, 1971
- *Cretarhabdus conicus* Bramlette & Martini, 1971
- *Cretarhabdus surirellus* (Deflandre & Fert) Reinhardt, 1970
- *Cribrosphaerella daniae* Perch-Neilsen, 1973
- *Cribrosphaerella ehrenbergii* (Arkhangelsky) Deflandre, 1952
- *Cyclogelosphaera reinhardtii* (Perch-Nielsen) Roth, 1978
- *Eiffellithus turriseiffeli* (Deflandre) Reinhardt, 1965
- *Gartnerago* sp.
- *Grantarhabdus camaratus* (Bukry) Wise, 1983
- *Kamptnerius magnificus* Deflandre, 1959
- *Lithraphidites carniolensis* Deflandre, 1963
- *Lithraphidites praequadratus* Roth, 1978
- *Lithraphidites quadratus* Bramlette & Martini, 1964
- *Markalius astroporus* (Stradner) Hay & Mohler, 1967
- *Micula concava* (Stradner) Bukry, 1969
- *Micula staurophora* (Gardet) Stradner, 1963
- *Nephrolithus corystus* Wise, 1983 (a single specimen)
- *Nephrolithus frequens* Gorka, 1957
- *Placozygus fibuliformis* (Reinhardt) Hoffmann, 1970
- *Prediscosphaera cretacea* (Arkhangelsky) Gartner, 1968
- *Prediscosphaera grandis* Perch-Nielsen, 1979 (very rare)
- *Prediscosphaera spinosa* (Bramlette & Martini) Gartner, 1968
- *Prediscosphaera stoveri* (Perch-Nielsen) Shafik & Stradner, 1971
- *Teichorhabdus ethmos* Wind & Wise *in* Wise & Wind, 1977
- *Tetrapodorhabdus decorus* (Deflandre) Wind & Wise, 1983
- *Watznaueria barnesae* (Black) Perch-Nielsen, 1968

Like the Maastrichtian assemblage of 66DR03A, this assemblage includes several elements indicative of deposition in a neritic environment at high-latitude location; the sandstone/shale of 66DR01F was collected from water 3280–2950 m deep. The presence of typical *Nephrolithus frequens* suggests that it is late Maastrichtian and may be slightly younger than the assemblage of 66DR03A. Other differences between these two assemblages are worth mentioning: (a) *Arkhangelskiella speciallata*, frequent to common in 66DR03A, is very rare in 66DR01F, (b) *Nephrolithus corystus* is abundant in 66DR03A, but extremely rare in 66DR01F, and (c) *Teichorhabdus ethmos*, represented mainly by large specimens in 66DR03A, is much smaller in 66DR01F.

The assemblages of 66DR03A and 66DR01F compare with similar assemblages from the Perth Basin (Shafik, in press). They differ from the Miria Marl assemblage of the Carnarvon Basin (Shafik, in press) in containing elements which suggest a more southerly location and in lacking low-latitude species such as *Micula murus* (Martini) Bukry, 1973 and *Cribrocorona gallica* (Stradner) Perch-Nielsen, 1973.

Discussion. Deposition of 66DR01F and 66DR03A was in neritic environments (nearshore or shelf), as evidenced by the presence of species such as *Acuturris scotus, Kamptnerius magnificus, Lucianorhabdus* sp., *Ahmuellerella octoradiata* and *Arkhangelskiella cymbiformis*. The lithologies of these samples support deposition in a shallow-water environment. To account for the present water depth of 3535–2950 m in Canyon B (Fig. 1) where 66DR01F and 66DR03A were collected, considerable subsidence of the seafloor since the Late Cretaceous must be presumed. (The term 'subsidence' is used here to denote deepening as a net balance between subsidence of seafloor and eustatic movements, either rises or falls, in sea level). Interpretation of the depositional palaeoenvironment of sample 66DR01C, a dolomitic bioturbated intraclastic silty wackestone collected from the same station as 66DR01F, as possibly paralic (based on Coniacian to Santonian dinoflagellate; Alley, 1988) supports the subsidence viewpoint. Sample 66DR01C lacked calcareous microplanktic (nannofossil and foraminiferid) remains. Indeed, evidence is available from other dredge stations confirming subsidence of the seafloor of the Great Australian Bight Basin since the Late Cretaceous or early Tertiary. For example, sample 66DR12G, a very dark greyish-brown silty mudstone dredged from Canyon H at water depths of 3670–2720 m (Fig. 1) contained Paleocene pollens which suggested non-marine deposition (Alley, 1988); no calcareous microplanktic remains were found in this sample.

Eocene

Eight distinct calcareous nannofossil assemblages are recognised: one early Eocene, four middle Eocene and three late Eocene.

Early Eocene

Sample 66DR08A, a fine-grained yellow brown interbedded mudstone/sandstone from Canyon F on Ceduna Terrace (Fig. 1), contains abundant and moderately preserved calcareous nannofossils. Species identified are:

Blackites creber (Deflandre) Sherwood, 1974
Braarudosphaera bigelowii (Gran & Braarud) Deflandre, 1947 (very rare)
Calcidiscus protoannulus (Gartner) Loeblich & Tappan, 1978
Campylosphaera dela (Bramlette & Sullivan) Hay & Mohler, 1967
Chiasmolithus consuetus (Bramlette & Sullivan) Hay & Mohler, 1967 (very rare)
Chiasmolithus eograndis Perch-Nielsen, 1971 (small, rare)
Chiasmolithus expansus (Bramlette & Sullivan) Gartner, 1970
Chiasmolithus solitus (Bramlette & Sullivan) Locker, 1968
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Cyclicargolithus gammation (Bramlette & Sullivan) n. comb. (basionym *Coccolithites gammation* Bramlette & Sullivan 1961, p. 152, pl. 7, figs 7a–c, 14a,b) (very rare)
Discoaster binodosus Martini, 1958 (very rare)
Discoaster lodoensis Bramlette & Riedel, 1954 (very rare)
Discoasteroides kuepperi (Stradner) Bramlette & Sullivan, 1961
Ellipsolithus distichus Bramlette & Sullivan, 1961
Ellipsolithus lajollaensis Bukry & Percival, 1971
Holodiscolithus macroporus (Deflandre) Roth, 1970
Lanternithus minutus Stradner, 1962
Lophodolithus mochlophorus Deflandre *in* Deflandre & Fert, 1954
Lophodolithus nascens Bramlette & Sullivan, 1961
Lophodolithus reniformis Bramlette & Sullivan, 1961
A species transitional between *Markalius astroporus* (Stradner) Hay & Mohler, 1967 and *M. inversus* (Deflandre) Bramlette & Martini, 1964
Micrantholithus vesper Deflandre, 1950
Neococcolithes dubius (Deflandre) Black, 1967
Neococcolites minutus (Perch-Nielsen) Perch-Nielsen, 1971
Pontosphaera ocellata (Bramlette & Sullivan) Perch-Nielsen, 1984
Pontosphaera pectinata (Bramlette & Sullivan) Sherwood, 1974
Pontosphaera plana (Bramlette & Sullivan) Haq, 1971
Pontosphaera versa (Bramlette & Sullivan) Sherwood, 1974
Scapholithus fossilis Deflandre *in* Deflandre & Fert, 1954
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Sphenolithus primus Perch-Nielsen, 1971
Sphenolithus radians Deflandre *in* Grasse, 1952
Toweius callosus Perch-Nielsen, 1971
Toweius? crassus (Bramlette & Sullivan) Perch-Nielsen, 1984
Toweius? magnicrassus (Bukry) Romein, 1979
Transversopontis pulcher (Deflandre) Perch-Nielsen, 1967
Tribrachiatus orthostylus Shamarai, 1963
Zygodiscus adamas Bramlette & Sullivan, 1961
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959

The association of *Tribrachiatus orthostylus, Discoaster lodoensis, Discoasteroides kuepperi, Chiasmolithus solitus, Coccolithus formosus, Lophodolithus reniformis* and *Toweius callosus* indicates an early Eocene age. A correlation is suggested with the foraminiferal zonal interval late P7 to early P9 according to data in Martini (1971), or more precisely to the foraminiferal zone P8 according to data in Berggren & others (1985); the latter is adopted here. In Figure 8, this assemblage is referred to as the 66DR08A *Discoaster lodoensis* ingression.

The occurrence of the hemipelagic species *Zygrhablithus bijugatus bijugatus, Holodiscolithus macroporus, Micrantholithus vesper, Transversopontis pulcher* and several species of the genus *Pontosphaera* suggests deposition in a shallow-water environment (nearshore or shelf, possibly inner to middle neritic). Water depth at Station 66DR08 (in Canyon F, Fig. 1) is now 2826–2244 m. It is worth noting that several sediment samples from this station, 66DR08C, 66DR08D, 66DR08E and 66DR08F, which lack calcareous microplanktic remains, were found by Alley (1988) either to be totally barren or to contain late Paleocene and early Eocene pollens indicative of possible paralic to marginal marine environments. Considerable subsidence must have occurred since the Paleocene for these coastal and non-marine sediments to be now at water depths of more than 2200 m.

Middle Eocene

Assemblage A. Sample 66DR01D, from Canyon B (Fig. 1), contains abundant and well preserved calcareous nannofossils in a pale green-beige poorly sorted sandstone. Species identified are:

Blackites creber (Deflandre) Sherwood, 1974
Blackites tenuis (Bramlette & Sullivan) Sherwood, 1974
Calcidiscus protoannulus (Gartner) Loeblich & Tappan, 1978 (very rare)
Chiasmolithus expansus (Bramlette & Sullivan) Gartner, 1970
Chiasmolithus gigas (Bramlette & Sullivan) Radomski, 1968 (frequent)
Chiasmolithus grandis (Bramlette & Riedel) Radomski, 1968
Chiasmolithus solitus (Bramlette & Sullivan) Locker, 1968
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961

Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Cyclicargolithus floridanus (Roth & Hay) Bukry, 1971
Discoaster barbadiensis Tan Sin Hok, 1927
Discoaster bifax Bukry, 1971
Discoaster deflandrei Bramlette & Riedel, 1954 'group'
Discoaster delicatus Bramlette & Sullivan, 1961
Discoaster gemmifer Stradner, 1961 (very rare)
Discoaster saipanensis Bramlette & Riedel, 1954
Discoaster tanii Bramlette & Riedel, 1954
Gartnerago sp. (rare)
Helicosphaera sp. (rare)
A species transitional between *Markalius astroporus* (Stradner) Hay & Mohler, 1967 and *M. inversus* (Deflandre) Bramlette & Martini, 1964
Nannotetrina pappi (Stradner) Perch-Nielsen, 1971
Neococcolithes dubius (Deflandre) Black, 1967
?Reinhardtites sp. (very rare)
Reticulofenestra dictyoda (Deflandre & Fert) Stradner, 1968
Reticulofenestra umbilica (Levin) Martini & Ritzkowski, 1968 (two sizes)
Transversopontis pulcher (Deflandre) Perch-Nielsen, 1967
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959

Discoaster barbadiensis is appreciably more common than *Discoaster saipanensis*. A few specimens of *Reticulofenestra scissura* Hay & others, 1967 were encountered, but in the absence of *Cyclicargolithus reticulatus* (Gartner & Smith) and because most other members of the assemblage are typical of a pre-*scissura* assemblage, they are thought to be contaminants. The association of *Reticulofenestra umbilica, Discoaster bifax, Chiasmolithus grandis, C. solitus* and *Discoaster barbadiensis* suggests a middle Eocene age (Gartner, 1971; Bukry, 1973) and a correlation with the foraminiferal mid to late zone P12 of the tropics according to data in Berggren & others (1985). This assemblage, referred to as the 66DR01D *Discoaster bifax–Reticulofenestra umbilica* assemblage in Figure 8, contains the obviously displaced Upper Cretaceous species of *Gartnerago* and *?Reinhardtites*. Both *Chiasmolithus gigas* and *Nannotetrina pappi* could also be reworked from lower in the middle Eocene.

Deposition in shallow waters (?outer neritic environment) is indicated by the rare occurrence of *Transversopontis pulcher* and *Zygrhablithus bijugatus bijugatus*. Water depth today at Station 66DR01 is 3280–2950 m, and considerable subsidence must have occurred since the middle Eocene. Sample 66DR01I from the same station, which contains no calcareous microplanktic remains, yielded palynomorphs indicative of a late Paleocene marginal marine environment (see Alley, 1988). Upper Cretaceous sediments dredged from the same station include evidence for subsidence since probably the Coniacian (discussed above).

Assemblage B. Sample 66DR10A, a fine-grained limestone from water 3614–2925 m deep in Canyon G on Ceduna Terrace (Fig. 1), contains abundant and moderately preserved calcareous nannofossils. Species identified are:

Blackites creber (Deflandre) Sherwood, 1974
Blackites spinulus (Levin) Roth, 1970
Calcidiscus protoannulus (Gartner) Loeblich & Tappan, 1978
Chiasmolithus eograndis Perch-Nielsen, 1971
Chiasmolithus expansus (Bramlette & Sullivan) Gartner, 1970
Chiasmolithus grandis (Bramlette & Riedel) Radomski, 1968
Chiasmolithus solitus (Bramlette & Sullivan) Locker, 1968
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Cyclicargolithus floridanus (Roth & Hay) Bukry, 1971
Cyclicargolithus reticulatus (Gartner & Smith) Bukry, 1971 (rare and poorly preserved)
Daktylethra punctulata Gartner *in* Gartner & Bukry, 1969
Discoaster barbadiensis Tan Sin Hok, 1927
Discoaster distinctus Martini, 1958
Discoaster saipanensis Bramlette & Riedel, 1954
Discoaster tanii Bramlette & Riedel, 1954
Helicosphaera seminulum Bramlette & Sullivan, 1961
Helicosphaera sp. cf. *H. bramlettei* (Müller) Jafar & Martini, 1975
A species transitional between *Markalius astroporus* (Stradner) Hay & Mohler, 1967 and *M. inversus* (Deflandre) Bramlette & Martini, 1964
Nannotetrina pappi (Stradner) Perch-Nielsen, 1971
Neococcolithes dubius (Deflandre) Black, 1967
Pontosphaera multipora (Kamptner) Roth, 1970 (very rare)
Reticulofenestra hampdenensis Edwards, 1973 (small)
Reticulofenestra umbilica (Levin) Martini & Ritzkowski, 1968 (two sizes)
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Transversopontis pulcher (Deflandre) Perch-Nielsen, 1967
Trochaster simplex Klumpp, 1953
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959 (very rare)

The rare occurrence of *Cyclicargolithus reticulatus* in association with *Chiasmolithus solitus* and *C. grandis*, in the absence of *Reticulofenestra scissura*, suggests a mid middle Eocene age and a correlation with the foraminiferal late zone P12 (Shafik, 1978, 1983).

Deposition in shallow waters (?middle neritic environment) was indicated by the presence of *Daktylethra punctulata, Pontosphaera multipora* and *Zygrhablithus bijugatus bijugatus*. It is worth noting that sediments dredged from Canyon G (Fig. 1), at water depths similar to those at which 66DR10A was obtained, contain evidence suggesting subsidence since the Paleocene. A dark brown, pyritic, organic-rich, silty mudstone (66DR09C) contains pollen grains indicative of marginal marine conditions during the Paleocene–early Eocene at the site of Canyon G (Alley, 1988).

Discoasters in 66DR10A are relatively less abundant than in 66DR01D, suggesting slightly cooler surface waters for the assemblage from 66DR10A.

Nannotetrina pappi is probably a displaced species from a lower middle Eocene level. However, the taxa of 66DR10A are referred to in Figure 8 as the 66DR10A *Nannotetrina pappi–Cyclicargolithus reticulatus* assemblage.

Sample 66DR015B, a light greyish-brown calcareous siltstone from water 3394–2494 m deep at Canyon K on Ceduna Terrace, yielded a calcareous nannofossil assemblage similar to that of 66DR10A, except for the lack of *Nannotetrina pappi* and the presence of *Helicosphaera heezenii* (Bukry) Jafar & Martini, *H. compacta* Bramlette & Wilcoxon, *Orthozygus aureus* (Stradner) Bramlette & Wilcoxon, *Syracosphaera labrosa* Bukry & Bramlette, 1969 and more species of *Transversopontis*. Specimens of *Cyclicargolithus* *reticulatus* are small in the assemblage from 66DR015B, but undeniable.

Assemblage C. Sample 66DR14A(5), a light grey argillaceous limestone from Canyon J on Ceduna Terrace (Fig. 1), yielded calcareous nannofossils. These are abundant and moderately preserved, though their debris abounds. Species identified are:

Blackites spinulus (Levin) Roth, 1970 (rare)
Calcidiscus protoannulus (Gartner) Loeblich & Tappan, 1978
Chiasmolithus expansus (Bramlette & Sullivan) Gartner, 1970
Chiasmolithus grandis (Bramlette & Riedel) Radomski, 1968
Chiasmolithus solitus (Bramlette & Sullivan) Locker, 1968
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Cyclicargolithus floridanus (Roth & Hay) Bukry, 1971
Cyclicargolithus reticulatus (Gartner & Smith) Bukry, 1971
Discoaster barbadiensis Tan Sin Hok, 1927
Discoaster saipanensis Bramlette & Riedel, 1954
Discoaster sp.
Discoaster tanii nodifer Bramlette & Riedel, 1954
Helicosphaera heezenii (Bukry) Jafar & Martini, 1975 (common)
Helicosphaera sp. aff. *H. reticulata* Bramlette & Wilcoxon, 1967
A species transitional between *Markalius astroporus* (Stradner) Hay & Mohler, 1967 and *M. inversus* (Deflandre) Bramlette & Martini, 1964 (very rare)
Neococcolithes dubius (Deflandre) Black, 1967
Pontosphaera multipora (Kamptner) Roth, 1970 (poorly preserved, very rare)
Reticulofenestra hampdenensis Edwards, 1973
Reticulofenestra umbilica (Levin) Martini & Ritzkowski, 1968
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Sphenolithus predistentus Bramlette & Wilcoxon, 1967
Zygrhablithus bijugatus crassus Locker, 1967 (rare)

This assemblage is middle Eocene in age, based on the co-occurrence of *Cyclicargolithus reticulatus* and *Chiasmolithus grandis*, and the absence of *Reticulofenestra scissura* (Shafik, 1978). It correlates with the foraminiferal late zone P12 of the tropics (Shafik, 1978, 1983). Abundant *C. reticulatus* suggests that the assemblage is slightly younger than the assemblages from 66DR10A and 66DR15B; the latter can probably be placed very close to the appearance (lowest occurrence) datum of *Cyclicargolithus reticulatus* (Shafik, 1973), with the 66DR14A(5) assemblage at a slightly higher stratigraphic level. This assemblage is referred to as the 66DR14A(5) *Cyclicargolithus reticulatus* assemblage in Figure 8.

The scarcity of *Pontosphaera multipora* and *Zygrhablithus bijugatus crassus* and the absence of other indicators of shallow-water deposition (neritic environment) — such as *Daktylethra punctulata* and *Transversopontis pulcher*, which are present in the assemblages from 66DR10A and 66DR15B — suggest deposition in deeper waters, probably on the outer shelf or upper continental slope. A comparison of the diversity and abundance of shallow-water indicators in the assemblages from 66DR10A and 66DR15B with those in the slightly younger assemblage from 66DR14A(5) shows noticeable deepening during the middle Eocene biostratigraphic interval bracketed by the lowest occurrences of *Cyclicargolithus reticulatus* and *Reticulofenestra scissura* in the Great Australian Bight Basin. Present water depth at Station 66DR14 is 3064–2627 m.

Assemblage D. Sample 66DR08B, a fine-grained yellow-green carbonate mudstone from Canyon F (Fig. 1), contains abundant and moderately preserved calcareous nannofossils. Taxa identified are:

Amitha prolata Shafik, 1989
Blackites tenuis (Bramlette & Sullivan) Sherwood, 1974
Calcidiscus protoannulus (Gartner) Loeblich & Tappan, 1978
Chiasmolithus expansus (Bramlette & Sullivan) Gartner, 1970
Chiasmolithus grandis (Bramlette & Riedel) Radomski, 1968
Chiasmolithus solitus (Bramlette & Sullivan) Locker, 1968
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Cyclicargolithus floridanus (Roth & Hay) Bukry, 1971
Cyclicargolithus reticulatus (Gartner & Smith) Bukry, 1971
Discoaster barbadiensis Tan Sin Hok, 1927
Discoaster saipanensis Bramlette & Riedel, 1954
Discoaster tanii Bramlette & Riedel, 1954
Lanternithus minutus Stradner, 1962 (rare, poorly preserved)
A species transitional between *Markalius astroporus* (Stradner) Hay & Mohler, 1967 and *M. inversus* (Deflandre) Bramlette & Martini, 1964
Neococcolithes dubius (Deflandre) Black, 1967
Reticulofenestra scissura Hay & others, 1966 (small & rare)
Reticulofenestra scrippsae (Bukry & Percival) Roth, 1973
Reticulofenestra umbilica (Levin) Martini & Ritzkowski, 1968
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Sphenolithus predistentus Bramlette & Wilcoxon, 1967
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959

The association of *Reticulofenestra scissura, Cyclicargolithus reticulatus* and *Chiasmolithus grandis* suggests a later middle Eocene age and, in the absence of *Daktylethra punctulata*, may correlate with the foraminiferal zone P14 (according to data in Shafik, 1983). The holococcolith *Daktylethra punctulata* is usually absent from oceanic sediments as it is solution-prone, and thus its absence can be biostratigraphically unreliable. However, the presence of other holococcoliths in the assemblage (see below) suggests that the absence of *D. punctulata* may not be due to its dissolution.

Deposition was in outer neritic waters as indicated by the rare occurrence of only two holococcoliths, *Lanternithus minutus* and *Zygrhablithus bijugatus bijugatus*; poor preservation (recrystallisation) of *L. minutus* may account for its scarcity. In comparison with the lower Eocene assemblage from the same dredge haul (66DR08A), the younger (middle Eocene) assemblage from 66DR08B contains fewer species characteristic of neritic water masses. This suggests deposition at greater depth than during the early Eocene. Water depth at Station 66DR08 (in Canyon F on Ceduna Terrace, Fig. 1) is 2826–2244 m. Evidence for subsidence since the Paleocene is given above, based on other samples from the same dredge station at Canyon F.

Sample 66DR14A(6), a light grey argillaceous limestone from water 3064–2627 m deep in Canyon J, yielded a middle Eocene nannofossil assemblage similar to that from 66DR08B: abundant *Cyclicargolithus reticulatus*, common *Helicosphaera reticulata* and rare, small, *Reticulofenestra scissura*. Indicators of shallow-water deposition are rare; the presence of *Zygrhablithus bijugatus* suggests an outer neritic or bathyal environment. The assemblage from 66DR14A(6) differs, however, in containing *Daktylethra* sp. cf. *D. punctulata*. Shafik (1983) used the highest occurrence of typical *D. punctulata* in Otway Basin sections as a biostratigraphic datum high in the foraminiferal zone P13. In Figure 8, the assemblages from 66DR08B and 66DR14A(6) are tentatively considered equivalents, and are placed against the foraminiferal zone P14.

Late Eocene

Assemblage A. Sample 66DR01A, a fine-grained white chalk, dredged from Canyon B between the Eyre and Ceduna Terraces (Fig. 1), yielded a rich nannofossil assemblage. This included:

Blackites spp. (stems)
Bramletteius serraculoides Gartner, 1969 (rare)
Chiasmolithus altus Bukry & Percival, 1971
Chiasmolithus oamaruensis (Deflandre) Hay & others, 1966 (common)
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Cyclicargolithus floridanus (Roth & Hay) Bukry, 1971
Cyclicargolithus reticulatus (Gartner & Smith) Bukry, 1971
Discoaster barbadiensis Tan Sin Hok, 1927 (very rare)
Discoaster saipanensis Bramlette & Riedel, 1954 (frequent)
Markalius inversus (Deflandre) Bramlette & Martini, 1964 (very rare)
?Reticulofenestra hampdenensis Edwards, 1973
Reticulofenestra orangensis (Bukry) n. comb. (basionym *Coccolithus? orangensis* Bukry, 1971, p. 312, pl. 2, fig. 10; pl. 3, figs 1–3)
Reticulofenestra scissura Hay & others, 1966
Reticulofenestra scrippsae (Bukry & Percival) Roth, 1973
Reticulofenestra umbilica (Levin) Martini & Ritzkowski, 1968
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967

Based on the presence of *Chiasmolithus oamaruensis, Discoaster barbadiensis, D. saipanensis* and *Cyclicargolithus reticulatus* in the absence of *Isthmolithus recurvus*, the age of the assemblage is early late Eocene (Gartner, 1971; Shafik, 1973, 1983). Based on the same evidence, a correlation with a position low within the foraminiferal zone P15 (according to Shafik, 1983) or with the zonal interval P15–early P16 (according to Berggren & others, 1985) can also be made. This assemblage is referred to as the 66DR01A *Chiasmolithus oamaruensis* assemblage in Figure 8, where it is placed against the foraminiferal mid zone P15.

There are appreciably more specimens of the genus *Chiasmolithus* than of the genus *Discoaster*, suggesting cooler surface waters than earlier in the mid middle Eocene.

Deposition in deep waters (probably on the continental slope) is suggested by the rare occurrence of the oceanic *Bramletteius serraculoides* and by the lack of indicators of shallow-water deposition (such as *Lanternithus minutus*). Present water depth at Station 66DR01 (in Canyon B, Fig. 1) is 3280–2950 m. Evidence from the same station (see above) suggests that subsidence must have occurred since the Coniacian, and the assemblages of the upper Eocene (66DR01A) and the middle Eocene (66DR01D) are in harmony with that evidence. Thus, indicators of shallow-water (neritic environment) deposition, although few in number of species, are present in the middle Eocene (66DR01D) but absent from the upper Eocene (66DR01A). Subsidence, being first noticeable in middle Eocene nannofossils, seems to have continued on and, by the late Eocene, Station 66DR01 was on the continental slope (bathyal environment). Table 1 summarises the depositional palaeoenvironments of sediments sampled at this station.

Table 1. Depositional palaeoenvironments of samples from dredge 66DR01, showing deepening with time as an effect of a possible increase in the rate of subsidence of the seafloor of the Great Australian Bight during the middle Eocene.

Age	*Sample*	*Depositional palaeoenvironment*
Late Eocene	66DR01A	bathyal (continental slope)
Middle Eocene	66DR01D	outer neritic (outer shelf)
Early Eocene		not represented
Paleocene	66DR01I	marginal marine
Maastrichtian	66DR01F	(?middle) neritic (marine ingression)
Maastrichtian	66DR01H	(?inner) neritic (marine ingression)
Coniacian–Santonian	66DR01C	possibly paralic

Assemblage B. Sample 66DR12A(5), a fine-grained limestone from Canyon H (Fig. 1), yielded a poorly preserved calcareous nannofossil assemblage which is characterised by the presence of the taxa:

Chiasmolithus altus Bukry & Percival, 1971
Chiasmolithus oamaruensis (Deflandre) Hay & others, 1966
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
?Cyclicargolithus reticulatus (Gartner & Smith) Bukry, 1971
Discoaster saipanensis Bramlette & Riedel, 1954
Helicosphaera compacta Bramlette & Wilcoxon, 1967
Isthmolithus recurvus Deflandre *in* Deflandre & Fert, 1954
Markalius inversus (Deflandre) Bramlette & Martini, 1964
Pontosphaera spp.
Reticulofenestra hampdenensis Edwards, 1973
Reticulofenestra orangensis (Bukry) n. comb.
Reticulofenestra scissura Hay & others, 1966
Reticulofenestra umbilica (Levin) Martini & Ritzkowski, 1968
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Transversopontis zigzag Roth & Hay *in* Hay & others, 1967
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959

The overlap in the ranges of *Discoaster saipanensis* and *Isthmolithus recurvus* indicates a late Eocene age (Martini, 1971; Gartner, 1971; Shafik, 1973). Identification of *Cyclicargolithus reticulatus* is doubtful, and the presence of this species is critical to accurately pointing the age and evaluating correlation with the foraminiferal P zones (Shafik, 1973). *C. reticulatus* would suggest correlation with the foraminiferal zonal interval late P15–early P16 (Shafik, 1983). Its absence may suggest a later Eocene age and correlation near the P16/P17 zonal boundary. This assemblage, being correlated within the foraminiferal P16 zone, is referred to as the 66DR12A(5) *Isthmolithus recurvus* assemblage in Figure 8.

Deposition of 66DR12A(5) was in a neritic environment, as evidenced by the presence of species of the genera *Pontosphaera, Transversopontis* and *Zygrhablithus*. Water depth at Station 66DR12 is now 3670–2720 m. Evidence of non-marine Paleocene sediment from the same dredge station (sample 66DR12G; Alley, 1988) has been cited above to suggest that subsidence/deepening must have occurred since the Paleocene.

Assemblage C. Sample 66DR14D, a light brownish-grey limestone from Canyon J (Fig. 1), yielded moderately preserved nannofossils, including:

Blackites tenuis (Bramlette & Sullivan) Sherwood, 1974
Chiasmolithus altus Bukry & Percival, 1971
Chiasmolithus oamaruensis (Deflandre) Hay & others, 1966
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Discoaster barbadiensis Tan Sin Hok, 1927
Discoaster saipanensis Bramlette & Riedel, 1954
Discoaster tanii Bramlette & Riedel, 1954
Discoaster tanii nodifer Bramlette & Riedel, 1954 (frequent)
Helicosphaera heezenii (Bukry) Jafar & Martini, 1975
Holodiscolithus macroporus (Deflandre) Roth, 1970 (very rare)
Isthmolithus recurvus Deflandre *in* Deflandre & Fert, 1954
Markalius inversus (Deflandre) Bramlette & Martini, 1964
Pedinocyclus larvalis (Bukry & Bramlette) Loeblich & Tappan, 1973
Pontosphaera multipora (Kamptner) Roth, 1970 (single specimen, corroded)
Reticulofenestra hampdenensis Edwards, 1973
Reticulofenestra orangensis (Bukry) n. comb.
Reticulofenestra scissura Hay & others, 1966
Reticulofenestra umbilica (Levin) Martini & Ritzkowski, 1968
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Transversopontis zigzag Roth & Hay *in* Hay & others, 1967
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959

Discoaster barbadiensis is more prominent than *D. saipanensis*. The presence of these species with *Isthmolithus recurvus*, in the absence of *Cyclicargolithus reticulatus*, suggests a latest late Eocene age (Shafik, 1973), and probably a correlation with the foraminiferal zone early P17 according to Berggren & others (1985). This assemblage is referred to as the 66DR14D *Discoaster barbadiensis* assemblage in Figure 8.

Deposition was in a shallow water nearshore or shelf environment, based on the presence of hemipelagic species such as *Holodiscolithus macroporus* and *Transversopontis zigzag*. Present water depth at Station 66DR14 (in Canyon J, Fig. 1) is 3064–2627 m.

Discussion. During the middle Eocene, Station 66DR14 was probably on the outer shelf or the upper continental slope, as evidenced by the 66DR14A(5) nannofossil assemblage which contains scarce indicators of neritic water mass. Subsidence must have been occurring since that time. The younger Eocene assemblage from 66DR14D includes more common indicators of shallow-water deposition. This suggests a drastic latest late Eocene fall in sea level, on a presumably subsiding seafloor. Table 2 summarises the depositional palaeoenvironments of sediments sampled at Station 66DR14.

Table 2. Depositional palaeoenvironments of samples from dredge 66DR14, showing effect of a possible increase in the rate of subsidence of the seafloor of the Great Australian Bight during the middle Eocene; a later Eocene fall in sea level reversed this effect.

Age	*Sample*	*Depositional palaeoenvironment*
Early Oligocene	66DR14B	neritic (?middle shelf)
Latest late Eocene	66DR14D	neritic (?middle shelf)
Late Eocene		not represented
Later Middle Eocene	66DR14A(6)	outer neritic or bathyal
Middle Eocene	66DR14A(5)	outer neritic or bathyal
Early Eocene		not represented
Paleocene		not represented
Maastrichtian	66DR14F	(?inner) neritic (marine ingression)

Oligocene

Four distinct Oligocene assemblages are identified.

Early Oligocene

Assemblage A. The assemblage extracted from sample 66DR14B, a white argillaceous limestone in Canyon J on Ceduna Terrace (Fig. 1), included:

Blackites spinulus (Levin) Roth, 1970
Blackites tenuis (Bramlette & Sullivan) Sherwood, 1974
Chiasmolithus altus Bukry & Percival, 1971
Chiasmolithus oamaruensis (Deflandre) Hay & others, 1966 (abundant)
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Discoaster tanii Bramlette & Riedel, 1954
Helicosphaera sp. cf. *H. bramlettei* (Müller) Jafar & Martini, 1975
Isthmolithus recurvus Deflandre *in* Deflandre & Fert, 1954
Lanternithus minutus Stradner, 1962
Pedinocyclus larvalis (Bukry & Bramlette) Loeblich & Tappan, 1973 (rare)
Pontosphaera multipora (Kamptneri) Roth, 1970
Pontosphaera plana (Bramlette & Sullivan) Haq, 1971 (rare)
Reticulofenestra hampdenensis Edwards, 1973 (frequent to common)
Reticulofenestra oamaruensis (Deflandre) Stradner *in* Stradner & Edwards, 1968 (rare)
Reticulofenestra scissura Hay & others, 1966
Reticulofenestra scrippsae (Bukry & Percival) Roth, 1973
Reticulofenestra umbilica (Levin) Martini & Ritzkowski, 1968
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Transversopontis pulcher (Deflandre) Perch-Nielsen, 1967
Transversopontis pulcheroides (Sullivan) Perch-Nielsen, 1971
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959.

This assemblage is early Oligocene in age, based on the co-occurrence of *Coccolithus formosus, Isthmolithus recurvus, Lanternithus minutus, Reticulofenestra oamaruensis* and *R. umbilica*, in the absence of the key Eocene species *Cyclicargolithus reticulatus* and *Discoaster saipanensis* (Shafik, 1973; 1983). The same evidence suggests correlation with the foraminiferal zonal interval late P17–early P18 according to Berggren & others (1985).

Deposition was in shallow waters as indicated by the presence of several hemipelagic species such as *Lanternithus minutus, Pontosphaera multipora* and *Zygrhablithus bijugatus bijugatus*. The effect of the latest late Eocene fall in sea level (concluded above) seems to have been maintained during the early Oligocene. In other words, the net effect of this fall in sea level as against a presumed continuing subsidence of the seafloor at Canyon J (probably since the middle Eocene, see Table 2) is a shallow-water environment during the early Oligocene at Station 66DR14. Present water depth at this station is 3064–2627 m.

Assemblage B. The assemblage recovered from sample 66DR06A, a fine-grained white chalk dredged from Ceduna Canyon (Fig. 1), included:

Chiasmolithus altus Bukry & Percival, 1971
Chiasmolithus oamaruensis (Deflandre) Hay & others, 1966
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus pelagicus (Wallich) Schiller, 1930
Pontosphaera plana (Bramlette & Sullivan) Haq, 1971 (corroded)
Reticulofenestra hampdenensis Edwards, 1973
Reticulofenestra oamaruensis (Deflandre) Stradner *in* Stradner & Edwards, 1968
Reticulofenestra scissura Hay & others, 1966
Reticulofenestra umbilica (Levin) Martini & Ritzkowski, 1968
Transversopontis pulcheroides (Sullivan) Perch-Nielsen, 1971
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959.

The presence of *Reticulofenestra oamaruensis* and *R. umbilica* in the absence of the key Eocene species *Discoaster saipanensis, D. barbadiensis* and *Cyclicargolithus reticulatus* indicates an early Oligocene age (Martini, 1971; Shafik, 1973) and a correlation with the foraminiferal zone P18 according to Berggren & others (1985). This assemblage is younger than that of 66DR14B because the latter contains *Coccolithus formosus*.

Deposition of 66DR06A was in shallow waters, based on the presence of *Pontosphaera plana, Transversopontis pulcheroides* and *Zygrhablithus bijugatus bijugatus*. The fall in sea level which began during the latest late Eocene (see discussion above) continued to show its effect during the early Oligocene, permitting the presence of hemipelagic species in the 66DR06A assemblage. Deepening of the water (as a net balance between seafloor subsidence and eustatic fluctuation in sea level) above the Ceduna Terrace (Station 66DR06) must later have resumed, to account for the present water depth at Station 66DR06 of 2620–2015 m.

Mid Oligocene

Sample 66DR12B, a soft fine-grained white limestone dredged from Canyon H on Ceduna Terrace (Fig. 1), yielded a well-preserved assemblage. This included:

Blackites spinulus (Levin) Roth, 1970
Blackites tenuis (Bramlette & Sullivan) Sherwood, 1974
Blackites vitreus (Deflandre) Shafik, 1981
Chiasmolithus altus Bukry & Percival, 1971
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus pelagicus (Wallich) Schiller, 1930
Coronocyclus nitescens (Kamptner) Bramlette & Wilcoxon, 1967
Cyclicargolithus floridanus (Roth & Hay) Bukry, 1971
Helicosphaera intermedia Martini, 1965
Helicosphaera obliqua Bramlette & Wilcoxon, 1967
Helicosphaera sp. (see Fig. 5)
Lanternithus minutus Stradner, 1962 (one poorly preserved specimen)
Orthozygus aureus (Stradner) Bramlette & Wilcoxon, 1967
Pontosphaera multipora (Kamptner) Roth, 1970
Reticulofenestra scissura Hay & others, 1966
Reticulofenestra scrippsae (Bukry & Percival) Roth, 1973
Reticulofenestra spp.
Sphenolithus distentus (Martini) Bramlette & Wilcoxon, 1967
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Sphenolithus predistentus Bramlette & Wilcoxon, 1967
Sphenolithus sp. (see Fig. 7)
Transversopontis zigzag Roth & Hay *in* Hay & others, 1967
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959.

Based on the presence of the index species *Sphenolithus distentus*, in the absence of both *Sphenolithus ciperoensis* Bramlette & Wilcoxon, 1967 and *Cyclicargolithus abisectus* (Muller) Wise, the age of the assemblage is mid Oligocene (Martini, 1971; Bukry, 1973). A correlation with the foraminiferal zonal interval late P18–early P21 of the tropics is made, based on Berggren & others (1985).

Deposition was in a neritic (nearshore or shelf) environment, as evidenced by the presence of several hemipelagic species such as *Orthozygus aureus, Transversopontis zigzag* and *Zygrhablithus bijugatus bijugatus*. The non-marine sediments at the same station (sample 66DR12G; Alley, 1988) are considered further indication of the early Tertiary shallowness of the water above Canyon H. Subsidence must have occurred since then, to account for the present water depth of 3670–2720 m at the station in Canyon H (Fig. 1).

Late Oligocene

Sample 66DR06B, a fine-grained pale yellowish-white chalk dredged from Ceduna Canyon (Fig. 1), yielded a late Oligocene assemblage which contained rare displaced Eocene elements:

Chiasmolithus altus Bukry & Percival, 1971
Chiasmolithus oamaruensis (Deflandre) Hay & others, 1966 (probably displaced from older level)
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus pelagicus (Wallich) Schiller, 1930
Coronocyclus nitescens (Kamptner) Bramlette & Wilcoxon, 1967
Cyclicargolithus abisectus (Müller) Wise, 1973
Cyclicargolithus floridanus (Roth & Hay) Bukry, 1971
Discoaster deflandrei Bramlette & Riedel, 1954 'group'
Discoaster saipanensis Bramlette & Riedel, 1954 (displaced from Eocene)
Discoaster tanii Bramlette & Riedel, 1954
Helicosphaera euphratis Haq, 1966
Helicosphaera recta (Haq) Martini, 1969
Reticulofenestra hampdenensis Edwards, 1973 (displaced from Eocene/lower Oligocene)
Reticulofenestra orangensis (Bukry) n. comb.
Reticulofenestra scissura Hay & others, 1966
Reticulofenestra scrippsae (Bukry & Percival) Roth, 1973
Reticulofenestra spp.
Reticulofenestra umbilica (Levin) Martini & Ritzkowski, 1968 (displaced from Eocene/lower Oligocene)
Sphenolithus ciperoensis Bramlette & Wilcoxon, 1967
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959

The co-occurrence of *Helicosphaera recta, Sphenolithus ciperoensis* and *Cyclicargolithus abisectus*, in the absence of *Sphenolithus distentus*, indicates a late Oligocene age (Martini, 1971; Bukry, 1973) and a correlation with the foraminiferal zone P22, based on Berggren & others (1985). The abundant occurrence of *Zygrhablithus bijugatus bijugatus* usually suggests deposition in neritic waters, but the presence of this species in 66R06B may be a result of reworking from older levels. The assemblage contains several displaced species mainly from Eocene levels, and *Z. bijugatus bijugatus* is known to range through the Eocene and Oligocene. Present water depth at Station 66DR06 is 2620–2015 m.

Comparison with onshore and well assemblages

Maastrichtian

Hitherto, *in situ* Cretaceous calcareous nannofossils were unknown from southern Australia. The Maastrichtian assemblages, from Canyon B between the Eyre and Ceduna Terraces in the central Great Australian Bight Basin, are the first found in southern Australia, and are considered to represent a marine ingression. The lithologies of 66DR01H, 66DR03A and 66DR01F, being organic-rich fine-grained and terrigenous, are consistent with this view. The 66DR03A assemblage is probably coeval with the initiation of the high sea-level stand which peaked during the late Maastrichtian on the Australian western margin (Shafik, in press). The slightly younger 66DR01F assemblage probably corresponds with the peak of this sea level.

Shafik (1985) described a significant reworking episode along the Australian western and southern margins, which involved the redeposition of Upper Cretaceous coccoliths in the Eucla and Otway Basins during the middle Eocene. The provenance of these Upper Cretaceous coccoliths was thought to be the Naturaliste Plateau, in the absence of known *in situ* Cretaceous coccoliths in southern Australia. The record herein of what appear to be *in situ* Maastrichtian coccoliths presents an alternative and nearer source for the reworked Cretaceous coccoliths in the Eocene of the Eucla and Otway Basins.

The Cretaceous *Gartnerago* sp. found in the middle Eocene 66DR01D assemblage is seen as a result of localised reworking (both Maastrichtian and middle Eocene strata crop out in Canyon B at Station 66DR01), and therefore may not belong to the same reworking episode described by Shafik (1985). The 66DR01D assemblage is slightly older than the middle Eocene levels with reworked Cretaceous nannofossils in the Eucla and Otway Basins.

Early Eocene

The early Eocene 66DR08A *Discoaster lodoensis* assemblage from Canyon F on Ceduna Terrace (Fig. 1), central Great Australian Bight Basin, is older than any known calcareous nannofossil assemblage in southern Australia. It is also distinctly older than the early Eocene assemblages at the base of the Eocene section on the Naturaliste Plateau (DSDP Site 264). This is based on the presence of the key species *Discoaster sublodoensis* in the Naturaliste Plateau (Shafik, 1985) and not in the 66DR08A assemblage.

In Potoroo No.1 well in the central Great Australian Bight Basin (Fig. 1A), an isolated early Eocene assemblage with *Discoaster sublodoensis* (i.e. correlatable with the Naturaliste Plateau assemblage) is here identified from the 945.5 m level; intervals immediately below and above this level in Potoroo No.1 well are barren of calcareous microplanktic remains. This assemblage included the taxa:

Blackites creber (Deflandre) Sherwood, 1974
Braarudosphaera bigelowii (Gran & Braarud) Deflandre, 1947
Braarudosphaera discula Bramlette & Riedel, 1954
Calcidiscus protoannulus (Gartner) Loeblich & Tappan, 1978
Campylosphaera dela (Bramlette & Sullivan) Hay & Mohler, 1967
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
A form transitional between *Chiasmolithus bidens* (Bramlette & Sullivan) Hay & Mohler, 1967 and *C. expansus* (Bramlette & Sullivan) Gartner, 1970
Chiasmolithus grandis (Bramlette & Riedel) Radomski, 1968
Chiasmolithus solitus (Bramlette & Sullivan) Locker, 1968
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Cyclicargolithus gammation (Bramlette & Sullivan) n. comb.
Discoaster barbadiensis Tan Sin Hok, 1927
Discoaster lodoensis Bramlette & Riedel, 1954
Discoaster sublodoensis Bramlette & Sullivan, 1961
Discoasteroides kuepperi (Stradner) Bramlette & Sullivan, 1961
Helicosphaera seminulum Bramlette & Sullivan, 1961
Lophodolithus mochlophorus Deflandre *in* Deflandre & Fert, 1964
Lophodolithus nascens Bramlette & Sullivan, 1961
Lophodolithus reniformis Bramlette & Sullivan, 1961
A species transitional between *Markalius astroporus* (Stradner) Hay & Mohler, 1967 and *M. inversus* (Deflandre) Bramlette & Martini, 1964
Micrantholithus altus Bybell & Gartner, 1972
Micrantholithus attenuatus Bramlette & Sullivan, 1961
Micrantholithus bramlettei Deflandre, 1954
Micrantholithus pinguis Bramlette & Sullivan, 1961
Neochiastozygus chiastus (Bramlette & Sullivan) Perch-Nielsen, 1971
Neococcolithes dubius (Deflandre) Black, 1967
Pontosphaera ocellata (Bramlette & Sullivan) Perch-Nielsen, 1984
Pontosphaera plana (Bramlette & Sullivan) Haq, 1971
Reticulofenestra dictyoda (Deflandre & Fert) Stradner, 1968
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Sphenolithus radians Deflandre *in* Grasse, 1952
Striatococcolithus pacificanus Bukry & Percival, 1971
Toweius callosus Perch-Nielsen, 1971
Toweius? magnicrassus (Bukry) Romein, 1979
Transversopontis pulcher (Deflandre) Perch-Nielsen, 1967
Tribrachiatus orthostylus Shamarai, 1963
Zygodiscus adamas Bramlette & Sullivan, 1961
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959.

The co-occurrence of *Discoaster sublodoensis* and *Discoasteroides kuepperi* suggests a late early Eocene age (Martini, 1971; Bukry, 1973), and a correlation with the foraminiferal late zone P9 according to data in Berggren & others (1985). The presence of *Tribrachiatus orthostylus* in the assemblage is problematic because this species is thought to disappear before the appearance of *D. sublodoensis* (see, for example, Martini, 1971). However, it is possible that *T. orthostylus* may have lasted longer in the Great Australian Bight Basin than elsewhere. The assemblage contains evidence to suggest warmer waters than earlier, during the deposition of the 66DR08A *Discoaster lodoensis* assemblage. Species of *Discoaster* are more frequent in the Potoroo assemblage than in the assemblage from 66DR08A.

Table 3. Depositional palaeoenvironments of samples from dredge 66DR08, showing effect of possible increase in the rate of subsidence of the seafloor of the Great Australian Bight during the middle Eocene.

Age	*Sample*	*Depositional palaeoenvironment*
Later Middle Eocene	66DR08B	outer neritic
Early Eocene	66DR08A	middle neritic (marine ingression)
Paleocene to early Eocene	66DR08E	possibly paralic (pollens)
Late Paleocene	66DR08F	possibly paralic (pollens)

It can be argued that the early Eocene 66DR08A *Discoaster lodoensis* assemblage is an isolated assemblage within the sequence at Canyon F, similar to the *Potoroo* assemblage which is sandwiched between nannofossil-free intervals, and thus representing a marine ingression. The lower Eocene section in the nearby Platypus No.1 well (Fig. 1A) is largely non-marine. McGowran (in press) considered the planktic foraminiferal assemblage of 66DR08A as representing what he termed the Burrungule ingression.

Thus, the 66DR08A *Discoaster lodoensis* assemblage (correlatable with the foraminiferal zone P8) and the Potoroo *Discoaster sublodoensis* assemblage (correlatable with the foraminiferal late zone P9) are considered to represent marine ingressions into the Great Australian Bight Basin. These are referred to in Figure 8 as the 66DR08A *Discoaster lodoensis* and the Potoroo *Discoaster sublodoensis* ingressions. No such ingressions could be detected in the Eucla Basin, and the middle Eocene calcareous nannofossil assemblages recovered from the Hampton Sandstone and the base of the Wilson Bluff Limestone (base of a major transgression) include elements (such as abundant *Cyclicargolithus reticulatus* and *Chiasmolithus grandis*) correlatable with the foraminiferal late zone P12 of the tropics.

Based on a relatively diverse planktic foraminiferal assemblage in 66DR14F — including *Pseudohastigerina wilcoxensis, Planorotalites australiformis, P. pseudoscitula, P.* cf. *imitata, 'Turborotalia'* sp., *Acarinina nitida, A. collactea, Subbotina patagonica, S.* cf. *linaperta* and *Chiloguembelina wilcoxensis* — dredged from Canyon J (Fig. 1), McGowran (1988a,b, in press) was able to recognise an (earlier) early Eocene marine ingression in the Great Australian Bight Basin. Conditions during this ingression were apparently not suited for coccolith-forming nannoplankton (the production of coccoliths and nannoliths was inhibited, and nannoplankton may have survived naked); no calcareous nannofossils could be found in 66DR14F. McGowran correlated the foraminiferal assemblage from 66DR14F with a much less diverse assemblage from the Otway Basin known from the Princetown Member of the Dilwyn Formation; no calcareous nannofossils were ever recovered from this level in the Dilwyn Formation.

Middle Eocene

The middle Eocene assemblages of the Great Australian Bight Basin represent four distinct levels (Fig. 8), the younger two of which can be related to assemblages previously recorded from the Gambier Embayment in the Otway Basin to the east. The older two assemblages can be linked with the Naturaliste Plateau sequence.

The 66DR01D *Discoaster bifax–Reticulofenestra umbilica* and the 66DR10A *Nannotetrina pappi–Cyclicargolithus reticulatus* assemblages are considered to represent the base of the transgression in the Great Australian Bight Basin, but their equivalents on the Naturaliste Plateau, due to erosion, are at the top of the truncated Eocene section at DSDP Site 264.

The assemblage from 66DR14A(5) is correlated with a coeval assemblage recorded previously from the Gambier Embayment, western Otway Basin (referred to as the *Chiasmolithus solitus–Cyclicargolithus reticulatus* association from the 65.2 m level in the Kingston Construction Camp Bore — see Shafik, 1983). However, the Gambier Embayment assemblage is more diverse. It includes several shallow-water indicators such as *Braarudosphaera bigelowii, Daktylethra punctulata, Lanternithus minutus, Pemma basquensis* (Martini) Baldi-Beke, 1967, *Pemma papillatum* Martini, 1959, *Pontosphaera multipora, Transversopontis pulcher, T. zigzag* and *Zygrhablithus bijugatus bijugatus*. Other differences between the two assemblages include (a) the presence of the warmer-water species *Helicosphaera heezenii, H.* sp. aff. *H. reticulata* and *Sphenolithus predistentus* in the 66DR14A(5) assemblage and not in the Gambier Embayment assemblage, (b) most species, and in particular *Reticulofenestra umbilica*, are larger in 66DR14A(5), and (c) the abundance of the species is much greater in 66DR14A(5). These differences would be explained if 66DR14A(5) was deposited at deeper levels (continental slope) beneath warmer surface waters which had much better connection to the open sea, being a part of the middle Eocene transgression. The Gambier Embayment assemblage, representing a marine ingression (discussed in Shafik, 1983), was deposited at shallower (continental shelf) depths; surface waters were evidently cooler than in the Great Australian Bight Basin.

The nearest assemblage in the Gambier Embayment (Otway Basin) to the younger middle Eocene assemblages from 66DR08B and 66DR14A(6) is an assemblage referred to as the *Daktylethra punctulata–Reticulofenestra scissura* association by Shafik (1983, recorded from Kingston Construction Camp Bore and Observation Bore No.1 well). The presence of *Daktylethra punctulata* in the Gambier Embayment assemblage suggests that it is slightly older (correlatable with the foraminiferal zone P13, Shafik, 1983) than these middle Eocene assemblages from the Great Australian Bight Basin (which are correlatable with the foraminiferal zone P14, being above the highest occurrence of *D. punctulata*). The Gambier Embayment assemblage differs also in containing a large number of hemipelagic species (i.e. indicators of deposition in a shallow-water environment), and in lacking the warm-water species *Sphenolithus predistentus* or *Helicosphaera reticulata*. These differences are consistent with the possibility that the Gambier Embayment assemblage represents a marine ingression with cooler surface waters (see Shafik, 1983), whereas the 66DR08B and the 66DR14A(6) assemblages are part of a full transgression with warmer surface waters.

Based on several Eocene nannofossil assemblages from the offshore Otway Basin, Shafik (1987b) suggested a trend of temperature decline begining very late in the middle Eocene, after a peak represented by an assemblage characterised by the presence of the key *Reticulofenestra scissura* and *Daktylethra punctulata* (and thus correlatable with the foraminiferal zone P13). The assemblages from 66DR08B and 66DR14A(6), which include the warm-water species *Sphenolithus predistentus* and/or *Helicosphaera reticulata*, are thought to be slightly younger than this peak.

In the Gambier Embayment (western onshore Otway Basin), the ranges of *Chiasmolithus solitus* and *Reticulofenestra scissura* do not overlap. In the offshore Otway Basin (Shafik, 1987a) and in the Great Australian Bight Basin these taxa co-occur.

Late Eocene–early Oligocene

The rare occurrence of the oceanic species *Bramletteius serraculoides* and the absence of hemipelagic taxa (such as *Lanternithus minutus*) in the late Eocene 66DR01A *Chiasmolithus oamaruensis* assemblage in the Great Australian Bight Basin, distinguish it from coeval assemblages in the onshore Otway Basin; the latter usually include a large number of hemipelagic taxa (Shafik, 1983).

The late Eocene assemblages recovered from 66DR12A(5) and 66DR14D have counterparts in the onshore Otway Basin. The Otway Basin assemblages lack *Discoaster barbadiensis* and *Helicosphaera compacta* which are present in the Great Australian Bight Basin. This suggests that surface waters during the late Eocene were probably warmer in the Great Australian Bight Basin than in the Otway Basin, to the east. *Discoaster barbadiensis* ranges higher in the Great Australian Bight Basin sequence (upper Eocene) than in the equivalent sequence in the Otway Basin, where it disappears high in the middle Eocene (Shafik, 1983). Further to the east in the New Zealand sequence, *D. barbadiensis* disappears at a lower level within the middle Eocene (Edwards, 1971).

The early Oligocene assemblages recovered from 66DR14B and 66DR06A are similar to coeval assemblages in the onshore and offshore parts of the Otway Basin which are recorded by Shafik (1983, 1987a,b).

Mid-late Oligocene

The presence of the low-latitude key species *Sphenolithus distentus* indicates warmer surface waters during the mid Oligocene in the Great Australian Bight Basin (66DR12B) than in the Otway Basin where the species is not known (being either very rare or absent). The late Oligocene 66DR06B assemblage with *Sphenolithus ciperoensis* is correlated with coeval assemblages (also containing *S. ciperoensis*) which were recorded previously from three dredge stations in the offshore Otway Basin and off West Tasmania (Shafik, 1987b) and also noted in the onshore Otway Basin (in the Kingston Construction Camp Bore, location in Shafik, 1983).

Shafik (1987b) concluded that an excursion by *Sphenolithus ciperoensis* into the Otway Basin and West Tasmania occurred as a response to a 'short' warm episode during the late Oligocene. This same warm episode apparently may also be responsible for the presence of *S. ciperoensis* in the Great Australian Bight Basin.

Discussion of results

Maastrichtian–early Eocene marine ingressions

Samples 66DR01G and 66DR01L (from Canyon B between Eyre and Ceduna Terraces, Fig. 1) yielded planktic Maastrichtian foraminiferids (McGowran, 1988a,b), but not calcareous nannofossils. Similarly, sample 66DR14F (from Canyon J on Ceduna Terrace, Fig. 1) yielded early Eocene planktic foraminiferids (McGowran, 1988a,b), but not calcareous nannofossils. Similar situations occur in the onshore lower Tertiary sequence of southern Australia where levels bearing calcareous foraminiferids represent isolated marine ingressions. Several attempts by the writer to extract nannofossils from the Pebble Point Formation, several subunits of the Dilwyn Formation (Rivernook A, Rivernook Member, *Trochocyathus* Bed and Princetown member), and the Burrungule Member of the Knight Formation in the Otway Basin have been unsuccessful. Levels examined from these sediments are known to contain *sparse* calcareous foraminiferids, which include *few* planktic forms, representing early Tertiary marine ingressions (documentation in McGowran, 1965, 1968, 1970; Taylor *in* Singleton, 1967; McGowran & others, 1971; Taylor, 1971). This lack of calcareous nannofossils is probably a consequence of their extreme scarcity in these sediments, which may be initially a result of very shallow-water palaeoenvironments; nannofossil concentration involving very large volumes of samples is needed. However, it could also be the result of a combination of certain other environmental conditions which inhibited the production of coccoliths and nannoliths, while favouring non-coccolith bearing (naked) strains of nannoplankton, and at the same time did not affect the associated planktic foaminiferids. These conditions could have involved some imbalance in the supply of certain nutrients.

Modern nannofloras are generally more tolerant than planktic foraminiferids of marginal marine conditions. They are found in hostile environments such as the low-salinity Black Sea (Bukry, 1974) without the association of planktic foraminiferids, and the highly saline Gulf of Aqaba (Elat), associated with planktic foraminiferids (Winter & others, 1979). However, in a nascent (Cretaceous–Early Tertiary) ocean, the supply of critically limiting nutrients (such as dissolved phosphorus and calcium) and/or an imbalance in other essential components (such as carbon dioxide) may have different effects to those in the open sea, and thus may eventually produce sediments on its floor lacking coccoliths and nannoliths, but containing planktic foraminiferal tests. In addition to a limited planktic foraminiferal fauna, naked nannoflora may have flourished in the top water layers in such an 'ocean'. This scenario is highly likely for the *narrow* Late Cretaceous–early Eocene incipient Southern Ocean which had restricted connection to the world ocean. Changes in the chemistry of surface waters of this Cretaceous–Early Tertiary nascent ocean, which could be brought about temporarily by good connection to the world ocean during times of marine ingressions, may induce its non-coccolith forming nannoplankton to produce plates of calcium carbonate.

It has been shown, in laboratory culture studies of the extant coccolith-bearing *Emiliania huxleyi* (Lohmann) Hay & Mohler *in* Hay & others (1967), that an increase in the phosphate content of the medium in which it was grown may cause its cells to cease secretion of its coccoliths, without affecting the survival of the resultant naked form (Paasche, 1964). Tappan (1980, p. 723) stated that 'cultures can be maintained in a calcium-deficient medium, but although growth is otherwise normal, no coccoliths are produced' (see also Crenshaw, 1964; Paasche, 1964, 1965). Studies by Wilbur & Watabe (1963) and Paasche & Klaveness (1970) have shown that cells of *Emiliania huxleyi* could be decalcified in life by increasing the amount of carbon dioxide in the medium in which they were grown.

Data from southern Australia pertinent to the observations made above are scarce. However, two dredge hauls recovered during BMR Survey 66 by R.V. *Rig Seismic* were found to include phosphatic sediments of the right age, being within the Late Cretaceous and middle Eocene interval. These were sample 66DR01I (from Canyon B, Fig. 1), a laminated micrite and fine sandstone which includes a phosphorite interbed

25 mm thick, dated as late Paleocene by Alley (1988, based on pollen grains) and sample 66DR11F (from Canyon H, Fig. 1), nodules of hard calcareous phosphatic muddy quartz arenite or siltstone, dated as Late Cretaceous to Tertiary by Alley (1988). Sediments with reasonably high calcium carbonate content were not deposited in the Otway Basin before the middle Eocene, when shelf carbonates (Wilson Bluff Limestone) began accumulating in the Eucla Basin. The Paleocene and Lower Eocene sediments of the Otway Basin, which contain planktic foraminiferids, apparently without the association of calcareous nannofossils, are terrigenous, being largely carbonaceous sandy clays or silts, commonly micaceous and pyritic, with minor calcareous sandstones. Evidently, these sediments were deposited in a hostile environment which occasionally permitted planktic foraminiferids, coming from the Indian Ocean in the west, to survive. Coccolith secretion in the associated nannoflora was inhibited, probably due to high dissolved phosphorus and low calcium concentration in the surface waters of the young early Eocene ocean south of Australia.

The occurrence of planktic foraminiferids without the association of nannofossils in the Maastrichtian and early Eocene samples 66DR01G, 66DR01L and 66DR14F from the Great Australian Bight Basin is taken to indicate transient marine conditions, which although not necessarily inhibiting the growth and production of the non-coccolith bearing nannofloral cells, were not favourable for their calcification. Connection to the open sea was probably very restricted and intermittent. On the other hand, the presence of calcareous nannofossils in association with planktic foraminiferids in the Maastrichtian and early Eocene samples 66DR01H, 66DR03A, 66DR01F and 66DR08A, which represent marine ingressions into the Great Australian Bight Basin, is taken to indicate temporary changes to true marine conditions brought about by good connection to the open sea. Such an invasion by the open sea may result, for example, in nitrogen depletion (Tappan, 1986) which in turn may cause non-coccolith forming nannoplankton to produce coccoliths as indicated by studies *in vitro*. (Wilbur & Watabe (1963) showed that secretion of coccoliths occurred in a strain of *Emiliania huxleyi*, which normally lacks coccoliths, when grown in a nitrogen-deficient medium; see also Paasche, 1964.) A good connection with the open sea would also bring a fresh supply of coccolith-bearing nannoplankton and planktic foraminiferids.

Maastrichtian ingression. During the Late Cretaceous, the nascent Southern Ocean was narrow, relatively shallow, and generally unsuitable for coccoliths (Shafik, 1985). However, the data in this study demonstrate that marine conditions were established gradually during the late Maastrichtian in its western part, that is, in the region of the Great Australian Bight Basin. Three phases are probably discernible for the Maastrichtian ingression into the Great Australian Bight Basin, corresponding to a progressive increase in oceanic parameters over time. During the earliest phase, represented by samples 66DR01G and 66DR01L, connection with the open sea was probably restricted and conditions were apparently not favourable for coccolith-forming nannoplankton. Surface-water conditions during the second phase, represented by the 66DR01H assemblage, evidently began to resemble those of the open sea as coccolith-bearing nannoplankton began to flourish in the Great Australian Bight Basin. During the last phase, represented by the 66DR03A and 66DR01F assemblages, open-marine conditions were well established and calcareous nannofossils accumulated between the Eyre and Ceduna Terraces.

Early Eocene ingressions. The 66DR14F foraminiferal assemblage represents an early Eocene marine ingression into the Great Australian Bight Basin (McGowran, 1988a,b, in press) which apparently was incapable of supporting coccolith-forming nannoplankton. Conditions during this early Eocene ingression were less completely marine than during the following early Eocene 66DR08A *Discoaster lodoensis* and Potoroo *Discoaster sublodoensis* nannofossil ingressions. (According to McGowran (1988a,b, in press), the foraminiferids of 66DR14F are older than those of 66DR08A). The 66DR14F foraminiferal ingression (Fig. 8) may be regarded as a prelude to these other early Eocene ingressions. McGowran (in press) correlated the foraminiferids of 66DR14F with zone P7, and pointed out that they are either coeval or very close in age to the early Eocene Princetown marine ingression into the Otway Basin. This correlation is adopted here (see Fig. 8). The 66DR14F ingression (with a relatively diverse planktic foraminiferal fauna in the Great Australian Bight Basin) apparently reached the Otway Basin leaving *rare, sporadic* foraminiferids in the Princetown Member of the Dilywn Formation.

Framework of Eocene marine sedimentation along the Australian southern margin

In the Eocene sequence of the Otway Basin, calcareous nannofossil assemblages sandwiched between barren sediments have been used to define marine ingressions, and their uninterrupted vertical record to define marine transgression (see Shafik, 1983). On this evidence, the base of the Eocene transgression along the Australian southern margin is diachronous (Shafik, 1973, 1983), becoming younger eastward. The sea advanced from the west. The base of the uninterrupted record of nannofossil assemblages is middle Eocene in the Eucla Basin and late Eocene in the Otway Basin, where Eocene marine sedimentation included isolated middle Eocene assemblages representing marine ingressions. In the Eucla Basin no such ingressions (preceding the transgression) were detected. There, the base of the Tertiary (=middle Eocene) calcareous planktic sequence rests directly on Cretaceous or older rocks. The middle Eocene ingressions in the Otway Basin are here considered to represent the distal tongue of the Eucla Basin transgression — the advance of marine influence being from the west.

Like the 66DR14F ingression in the Great Australian Bight Basin, the Burrungule ingression into the Otway Basin, which lacks calcareous nannofossils but not planktic foraminiferids, could be a prelude to other (middle) Eocene marine ingressions (the *Cyclicargolithus reticulatus* and the *Reticulofenestra scissura* ingressions). This is based on an earlier correlation of the foraminiferids of the Burrungule Member with the middle Eocene zone P10 or equivalent (Ludbrook & Lindsay, 1969; McGowran & others, 1971). Recently the Burrungule Member has been correlated with the early Eocene zone P9 (McGowran, 1978) or the early Eocene P8 (McGowran, in press). It may therefore be regarded as representing an extension into the Otway Basin of the Potoroo *Discoaster sublodoensis* (=foraminiferal zone P9) or the 66DR08A *Discoaster lodoensis* (=zone P8) marine ingressions into the Great Australian Bight Basin. In Figure 8, correlation of the Burrungule foraminiferids with zone P8 is adopted, following McGowran (in press).

Data from both the offshore Otway Basin (Shafik, 1987a,b) and the present study suggest that the base of the marine transgression along the Australian southern margin becomes older seawards and in a westward direction, as would be expected. The same data suggest that the marine ingressions with coccolith-bearing nannoplankton, preceding the Eocene transgressions on the same margin, are also diachronous, becoming younger eastward and towards the continent. In the Great Australian Bight Basin, the base of the transgression (taken to be represented by the middle Eocene 66DR01D *Discoaster bifax–Reticulofenestra umbilica* assemblage) is older than the base of the transgression in the Eucla and Otway Basins (Fig. 8). The two early Eocene ingressions with coccolith-bearing nannoplankton (which are indicated by the nannofossil 66DR08A *Discoaster lodoensis* and Potoroo *Discoaster sublodoensis* assemblages) preceding this mid Eocene transgression in the Great Australian Bight Basin are obviously older than the (middle Eocene) *Cyclicargolithus reticulatus* and *Reticulofenestra scissura* ingressions which preceded the (late) Eocene transgression in the western Otway Basin (Gambier Embayment, Fig. 8).

Shafik (1983) suggested that the two middle Eocene ingressions in the Gambier Embayment of the Otway Basin which contained calcareous nannoplankton were related to a major acceleration in the seafloor spreading rate occurring south of Australia at about 44 Ma (Anomaly 20) as documented by Cande & others (1981) and Cande & Mutter (1982); the same is true for the coeval Eucla Basin transgression. This sudden increase in the spreading rate between Australia and Antarctica has been linked with seemingly coeval events in the Indian Ocean: a change in the direction of motion of the Indian Plate and termination of spreading between India and Australia as results of termination of subduction beneath Tibet and crustal shortening/thickening at the time of Anomaly 20, according to Patriat & Achache (1984).

The cause(s) of the (earlier) early Eocene ingressions in the Great Australian Bight Basin may also be related to major tectonic events. For example, the age of the first of these ingressions which contained coccolith-forming nannoplankton (the 66DR08A *Discoaster lodoensis* assemblage) equates with the time, about 54 Ma ago, of a global plate tectonic readjustment initiated by collision of India with the Ladakh island arc (Patriat & Achache, 1984).

Great Australian Bight seafloor subsidence since the Late Cretaceous, and latest Eocene–early Oligocene sea-level fall

Palaeontological data presented above suggest substantial subsidence of the seafloor of the Great Australian Bight Basin since the Late Cretaceous. These data are based on palynological and nannofossil evidence. There is palynological evidence, for example, for a non-marine environment during the Paleocene at a site now at a water depth of 3670–2720 m (in Canyon H, Fig. 1). The nannofossil evidence is based on the presence of certain species (including holococcoliths, braarudosphaerids, pontosphaerids) characteristic of neritic water masses, which I loosely describe as hemipelagic species or indicators of shallow-water deposition. Indeed, some of these species have been used to indicate different *neritic* environments for parts of the middle Eocene Weches Formation of Texas (Sherwood, 1974), deposition in *shallow-water nearshore basins* for Paleocene and Eocene sediments in Western Australia (Shafik, 1978), and to indicate *inner shelf* environments during the late Eocene in Northern Italy (Barbin, 1989) or *shallow-water* conditions for the late Paleocene Patala of Pakistan (Kothe & others, 1989).

Because nannofossils are the remains of mostly planktic algae, it can be argued that they cannot be used directly to indicate shallow-water deposition. However, observations over a number of years and in a number of localities (see, for example, Martini, 1965, 1970; Bukry, 1970; Bukry & others, 1971; Bybell & Gartner, 1972; Roth, 1974; Baldi-Beke, 1984) indicate that certain genera are characteristic of sediments known to have been deposited in shelf environment, and are usually absent from deeper marine sediments. Examples are the Late Cretaceous *Acuturris, Kamptnerius* and *Lucianorhabdus*, and the Tertiary *Daktylethra, Holodiscolithus, Lanthernithus, Micrantholithus, Pontosphaera, Transversopontis* and *Zygrhablithus*.

Thus, based purely on empirical evidence from the observational data record, these genera are putative indicators of a shelf environment. Sediment samples as old as Maastrichtian, in which species of these genera were found, came from sites in the Great Australian Bight Basin (discussed above) where water depth today exceeds 2000–3000 m. The lithologies of the samples which contain nannofossil indicators for deposition in neritic waters, together with the palynological evidence in associated samples, support deposition in a shallow-water environment. Accepting that deposition in the Great Australian Bight Basin occurred on the shelf for most of the Late Cretaceous–mid Eocene interval, it must be concluded, in the absence of any evidence of mass redeposition or slumping, that deepening occurred subsequently.

Details of the deepening/subsidence history of the seafloor of the Great Australian Bight Basin are beyond the scope of this paper. The deepening/subsidence might be due solely to sag as a result of sediment loading (thick sediments resulting from high sedimentation rates during the rifting between Australia and Antarctica) and thermal contraction over time during the drift phase (cooling of the crust being increasingly distant from the mid-ocean ridge over time), periodic sea level rise, or the net balance between such sag of seafloor and eustatic fluctuations in sea level.

The evidence from this study, however, suggests that the effect of deepening on the nannoflora was first noticeable in the middle Eocene (probably during the biostratigraphic interval bracketed by the lowest occurrences of *Cyclicargolithus reticulatus* and *Reticulofenestra scissura*, which equates with a position high in the foraminiferal zone P12). It is thus coincident with the onset of rapid spreading in the Southern Ocean (Cande & Mutter, 1982; Royer & Sandwell, in press). Until that time, the separation of the continental crust of Australia and Antarctica was less than 200 km (see Royer & Sandwell, in press, fig. 13).

Both the Australian and Antarctic margins were under the influence of the thermal anomaly associated with the slow phase of seafloor spreading which lasted to the middle Eocene. Rapid movement of the thermal anomaly, associated with the rapid seafloor spreading phase (middle Eocene onward), caused rapid thermal contraction, and thus faster subsidence of the Australian southern margin since the middle Eocene. Mutter & others (1985) and Hegarty & others (1988) indicated a two-stage subsidence history for the Australian southern margin: an Early Cretaceous very rapid subsidence phase associated with the rifting between Australia and Antarctica (which is indicated as having two stages by Williamson & others, 1990) and a very slow subsidence phase which began about 90 Ma ago, at the onset of seafloor spreading between the two continents. Unlike the initial phase, the slow subsidence phase was thermally-controlled, occurring during a period of a relative tectonic quiescence (Hegarty & others, 1988).

It is this slow subsidence phase (mid Cretaceous onward) which concerns the present study, and it is within this phase that the data presented here suggest an acceleration in the rate of subsidence during the middle Eocene. This change in the subsidence rate seems to represent an inflection point at least in one subsidence curve based on data from Jerboa No.1 well in the Great Australian Bight Basin (see Hegarty & others, 1988; Williamson & others, 1990), and also in the Mussel Platform wells in the Otway Basin (see Williamson & others, 1988).

The depositional palaeoenvironments of all Coniacian–Santonian, Maastrichtian, Paleocene and lower Eocene sediment samples discussed from the Great Australian Bight Basin range between non-marine, marginal marine and neritic (mainly middle shelf), and are incompatible with the present-day water depths from which they were collected. In contrast, some of the younger Eocene sediments, which were collected from similar water depths in the same basin, contain evidence for deeper depositional palaeoenvironments (outer shelf and continental slope) (see, for example, Tables 1–3). It is concluded that during the middle Eocene the rate of subsidence of the seafloor of the Great Australian Bight Basin accelerated, although it was masked during the latest late Eocene by a fall in sea level.

During the latest late Eocene and early Oligocene, the deepening process must have been reversed, with a fall in sea level exceeding the rate of subsidence of the seafloor of the Great Australian Bight Basin. This was indicated above by the presence/absence of indicators of shallow-water deposition in the middle Eocene, latest late Eocene and early Oligocene nannofossil assemblages recovered from dredge haul 66DR14 (see Table 2). This conclusion is consistent with a global fall in sea level which seems to have occurred during the latest late Eocene (see Haq & others, 1988).

Influence of proto-Leeuwin Current

Shafik (1983) suggested that surface-water temperatures decreased progressively in an eastward direction along the southern margin of Australia during the Eocene. The data from the Great Australian Bight Basin support this. The presence of the warmer-water species *Sphenolithus predistentus, Helicosphaera heezenii* and *H.* sp. aff. *H. reticulata* in the 66DR14A(5) assemblage, and not in the coeval Eocene Gambier Embayment assemblage, suggests warmer surface waters in the west (Great Australian Bight Basin) than in the east (Otway Basin). This is supported by the presence of *Sphenolithus predistentus* in the slightly younger 66DR08B assemblage and not in its Gambier Embayment near-equivalent, and by the presence of *Helicosphaera reticulata* in 66DR14A(6). Moreover, other data presented here suggest a similar eastward decrease in surface-water temperatures during the mid to late Oligocene: the low-latitude key species *Sphenolithus distentus* is abundant in the Ceduna Terrace material, whereas it is not known (being either very rare or absent) from the Otway Basin.

Only speculation can be offered on why surface waters were progressively cooler in an eastward direction along the southern margin of Australia during the middle Eocene–late Oligocene. This speculation draws on a modern analogy, although the scenario considered was before the formation of the deep-sea passage south of the South Tasman Rise (Kennett & others, 1975; Kennett, 1977).

Although it is commonly held that currents along the western margins of continents are usually northerly flowing in the southern hemisphere, the Leeuwin Current, off Western Australia, flows in a southerly direction, bringing warm waters from the northwest corner of Australia into its southwest corner and southern Australia (Cresswell & Golding, 1980; Legeckis & Cresswell, 1981; Rochford, 1984, 1986). The Leeuwin Current today contributes to the occurrence of a significant tropical fauna of benthic invertebrates, holothurians and several species of pelagic tuna in the Great Australian Bight (Maxwell & Cresswell, 1981). A similar current, a proto-Leeuwin Current (Fig. 9), seems to have existed during much of the Eocene and Oligocene. It may have begun during the middle Eocene, intermittently bringing warm waters into southern Australia from the Indian Ocean. Dilution of the effect of such current would be expected to occur along the southern margin in an easterly direction, with the result that surface waters in the Otway Basin would be cooler than those in the Great Australian Bight Basin.

The evidence for a proto-Leeuwin Current, presented earlier, suggests that the flow of the current was intermittent, being particularly prominent at times during the middle and late Eocene, and during the mid Oligocene.

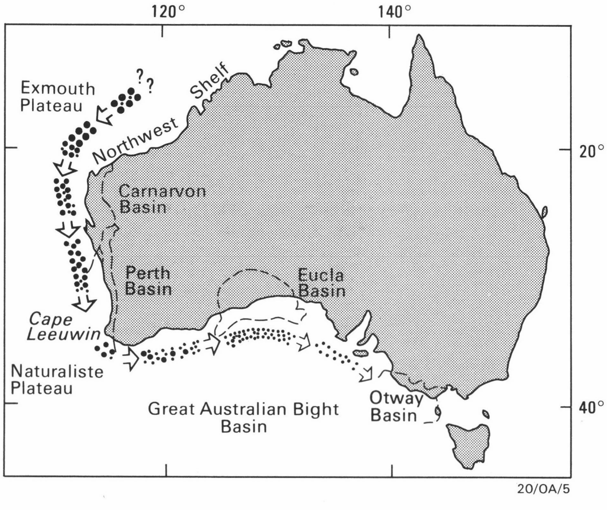


Figure 9. Sketch map of Australia and surroundings, showing the southward flow of a warm proto-Leeuwin Current along the western continental slope and its eastward turning into the southern Australian waters after passing Cape Leeuwin.
This intermittent current was initiated during the middle Eocene. Larger circles correspond to higher surface-water temperatures.

Important Oligocene biostratigraphic datums in the Great Australian Bight Basin sequence

Records of the low-latitude *Sphenolithus distentus* and *S. ciperoensis* in southern Australia (Shafik, 1987b; this study) should in due course provide two important datums for the calcareous microplanktic biostratigraphy of the Oligocene of southern Australia, because they allow a direct link with global time scales. The lowest occurrences of these key nannofossil species have been linked with low-latitude foraminiferal zonations (see, for example, Martini, 1971).

Conclusions

The study documents several new calcareous nannofossil assemblages in southern Australia. These are (a) Maastrichtian assemblages from Canyon B between the Eyre and Ceduna Terraces, which abound with high-latitude elements such as *Nephrolithus corystus, N. frequens, Cribrosphaerella daniae* and *Kamptnerius magnificus*, and (b) Eocene assemblages older than the middle Eocene assemblage known from the base of the Wilson Bluff Limestone (and Hampton Sandstone) in the Eucla Basin. These include two early Eocene (the *Discoaster lodoensis* and *D. sublodoensis*) assemblages and a mid Eocene (*Discoaster bifax-Reticulofenestra umbilica*) assemblage. The *D. lodoensis* assemblage is also older than any known from the Eocene section of the Naturaliste Plateau. The *D. sublodoensis* assemblage is based on material from Potoroo No.1 well, whereas all other assemblages were recovered from dredged samples from the Great Australian Bight Basin. These new Maastrichtian and early Eocene assemblages, apparently individually bracketed by barren intervals, are considered to represent marine ingressions.

Correlation of foraminiferal and nannofossil results on material from the Great Australian Bight and Otway Basins indicates that before the marine ingressions which contained both calcareous nannofossil and foraminiferal assemblages, there are usually other ingressions which apparently were suited for planktic foraminiferids but not coccolith-bearing nannoplankton. Conditions during these early ingressions were not completely marine, probably because of restricted access to the open sea. During later ingressions, better access to the open sea substantially increased the oceanic influence, causing both calcareous foraminiferids and coccolith-forming nannoplankton to flourish.

A comparison of the offshore (Great Australian Bight Basin) and onshore (Otway Basin) sequences reveals an offset parallelism in their history. In the Great Australian Bight Basin, early Eocene ingressions preceded a middle Eocene transgression, while in the onshore Otway Basin, middle Eocene ingressions preceded a late Eocene transgression. The timing of the first early Eocene ingression, which contained coccolith-bearing nannoplankton, into the Great Australian Bight Basin seems to coincide with the timing of a global plate readjustment, initiated by the collision of India with the Ladakh Island Arc at about 54 Ma ago. The first middle Eocene ingression with coccolith-bearing nannoplankton into the Otway Basin was the distal tongue of the Eucla Basin transgression. This ingression has been linked with a major acceleration in the seafloor spreading rate south of Australia at about 44 Ma ago (Shafik, 1983).

Based on interpretations of the depositional palaeoenvironments of sediment samples, using nannofossils and lithological evidence, together with palynological data (Alley, 1988), it is concluded that the seafloor of the Great Australian Bight Basin must have subsided considerably since the Late Cretaceous. The effect of this subsidence on the nannoflora was first noticeable in middle Eocene assemblages, coincident with a major acceleration in the rate of seafloor spreading south of Australia. This middle Eocene increase in the subsidence rate evidently ended a distinctive stage of a very slow subsidence which was initiated at about 90 Ma ago. A latest late Eocene drastic fall in sea level masked the effect of the subsidence well into the Oligocene.

There is evidence to suggest that surface-water temperatures decreased in an eastward direction along the Australian southern margin during much of the Eocene and Oligocene. This was probably caused by an eastward declining effect of a warm current, similar to the present Leeuwin Current, coming from the Indian Ocean since the middle Eocene. The flow of this proto-Leeuwin Current was intermittent, being prominent at times during the middle and late Eocene and during the mid Oligocene.

The excursion of the key low-latitude nannofossil *Sphenolithus ciperoensis* into southern Australia, previously documented in the onshore and offshore areas of the Otway Basin, is demonstrated in the Great Australian Bight Basin.

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