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Upper Cretaceous and Tertiary stratigraphy of the Fremantle Canyon, South Perth Basin: a nannofossil assessment

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The nannostratigraphy of material dredged from the Fremantle Canyon, west of Perth (Western Australia), indicates that the Maastrichtian–Miocene section in the South Perth Basin is more complete than contemporaneous sections in the Perth Abyssal Plain and on the Naturaliste Plateau. The data point to a possible continuous sequence through most of the Paleocene and the entire Eocene in the Fremantle Canyon. In addition to the five rock units previously known to form the Maastrichtian–Miocene succession of the Perth Basin, two (or possibly three) new units have been discovered. The new units, yet to be named, are of Early Eocene and mid Oligocene age; in addition a previously unreported Lower Paleocene sequence could be the lower extension of the Kings Park Formation offshore. The unnamed new Lower Eocene unit fills the stratigraphic gap between the (mainly) Upper Paleocene Kings Park Formation and the Middle Eocene Porpoise Bay Formation. The unnamed new mid (upper Lower) Oligocene unit fits between the 'Upper Eocene' Challenger Formation and the Lower–Middle Miocene Stark Bay Formation, still leaving a large stratigraphic gap between these two formations. The lithological evidence, supported by nannofossil data, indicates that the Porpoise Bay and Challenger Formations merge into a single unit along the canyon walls. This unit is similar to the Lower Eocene and Paleocene carbonates there. A widespread Late Maastrichtian transgression over the Carnarvon and Perth Basins, reaching the Great Australian Bight Basin as an ingression, is seen in the Fremantle Canyon as occurrences of nannofossil association characteristic of the Upper Maastrichtian Breton Marl onshore. Several lines of evidence are discussed to suggest that the onshore Kings Park Formation represents a rapid sea level rise and culmination of the Paleocene transgression over the Perth Basin. Indications of a previously reported significant Middle Eocene reworking episode are recorded at the right level in the Fremantle Canyon succession. Middle Eocene microplanktic components found in the newly reported mid Oligocene of the canyon are thought to have been derived from the Naturaliste Plateau during a major Oligocene erosional event, whose effects have been recorded previously in several DSDP sites in the Southwest Pacific region.

Introduction

With the exception of the Upper Paleocene–Lower Eocene Kings Park Formation, the Upper Cretaceous–lower Tertiary marine sequence in the Perth Basin (Western Australia) was poorly known biostratigraphically until fairly recently. Two unnamed Eocene units containing calcareous nannofossils and/or planktic foraminiferids have been recently discovered: a Middle Eocene unit in the Rottnest Island Bore (Fig. 1) investigated by Shafik (1978), who recorded its calcareous nannofossils, and an 'Upper Eocene' unit in the Challenger No. 1 well (Fig. 1) investigated by Quilty (1978), who documented its planktic foraminiferids. Cockbain & Hocking (1989) proposed the names Porpoise Bay and Challenger Formations for these Eocene units. More recently, Shafik (1990a) discovered an Upper Maastrichtian marine unit in two coreholes at Breton Bay (31°10′36″S, 115°24′06″E), rich with abundant calcareous nannofossils, which he named the Breton Marl.

Material examined in the present study came from the Fremantle Canyon in the offshore South Perth Basin (Fig. 2). It fills most of the nannofossil biostratigraphic gap between the type sections of the Upper Paleocene–Lower Eocene Kings Park Formation and the Middle Eocene Porpoise Bay Formation, and includes records of several other new nannofossil-bearing levels within the Palaeogene and Miocene (see Fig. 3). Equivalents of the previously known five lithostratigraphic units, which form the marine Maastrichtian–Miocene sequence in the Perth Basin (Fig. 3), are identified, based on occurrences of their nannofossil assemblages in the material studied.

The study is based on dredge samples recovered during BMR Cruise 80 by R/V *Rig Seismic*. Dredging during this survey was successful at 17 stations. Calcareous nannofossil-bearing sediments came from 14 stations along the walls of the Fremantle Canyon and also from one station (80DR/003) on the continental slope north of the canyon. Water depths at these stations, and their locations, are given in Table 1. The continental slope west of Perth is fairly smooth, but it is incised occasionally by submarine canyons and gullies. Notable among these canyons is the Fremantle Canyon, whose head is near the

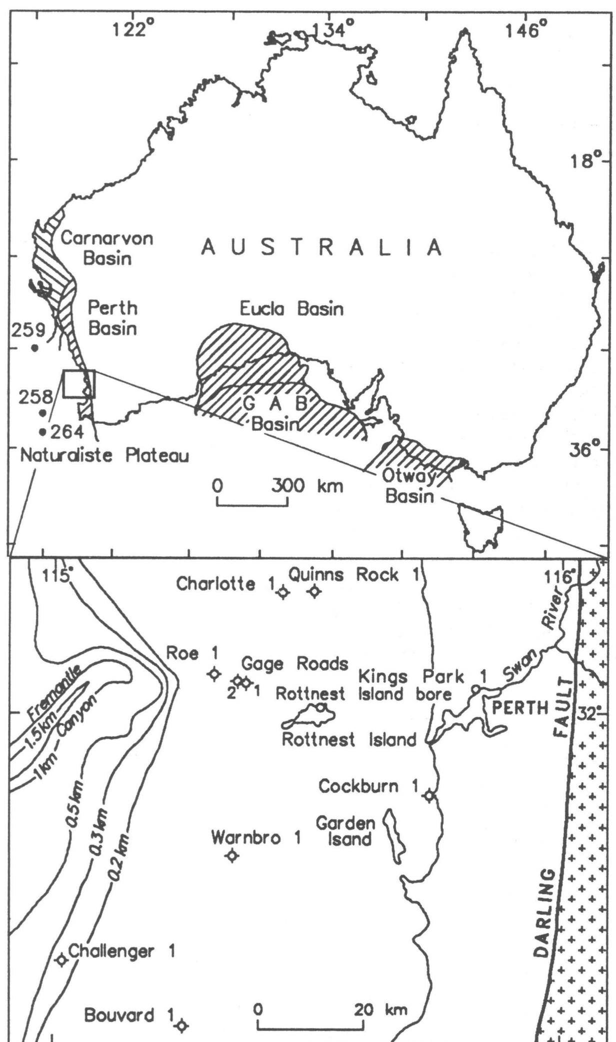

Figure 1. South Perth Basin, Western Australia, showing location of relevant wells.

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shelf break directly off Perth. This canyon is about 160 km long, and consists of three discrete segments of similar length (Fig. 2; see Marshall & others, 1989; Quilty & others, in press). Initially, the canyon trends southwesterly for about 50 km, to an axial depth of 1700 m, where it suddenly changes direction to join a northwesterly-trending arm. This northwesterly arm of the canyon extends for about 60 km, to an axial depth of 3000 m, before abruptly changing direction to a westerly orientation. The canyon extends in this direction to a depth of 4600 m where it opens out onto a submarine fan.

Table 1. Location of dredge stations where nannofossil-bearing Maastrichtian and Tertiary sediments outcrop, and water depth at these stations.

Dredge station	*Latitude (°S)*	*Longtitude (°E)*	*Depth (m)*
80DR/003	31°13.64′	114°35.96′	2415
80DR/005	32°00.70′	114°58.00′	730–1350
80DR/007	32°03.30′	115°01.13′	650–850
80DR/008	32°02.50′	115°00.30′	850–1150
80DR/009	32°01.70′	114°58.60′	1200–1650
80DR/013	32°03.60′	114°45.00′	1940–2500
80DR/014	32°03.10′	114°45.50′	1135–1965
80DR/016	32°06.05′	114°43.00′	1750–2470
80DR/017	31°57.40′	114°44.20′	1800–2814
80DR/018	31°59.80′	114°39.50′	2400–2810
80DR/019	32°00.00′	114°38.00′	1600–2700
80DR/020	31°50.05′	114°37.60′	2420–3000
80DR/021	31°48.00′	114°39.00′	1420–2650
80DR/022	31°51.80′	114°36.30′	2310–2970
80DR/023	31°53.40′	114°34.50′	1920–2520

Detailed lithological descriptions and other relevant data concerning the samples examined in this study are given by Marshall & others (1989). In general, the lithologies of the Tertiary samples reflect carbonate deposition on the outer shelf and upper continental slope.

Previously known Maastrichtian and early Tertiary calcareous microplankton biostratigraphy of the Perth Basin

Shafik (1990a) detailed the Late Cretaceous nannofossil biostratigraphy of onshore parts of the Perth Basin. The documentation of Late Maastrichtian assemblages, from what was referred to as the Breton Marl, is relevant to the present study. These assemblages are characterised by the occurrence of *Nephrolithus frequens, Lithraphidites quadratus* and *Cribrosphaerella daniae*.

The Breton Marl is best known from the Breton Bay corehole No. 1 (31°10′36″S, 115°24′06″E). There, it consists of an approximately 6 m thick section of soft marl. The underlying Lancelin Formation is about 60 m thick in Breton Bay corehole No. 1, and is separated from the Breton Marl by an intra-Maastrichtian disconformity. The Breton Marl is a part of a wide Late Maastrichtian transgression which occurred in both the Perth and Carnarvon Basins (Shafik, 1990a), and reached the Great Australian Bight Basin as a marine ingression (Shafik, 1990b).

The Kings Park Formation (Fairbridge *in* Coleman, 1952; amended Quilty, 1974a,b) has the oldest Tertiary marine sediments in the onshore Perth Basin. Its type section is 275 m thick in the Kings Park No. 2 Bore (Perth metropolitan area) (Fig. 1), but a thickness of more than 500 m has been reported elsewhere in the Perth area (Playford & others, 1975). The formation consists of grey, calcareous, mostly glauconitic shale and siltstone, containing bryozoans, foraminiferids, calcareous nannofossils, molluscs, ostracods and sponge spicules (McWhae & others, 1958; Shafik, 1978). McGowran (1964, 1968) revised the age of the Kings Park Formation to Late Paleocene, and correlated its planktic foraminiferids with his *Acarinina mckannai* zonule which roughly equates with zone P4. Cockbain (1973) recorded a foraminiferal assemblage of Late Paleocene to Early Eocene age from the formation, and Quilty (1974a,b) indicated that foraminiferids recovered from offshore are younger than Late Paleocene.

Shafik (1978) recorded the nannofossil assemblages of the Kings Park Formation in several boreholes as well as its type section, and correlated these assemblages with the Late Paleocene foraminiferal zones late P4 and P5, but also argued for an Early Eocene age (zone P6). Assemblages from the younger levels (Upper Paleocene–Lower Eocene) include the key species *Campylosphaera eodela, Chiasmolithus eograndis, Coccolithus* sp. cf. *C. formosus, Discoaster* sp. cf. *D. diastypus, D. multiradiatus* and *Transversopontis* sp. aff. *T. pulcher*, whereas those from the Upper Paleocene levels lack discoasters, but include the index species *Heliolithus kleinpellii* and *H. riedelii*, in addition to several species of *Fasciculithus*.

Shafik (1978) dated nannofossils from a unit in the Rottnest Island Bore, formally regarded as Kings Park Formation, as Middle Eocene in age. He recommended that this unit be given separate lithostratigraphic status, because it was deposited during a separate sedimentary cycle from that which produced the Kings Park Formation. Subsequently, Cockbain & Hocking (1989) named the unit in the Rottnest Island Bore the Porpoise Bay Formation. The type section of the Porpoise Bay Formation consists of 382 m of brown calcareous shale and siltstone, unconformably overlying the Lower Cretaceous Leederville Formation.

According to data in Shafik (1978), the lower part of the type section of the Porpoise Bay Formation contains rich nannofossil assemblages which include *Braarudosphaera bigelowii, Chiasmolithus grandis, Coccolithus eopelagicus, Coccolithus formosus, Daktylethra punctulata, Discoaster tanii nodifer, Helicosphaera lophota, Lanternithus minutus, Micrantholithus procerus, Pemma basquensis, P. papillatum, P. rotundum, Pontosphaera multipora, P. ocellata, Reticulofenestra dictyoda, R. scrippsae, R. umbilicus* and *Zygrhablithus bijugatus*. The key species *Chiasmolithus solitus, Cyclicargolithus reticulatus* and *Helicosphaera reticulata* are also present, suggesting correlation with the Middle Eocene foraminiferal zone P12. Several species of planktic foraminiferids from the type section of the Porpoise Bay Formation, indicating Early Eocene age (zone P6), were recorded earlier by Quilty (1974a), and later augmented (Quilty, 1978) by others including a few index forms indicative of Middle Eocene age (P11–P13 zonal interval) from the same section. Quilty (1978) accepted the Middle Eocene age which was supported by both nannofossil and dinoflagellate data.

Quilty (1978) described an unnamed 'Upper Eocene' unit from the offshore South Perth Basin (in the Challenger No. 1 well, Fig. 1), in addition to recording its foraminiferids. This unit was named the Challenger Formation by Cockbain & Hocking (1989). The type section of the Challenger Formation in the Challenger No. 1 well consists of 67 m of chalk, calcarenite and chert, disconformably overlying the Kings Park Formation, and disconformably overlain by an unnamed Upper Miocene unit. The foraminiferal determinations (and consequently the age) of the type section of the Challenger Formation are based on two samples of ditch cuttings, taken at 15 m interval. According to Quilty (1978), the planktic foraminiferal species *Chiloguembelina cubensis, Hantkenina alabamensis, H. primitiva, Pseudohastigerina micra, Tenuitella gemma* (reported as *Globorotalia*), *Globorotalia*

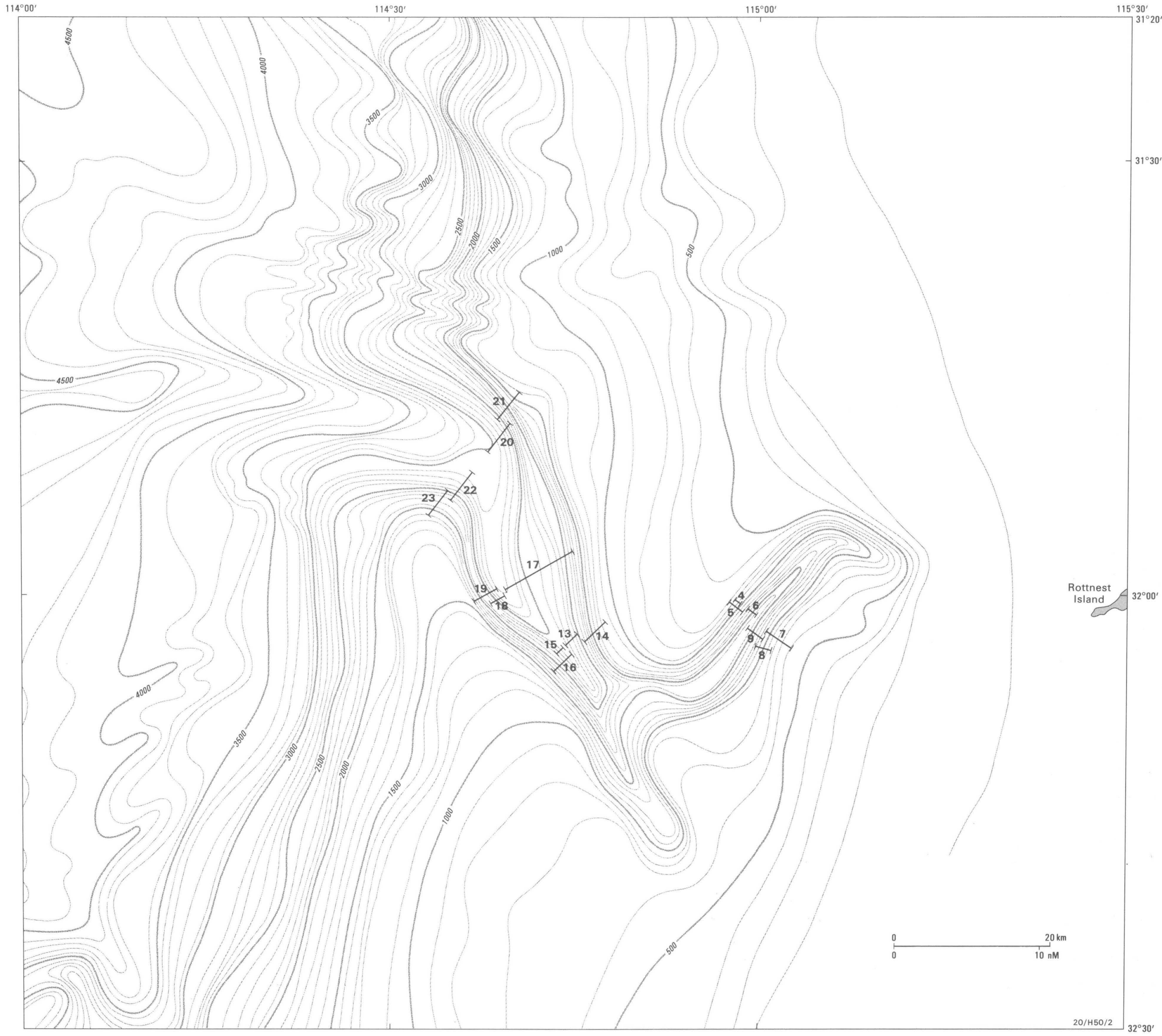


Figure 2. The Fremantle Canyon, South Perth Basin, showing location of dredge samples studied.

cerroazulensis, G. opima nana, Subbotina linaperta, Acarinina primitiva (reported as *Pseudoquadrina*), *Globorotaloides suteri* and *Catapsydrax pera* are restricted to the lower sample (which is probably from about 7 m from the base of the formation). *Globigerinatheka index index, G. subconglobatus luterbacheri, Globigerina corpulenta, G. eocenica* and *Subbotina angiporoides* occur in both samples (see Quilty, 1978, fig. 2). These faunal lists include not only Upper Eocene species and several other species known to range into the Upper Eocene (such as *Hantkenina primitiva* and *Globigerinatheka index index*; see, e.g., Blow, 1969, 1979; McGowran, 1978), but also species indicative of Middle Eocene age (see below).

The key species *Acarinina primitiva* is known to disappear below the Upper Eocene in southern Australia (McGowran, 1978; see also discussion in Shafik (1983) about correlating the extinction datum of this species within the Middle Eocene zone P13) and elsewhere (Blow, 1969, 1979; Stainforth & others, 1975; Jenkins, 1985; Toumarkine & Luterbacher, 1985). Significantly, it is among the species restricted to the lower sample. Because of the problems of downhole contamination associated with the study of ditch cuttings, it is generally accepted that the tops of species stratigraphic ranges are the best reliable biostratigraphic evidence. Consequently, the presence of *Acarinina primitiva* suggests that the basal part of the type section of the Challenger Formation is likely to be Middle Eocene (zone P13 or P14), in spite of the apparent association of species indicating a younger age (which can be attributed to downhole contamination).

The planktic foraminiferids restricted to the higher sample (15 to 30 m below the upper boundary of the type Challenger Formation) include *Globorotalia opima opima, Globigerina officinalis, G. praebulloides praebulloides, Catapsydrax martini martini* and *C. unicavus* (see Quilty, 1978, fig. 2). *Globorotalia opima opima*, an Oligocene species (Blow, 1969, 1979; Stainforth & others, 1975; Bolli & Saunders, 1985), cannot be regarded as a result of downhole contamination from the overlying unit because foraminiferids of the latter unit are Late Miocene as dated by Quilty (1978). Therefore, *G. opima opima* is regarded as a good indication that the uppermost part of the type section of the Challenger Formation is Oligocene. The presence of *Subbotina angiporoides* (in the higher sample, Quilty, 1978) may also support an (Early) Oligocene age. The type section of the Challenger Formation covers the Middle Eocene to the (Early) Oligocene (Fig. 3; see also below). *Hantkenina primitiva* has a very short range within the Upper Eocene of southern Australia, disappearing either late in zone

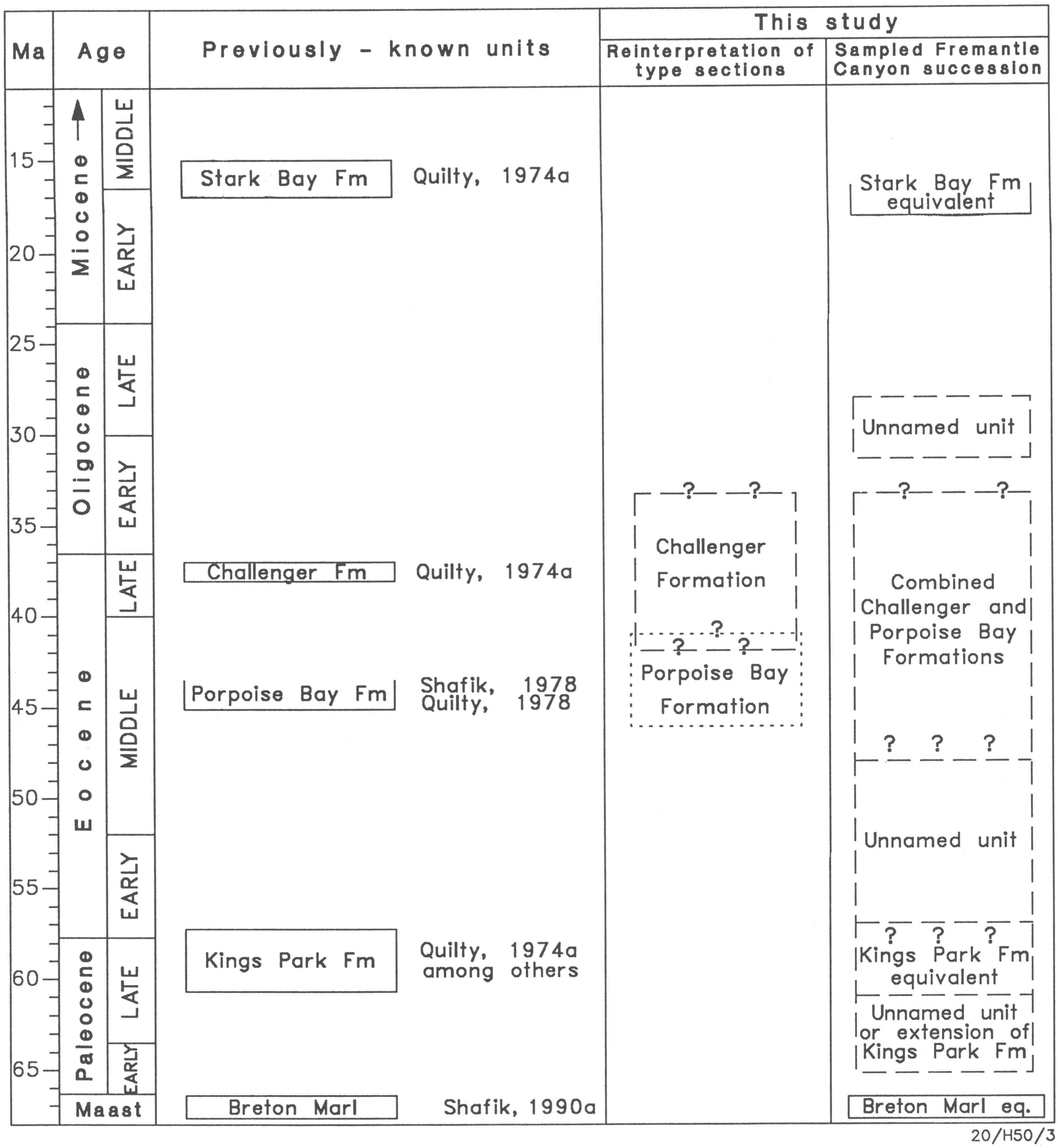


Figure 3. The Maastrichtian–Middle Miocene stratigraphy of the South Perth Basin.

P15 (McGowran, 1986) or within zone P16 (Shafik, 1981). Its presence in the lower sample (and absence from the higher sample) in the type section of the Challenger Formation in the Challenger No. 1 well (Quilty, 1978, fig. 2) suggests that the middle part of this section includes an Upper Eocene segment (probably spanning zones P15 and P16). (Because of its association with *Acarinina primitiva, Hantkenina primitiva* is regarded as a downhole contaminant from the middle part of the section, being absent from the higher sample.) *Globigerinatheka subconglobata luterbacheri* ranges elsewhere from the top of zone P13 to within zone P16 (Toumarkine & Luterbacher, 1985). Its presence in the lower sample supports the age assignment of Middle to Late Eocene for a substantial part of the type section of the Challenger Formation, as concluded above from the presence of both *Acarinina primitiva* and *Hantkenina primitiva*; correlation with the foraminiferal zonal interval P14–P16 can be thus demostrated. The occurrence of *Globigerina praebulloides praebulloides*, which is known to be restricted to the Late Eocene zonal interval P15–P16 (Blow, 1969, 1979) in the higher sample, shows an Upper Eocene part (P16 above the extinction of *Hantkenina primitiva*) extending to the level of the higher sample, and points to a thin Oligocene. Quilty (1978) correlated the planktic foraminiferids from the type section of the Challenger Formation with the Late Eocene P16 zone, though he referred the lower sample to the P15–P16 zonal interval in his figure 2.

It is my opinion that the choice of the type section of the Challenger Formation from the Challenger No. 1 well (Cockbain & Hocking, 1989) is unfortunate, because of the lack of adequate material to date it more precisely. This 67 m section was apparently not cored and probably not more than two samples of ditch cuttings were taken. The Challenger Formation was originally intended as an Upper Eocene unit. Reinterpretation of its planktic foraminiferids indicates that it ranges from the Middle Eocene through to within the (Early) Oligocene (see Fig. 3).

Late Cretaceous to Early Oligocene nannofossil assemblages from the Fremantle Canyon

The distribution of the calcareous nannofossils recovered from most of the Fremantle Canyon dredges (Checklists 1, 2) and the illustrations in this paper (Figs 5, 6, 8–12) are based on optical microscopic examination of smear slides. In the discussion below, the assemblages are arranged in chronological order. Nannofossil biostratigraphic assignments made below (see also Figs 4, 5) are to datum intervals (DI) rather than zones, in order to avoid difficulties inherent in the usage of formally defined zonations; see Shafik (*in* Shafik & Chaproniere, 1978) and Shafik (1990a,b) on the reasons for preferring the use of the concept of datum interval. (The symbols * and + are used to denote lowest and highest occurrences of species respectively when naming a datum interval.) Correlations with the foraminiferal P and N zones are made when possible. This facilitates comparison of results obtained here with those based on planktic foraminiferids, either from the same material (Apthorpe *in* Marshall & others, 1989), or from other sections elsewhere in the Perth Basin (e.g. Quilty, 1974a, 1978).

Late Maastrichtian (Breton Marl equivalent)

Three samples (80DR/020–9 to -11; see Fig. 2 for location) of light to medium grey, fairly soft calcilutite were dredged from the northeastern wall of the Fremantle Canyon. These contained rich nannofossil assemblages (see Checklist 1). The presence of the age-diagnostic species *Nephrolithus frequens, Cribrosphaerella daniae* and *Lithraphidites quadratus* in all three samples suggests a Late Maastrichtian age, and that these samples are from the same stratigraphic unit. The overall composition of the assemblages suggests cool to cold surface waters, and deposition on the shelf or upper continental slope. The solution-prone *Kamptnerius magnificus* (Roth, 1973) is present in two of these samples.

Discussion. The evidence of age and depositional palaeoenvironment derived from the Fremantle Canyon samples matches similar evidence in land-based assemblages from the Breton Marl (Shafik, 1990a). The latter contain more solution-prone taxa (such as *Calculites obscurus* and *Acuturris scotus*), which suggests shallower depositional depths. Thus, the canyon samples represent the offshore equivalent of the Breton Marl, notwithstanding the more calcareous nature of these samples.

It is worth noting that the nannofossil key species for the latest Maastrichtian, *Micula prinsii* (Perch-Nielsen, 1979), was not found in either the onshore Breton Marl (Shafik, 1990a) or its offshore equivalent in the Fremantle Canyon. This apparent absence could indicate a hiatus at the Cretaceous/Tertiary boundary. *M. prinsii* was found in reworked Miria Marl at the base of the Paleocene Boongerooda Greensand, in the Giralia Anticline north of the Carnarvon Basin (Shafik, 1990a), but it is highly likely that this species preferred warmer waters than those in the South Perth Basin.

Early Paleocene (no known onshore equivalent)

Three assemblages, corresponding to three biostratigraphic levels, are described below.

Assemblage A. Sample 80DR/014–5, a grey friable to well-cemented glauconitic calcilutite dredged from the northern wall of the canyon (Fig. 2), yielded a fairly well-preserved nannofossil assemblage. The assemblage is an admixture of Late Cretaceous and Early Paleocene forms (see Checklist 1). The Late Cretaceous forms are diversified. They include Late Maastrichtian species, such as the key species *Nephrolithus frequens*. The Paleocene forms are fewer in number of species. They include *Cruciplacolithus asymmetricus* and *Ericsonia subpertusa. Thoracosphaera operculata* and *Markalius astroporus* are also present. The assemblage is assigned to the Early Paleocene biostratigraphic interval, immediately below the lowest occurrence of *Cruciplacolithus tenuis* (Fig. 4). A correlation with the foraminiferal zone late P1b is indicated.

Remarks. It is interesting to note that Apthorpe (*in* Marshall & others, 1989) assigned sample 80DR/014–5 an age of Late Campanian to Maastrichtian, based on the foraminiferal species *Gublerina cuvillieri*. Evidently the foraminiferids are extremely rare in this sample, and what Apthorpe picked was the reworked part. This is consistent with the nannofossil evidence of a high percentage of reworked Upper Cretaceous nannofossil elements in the sample.

Assemblage B. Sample 80DR/014–10, a grey soft calcilutite, contains a very rich, moderately well-preserved nannofossil assemblage, dominated by species of *Cruciplacolithus* but including a large number of rare reworked Late Cretaceous species. The assemblage is assigned to the Early Paleocene biostratigraphic DI:**Chiasmolithus inconspicuus*/**Ellipsolithus macellus* (see Fig. 4), on the presence of *C. inconspicuus* and *Cruciplacolithus tenuis* (see Fig. 5). This assignment suggests a correlation with the foraminiferal zone early P1c. The foraminiferal evidence of *Nuttallides truempi* and high planktic percentage (Apthorpe *in* Marshall & others, 1989), and the notable absence of pentaliths and other nannofossil shallow-water indicators, suggest that deposition was probably on the continental slope.

Assemblage C. Sample 80DR/020–08, a grey friable calcilutite dredged from the northeastern wall of the canyon (Fig. 2), contains a moderately well-preserved assemblage, with *Chiasmolithus edentulus* but without species of *Fasciculithus* and *Sphenolithus* (see Checklist 1). Reworked Upper Cretaceous forms are very rare, and are apparently confined to a few species. The assemblage is assigned to the Early Paleocene biostratigraphic DI:**Chiasmolithus edentulus*/**Fasciculithus tympaniformis* (Fig. 4), which correlates with the foraminiferal zonal interval P2–P3a.

Discussion. The three samples examined above are thought to represent biostratigraphic levels unknown from the onshore sequence of the Perth Basin. Our current knowledge confines the onshore Kings Park Formation to the Late Paleocene–Early Eocene interval. There are two alternative interpretations regarding these Lower Paleocene levels: (1) they are a new unit (or units) separate from the Kings Park Formation, or (2) they are a part of the offshore Kings Park Formation, i.e. the lower boundary of the Kings Park Formation becomes older offshore, suggesting that this formation is transgressive.

The apparent absence of basal Paleocene assemblages below the lowest occurrence of *Cruciplacolithus asymmetricus* (Fig. 4) lends some support to the notion of a biostratigraphic gap at the Cretaceous/Tertiary boundary.

Age	Calcareous nannofossil biostratigraphic events	(Foraminiferal P zones)	Dredges and Rock units	
Early Eocene	+*Fasciculithus* spp.	(early P6b)		Kings Park Formation equivalent
	* *Tribrachiatus bramlettei; Discoaster diastypus*		80DR/020-06	
Late Paleocene			80DR/021-05	
	* *Campylosphaera eodela*	(P5/P6 boundary)	80DR/017-03	
	* *Discoaster multiradiatus*	(late P4)	80DR/014-12 80DR/014-13	
	* *Discoaster nobilis;* * *Heliolithus riedelii*	(mid P4)		
			80DR/005-08 80DR/005-09 80DR/014-03 80DR/016-02 80DR/016-03 80DR/022-03	
	* *Discoaster mohleri*	(early P4)	80DR/004-02 80DR/014-08	
	* *Toweius pertusus*	(early P4)		
Early Paleocene	* *Cruciplacolithus frequens*	(late P3b)		Unnamed new unit(s) or old phase of Kings Park Formation
	* *Heliolithus kleinpellii*	(mid P3b)		
	* *Fasciculithus tympaniformis*	(P3a/P3b boundary)	80DR/020-08	
	* *Chiasmolithus edentulus*	(P2)		
	* *Ellipdolithus macellus*	(mid P1c)	80DR/014-10	
	* *Chiasmolithus inconspicuus*			
	* *Cruciplacolithus tenuis*	(earliest P1c)		
	* *Cruciplacolithus asymmetricus*	(late P1b)	80DR/014-05	
	* *Cruciplacolithus primus*	(early P1b)		
	* *Biantholithus sparsus*			
Late Maastrichtian	* *Micula prinsii*		80DR/020-09 80DR/020-10 80DR/020-11	Breton Marl
	* *Nephrolithus frequens*			
Middle Maastrichtian: A disconformity in the onshore sequence (Shafik,1990a)				

* *Lowest occurrence* + *Highest occurrence* 20/H50/6

Figure 4. Calcareous nannofossil biostratigraphic assignment of Fremantle Canyon dredges and their lithostratigraphic assessment — Late Cretaceous to Early Eocene.

Late Paleocene–Early Eocene (Kings Park Formation equivalent)

A large number of samples from several dredge stations yielded abundant nannofossils which are mainly Late Paleocene in age. Assemblages recorded from these samples (Checklist 1) are assignable to at least five nannofossil biostratigraphic datum intervals, being bracketed by the lowest occurrence of *Toweius pertusus* and the highest occurrence of species of *Fasciculithus*. These assemblages represent a fairly continuous nannofossil biostratigraphic sequence, which may be equated with the foraminiferal zonal interval P4–early P6b (Fig. 4). Consequently, they are regarded as the offshore equivalent of the Kings Park Formation, although some of these assemblages are slightly older than those recorded by Shafik (1978) from onshore occurrences. Reworking from Cretaceous source(s) is minimal, in terms of number of species and samples containing them. The assemblage from sample 80DR/014–8 includes a

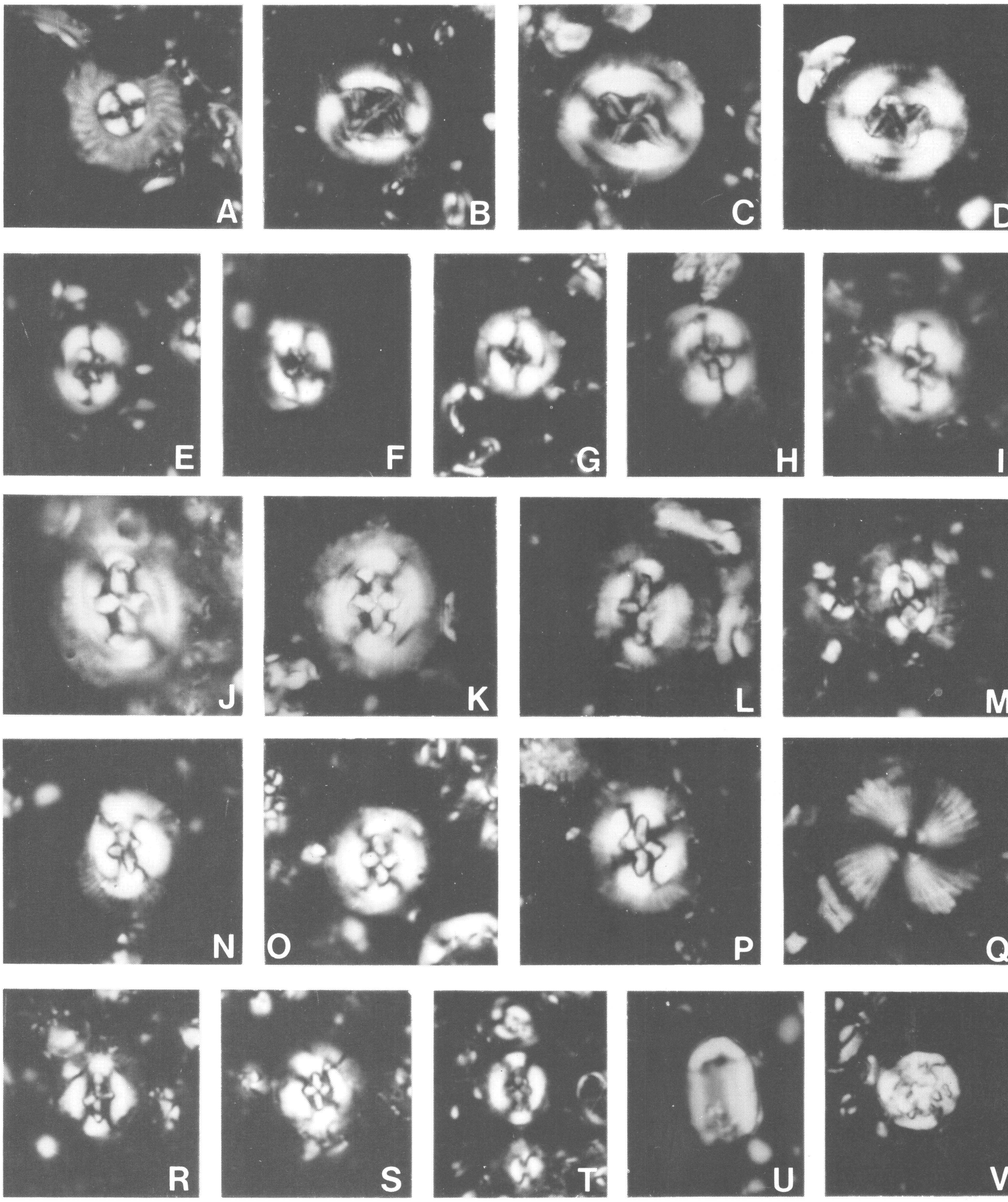


Figure 5. Optical microscopic micrographs of Palaeogene nannofossil taxa from the Fremantle Canyon, South Perth Basin.
A, *Markalius astroporus* (Stradner), CPC 30247 from 80DR/014–10; **B,** *Chiasmolithus edentulus* van Heck & Prins, CPC 30248 from 80DR/014–08; **C, D,** *Chiasmolithus bidens* (Bramlette & Sullivan), C, CPC 30249, D, CPC 30250, both from 80DR/005–08; **E–G,** *Chiasmolithus inconspicuus* van Heck & Prins, E, CPC 30251, F, CPC 30252, G, CPC 30253, all from 80DR/014–10; **H,** *Chiasmolithus edwardsii* (Romein), CPC 30254 from 80DR/014–10; **I,** *Chiasmolithus danicus* (Brotzen), CPC 30255 from 80DR/014–10; **J, K,** *Cruciplacolithus frequens* (Perch-Nielsen), J, CPC 30256, K, CPC 30257, both from 80DR/014–08; **L,** *Cruciplacolithus tenuis* (Stradner), CPC 30258 from 80DR/014–10; **M,** *Cruciplacolithus latipons* Romein, CPC 30259 from 80DR/014–05; **N–P,** *Cruciplacolithus asymmetricus* van Heck & Prins, N, CPC 30260 from 80DR/014–05, O, CPC 30261 from 80DR/014–10, P, CPC 30262 from 80DR/014–05; **Q,** *Heliolithus kleinpellii* Sullivan, CPC 30263 from 80DR/005–08; **R–T,** *Cruciplacolithus primus* Perch-Nielsen, R, CPC 30264 from 80DR/014–05, S, CPC 30265 from 80DR/014–05, T, CPC 30266 from 80DR/014–10; **U,** *Lapideacassis* sp., CPC 30267 from 80DR/014–05; **V,** *Thoracosphaera operculata* Bramlette & Martini, CPC 30268 from 80DR/014–10.
All specimens ×2000.

few reworked Upper Cretaceous species, but the exceptionally high abundance of *Placozygus sigmoides* suggests a possible reworking from a Lower Paleocene source as well.

Only one assemblage is possibly Early Eocene. This was recovered from sample 80DR/020–6. It is assigned to the (broad) Late Paleocene–Early Eocene DI:**Campylosphaera eodela*/ + *Fasciculithus* spp. (Fig. 4), because there is uncertainty regarding the presence or absence of typical *Discoaster diastypus*. Nevertheless, the occurrence of both *Fasciculithus involutus* and *Transversopontis pulcher* in the presence of *Discoaster multiradiatus* and *Campylosphaera eodela* suggests proximity to the base of the Eocene. The assemblages of the other samples are Late Paleocene (see Fig. 4).

Warm-water species of the genus *Discoaster* are either rare or absent in those samples below the lowest occurrence of *Discoaster multiradiatus* in Figure 4. On the other hand, individual specimens of the species of the genera *Chiasmolithus* and *Cruciplacolithus*, which are thought of as more suited to cool surface waters, are abundant in most of the assemblages below sample 80DR/017–3 (as stacked in Fig. 4). These two observations suggest that, for most of the Late Paleocene, surface waters were cool in the Perth Basin. Conversely, specimens of *Discoaster* are abundant in the younger assemblages containing the index species *Discoaster multiradiatus*, suggesting some warming during the latest Paleocene and earliest Eocene in the basin. Similar evidence for this trend is apparent in assemblages from the onshore Kings Park Formation (Shafik, 1978).

Pentaliths (such as *Braarudosphaera bigelowii* and *Micranthololithus* spp.) and other hemipelagic species (such as *Hemihololithus kerabyi* or *Zygrhablithus bijugatus*) are common in most of the assemblages, suggesting that the offshore equivalent of the Kings Park Formation was deposited mainly on the shelf and upper slope (neritic to upper bathyal environments); the nannofossil evidence from onshore occurrences of the formation suggested nearshore environments (Shafik, 1978).

Discussion. The data presented above indicate that the offshore equivalent of the Kings Park Formation is widespread along the walls of the Fremantle Canyon. The presence in these offshore occurrences of levels older than the onshore (type) Kings Park Formation indicates that the formation is transgressive.

The samples representing the offshore equivalent of the Kings Park Formation in the present study (listed in Fig. 4) are grey

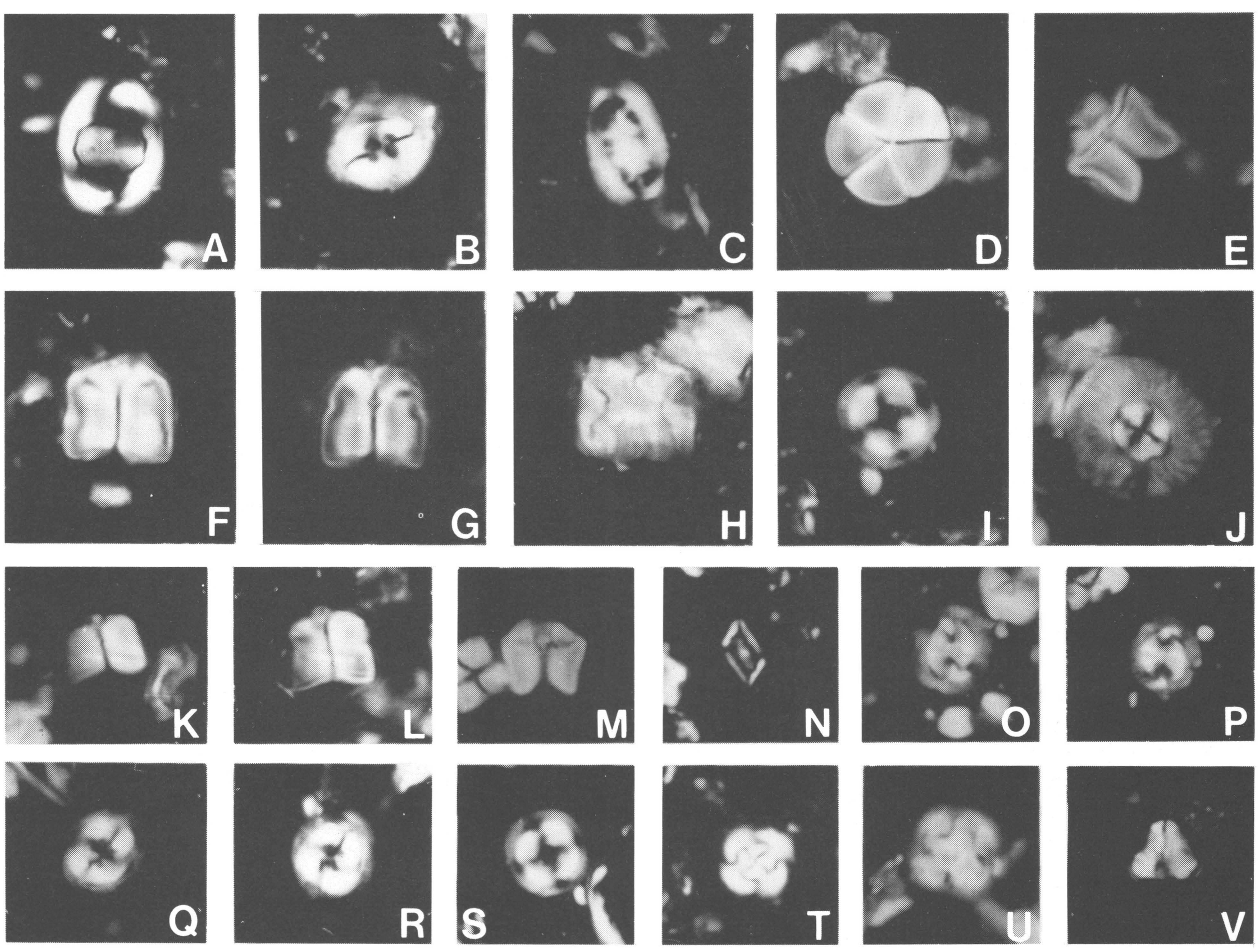


Figure 6. Optical microscopic micrographs of Paleocene nannofossil taxa from the Fremantle Canyon, South Perth Basin.
A, *Zygodiscus adamas* Bramlette & Sullivan, CPC 30269 from 80DR/005–08; **B,** *Toweius eminens* (Bramlette & Sullivan), CPC 30270 from 80DR/005–08; **C,** *Ellipsolithus distichus* (Bramlette & Sullivan), CPC 30271 from 80DR/005–08; **D,** *Braarudosphaera discula* Bramlette & Riedel, CPC 30272 from 80DR/005–08; **E, M,** *Fasciculithus ulii* Perch-Nielsen, E, CPC 30273, M, CPC 30274, both from 80DR/014–08; **F,** *Fasciculithus involutus* Bramlette & Sullivan, CPC 30275 from 80DR/005–08; **G, L,** *Fasciculithus bobii* Perch-Nielsen, G, CPC 30276, L, CPC 30277, both from 80DR/005–08; **H,** *Fasciculithus* sp., CPC 30278 from 80DR/005–08; **I, S,** *Ericsonia subpertusa* Hay & Mohler, I, CPC 30279, S, CPC 30280, both from 80DR/014–10; **J,** *Markalius astroporus* (Stradner), CPC 30281 from 80DR/014–10; **K,** *Fasciculithus tympaniformis* Hay & Mohler, CPC 30282 from 80DR/005–08; **N,** *Scapholithus rhombiformis* Hay & Mohler, CPC 30283 from 80DR/005–08; **O, P,** *Prinsius bisulcus* (Stradner), O, CPC 30284, P, CPC 30285, both from 80DR/020–08; **Q, R,** *Toweius pertusus* (Sullivan), Q, CPC 30286, R, CPC 30287, both from 80DR/005–08; **T,** *Cyclagelosphaera alta* Perch-Nielsen, CPC 30288 from 80DR/014–05; **U,** *Cyclagelosphaera reinhardtii* (Perch-Nielsen), CPC 30289 from 80DR/014–10; **V,** *Semihololithus kerabyi* Perch-Nielsen, CPC 30290 from 80DR/005–08.
All specimens ×2000.

calcilutites with some calcarenites, occasionally siliceous but mostly glauconitic, which vary mainly in their degree of induration. Thus the Kings Park Formation becomes siliceous and much more calcareous offshore.

The terrigenous aspect and the great thickness of the type section of the Kings Park Formation was viewed by Shafik (1978) as a result of a high rate of sedimentation, largely from the nearby mainland. This also explained the uniformity of the microfauna and microflora of the formation in the Perth metropolitan area. The terrigenous components were thought to be contributed by a river system (Shafik, 1978) which is probably related to the now submerged drainage system of the old Swan River (Quilty, 1974b; Playford & others, 1975, 1976). Evidently, these components did not reach the depositional sites now occupied by the Fremantle Canyon, where the formation is highly calcareous. This conclusion is consistent with the bathymetry of the shelf area west of Perth. There is no channel between the mouth of the Swan River (Perth area) and the head of the Fremantle Canyon which occurs at the shelf break (Fig. 1; see also Marshall & others, 1989; Quilty & others, in press). The onshore part of the Kings Park Formation may represent a rapid rise in sea level and culmination of the Paleocene transgression over the Perth Basin.

Samples from the offshore equivalent of the Kings Park Formation were recovered from water 700 m and 3000 m deep. As indicated above, these samples bear nannofossil elements which suggest deposition on the shelf or upper continental slope. An overall deepening is thus demonstrated since the Early Eocene in the area of the Fremantle Canyon.

Early to (early) Middle Eocene (no known onshore equivalent)

Nannofossil assemblages representing the Early to (early) Middle Eocene in the offshore succession in the South Perth Basin came from a large number of samples (Fig. 7, Checklist 2) collected from nine dredge stations, the youngest sample being 80DR/019–4. These assemblages seem to form a continuous nannofossil biostratigraphic sequence consisting of five biostratigraphic units. This sequence is bracketed by the disappearance of *Fasciculithus* spp. and the appearance of *Nannotetrina fulgens*, and may be correlated with the foraminiferal zonal interval P6b–P10 (see Fig. 7).

Biostratigraphic unit A. This is the oldest unit in the sequence. It is based on three samples (80DR/018–1, 80DR/014–14, 80DR/020–7; see Fig. 2 for location) of grey, soft to weakly-cemented calcilutite which were collected from the southern, northern and northeastern walls of the Fremantle Canyon. This unit predates the lowest occurrence of the index species *Tribrachiatus orthostylus* (see Fig. 7), and is characterised by the presence of several Eocene-originated species (such as *Chiasmolithus eograndis, C. grandis, Coccolithus formosus*) among a suite of Paleocene-originated species (such as *Ellipsolithus macellus, Toweius pertusus* and *T.? magnicrassus*). Forms transitional between *Discoaster multiradiatus* and *D. barbadiensis* are present. A correlation with the foraminiferal zone P6b is indicated (see Fig. 7). Very scarce reworked Cretaceous forms were noted among the assemblages of this biostratigraphic unit (see Checklist 2).

Biostratigraphic unit B. This unit is also based on three samples (80DR/020–5, 80DR/017–1, 80DR/003–6; see Fig. 2 for location) — chalky and weakly-cemented calcilutites — which were dredged from the northeastern wall of the Fremantle Canyon and from the continental slope to its north. Two other samples (80DR/003–1, 80DR/003–9), fairly well-cemented calcarenites from the continental slope to the north of Perth, should possibly be included in this unit. The reason for the uncertainty is the poor preservation of the already rare fossils in these two samples; the presence of abundant calcite rhombs indicates recrystallisation.

Assemblages forming this biostratigraphic unit predate the lowest occurrence of *Discoaster lodoensis*, and are characterised by the presence of the index species *Tribrachiatus orthostylus* (Figs 7, 8). Forms transitional between *Discoaster multiradiatus* and *D. barbadiensis* persist. Specimens of the genus *Discoaster* are appreciably more abundant than those of the genera *Chiasmolithus* and *Cruciplacolithus*, particularly in sample 80DR/017–1. This suggests some warming during the Early Eocene biostratigraphic DI:**Tribrachiatus orthostylus*/**Discoaster lodoensis* (foraminiferal zonal interval late P6b–late P7).

The index species *Tribrachiatus orthostylus* was not encountered in samples 80DR/003–1 and 80DR/003–9, but rare *Cyclicargolithus gammation* was found in the latter sample.

Biostratigraphic unit C. This unit is based on an assemblage recovered from sample 80DR/003–2, a greenish grey, glauconitic calcarenite from the continental slope north of Perth. This assemblage contained the index species *Discoaster lodoensis*, without *D. sublodoensis*.

Biostratigraphic units D and E. Based on the available data, by far the most widespread (and probably the thickest) part of the offshore Eocene succession in the Perth Basin is apparently that with the many nannofossil assemblages containing *Discoaster sublodoensis* (Fig. 7). This key species was found in the two highest biostratigraphic units of the Lower to basal Middle Eocene sequence under discussion. The younger of these units, being discriminated by the presence of *Rhabdosphaera inflata*, is based on an assemblage from sample 80DR/019–4, a grey, soft calcilutite dredged from the southwestern wall of the Fremantle Canyon (Fig. 2). The nannofossil assemblage from 80DR/019–4 is correlated with the Middle Eocene foraminiferal zone P10, whereas the assemblages from the older biostratigraphic unit (with *Discoaster sublodoensis*) are correlated with the Early Eocene foraminiferal zone P9.

The biostratigraphic unit with *Discoaster sublodoensis* and without *Rhabdosphaera inflata* is based on assemblages from six samples of grey calcarenite and calcilutite which were dredged from the southern and northeastern walls of the Fremantle Canyon (Fig. 2) and from the continental slope to its north. Of these, the assemblage in sample 80DR/023–1C is of particular interest: it includes forms transitional between *Discoaster sublodoenis* and *D. saipanensis*, with some being typical *D. saipanenis*. The vertical ranges of the latter species and of *D. sublodoensis* do not usually overlap. Other members of the assemblage in sample 80DR/023–1C (such as *Cyclicargolithus gammation, Campylosphaera dela, Discoasteroides kuepperi, Discoaster lodoensis, Lophodolithus* spp. and *Reticulofenestra dictyoda*) are those normally present in the biostratigraphic DI:**D. sublodoensis*/**Rhabdosphaera inflata*.

Discussion. The Early to early Middle Eocene biostratigraphic sequence discussed above has no known counterpart in onshore sections. Assemblages from the basal part of the Porpoise Bay Formation in the Rottnest Island Bore (data in Shafik, 1978) are referable to the biostratigraphic DI:**Reticulofenestra umbilicus*/**Cyclicargolithus reticulatus* and the slightly younger DI:**Cyclicargolithus reticulatus*/**Reticulofenestra scissura*. These assemblages together correlate with the foraminiferal zone late P12 and probably with early P13, and are substantially younger than the youngest level in the Lower–Middle Eocene sequence discussed above. This sequence,

Age	Calcareous nannofossil biostratigraphic events	(Foraminiferal P zones)	Dredges and Rock units	
Early Oligocene	+*Coccolithus formosus*	(mid P18)		?
	+*Reticulofenestra hampdenensis*	(?early P18)	80DR/014-04	Challenger Fm equivalent
	+*Discoaster saipanensis*	(P17)		
Late Eocene	+*Cyclicargolithus reticulatus*	(P16)		
	∗*Isthmolithus recurvus*	(mid P16)	80DR/014-11	
	+*Neococcolithes dubius*	(early P16)		
	∗*Chiasmolithus oamaruensis*	(early P15)		
	+*Chiasmolithus grandis*			
Middle Eocene	+*Daktylethyra punctulata*	(P13)		Porpoise Bay Fm equivalent
	∗*Reticulofenestra scissura*	(P13)	80DR/008-02 80DR/013-01 80DR/009-01	
	∗*Cyclicargolithus reticulatus*	(P12)	?80DR/018-02 ?80DR/019-03	
	∗*Reticulofenestra umbilicus*	(late P12)		
	+*Chiasmolithus gigas*	(late P11)	80DR/019-01	
	∗*Chiasmolithus gigas*	(early P11)		?
	∗*Nannotetrina fulgens*	(late P10)	80DR/019-04	
	∗*Rhabdosphaera inflata*	(P9/P10 boundary)		
Early Eocene			80DR/023-01c 80DR/021-11 80DR/022-01 80DR/003-08 80DR/003-07 80DR/003-03	Unnamed new unit
	∗*Discoaster sublodoensis*	(late P9)		
	∗*Toweius? crassus*	(late P8)	80DR/003-02	
	∗*Discoaster lodoensis*	(latest P7)		
			?80DR/003-01 ?80DR/003-09 80DR/003-06 80DR/017-01 80DR/020-05	
	+*Tribrachiatus contortus*	(late P6b)		
	∗*Tribrachiatus orthostylus*	(late P6b)		
			80DR/020-07 80DR/014-14 80DR/018-01	
	+*Fasciculithus* spp.	(early P6b)		
	∗*Tribrachiatus bramlettei; Discoaster diastypus*	(P6a/P6b boundary)		
Paleocene:	Figure 4			

∗*Lowest occurrence* +*Highest occurrence*

20/H50/7

Figure 7. Calcareous nannofossil biostratigraphic assignment of Fremantle Canyon dredges and their lithostratigraphic assessment — Early Eocene to Early Oligocene.

therefore, is considered to represent an unnamed new unit, consisting of calcilutites and calcarenites. The nannofossil evidence given above suggests that it is exposed at many locations in the Fremantle Canyon and also on the continental slope to its north.

Differentiation between this unnamed new unit and the offshore equivalent of the Kings Park Formation may pose a problem, because of similar lithologies. A good nannofossil working criterion for the separation of these two formations is the disappearance (highest occurrence) of species of the genus

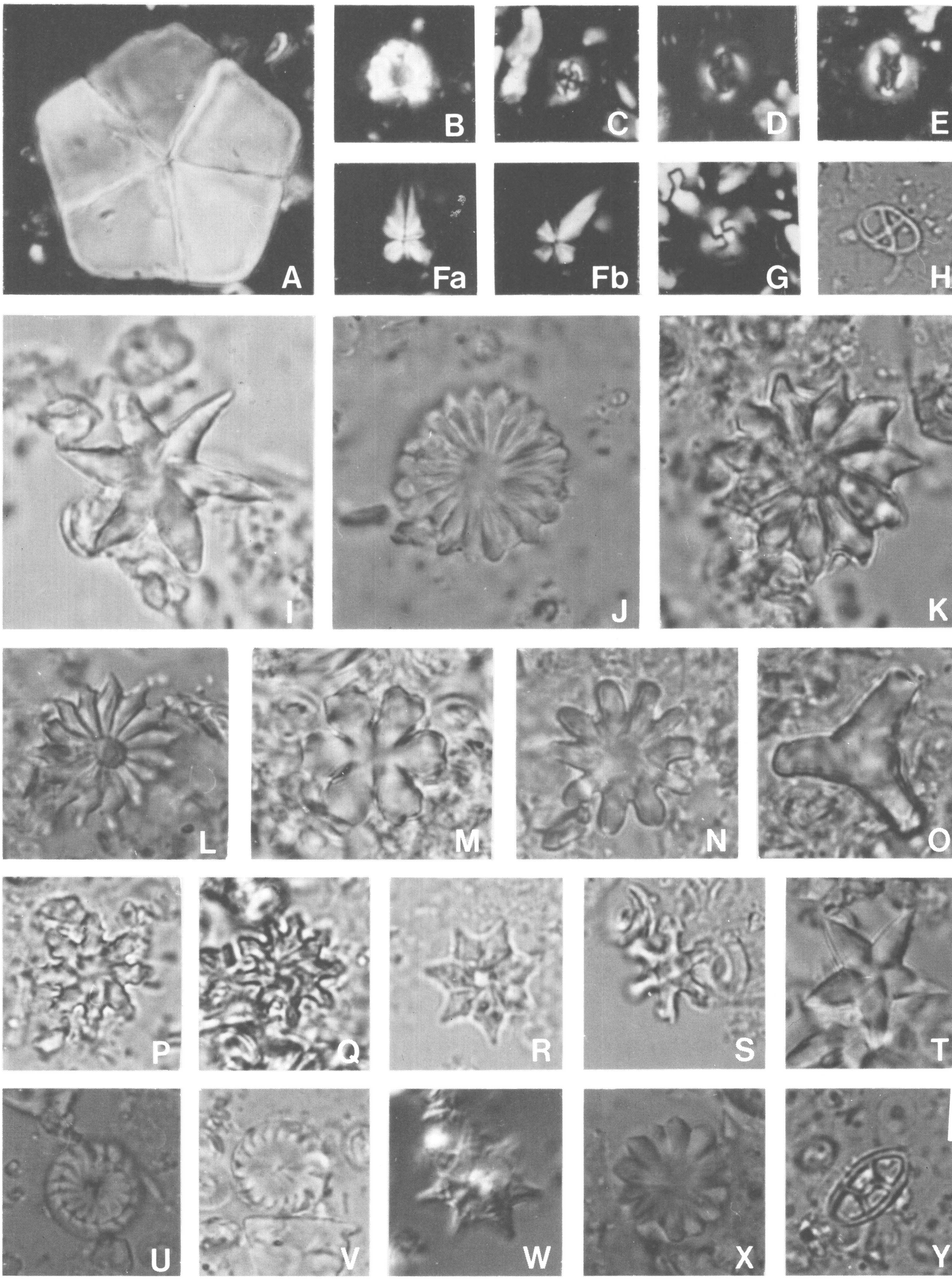


Figure 8. Optical microscopic micrographs of Palaeogene nannofossil taxa from the Fremantle Canyon, South Perth Basin.
A, *Braarudosphaera bigelowii* (Gran & Braarud), CPC 30291 from 80DR/020–05; **B,** *Daktylethra punctulata* Gartner, CPC 30292 from 80DR/009–01; **C,** *Chiasmolithus titus* Gartner, CPC 30293 from 80DR/003–03; **D, E,** *Cruciplacolithus* sp., D, CPC 30294 from 80DR/020–05, E, CPC 30295 from 80DR/003–06; **Fa, Fb,** *Sphenolithus radians* Deflandre, CPC 30296 from 80DR/019–01; **G,** *Cyclicargolithus gammation* (Bramlette & Sullivan), CPC 30298 from 80DR/003–03; **H,** *Neococcolithes protenus* (Bramlette & Sullivan), CPC 30297 from 80DR/020–05; **I,** *Discoaster lodoensis* Bramlette & Riedel, CPC 30299 from 80DR/003–03; **J,** a form transitional between *Discoaster multiradiatus* Bramlette & Riedel and *D. barbadiensis* CPC 30300 from 80DR/003–06; **K, L,** *Discoaster barbadiensis* Tan Sin Hok, K, CPC 30301 from 80DR/003–06, L, CPC 30302 from 80DR/020–05; **M,** *Discoaster deflandrei* Bramlette & Riedel, CPC 30303 from 80DR/022–04; **N,** *Discoaster mediosus* Bramlette & Sullivan, CPC 30304 from 80DR/003–06; **O,** *Tribrachiatus orthostylus* Shamarai, CPC 30305 from 80DR/003–06; **P, Q,** *Discoaster binodosus* Martini, P, CPC 30306, Q, CPC 30307, both from 80DR/020–05; **R, W,** *Discoaster saipanensis* Bramlette & Riedel, R, CPC 30308 from 80DR/014–11, W, CPC 30313 from 80DR/019–01; **S,** *Discoaster distinctus* Martini, CPC 30309 from 80DR/019–01; **T,** *Discoaster sublodoensis* Bramlette & Sullivan, CPC 30310 from 80DR/003–08; **U, V,** *Discoaster* sp., U, CPC 30311, V, CPC 30312, both from 80DR/020–05; **X,** *Discoaster mohleri* Bukry & Percival, CPC 30314 from 80DR/005–08; **Y,** *Neococcolithes dubius* (Deflandre), CPC 30315 from 80DR/020–05.
All specimens ×2000.

Fasciculithus. The Kings Park Formation, as it is currently known, contains species of *Fasciculithus*, which are notably absent from assemblages of the unnamed new (mainly) Lower Eocene unit; species of *Fasciculithus* are also absent from the new Lower Paleocene levels described above (see Fig. 4).

Minor reworking from Cretaceous and probably Paleocene sources can be detected in the unnamed new (mainly) Lower Eocene unit, particularly among the assemblage from sample 80DR020–5.

Middle Eocene (Porpoise Bay Formation equivalent)

Several Middle Eocene assemblages were extracted from samples obtained from four dredge stations in the Fremantle Canyon (Checklist 2). These are assignable to three biostratigraphic units.

Biostratigraphic unit A. Sample 80DR/019–1, a grey, soft calcilutite from the southwestern wall of the canyon (Fig. 2), yielded a particularly well-preserved assemblage. This included the key Middle Eocene species *Nannotetrina fulgens* and abundant *Chiasmolithus* spp. but not *C. gigas*. The short vertical range of *C. gigas* is used to subdivide the biostratigraphic interval between the lowest occurrences of *Nannotetrina fulgens* and *Reticulofenestra umbilicus* into three biostratigraphic divisions (Fig. 7; see also Bukry, 1973). However, it is difficult to determine whether this assemblage belongs to the biostratigraphic division below or above the range of *Chiasmolithus gigas*. The assemblage from 80DR/019–1 is correlated with the foraminiferal zonal interval P11–P12 (Fig. 7).

Biostratigraphic unit B. Samples 80DR/019–3 and 80DR/018–2, well-cemented calcilutites from the southwestern wall of the canyon (Fig. 2), yielded moderately well-preserved assemblages which included Middle Eocene species of *Nannotetrina* and forms of *Reticulofenestra* approaching the typical *R. umbilicus*. These assemblages are tentatively placed in the biostratigraphic DI:**Reticulofenestra umbilicus*/**Cyclicargolithus reticulatus* (foraminiferal zone P12). Deposition was on the shelf or upper continental slope, as indicated by the presence of several species including *Zygrhablithus bijugatus crassus*.

In the assemblage of 80DR/019–3, specimens of *Chiasmolithus solitus* are more abundant than specimens of *Discoaster*. This suggests conditions for cool to cold surface-waters.

Biostratigraphic unit C. Assemblages recovered from the calcarenites and calcilutites of samples 80DR/009–1, 80DR/013–1 and 80DR/008–2, which were obtained from the southeastern and northern walls of the canyon (Fig. 2), are diverse. They contain the index species *Cyclicargolithus reticulatus* (see Checklist 2 and Fig. 9). These assemblages are assigned to the biostratigraphic DI:**Cyclicargolithus reticulatus*/**Reticulofenestra scissura*, and a correlation with the foraminiferal zonal interval late P12–early P13 is made (see Fig. 7). Each of these assemblages has a large number of Upper Cretaceous nannofossil species, suggesting a substantial reworking episode from Cretaceous source(s). This contrasts with the levels above and below, where reworked nannofossils are non-existent, very minor, or from Paleocene rather than from Upper Cretaceous sources.

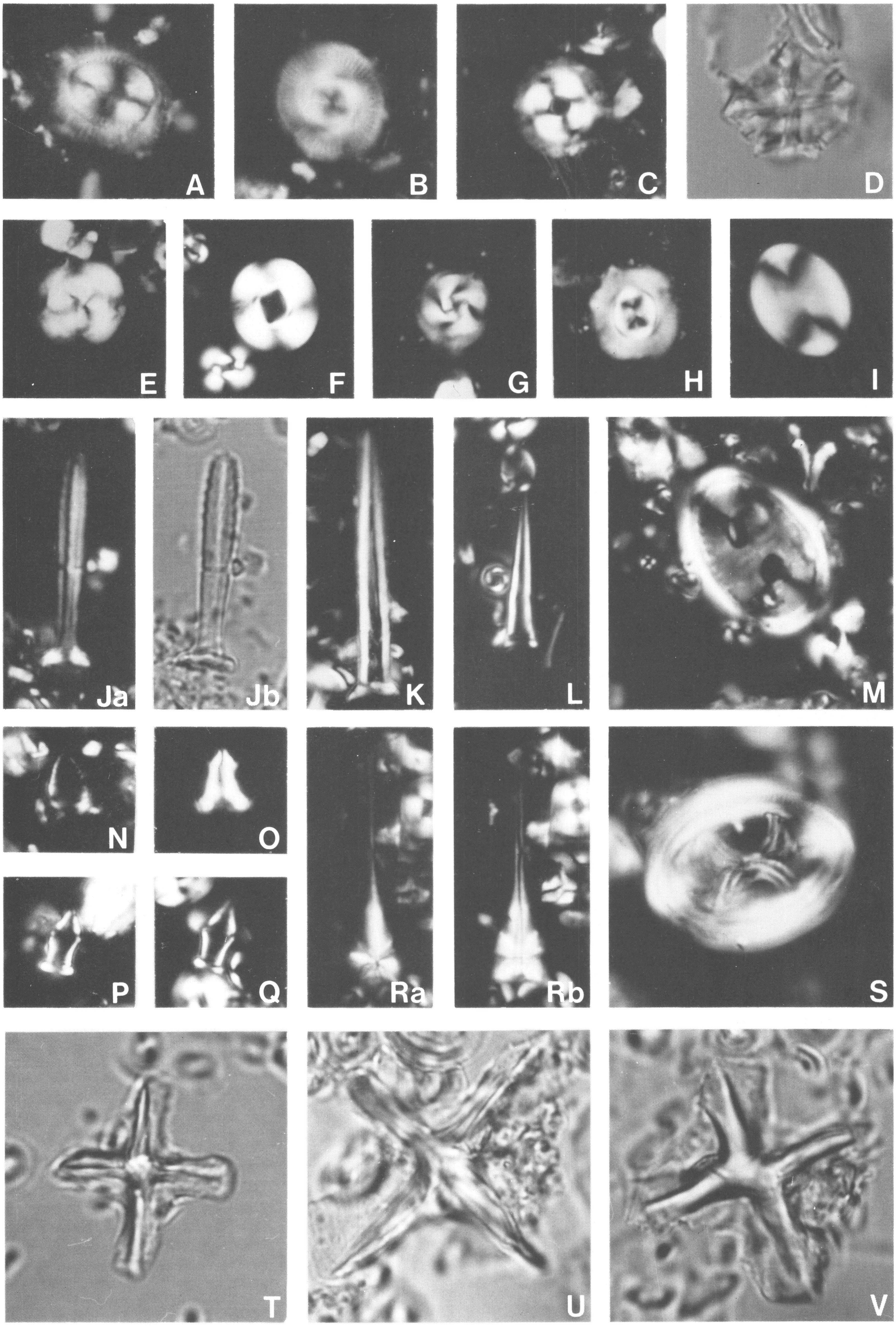
Species indicative of deposition on the shelf or upper continental slope (neritic or upper bathyal environments) are common in the assemblages from samples 80DR/009–1, 80DR/013–1 and 80DR/008–2. These include *Braarudosphaera bigelowii, Daktylethra punctulata, Lanternithus minutus, Micrantholithus procerus, Pemma papillatum, Pontosphaera plana* and *Zygrhablithus bijugatus crassus*. As the samples were dredged over a range of present-day water depths from 850 m to 2500 m, deepening must have occurred since the Middle Eocene at the sites of these dredge stations (Fig. 2), probably mainly due to subsidence of the seafloor.

Discussion. The basal metre of the type section of the Porpoise Bay Formation, as defined by Cockbain & Hocking (1989), was not studied by Shafik (1978) who reported on the lower part of that section. The nannofossil content of the lower part of the Porpoise Bay Formation in the Rottnest Island Bore is therefore known except for that single metre at the base. The recorded assemblages from the Rottnest Island Bore equate well with the assemblages from the Fremantle Canyon samples 80DR/009–1, 80DR/013–1 and 80DR/008–2. The older Middle Eocene assemblages from samples 80DR/019–1, 80DR/019–3 and 80DR/018–2 (see above; Fig. 7) either equate with the unknown assemblages of the basal metre, or have no counterparts in the type section of the Porpoise Bay Formation, because they are older. The assemblage from sample 80DR/019–4, dated as earliest Middle Eocene, is still older than the assemblage from sample 80DR/019–1, and is thought to represent the upper part of an unnamed (mainly Lower Eocene) unit, underlying the equivalent of the Porpoise Bay Formation (see Fig. 7).

The type section of the Porpoise Bay Formation in the Rottnest Island Bore consists of brown calcareous shale and siltstone, whereas the Middle Eocene equivalent of the formation (samples 80DR/009–1, 80DR/013–1 and 80DR/008–2) in the canyon succession is apparently a sequence of intercalating fine calcarenites and calcilutites. Obviously, the formation becomes more calcareous further offshore, and probably cannot be discriminated lithologically from both the underlying and overlying carbonates in the Fremantle Canyon succession.

Based on occurrences of Upper Cretaceous nannofossils in the lower part of the type section of the Porpoise Bay Formation, as well as at contemporaneous levels elsewhere along the western and southern margins of Australia (Carnarvon, Eucla and Otway Basins), Shafik (1985) indicated a widespread reworking episode during the Middle Eocene. This was linked to some important events occurring south of Australia, such as major acceleration in the seafloor spreading rate and initiation of a short-lived strong bottom current. The occurrence of a large number of reworked Upper Cretaceous nannofossils in the Middle Eocene equivalent of the Porpoise Bay Formation in

Figure 9. Optical microscopic micrographs of Eocene nannofossil taxa from the Fremantle Canyon, South Perth Basin.
A, *Coccolithus eopelagicus* (Bramlette & Riedel), CPC 30316 from 80DR/009–01; **B, H,** *Toweius?* sp. cf. *T. crassus* (Bramlette & Sullivan), B, CPC 30317, H, CPC 30318, both from 80DR/003–06; **C,** *Coccolithus formosus* (Kamptner), CPC 30319 from 80DR/009- 01; **D,** *Nannotetrina cristata* (Martini), CPC 30320 from 80DR/019–01; **E,** *Cyclicargolithus reticulatus* (Gartner & Smith), CPC 30321 from 80DR/008–02; **F,** *Reticulofenestra dictyoda* (Deflandre), CPC 30322 from 80DR/019–01; **G,** *Cyclicargolithus gammation* (Bramlette & Sullivan), CPC 30323 from 80DR/003–03; **I,** *Pontosphaera plana* (Bramlette & Sullivan), CPC 30324 from 80DR/003–06; **Ja, Jb,** *Rhabdosphaera solus* Perch-Nielsen, CPC 30325 from 80DR/003–03; **K, L,** *Blackites spinulus* (Levin), K, CPC 30326, L, CPC 30327, both from 80DR/019–01; **M,** *Transversopontis fimbriatus* (Bramlette & Sullivan), CPC 30328 from 80DR/019–01; **N,** *Naninfula* sp., CPC 30329 from 80DR/003–06; **O,** *Zygrhablithus bijugatus bijugatus* (Deflandre), CPC 30330 from 80DR/019–01; **P, Q,** *Rhabdosphaera pseudomorionum* Locker, P, CPC 30331, Q, CPC 30332, both from 80DR/019–01; **Ra, Rb,** *Sphenolithus radians* Deflandre, CPC 30333 from 80DR/019–01; **S,** *Chiasmolithus grandis* (Bramlette & Riedel), CPC 30334 from 80DR/019–01; **T–V,** *Nannotetrina fulgens* (Stradner), T [*Nannotetrina alata* (Martini) of some authors] CPC 30335, U, CPC 30336, V, CPC 30337, all from 80DR/019–01.
All specimens ×2000.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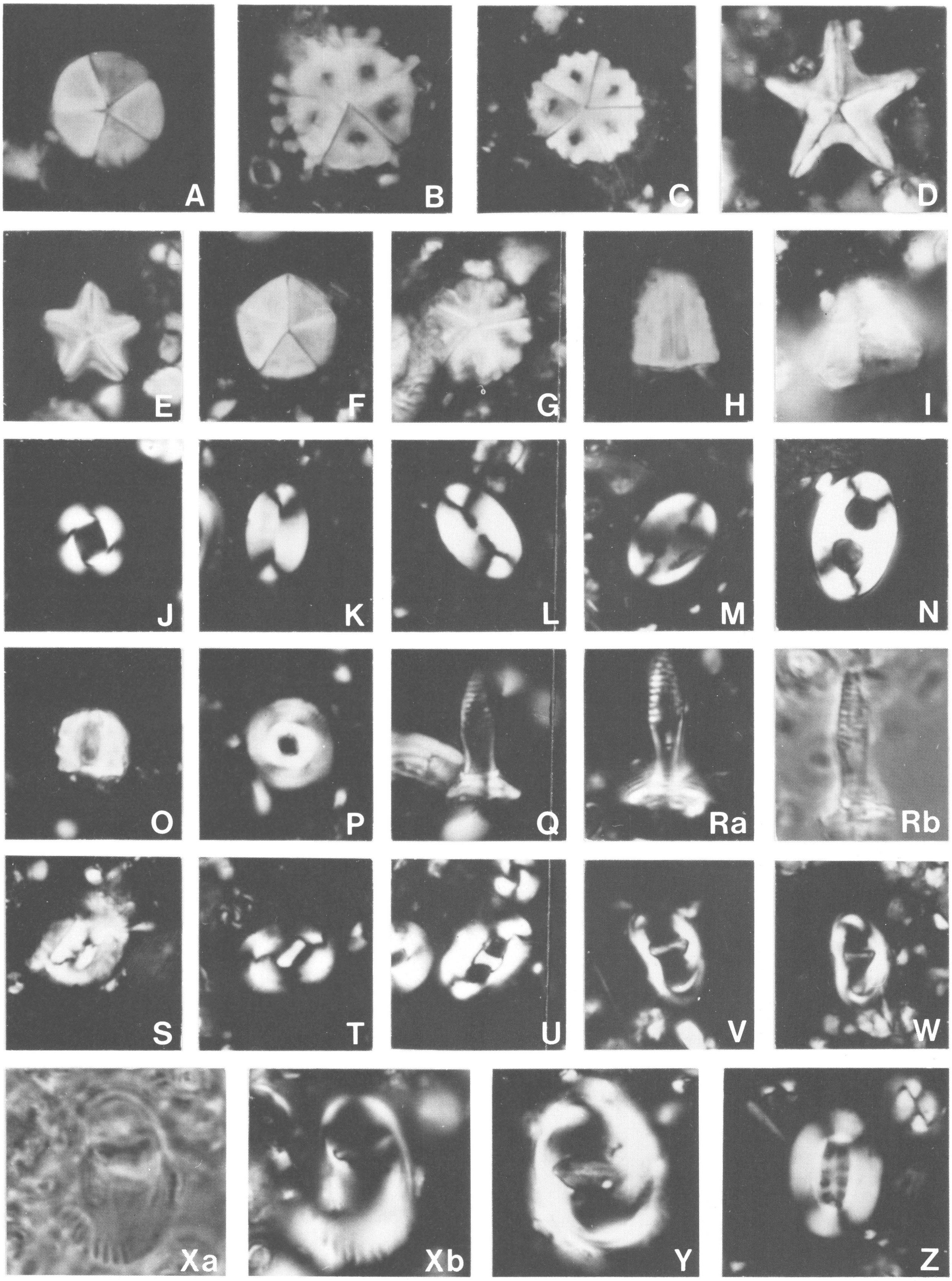

Figure 10. Optical microscopic micrographs of Eocene nannofossil taxa from the Fremantle Canyon, South Perth Basin.
A, *Braarudosphaera discula* Bramlette & Riedel, CPC 30338 from 80DR/003–06; **B,** *Pemma papillatum* Martini, CPC 30339 from 80DR/009–01; **C,** *Pemma basquensis* (Martini), CPC 30340 from 80DR/009–01; **D,** *Micrantholithus entaster* Bramlette & Sullivan, CPC 30341 from 80DR/020–05; **E,** *Micrantholithus flos* Deflandre, CPC 30342 from 80DR/003–06; **F,** *Micrantholithus crenulatus* Bramlette & Sullivan, CPC 30343 from 80DR/003–06; **G, H,** *Micrantholithus altus* Bybell & Gartner, G, CPC 30344, H, CPC 30345 both from 80DR/009–01; **I,** *Braarudosphaera orthia* Bybell & Gartner, CPC 30346 from 80DR/020- 05; **J,** *Reticulofenestra dictyoda* (Deflandre), CPC 30347 from 80DR/019–01; **K,** *Pontosphaera plana* (Bramlette & Sullivan), CPC 30348 from 80DR/019–01; **L,** *Pontosphaera ocellata*

the canyon succession (samples 80DR/009–1, 80DR/013–1 and 80DR/008–2) helps confirm the wide geographic evidence of that reworking episode.

Late Eocene (Challenger Formation)

Sample 80DR/014–11, a grey, fairly well-cemented calcilutite dredged from the northern wall of the Fremantle Canyon (Fig. 2), yielded a poorly-preserved Late Eocene nannofossil assemblage (Checklist 2). The Late Eocene age is based on the co-occurrence of the index species *Chiasmolithus oamaruensis* and *Cyclicargolithus reticulatus*. Signs of dissolution abound (but not in all preparations examined from the sample), and some reworking from Paleocene source(s) was detected. Neither *Neococcolithes dubius* nor the index species *Isthmolithus recurvus* was encountered; the stratigraphic ranges of these two species are usually exclusive. The assemblage can be assigned to either the biostratigraphic DI:**Chiasmolithus oamaruensis*/**Isthmolithus recurvus* or to the broader DI: **Chiasmolithus oamaruensis*/ + *Cyclicargolithus reticulatus*.

The former assignment, being pre-*I. recurvus*, assumes that the absence of *Neococcolithes dubius* is due to preservational factors. On the other hand, the absence of *I. recurvus* may signify an exclusion due to ecological factors such as warm surface waters. The presence of *Sphenolithus pseudoradians*, without the association of other warm-water species such as *Discoaster barbadiensis* in the assemblage from 80DR/014–11, is somewhat tenuous evidence for warming. Specimens of *Discoaster saipanensis* exceed in number those of *Chiasmolithus oamaruensis* in this assemblage, which favours a possible warming.

In constrast to its absence from this assemblage, the cold-water *Isthmolithus recurvus* was encountered frequently in a younger (latest Eocene to Early Oligocene) assemblage from the same dredge haul (sample 80DR/014–4; see below). This seems to be in general agreement with the considerable cooling which occurred near the end of the Eocene (see, e.g., Kennett & von der Borch, 1985, and references therein).

The presence of *Lanternithus minutus*, *Pontosphaera plana* and *Zygrhablithus bijugatus* suggests that deposition was probably on the shelf or upper slope (outer neritic to upper bathyal environments). These taxa are prone to dissolution, and they were not found in all preparations examined from sample 80DR/014–11. Post-depositional alterations, including dissolution, apparently did not occur uniformally throughout this sample. Some reworking from Paleocene source(s) is indicated by the presence of *Chiasmolithus bidens*, *C. consuetus*, *Coccolithus robustus*, *Toweius pertusus* and *Zygodiscus herlynii*.

Remarks. The foraminiferal assemblage from sample 80DR/014–11 is almost identical to Quilty's Challenger No. 1 lower sample at 567–597 m (Apthorpe *in* Marshall & others, 1989). Quilty (1978) labelled his assemblage as 'Late Eocene, P15/16', but Apthorpe correlated the similar assemblage from sample 80DR/014–11 with the Middle Eocene zone P14 equivalent, on the presence of *Acarinina primitiva* and *A. pseudotopilensis*. These two species could be either reworked or misidentified, however, considering the younger nannofossil evidence of *Chiasmolithus oamaruensis* in the sample. In southern Australia, older levels with foraminiferal assemblages from near the base of the nannofossil species *Chiasmolithus oamaruensis* (where *Chiasmolithus grandis* and *C. oamaruensis* co-occur) are distinctly higher than the highest occurrence of the foraminiferid *Acarinina primitiva* (see Shafik, 1983).

The nannofossil assemblage from sample 80DR/014–11 can be correlated with the foraminiferal zonal interval P15/P16 (Fig. 7). This correlation indicates that the sample came from the Challenger Formation (or from the combined Porpoise Bay/Challenger Formation; see discussion below). In the light of the argument presented above for a possible warming, based on the nannofossil assemblage from the same sample, it must be noted that Quilty (1978) has pointed out that the faunas and lithology of the type section of the Challenger Formation are consistent with warm-water deposition.

Latest Eocene–Early Oligocene (Challenger Formation)

Sample 80DR/014–4, a white, moderately-cemented, chalky calcilutite dredged from the northern wall of the canyon (Fig. 2), yielded a moderately to poorly-preserved nannofossil assemblage (Checklist 2). Discoasters are relatively rare, and most are heavily calcified. The assemblage is dominated by *Reticulofenestra scissura* and *R. umbilicus*. The holococcolith taxa *Zygrablithus bijugatus* and *Lanternithus minutus* are fairly common. The key species *Isthmolithus recurvus* is frequent but all specimens encountered were heavily calcified. The absence of the rosette-shaped discoasters (*Discoaster barbadiensis* and *D. saipanensis*) and the index species *Cyclicargolithus reticulatus*, in the presence of other key species such as *Reticulofenestra hampdenensis*, *Isthmolithus recurvus* and *Coccolithus formosus*, suggests an Early Oligocene age. However, as discoasters are rare in this sample, the absence of *Discoaster barbadiensis* and *D. saipanensis* may be considered as an unreliable criterion. The assemblage is, therefore, assigned to the (broad) biostratigraphic DI: + *Cyclicargolithus reticulatus*/ + *Reticulofenestra hampdenensis*, which spans the latest Eocene and earliest Oligocene (see Fig. 7). Unfortunately, the foraminiferal evidence from the same sample is not very helpful for narrowing down this age assignment. According to Apthorpe (*in* Marshall & others, 1989), the assemblage is dominated by *Globigerina ampliapertura* and *Turborotalia increbescens* which normally are found not only in Late Eocene but also in younger assemblages. Furthermore, the associated presence of very rare *Acarinina primitiva* and *A. pseudotopilensis*, which are known to disappear earlier in the Eocene, complicated the matter. (These two species of *Acarinina* in sample 80DR/014–4 are considered here either to be reworked or misidentified, based on their association with the Late Eocene–Early Oligocene nannofossil key species *Isthmolithus recurvus*. The presence of the same foraminiferids in the Upper Eocene assemblage from sample 80DR/014–11 has been treated above as a result of reworking, but their misidentification cannot be ruled out.)

The depositional environment is similar to that deduced for the Upper Eocene sample 80DR/014–11, based on the similar occurrence of *Lanternithus minutus* and *Zygrhablithus bijugatus*. However, surface waters were probably colder during the deposition of 80/DR014–4, as suggested by the

(Bramlette & Sullivan), CPC 30349 from 80DR/020–05; **M,** *Pontosphaera panarium* (Bramlette & Sullivan), CPC 30350 from 80DR/020–05; **N,** *Transversopontis pulcher* (Deflandre), CPC 30351 from 80DR/019–01; **O,** *Daktylethra punctulata* Gartner, CPC 30352 from 80DR/009–01; **P,** *Toweius?* sp. cf. *T. crassus* (Bramlette & Sullivan), CPC 30353 from 80DR/020–05; **Q, Ra, Rb,** *Rhabdosphaera galdius*, Q, CPC 30354, R, CPC 30355, both from 80DR/019–01; **S,** *Helicosphaera compacta* Bramlette & Wilcoxon, CPC 30356 from 80DR/009–01; **T,** *Helicosphaera lophota* Bramlette & Sullivan, CPC 30357 from 80DR/019–01; **U,** *Helicosphaera seminulum* Bramlette & Sullivan, CPC 30358 from 80DR/019–01; **V, W,** *Lophodolithus reniformis* Bramlette & Sullivan, V, CPC 30359, W, CPC30360, both from 80DR/003–03; **Xa, Xb,** *Lophodolithus rotundus* Bukry & Percival, CPC 30361 from 80DR/019–01; **Y,** *Lophodolithus mochlophorus* Deflandre, CPC 30362 from 80DR/020–05; **Z,** *Ellipsolithus lajollaensis* Bukry & Percival, CPC 30363 from 80DR/019–01.
All specimens ×2000.

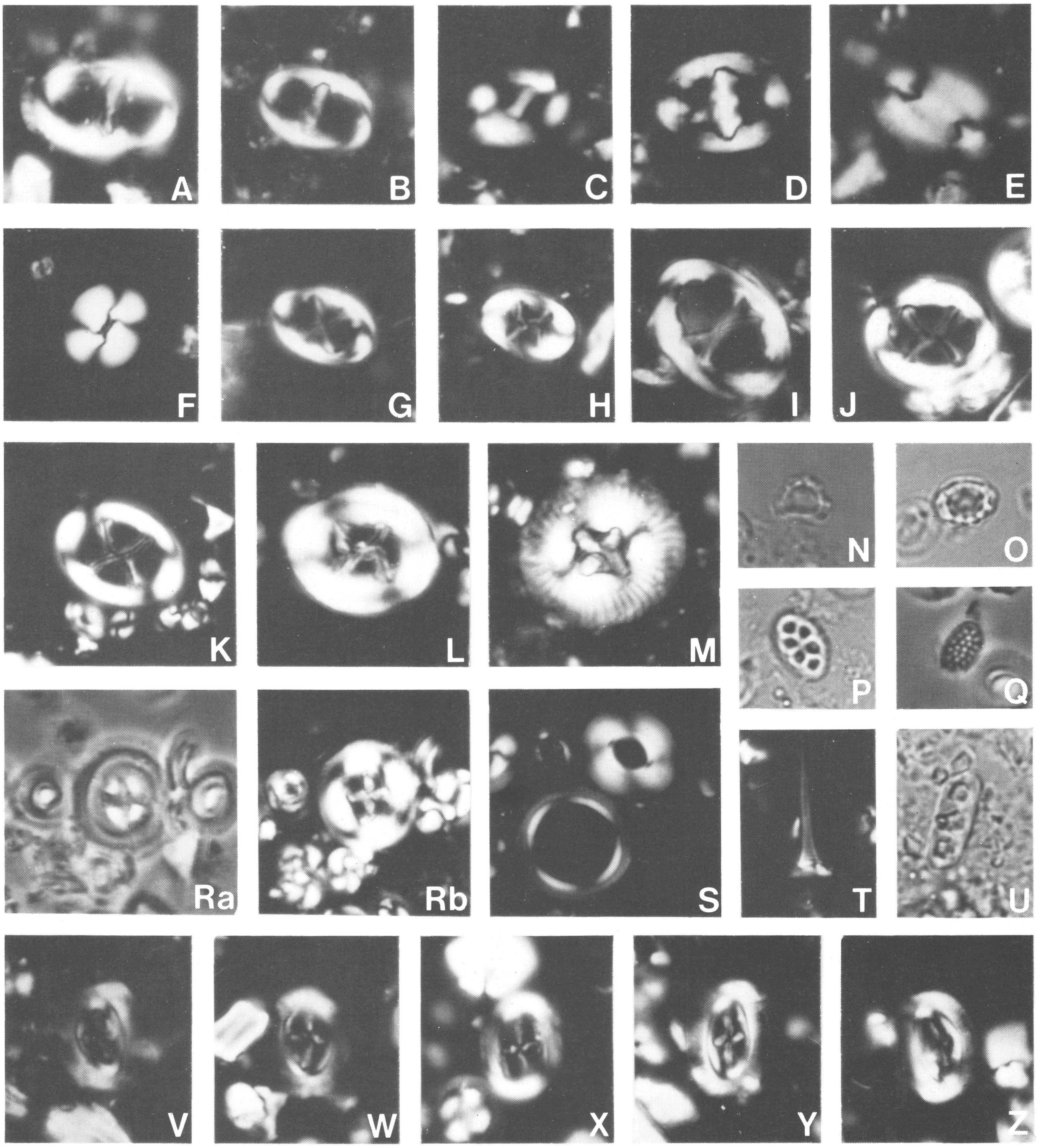

Figure 11. Optical microscopic micrographs of Eocene nannofossil taxa from the Fremantle Canyon, South Perth Basin.
A, *Lophodolithus mochlophorus* Deflandre, CPC 30364 from 80DR/003–06; **B,** *Lophodolithus nascens* Bramlette & Sullivan, CPC 30365 from 80DR/003–06; **C,** *Helicosphaera seminulum* Bramlette & Sullivan, CPC 30366 from 80DR/019–01; **D,** *Zygodiscus adamas* Bramlette & Sullivan, CPC 30367 from 80DR/003–03; **E,** *Ellipsolithus macellus* (Bramlette & Sullivan), CPC 30368 from 80DR/020–05; **F,** *Reticulofenestra* sp. cf. *R. dictyoda* (Deflandre), CPC 30369 from 80DR/019–01; **G,** *Neochiastozygus concinnus* (Martini), CPC 30370 from 80DR/003–06; **H,** *Neochiastozygus distentus* (Bramlette & Sullivan), CPC 30371 from 80DR/003–06; **I,** *Neochiastozygus junctus* (Bramlette & Sullivan), CPC 30372 from 80DR/020–05; **J, K,** *Chiasmolithus expansus* (Bramlette & Sullivan) Gartner, J, CPC 30373, K, CPC 30374, both from 80DR/019–01; **L,** *Chiasmolithus solitus* (Bramlette & Sullivan) Locker, CPC 30375 from 80DR/019–01; **M,** *Chiasmolithus californicus* (Sullivan), CPC 30376 from 80DR/020–05; **N, O,** *Orthozygus aureus* (Stradner), N, CPC 30377, O, CPC 30378, both from 80DR/019–01; **P,** *Holodiscolithus solidus* (Deflandre), CPC 30379 from 80DR/019–01; **Q,** *Holodiscolithus macroporus* (Deflandre), CPC 30380 from 80DR/019–01; **Ra, Rb,** *Birkelundia staurion* (Bramlette & Sullivan), CPC 30381 from 80DR/019–01; **S,** (upper specimen) *Reticulofenestra dictyoda* (Deflandre) CPC 30382A, (lower specimen) *Calcidiscus protoannulus* (Gartner) CPC 30382B from 80DR/019–01; **T,** *Rhabdosphaera* sp., CPC 30383 from 80DR/019–01; **U,** *Isthmolithus recurvus* Deflandre, CPC 30384 from 80DR/014–04; **V–Z,** *Campylosphaera* sp., V, CPC 30385 from 80DR/003–06, W, CPC 30386 from 80DR/003–03, X, CPC 30387 from 80DR/003–03, Y, CPC 30388 from 80DR/020–05, Z, CPC 30389 from 80DR/020–05.
All specimens ×2000.

notable absence of rosette-shaped discoasters. Thus, a comparison between the assemblages from 80DR/014–11 and 80DR/014–4 supports the possibility that the presence of *Isthmolithus recurvus* in the assemblage from 80DR/014–4 may be related to the chilling event which occurred near the end of the Eocene.

Discussion. Based on results given by Quilty (1978), Cockbain & Hocking (1989) described the Porpoise Bay Formation as Middle Eocene and the Challenger Formation as Late Eocene. This is not entirely correct (see Fig. 3). The discussion presented earlier shows that the type section of the Challenger Formation ranges from the Middle Eocene into Oligocene. Also, as discussed below, the type section of the Porpoise Bay Formation is likely to range into the Upper Eocene, with the implication that the two formations partly overlap. Quilty (1978, p. 115) raised the possibility that the Middle Eocene sediments in Rottnest Island Bore (type section of the Porpoise Formation) were 'formed during the early part of the transgression that led to the deposition of the Late Eocene sediments in Challenger No. 1' (type section of the Challenger Formation).

Both Quilty (1978) and Shafik (1978) studied the lower parts of the type section of Porpoise Bay Formation, but not its upper parts. A total of more than 100 m of sediment in the upper part of the type section of the Porpoise Bay Formation in the Rottnest Island Bore has not been studied, and the calcareous microfossil content is unknown. It is possible that this 100 m of the type Porpoise Bay Formation overlaps with the lower part of the Challenger Formation (as the latter extends into the Middle Eocene; discussed above), especially if this top 100 m of the type Porpoise Bay Formation includes an Upper Eocene interval, which is not unlikely. The nannofossil data in the present study suggest that a continuous sequence through (at least) the entire Eocene is likely in the canyon succession (see Fig. 7); only *minor* disconformities are expected within the Eocene sequence. It is thus possible that the Porpoise Bay and Challenger Formations merge into one unit in the canyon succession.

In Figure 7, the Middle/Upper Eocene boundary is *arbitrarily* used as the demarcation between equivalents of the Porpoise Bay and Challenger Formations. The similar lithologies of the canyon samples are consistent with the conclusion that the two formations merge into one unit along the walls of the canyon. Sample 80DR/014–4 is likely to have come from within the upper part of this combined (Porpoise Bay and Challenger Formations) unit.

Mid Oligocene nannofossils from the Fremantle Canyon (no known onshore equivalent)

Sample 80DR/022–4, a whitish soft calcilutite with abundant siliceous spicules dredged from the base of the southern wall of the Fremantle Canyon (Fig. 2), yielded a rich, moderately well-preserved nannofossil assemblage datable as mid Oligocene; some signs of partial dissolution are evident and discoasters are overgrown with secondary calcite. Some reworking from Eocene source(s) is apparent. The assemblage includes *Chiasmolithus altus*, (reworked) *C. eograndis, Coccolithus eopelagicus, Cyclicargolithus abisectus, C. floridanus*, (reworked) *Coccolithus formosus*, heavily calcified *Discoaster deflandrei* 'group', *Helicosphaera euphratis, H. recta*, (reworked) *Reticulofenestra hampdenensis, R. scissura, Scapholithus* sp., *Sphenolithus distentus, S. predistentus, S.* sp. aff. *S. ciperoensis, S. moriformis, Zygrhablithus bijugatus bijugatus* and *Z. bijugatus crassus*. A few specimens of severely etched *Pontosphaera plana* were also noted.

The association of the key species (illustrated in Fig. 12) *Chiasmolithus altus, Cyclicargolithus abisectus, Helicosphaera recta, Reticulofenestra scissura, Sphenolithus distentus*, and *S.* sp. aff. *S. ciperoensis* suggests a late Early Oligocene age. According to data in Martini (1971), and in the light of revised correlation by Berggren & others (1985), some elements in this association suggest correlation with the foraminiferal zone P21a. Deposition was probably on the upper continental slope (upper bathyal environment) as evinced by the rare occurrence of *Pontosphaera plana*; the presence of *Zygrhablithus bijugatus* also tends to support this conclusion. However, both *Pontosphaera plana* and *Zygrhablithus bijugatus* could be allochthonous, like some of the associated species (such as *Coccolithus formosus*), being reworked from an Eocene source(s).

Discussion

Previous biostratigraphic studies on the Tertiary sequences of the Perth Basin (e.g. Quilty, 1974a,b) suggest a significant biostratigraphic gap in the marine record, between the 'Upper Eocene' Challenger Formation and the Lower to Middle Miocene Stark Bay Formation; marine sediments of Oligocene age are apparently missing. Quilty (1977) indicated that the Oligocene period corresponds to the lowest Tertiary sea level reached along the Australian western margin. Moreover, seismic sections in the offshore area west of Perth suggested to Quilty & others (in press) that the Oligocene was a period of erosion. Accordingly, the late Early Oligocene nannofossil assemblage from sample 80DR/022–4 is a significant finding. It is regarded as being from an unnamed new unit.

Oligocene sediments containing calcareous microplanktic remains have never been recorded previously in the Perth Basin, or from nearby oceanic sections (discussed later), and very few such sediments are known from the Carnarvon Basin to the north. This suggests doubts about the wisdom of considering a new Oligocene unit, particularly with only one canyon sample (80DR/022–4) containing nannofossils of definite Oligocene age. Furthermore, planktic foraminiferids in the same sample have been interpreted as Middle Eocene in age (Apthorpe *in* Marshall & others, 1989). However, the presence of the nannofossil index species *Sphenolithus distentus* is compelling evidence for a mid Oligocene age. The associated Middle Eocene foraminiferids and their coeval nannofossils (those in the same 80DR/022–4 sample) are interpreted here as being reworked from the same source(s). The Middle Eocene section on the Naturaliste Plateau at DSDP site 264 is thought to be this source.

The truncated nature of the Eocene section at site 264 is likely to be a result of erosion; what is preserved from this section is rich with calcareous microplanktic remains (nannofossils and foraminiferids). The Eocene at site 264 is immediately overlain by Upper Miocene. It is tempting, therefore, to suggest that the Eocene section on the Naturaliste Plateau is the source for the Middle Eocene nannofossils and foraminiferids found (reworked) in the mid Oligocene assemblage in the Fremantle Canyon succession. Large scale erosion was postulated for the mid Oligocene in the Australian sector of the Southwest Pacific region (see Kennett & others, 1972; Kennett & others, 1975). It seems that during the (mid) Oligocene the Naturaliste Plateau was a site for erosion and not sedimentation; no Oligocene sediments have yet been recorded on the Naturaliste Plateau.

In the earlier discussion on the planktic foraminiferids of the Challenger Formation, the presence of both *Globorotalia opima opima* and *Subbotina angiporoides* was taken as an indication that the uppermost part of that formation is (Early) Oligocene in age; in Figure 3, the top of the type section of the

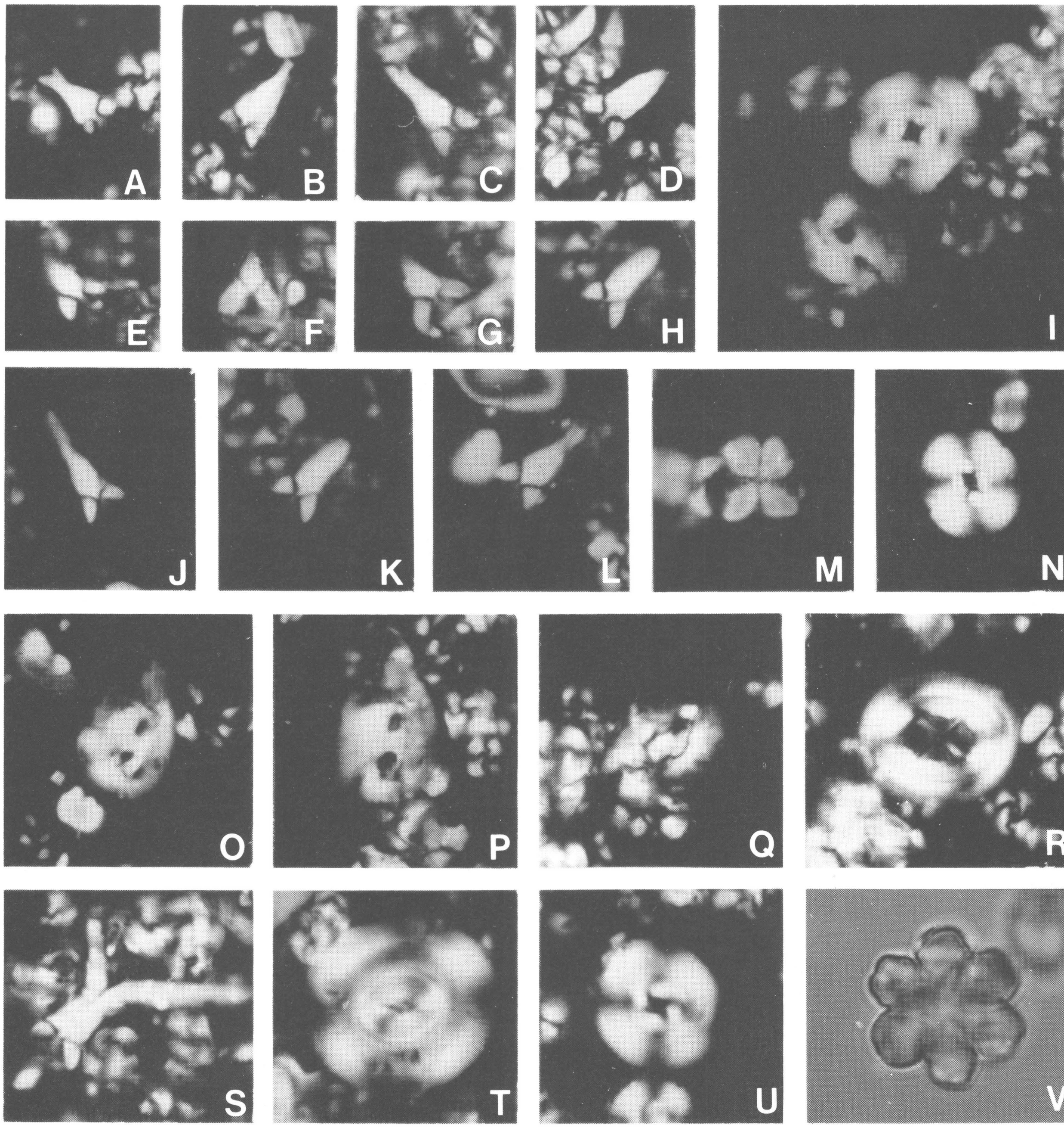

Figure 12. Optical microscopic micrographs of Oligocene nannofossil taxa from sample 80DR/022–04 from the Fremantle Canyon, South Perth Basin.

A–D, S, *Sphenolithus predistentus* Bramlette & Wilcoxon, A, CPC 30390, B, CPC 30391, C, CPC 30392, D, CPC 30393, S, CPC 30394; **E–H, J–L,** *Sphenolithus distentus* (Martini), E, CPC 30395, F, CPC 30396, G, CPC 30397, H, CPC 30398, J, CPC 30399, K, CPC30400, L, CPC 30401; **I,** (top specimen) *Cyclicargolithus abisectus* (Müller) CPC 30402A, (bottom specimen) *Helicosphaera recta* Haq CPC 30402B; **M,** *Sphenolithus moriformis* (Brönnimann & Stradner), CPC 30403; **N,** *Cyclicargolithus floridanus* (Roth & Hay), CPC 30404; **O, P,** *Helicosphaera recta* Haq, O, CPC 30405, P, CPC 30406; **Q,** *Helicosphaera euphratis* Haq, CPC 30407; **R,** *Chiasmolithus altus* Bukry & Percival, CPC 30408; **T,** *Reticulofenestra scissura* Hay, Mohler & Wade, CPC 30409; **U,** *Cyclicargolithus abisectus* (Muller), CPC 30410; **V,** *Discoaster deflandrei* Bramlette & Riedel, CPC 30411.
All specimens ×2000.

Challenger Formation is shown at a mid point within the Early Oligocene. Be this as it may, I cannot judge whether the type section of the Challenger Formation extends to the level of the mid Oligocene nannofossil assemblage recorded here, without studying the nannofossils of that formation. At this stage, I prefer to consider that the nannofossil assemblage containing *Sphenolithus distentus* (sample 80DR/022–4) is from a unit previously unreported (see Fig. 3). As indicated earlier, the type section of the Challenger Formation in the Challenger No. 1 well is inappropriate because initially it was not sampled adequately.

Early to Middle Miocene nannofossils from the Fremantle Canyon (Stark Bay Formation)

Three samples recovered from station 80DR/007, high along the southeastern wall of the Fremantle Canyon (Fig. 2), yielded poorly preserved nannofossil assemblages. The worst of these is from sample 80DR/007–1, where only a very few species could be identified. These are *Calcidiscus leptoporus*, *Cyclicargolithus abisectus* and *Sphenolithus moriformis*, which may collectively suggest an Early Miocene age.

Sample 80DR/007–3, a weakly-cemented calcilutite, yielded *Braarudosphaera bigelowii, B. discula, Calcidiscus leptoporus, Coronocyclus nitescens, Cyclicargolithus abisectus, C. floridanus*, heavily calcified *Discoaster* spp. (mainly members of the *D. deflandrei* 'group'), *Helicosphaera euphratis, H. kamptneri, Micrantholithus* sp., *Rhabdosphaera procera* and *Sphenolithus moriformis*. Severely etched specimens of *Pontosphaera* were also noted.

The association of *Calcidiscus leptoporus, Helicosphaera kamptneri, H. euphratis, Cyclicargolithus abisectus* and *C. floridanus* in the assemblage from 80DR/007–3 suggests an Early Miocene age. The abundant occurrence of pentaliths in this assemblage suggests shallow-water deposition on the continental shelf.

Rare nannofossils were found in preparations from the calcilutite of sample 80DR/007–2, but these include the key species *Sphenolithus heteromorphus*, whose lowest occurrence indicates a position late in the Early Miocene and a correlation within either the foraminiferal zone N6 (see Martini, 1971) or N7 (see base of the nannofossil zone CN3 relative to the N zonation in Berggren & others, 1985). The highest occurrence of *S. heteromorphus* has been placed within the foraminiferal zone N10 (data in Martini, 1971 and Berggren & others, 1986). Other nannofossils identified in 80DR/007–2 are *Braarudosphaera bigelowii, Calcidiscus leptoporus* and *Cyclicargolithus floridanus*. Deposition was on the continental shelf (probably in a nearshore environment), as shown by the presence of *Braarudosphaera bigelowii*.

Discussion

Quilty (1974a) introduced the Lower to Middle Miocene Stark Bay Formation based on material from several offshore wells west of Perth. The type section of this formation is in Gage Roads No. 2 (Fig. 1). It consists of 215 m of white bryozoan and echinodermal calcarenite, becoming brown dolomite and chert in places, especially in the lower parts. It unconformably overlies either Cretaceous sediments or the Kings Park Formation (Quilty, 1974a). Diagnostic foraminiferal species are abundant in places, mostly indicating zones N8 and N9. Based on *Globorotalia barisanensis* and *Globigerina woodi woodi* at the bottom of the formation in one section (Gage Roads No. 1; Fig. 1), zone N7 was suspected (Quilty, 1974b).

As indicated above, the nannofossil assemblage of sample 80DR/007–2 falls within the foraminiferal zonal interval N7–N10, which brackets the biostratigraphic range of the Stark Bay Formation in Gage Roads No. 1 and 2 (N7–N9). The other two (Lower) Miocene samples are probably older than sample 80DR/007–2, but lithologically similar to the Stark Bay Formation. Thus samples studied from dredge station 80DR/007 are thought to have come from the Stark Bay Formation. It is likely that this formation is a transgressive unit, having an older base in the canyon succession than in its type section (Gage Roads No. 2, Fig. 1).

Cretaceous and Tertiary sediments from nearby DSDP sites

Oceanic Cretaceous and Tertiary sediments were recovered from several Deep Sea Drilling Project sites in the Perth Abyssal Plain and on the Naturaliste Plateau, off the southwestern corner of Australia. The nannofossil data for the discussion below are derived from Thierstein (1974) for site 258, Proto-Decima (1974) for site 259, Bukry (1974, 1975) for sites 259 and 264, Hayes & others (1975) for site 264 and Shafik (1985) for site 264.

The Tertiary sections at these DSDP sites are discontinuous. At site 258, the entire Palaeogene is apparently missing, and a Santonian–Upper Miocene unconformity has been recorded. At site 259, the entire nannofossil-bearing Tertiary is represented by an Upper Paleocene–Lower Eocene section sandwiched between sediments free of nannofossils. At site 264, at least three disconformities have been recorded within the Tertiary, (a) at the base of the Tertiary (basal Tertiary being missing), (b) between the Paleocene and Eocene (Upper Paleocene and Lower Eocene are missing), and (c) between the Middle Eocene and Upper Miocene.

Cretaceous

No Maastrichtian sediments with calcareous planktic remains were recovered from the DSDP sites under discussion. The Cretaceous at site 258 is represented by a thick Albian to Santonian sequence directly underlying Upper Miocene sediments. The youngest Cretaceous nannofossils at site 259 are Albian. These Albian fossils came from a section separated from a nannofossil-bearing Paleocene above by sediments lacking nannofossils, seemingly as a result of dissolution. The youngest Cretaceous recorded from the Naturaliste Plateau is Early Campanian at site 264, based on the occurrence of *Broinsonia parca* and *Eiffellithus eximius* in core 264–11.

A widespread Late Maastrichtian transgression has been documented in onshore sediments along the Australian western margin in the Carnarvon and Perth Basins (Shafik, 1990a) and also in the offshore Fremantle Canyon (this study). This could be traced in the Great Australian Bight Basin as a marine ingression (Shafik, 1990b). It is based on occurrences of rich, moderately to well preserved nannofossils such as those recovered from the Breton Marl equivalent in the Fremantle Canyon succession. Obviously, evidence for this Late Maastrichtian transgression is lacking in the oceanic sections of the Perth Abyssal Plain and the Naturaliste Plateau. In these sections there is instead evidence for carbonate dissolution and/or disconformity. This contrast in the Upper Maastrichtian settings along both margins of Australia and in the nearby oceanic sections is probably a shelf/basin fractionation.

Paleocene

The assemblages representing the Paleocene at DSDP site 259 include the index species *Discoaster multiradiatus, D. nobilis, Fasciculithus tympaniformis, Chiasmolithus bidens* and *Placozygus sigmoides*. They suggest a Late Paleocene age, and a correlation with a level within the upper part of the Kings Park Formation, both onshore and offshore. However, the Paleocene assemblages recorded from DSDP site 264 are older than the base of the Kings Park Formation *sensu strictu*, and can be placed, in the canyon succession, between this base and the youngest Lower Paleocene level sampled at station 80DR/020 (see Fig. 4). No Paleocene sediments were recorded from DSDP site 258.

The occurrence of Upper Paleocene (and Lower Eocene, see below) marine sediments in the nearby Perth Abyssal Plain (site 259) supports the conclusion that, during the Late Paleocene–Early Eocene, there was a significant sea level rise indicated by the *onshore* Kings Park Formation which also represents the culmination of the Paleocene transgression over the Perth Basin.

Eocene

The Eocene section at DSDP site 259 spans the biostratigraphic interval from the highest occurrence of *Fasciculithus* spp. to the lowest occurrence of *Discoaster lodoensis*, and may be correlated with the lower part of the unnamed (mainly) Lower Eocene unit of the Fremantle Canyon. The Eocene section at DSDP site 264 is more substantial, spanning the biostratigraphic interval between the lowest occurrences of *Discoaster sublodoensis* and *Cyclicargolithus reticulatus*. It may be correlated with the upper part of the unnamed (mainly) Lower Eocene unit and the lower part of the combined Porpoise Bay and Challenger Formations of the Fremantle Canyon. No Eocene sediments were reported from DSDP site 258.

At DSDP site 264, the Eocene section is overlain by Upper Miocene sediments. Assemblages from immediately below this disconformity contain the key species *Cyclicargolithus reticulatus* but no reworked Cretaceous nannofossils. They are thought to be stratigraphically from immediately below the assemblages with *C. reticulatus* and reworked nannofossils, recorded from the Fremantle Canyon succession and elsewhere on the Australian western and southern margins (see Shafik, 1985, fig. 5). In other words, levels equivalent to these widespread Middle Eocene sediments with reworked Cretaceous nannofossils were either eroded from the Eocene section on the Naturaliste Plateau or not deposited in the first place. The erosion option accords with the possibility that during the mid Oligocene the Naturaliste Plateau was the provenance for the displaced Middle Eocene nannofossils and foraminiferids found in the Oligocene of the Fremantle Canyon succession at station 80DR/022.

Oligocene

No Oligocene nannofossil-bearing sediments were reported from DSDP sites 258, 259 and 264. This increases the significance of the late Early Oligocene nannofossil assemblage recorded here from the Fremantle Canyon at station 80DR/022.

The proposed mid Oligocene erosion of the Naturaliste Plateau (resulting in deposition of Middle Eocene components within Oligocene sediments at the Fremantle Canyon) may be connected with the Oligocene unconformity recorded widely in the Southwest Pacific region at several DSDP sites.

Miocene

Calcareous nannofossils found in the Upper Miocene sediments recovered from the Naturaliste Plateau at DSDP site 258 and 264 are distinctly younger than the calcareous planktic remains of the (mainly) Middle Miocene Stark Bay Formation. At site 258, the Upper Miocene directly overlies Santonian sediments, and at site 264 the Upper Miocene rests directly on Middle Eocene sediments. No Miocene nannofossil-bearing sediments were recorded from the Perth Abyssal Plain at site 259. Recovery here between the Pleistocene (core 1) and the Eocene (core 4) was very poor, and sediments obtained lacked nannofossils.

Summary and conclusions

Material from the Fremantle Canyon and the continental slope to its north has yielded several calcareous nannofossil assemblages which were fitted within a scheme of Late Maastrichtian–Early Miocene biostratigraphic events. Most of the assemblages could be correlated with the low-latitude foraminiferal P and N zones, and were used to elucidate the lithostratigraphic succession of the canyon. In addition to the five previously-known rock units forming the Maastrichtian–Miocene succession of the Perth Basin, two (or possibly three) new units were discovered in the Fremantle Canyon succession. The recovered nannofossil assemblages also helped confirm two important physical events known to have occurred during the Late Maastrichtian and Middle Eocene in several western and southern marginal basins of Australia. The age of the type section of the Challenger Formation, given previously as Late Eocene (Quilty, 1978; Cockbain & Hocking, 1989), was revised to Middle Eocene through to (Early) Oligocene, based on reinterpretation of its planktic foraminiferids as originally listed by Quilty (1978). The Maastrichtian–Tertiary section in the Fremantle Canyon, particularly the Paleocene–Eocene part, is more complete than contemporaneous sections in the Perth Abyssal Plain at DSDP site 259, and on the Naturaliste Plateau at DSDP sites 258 and 264. For most of the Maastrichtian–Tertiary section of the canyon, deposition occurred in outer shelf and upper slope palaeoenvironments.

A widespread Late Maastrichtian transgression occurred over the Carnarvon and Perth Basins (Shafik, 1990a) and over the Great Australian Bight Basin (as marine ingression; Shafik, 1990b). Evidence for this comes from the Fremantle Canyon succession, where an equivalent of the Upper Maastrichtian Breton Marl, known previously from land-based sections in the Perth Basin (Shafik, 1990a), was indicated. The nannofossil evidence from the canyon material, suggesting that surface waters were cool to cold during the Late Maastrichtian, matches the evidence from the onshore Perth Basin material. At the nearby DSDP sites 258, 259 and 264, sediments of Maastrichtian age are either missing or represented by barren intervals. This contrast in the Maastrichtian setting between sections along the Australian western margin and in the nearby oceanic sites is probably a result of shelf/basin fractionation.

The evidence from the Fremantle Canyon points to a hiatus at the Cretaceous/Tertiary boundary, because the uppermost Maastrichtian and lowermost Paleocene appear to be missing. Onshore, the hiatus between the Cretaceous and Tertiary is more substantial, with the absence of the entire Lower Paleocene sequence.

A Lower Paleocene sequence, previously unknown in the Perth Basin, was reported in the Fremantle Canyon. Available data are not enough to decide whether this sequence is a discrete unit(s) or a part of the younger Kings Park Formation. A consequence of the preferred latter option is that the lower boundary of the Kings Park Formation becomes older offshore, suggesting that the formation is transgressive. The transgressive nature of the Kings Park Formation is also indicated by other (younger) Paleocene assemblages in the canyon. Evidently, the Kings Park Formation occurs widely along the walls of the canyon, but mainly as calcilutites. Thus, the terrigenous components of the onshore Kings Park Formation, thought to have been provided (to the Perth metropolitan area) by a river system (Shafik, 1978), did not reach the depositional sites presently occupied by the Fremantle Canyon. The lithology and age of the Kings Park Formation in the Perth metropolitan area and in the Fremantle Canyon suggest that the onshore Kings Park Formation represents a rapid rise in sea level and culmination of the Paleocene transgression over the Perth Basin; the bathymetry of the shelf area west of Perth supports this conclusion. The Lower Paleocene sequence in the canyon has no counterparts in the nearby DSDP sections in the Perth Abyssal Plain and Naturaliste Plateau (sites 259, 258 and 264), but assemblages similar to those from the upper part of the Kings Park Formation are known from the Perth Abyssal Plain at site 259.

An Early to early Middle Eocene nannofossil biostratigraphic sequence of events, previously unknown in the Perth Basin, has been constructed on the basis of assemblages dredged from the Fremantle Canyon. It suggests a new unnamed rock unit in the Perth Basin, apparently consisting of a succession of calcilutites and calcarenites. Evidently, this (mainly) Lower

Eocene unit is widespread in the Fremantle Canyon, and also occurs on the continental slope to its north. Because the lithology of the new (mainly) Lower Eocene unit and that of the offshore equivalent of the Kings Park Formation are similar, the nannofossil genus *Fasciculithus* is suggested as a good working criterion for differentiating these two rock units. *Fasciculithus* is present in the Kings Park Formation equivalent but is absent from the younger unit; it is also absent from the newly reported Lower Paleocene sediments in the canyon.

In the Fremantle Canyon succession, the Middle Eocene equivalent of the Porpoise Bay Formation, being calcarenites and calcilutites, is difficult to distinguish lithologically from the similar Upper Eocene to Lower Oligocene carbonates correlatable with the Challenger Formation. This, together with the nannofossil data presented, suggests that the Porpoise Bay and Challenger Formations merge along the walls of the canyon. The Eocene section on the Naturaliste Plateau (DSDP site 264) corresponds to the upper part of the new unnamed (mainly) Lower Eocene unit and the lower part of the combined Porpoise Bay and Challenger Formations in the Fremantle Canyon succession.

Evidence of a reworking episode during the Middle Eocene of a Cretaceous source or sources was recorded in the Fremantle Canyon succession (at a Middle Eocene level within the unit comprising the Porpoise Bay and Challenger Formations). It agrees with Shafik's (1985) similar findings at contemporaneous levels in several sections in the Perth, Carnarvon, Eucla and Otway Basins; such evidence is missing from the Eocene section of DSDP site 264 on the Naturaliste Plateau.

The presence of the key species *Isthmolithus recurvus* in the uppermost Eocene–lowermost Oligocene sediments of the Fremantle Canyon and its absence from the Upper Eocene sediments in the same section confirm a previously-known climatic scenario: chilling of the ocean near the end of the Eocene after generally warm surface-water conditions during the Late Eocene.

An unnamed mid (upper Lower) Oligocene unit was discovered from the Fremantle Canyon succession, based on a nannofossil assemblage containing the index species *Sphenolithus distentus*, and indicating a correlation with the foraminiferal zone P21a. Apparently, this unit has no counterpart elsewhere in the Perth Basin or at the nearby DSDP sites 258, 259 and 264. It fits between the Lower–Middle Miocene Stark Bay Formation and the combined (mainly Eocene) Porpoise Bay–Challenger Formation in the canyon succession, still leaving a large biostratigraphic gap between them. This mid Oligocene unit contains evidence of reworking of Middle Eocene marine sediments which were probably on the Naturaliste Plateau. The already known mid Oligocene erosional event in the Southwest Pacific region, which has been recorded by Kennett and co-workers (see, e.g., Kennett & others, 1972) in several DSDP sites in the Australian sector, was apparently felt on the Naturaliste Plateau.

The key nannofossil species *Sphenolithus heteromorphus*, found in a calcilutite sample, was used to suggest that the Stark Bay Formation was sampled. Two slightly older Miocene levels were recorded in the Fremantle Canyon succession. The base of the Stark Bay Formation apparently becomes older in a westerly direction.

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List of calcareous nannofossils mentioned in this paper

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Biantholithus sparsus Bramlette & Martini, 1964
Birkelundia staurion (Bramlette & Sullivan) Perch-Nielsen, 1971
Blackites creber (Deflandre) Sherwood, 1974
Blackites spinulus (Levin) Roth, 1970
Braarudosphaera bigelowii (Gran & Braarud) Deflandre, 1947
Braarudosphaera discula Bramlette & Riedel, 1954
Braarudosphaera orthia Bybell & Gartner, 1972
Calcidiscus leptoporus (Murray & Blackman) Loeblich & Tappan, 1978
Calcidiscus protoannulus (Gartner) Loeblich & Tappan, 1978
Campylosphaera dela (Bramlette & Sullivan) Hay & Mohler, 1967
Campylosphaera eodela Bukry & Percival, 1971
Chiasmolithus altus Bukry & Percival, 1971
Chiasmolithus bidens (Bramlette & Sullivan) Hay & Mohler, 1967
Chiasmolithus californicus (Sullivan) Hay & Mohler, 1967
Chiasmolithus consuetus (Bramlette & Sullivan) Hay & Mohler, 1967
Chiasmolithus danicus (Brotzen) van Heck & Perch-Nielsen, 1987
Chiasmolithus edentulus van Heck & Prins, 1987
Chiasmolithus edwardsii (Romein) van Heck & Prins, 1987
Chiasmolithus eograndis Perch-Nielsen, 1971
Chiasmolithus expansus (Bramlette & Sullivan) Gartner, 1970
Chiasmolithus gigas (Bramlette & Sullivan) Radomski, 1968
Chiasmolithus grandis (Bramlette & Riedel) Radomski, 1968
Chiasmolithus inconspicuus van Heck & Prins, 1987
Chiasmolithus oamaruensis (Deflandre) Hay, Mohler & Wade, 1966
Chiasmolithus solitus (Bramlette & Sullivan) Locker, 1968
Chiasmolithus titus Gartner, 1970
Chiphragmalithus acanthodes Bramlette & Sullivan, 1961
Clathrolithus ellipticus Deflandre *in* Deflandre & Fert, 1954
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus robustus (Bramlette & Sullivan) Shafik, n. comb. (basionym: *Cyclolithus? robustus* Bramlette & Sullivan, 1961, p. 141, pl. 2, figs 7a–c)
Coronocyclus nitescens (Kamptner) Bramlette & Wilcoxon, 1967
Cruciplacolithus asymmetricus van Heck & Prins, 1987
Cruciplacolithus frequens (Perch-Nielsen) Romein, 1979
Cruciplacolithus latipons Romein, 1979
Cruciplacolithus primus Perch-Nielsen, 1977
Cruciplacolithus tenuis (Stradner) Hay & Mohler *in* Hay & others, 1967
Cyclagelosphaera alta Perch-Nielsen, 1979
Cyclagelosphaera reinhardtii (Perch-Nielsen) Romein, 1979
Cyclicargolithus abisectus (Müller) Wise, 1973
Cyclicargolithus floridanus (Roth & Hay) Bukry, 1971
Cyclicargolithus gammation (Bramlette & Sullivan) Shafik, 1990b
Cyclicargolithus luminis (Sullivan) Bukry, 1971
Cyclicargolithus reticulatus (Gartner & Smith) Bukry, 1971
Daktylethra punctulata Gartner *in* Gartner & Bukry, 1969
Discoaster barbadiensis Tan Sin Hok, 1929
Discoaster binodosus Martini, 1958
Discoaster deflandrei Bramlette & Riedel, 1964
Discoaster diastypus Bramlette & Sullivan, 1961
Discoaster distinctus Martini, 1958
Discoaster falcatus Bramlette & Sullivan, 1961
Discoaster lenticularis Bramlette & Sullivan, 1961
Discoaster lodoensis Bramlette & Riedel, 1954
Discoaster mediosus Bramlette & Sullivan, 1961
Discoaster mohleri Bukry & Percival, 1971
Discoaster multiradiatus Bramlette & Riedel, 1954
A form transitional between *D. multiradiatus* and *D. barbadiensis*
Discoaster nobilis Martini, 1961
Discoaster robustus Haq, 1969
Discoaster saipanensis Bramlette & Riedel, 1954
Discoaster septemradiatus (Klumpp) Martini, 1958
Discoaster sublodoensis Bramlette & Sullivan, 1961

Discoaster tanii nodifer Bramlette & Riedel, 1954
Discoaster tanii tanii Bramlette & Riedel, 1954
Discoaster wemmelensis Achuthan & Stradner, 1969
Discoasteroides kuepperi Bramlette & Sullivan, 1961
Ellipsolithus distichus (Bramlette & Sullivan) Sullivan, 1964
Ellipsolithus lajollaensis Bukry & Percival, 1971
Ellipsolithus macellus (Bramlette & Sullivan) Sullivan, 1964
Ericsonia subpertusa Hay & Mohler, 1967
Fasciculithus alanii, Perch-Nielsen, 1971
Fasciculithus bobii, Perch-Nielsen, 1971
Fasciculithus involutus Bramlette & Sullivan, 1961
Fasciculithus lillianiae Perch-Nielsen, 1971
Fasciculithus tonii Perch-Nielsen, 1971
Fasciculithus tympaniformis Hay & Mohler *in* Hay & others, 1967
Fasciculithus ulii Perch-Nielsen, 1971
Helicosphaera compacta Bramlette & Wilcoxon, 1967
Helicosphaera dinesenii Perch-Nielsen, 1971
Helicosphaera euphratis Haq, 1966
Helicosphaera kamptneri Hay & Mohler *in* Hay & others, 1967
Helicosphaera lophata Bramlette & Sullivan, 1961
Helicosphaera recta Haq, 1966
Helicosphaera reticulata Bramlette & Wilcoxon, 1967
Helicosphaera seminulum Bramlette & Sullivan, 1961
Heliolithus cantabriae Perch-Nielsen, 1971
Heliolithus kleinpellii Sullivan, 1964
Heliolithus riedelii Bramlette & Sullivan, 1961
Holodiscolithus macroporus (Deflandre) Roth, 1970
Holodiscolithus solidus (Deflandre) Roth, 1970
Isthmolithus recurvus Deflandre *in* Deflandre & Fert, 1954
Lithostromation opersum (Deflandre) Bybell, 1975
Lanternithus minutus Stradner, 1962
Lophodolithus mochlophorus Deflandre *in* Deflandre & Fert, 1954
Lophodolithus nascens Bramlette & Sullivan, 1961
Lophodolithus reniformis Bramlette & Sullivan, 1961
Lophodolithus rotundus Bukry & Percival, 1971
Markalius astroporus (Stradner) Hay, Mohler & Wade, 1967
Markalius inversus (Deflandre) Bramlette & Martini, 1964
Micrantholithus altus Bybell & Gartner,1972
Micrantholithus attenuatus Bramlette & Sullivan, 1961
Micrantholithus crenulatus Bramlette & Sullivan, 1961
Micrantholithus entaster Bramlette & Sullivan, 1961
Micrantholithus flos Deflandre *in* Deflandre & Fert, 1954
Micrantholithus procerus Bukry & Percival, 1971
Micrantholithus vesper Deflandre *in* Deflandre & Fert, 1954
Nannotetrina cristata (Martini) Perch-Nielsen, 1971
Nannotetrina fulgens (Stradner) Achuthan & Stradner, 1969
Neochiastozygus chiastus (Bramlette & Sullivan) Perch-Nielsen, 1971
Neochiastozygus concinnus (Martini) Perch-Nielsen, 1971
Neochiastozygus denticulatus (Perch-Nielsen) Perch-Nielsen, 1971
Neochiastozygus distentus (Bramlette & Sullivan) Perch-Nielsen, 1971
Neochiastozygus junctus (Bramlette & Sullivan) Perch-Nielsen, 1971
Neochiastozygus saepes Perch-Nielsen, 1971
Neococcolithes dubius (Deflandre) Black, 1967
Neococcolithes protenus (Bramlette & Sullivan) Black, 1967
Orthozygus aureus (Stradner) Bramlette & Wilcoxon, 1967
Pedinocyclus larvalis (Bukry & Bramlette) Loeblich & Tappan, 1973
Pemma basquensis (Martini) Baldi-Beke, 1971
Pemma papillatum Martini, 1959
Pemma rotundum Klumpp, 1953
Placozygus sigmoides (Bramlette & Sullivan) Romein, 1979
Pontosphaera multipora (Kamptner) Roth, 1970
Pontosphaera ocellata (Bramlette & Sullivan) Perch-Nielsen, 1984
Pontosphaera panarium (Deflandre) Shafik, n. comb. (basionym: *Discolithus panarium* Deflandre *in* Deflandre & Fert, 1954, p. 141, text-figs 39, 40)
Pontosphaera pectinata (Bramlette & Sullivan) Sherwood, 1974
Pontosphaera plana (Bramlette & Sullivan) Haq, 1971
Prinsius bisulcus (Stradner) Hay & Mohler, 1967
Reticulofenestra dictyoda (Deflandre) Stradner *in* Stradner & Edwards, 1968
Reticulofenestra hampdenensis Edwards, 1973
Reticulofenestra samodurovii (Hay, Mohler & Wade) Roth, 1970
Reticulofenestra scissura Hay, Mohler & Wade, 1966
Reticulofenestra scrippsae (Bukry & Percival) Shafik, 1981
Reticulofenestra umbilicus (Levin) Martini & Ritzkowski, 1968
Rhabdolithus gladius Locker, 1967
Rhabdosphaera inflata Bramlette & Sullivan, 1961
Rhabdosphaera perlongus Deflandre *in* Grassé, 1952
Rhabdosphaera procera Martini, 1969
Rhabdosphaera pseudomorionum Locker, 1968
Rhabdosphaera solus Perch-Nielsen, 1971
Scapholithus fossilis Deflandre *in* Deflandre & Fert, 1954
Scapholithus rhombiformis Hay & Mohler, 1967
Semihololithus kerabyi Perch-Nielsen, 1971
Sphenolithus anarrhopus Bukry & Percival, 1971
Sphenolithus ciperoensis Bramlette & Wilcoxon, 1967
Sphenolithus conicus Bukry, 1971
Sphenolithus distentus (Martini) Bramlette & Wilcoxon, 1967
Sphenolithus heteromorphus Deflandre, 1953
Sphenolithus moriformis (Brönnimann & Stradner) Bramlette & Wilcoxon, 1967
Sphenolithus predistentus Bramlette & Wilcoxon, 1967
Sphenolithus primus Perch-Nielsen, 1971
Sphenolithus pseudoradians Bramlette & Wilcoxon, 1967
Sphenolithus radians Deflandre in Grassé, 1952
Striatococcolithus pacificanus Bukry, 1971
Thoracosphaera operculata Bramlette & Martini, 1964
Toweius? crassus (Bramlette & Sullivan) Perch-Nielsen, 1984
Toweius eminens (Bramlette & Sullivan) Perch-Nielsen, 1971
Toweius pertusus (Sullivan) Romein, 1979
Toweius tovae Perch-Nielsen, 1971
Transversopontis fimbriatus (Bramlette & Sullivan) Locker, 1968
Transversopontis pulcher (Deflandre) Perch-Nielsen, 1967
Transversopontis pulcheroides (Sullivan) Baldi-Beke, 1971
Tribrachiatus bramlettei (Brönnimann & Stradner) Proto Decima & others, 1975
Tribrachiatus contortus (Stradner) Bukry, 1972
Tribrachiatus orthostylus Shamarai, 1963
Zygodiscus adamas Bramlette & Sullivan, 1961
Zygodiscus herlynii Sullivan, 1964
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959
Zygrhablithus bijugatus crassus Locker, 1967

Cretaceous species

Actinozygus regularis (Górka) Gartner, 1968
Acuturris scotus Wind & Wise *in* Wise & Wind, 1977
Ahmuellerella octoradiata (Górka) Reinhardt, 1967
Arkhangelskiella cymbiformis Vekshina, 1959
Arkhangelskiella orthocancellata (Bukry) Shafik, 1990a
Arkhangelskiella specillata Vekshina, 1959
Biscutum melaniae (Górka) Reinhardt, 1969
Broinsonia bukryi Shafik, 1990a
Calculites obscurus (Deflandre) Prins & Sissingh *in* Sissingh, 1977
Chiastozygus litterarius (Górka) Manivit, 1971
Corollithion exiguum Stradner, 1961
Cretarhabdus surrirellus (Deflandre & Fert) Reinhardt, 1970
Cribrosphaerella daniae Perch-Nielsen, 1973
Cribrosphaerella ehrenbergii (Arkhangelsky) Deflandre *in* Deflandre & Fert, 1954
Eiffellithus eximius (Stover) Perch-Nielsen, 1968
Eiffellithus turriseiffeli (Deflandre) Reinhardt, 1965
Gartnergo obliquum (Stradner) Reinhardt, 1970
Haqius circumradiatus (Stover) Roth, 1978
Heterorhabdus sinuosus Nöel, 1970
Kampterius magnificus Deflandre, 1959
Lithraphidites carniolensis Deflandre, 1963
Lithraphidites quadratus Bramlette & Martini, 1964
Manivitella pemmatoidea (Deflandre *in* Manivit) Thierstein, 1971
Micula prinsii Perch-Nielsen, 1979
Micula staurophora (Gardet) Stradner, 1963
Nephrolithus corystus Wind, 1983
Nephrolithus frequens Górka, 1957
Placozygus fibuliformis (Reinhardt) Hoffmann, 1970
Prediscosphaera bukryi Perch-Nielsen, 1973
Prediscosphaera cretacea (Arkhangelsky) Gartner, 1968
Prediscosphaera majungae Perch-Nielsen, 1973
Prediscosphaera spinosa (Bramlette & Martini) Gartner, 1968
Prediscosphaera stoveri (Perch-Nielsen) Shafik & Stradner, 1971
Quadrum gothicum (Deflandre) Prins & Perch-Nielsen *in* Manivit & others, 1977
Reinhardtites biperforatus (Gartner) Shafik, 1979
Reinhardtites levis Prins & Sissingh *in* Sissingh, 1977
Rhagodiscus angustus (Stradner) Reinhardt, 1971
Rhagodiscus reniformis Perch-Nielsen, 1973
Tetrapodorhabdus decorus (Deflandre) Wind & Wise, 1983

Tranolithus orionatus (Reinhardt) Reinhardt, 1966
Vekshinella elliptica Gartner, 1968
Watznauria barnesae (Black) Perch-Nielsen, 1968
Zygodiscus bicrescenticus (Stover) Wind & Wise *in* Wise & Wind, 1977
Zygodiscus deflandrei Bukry, 1969

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Checklist 1. Distribution of Maastrichtian and Paleocene calcareous nannofossils in Fremantle dredge samples, South Perth Basin.

	80DR/020–11	80DR/020–10	80DR/020–09	80DR/014–05	80DR/014–10	80DR/020–08	80DR/014–08	80DR/004–02	80DR/022–03	80DR/016–03	80DR/016–02	80DR/014–03	80DR/005–09	80DR/005–08	80DR/014–13	80DR/014–12	80DR/017–03	80DR/021–05	80DR/020–06
Actinozygus regularis		+		+		+													
Ahmuellerella octoradiata			+																
Arkhangelskiella cymbiformis	+	+	+	+	+														
Arkhangelskiella specillata		+	+																
Biscutum melaniae			+																
Calculites obscurus					+														
Corollithion exiguum				+															
Cretarhabdus surrirellus		+					+												
Cribrosphaerella daniae	+	+	+	+															
Cribrosphaerella ehrenbergii	+	+	+	+	+														
Eiffellithus eximius					+								+						
Eifellithus turriseiffeli	+	+	+	+	+														
Gartnerago obliquum							+												
Haqius circumradiatus						+													
Heterorhabdus sinuosus	+	+	+																
Kamptnerius magnificus	+	+																	
Lapideacassis spp.		+		+	+	+													
Lithraphidites carniolensis			+																
Lithraphidites quadratus	+	+																	
Manivitella pemmatoidea				+															
Micula staurophora	+	+	+	+			+												
Nephrolithus corystus	+																		
Nephrolithus frequens	+	+	+	+	+														
Placozygus fibuliformis	+	+	+	+															
Prediscosphaera bukryi-stoveri	+		+																
Prediscosphaera cretacea	+	+		+	+														
Prediscosphaera majungae	+	+			+														
Prediscosphaera spinosa		+			+														
Quadrum gothicum	+																		
Reinhardtites levis				+															
Rhagodiscus augustus	+	+																	
Rhagodiscus reniformis		+	+																
Tetrapodorhabdus decorus	+	+	+																
Vekshinella elliptica	+																		
Watznaueria barnesae	+	+	+					+					+	+					
Thoracosphaera operculata				+	+	+	+								+	+			
Biantholithus sparsus				+	+														
Braarudosphaera bigelowii								+		+	+	+	+	+	+	+	+		+
Braarudosphaera discula											+	+	+	+		+			
Campylosphaera eodela																		+	+
Chiasmolithus bidens								+	+	+	+	+	+	+		+	+	+	+
Chiasmolithus californicus																		+	+
Chiasmolithus consuetus							+					+	+	+	+	+		+	+
Chiasmolithus danicus					+		+												
Chiasmolithus edentulus							+												
Chiasmolithus edwardsii													+						
Chiasmolithus inconspicuus					+														
Coccolithus eopelagicus										+									+
Coccolithus robustus				+	+	+	+	+	+	+	+	+	+	+	+	+			
Cruciplacolithus asymmetricus				+	+		+				+	+		+	+				
Cruciplacolithus platipons				+			+								+				
Cruciplacolithus primus				+	+														
Cruciplacolithus tenuis					+	+	+	+			+	+	+						
Cyclagelosphaera alta				+															
Cyclagelosphaera reinhardtii					+														
Discoaster diastypus																			?
Discoaster lenticularis													+	+				+	
Discoaster mediosus																			+
Discoaster mohleri									+	+	+	+	+	+	+		+	+	
Discoaster multiradiatus																	+	+	+
Discoaster nobilis															+	+	+	+	
Ellipsolithus distichus								+				+	+	+	+	+	+	+	+
Ellipsolithus macellus											+								
Ericsonia subpertusa				+	+														
Fasciculithus alanii														+					
Fasciculithus bobii														+					
Fasciculithus involutus									+	+	+	+	+	+		+		+	+
Fasciculithus lillianiae														+					
Fasciculithus spp.							+	+	+	+	+	+		+	+	+	+	+	
Fasciculithus tonii														+					

Checklist 1 (cont'd).

	80DR/020–11	80DR/020–10	80DR/020–09	80DR/014–05	80DR/014–10	80DR/020–08	80DR/014–08	80DR/004–02	80DR/022–03	80DR/016–03	80DR/016–02	80DR/014–03	80DR/005–09	80DR/005–08	80DR/014–13	80DR/014–12	80DR/017–03	80DR/021–05	80DR/020–06
Fasciculithus tympaniformis									+	+				+		+			
Fasciculithus ulii							+												
Heliolithus cantabriae							+							+					
Heliolithus kleinpellii								+	+	+	+			+					
Heliolithus riedelii											?				?		?	+	+
Lophodolithus nascens																			+
Markalius astroporus				+	+	+	+			+		+					+		
Micrantholithus attenuatus										+			+						
Micrantholithus crenulatus														+		+			
Micrantholithus entaster								+				+		+			+		
Micrantholithus vesper														+					
Neochiastozygus chiastus					+	+	+	+				+	+	+				+	+
Neochiastozygus denticulatus					+														
Neochiastozygus junctus					+								+	+			+	+	
Placozygus sigmoides		+		+	+	+	+		+				+	+					
Pontosphaera plana																	+	+	+
Prinsius bisulcus						+			+					+		+			
Scapholithus fossilis																		+	
Scapholithus rhombiformis														+					
Scapholithus sp.											+		+						+
Semihololithus kerabyi													+	+	+	+			
Sphenolithus primus							+												
Sphenolithus anarrhopus										?					+				
Toweius eminens									+	+	+		+	+	+	+	+	+	+
Toweius pertusus							+	+	+	+	+	+	+	+	+	+	+		
Toweius tovae													+			?		+	
Toweius? magnicrassus																			+
Transversopontis pulcher																			+
Zygodiscus adamas														+					
Zygodiscus herlynii								+			+	+	+	+	+	+	+	+	
Zygrhablithus bijugatus																	+	+	+

Checklist 2. Distribution of Eocene and older calcareous nannofossils in Fremantle dredge samples, South Perth Basin.

	80DR/018–01	80DR/014–14	80DR/020–07	80DR/020–05	80DR/017–01	80DR/003–06	80DR/003–09	80DR/003–01	80DR/003–02	80DR/003–03	80DR/003–07	80DR/003–08	80DR/022–01	80DR/021–11	80DR/023–01C	80DR/019–04	80DR/019–01	80DR/019–03	80DR/018–02	80DR/009–01	80DR/013–01	80DR/008–02	80DR/014–11	80DR/014–04
Birkelundia staurion																	+							
Blackites creber														+										
Blackites spinulus																	+		+					
Braarudosphaera bigelowii	+	+	+	+	+	+	+		+	+	+	+	+	+	+					+	+	+		
Braarudosphaera discula	+		+		+	+			+	+	+	+	+											
Braarudosphaera orthia				+																				
Calcidiscus protoannulus		+	+	+	+	+		+		+	+	+	+	+	+	+	+		+	+				
Campylosphaera dela	+			+		+			+	+	+	+	+	+	+		+							
Campylosphaera eodela		+	+	+	+										+									
Campylosphaera sp. 1				+		+				+														
Chiamolithus bidens		+	+	+			+																+	
Chiasmolithus californicus		+		+		+					+	+												
Chiasmolithus consuetus	+	+	+	+	+	+																	+	
Chiasmolithus eogranids	+	+	+	+	+			+	+		+				+				+					
Chiasmolithus expansus						+											+			+				
Chiasmolithus grandis		+	+	+	+	+			+	+		+	+	+	+	+	+	+		+	+			
Chiasmolithus oamaruensis																							+	+
Chiasmolithus solitus	+		+	+			+		+		+	+	+	+	+	+	+	+	+	+	+	+		
Chiasmolithus titus	+			+	+	+			+	+		+	+	+								+		
Chiphragmalithus acanthodes																		+						
Clathrolithus ellipticus			+		+																			
Clausicoccus cribellum	+		+								+			+	+	+	+			+	+	+		
Coccolithus eopelagicus			+		+		+			+			+	+	+			+	+	+	+	+	+	+
Coccolithus formosus	+	+		+					+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Coccolithus robustus				+			+																+	
Cruciplacolithus latipons	+			+		+																		
Cruciplacolithus sp. 1		+	+	+		+																		
Cruciplacolithus tenuis														+										
Cyclicargolithus floridanus														+	+	+	+	+	+	+				
Cyclicargolithus gammation							+		+	+	+		+	+	+									
Cyclicargolithus luminis	+																+							
Cyclicargolithus reticulatus																				+	+	+	+	
Cyclicargolithus sp. 1 *(eogammtion)*														+		+								
Daktylethra punctulata																	+			+	+	+		
Discoaster barbadiensis	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+		+	+	+		
Discoaster binodosus				+	+																			
Discoaster deflandrei											+	+				+	+		+			+		+
Discoaster diastypus		+	?				+																	
Discoaster distinctus																	+							
Discoaster falcatus		+		?																				
Discoaster lodoensis									+	+	+	+	+	+	+									
Discoaster mediosus						+																		
Discoaster mobleri							+																	
Discoaster multiradiatus	+		+	+																				
Discoaster multiradiatus/ *D. barbadiensis*		+			+	+				+			+	+										
Discoaster robustus													+											
Discoaster saipanensis															+		+	+	+			+	+	
Discoaster septemradiatus			+																					
Discoaster sp. 1			+	+																				
Discoaster sublodoensis										+	+	+	+	+	+	+								
Discoaster tanii																							+	+
Discoaster tanii nodifer												?			+				+	+	+		+	+
Discoaster wemmelensis														+					+					
Discoasteroides kuepperi										+	+		+	+	+									
Ellipsolithus distichus	+	+		+																				
Ellipsolithus lajollaensis																	+							
Ellipsolithus macellus	+	+	+	+	+	+		+																
Fasciculithus involutus																							+	
Helicosphaera compacta																?				+	+			
Helicosphaera dinesenii																				+				
Helicosphaera lophata															+		+		+	+				
Helicosphaera reticulata																					+			
Helicosphaera seminulum										+	+	+	+	+	+	+	+	+	+					+
Holodiscolithus macroporus					+												+		+	+	+			
Holodiscolithus solidus			+		+												+		+	+	+			
Isthmolithus recurvus																								+
Lanternithus minutus																+	+			+	+	+	+	+
Lapideacassis sp.						+																		
Lithostromation opersum						+																		
Lophodolithus mochlophorus				+		+				+	+	+			+									
Lophodolithus nascens	+		+	+	+	+				+	+	+												
Lophodolithus reniformis					+				+	+	+	+			+									
Lophodolithus rotundus																	+							
Markalius astroporus			+	+		+				+												+		
Markalius inversus	+				+							+	+	+		+							+	
Micrantholithus altus																				+				
Micrantholithus attenuatus						+				+	+									+				

Checklist 2 (cont'd).

	80DR/018–01	80DR/014–14	80DR/020–07	80DR/020–05	80DR/017–01	80DR/003–06	80DR/003–09	80DR/003–01	80DR/003–02	80DR/003–03	80DR/003–07	80DR/003–08	80DR/022–01	80DR/021–11	80DR/023–01C	80DR/019–04	80DR/019–01	80DR/019–03	80DR/018–02	80DR/009–01	80DR/013–01	80DR/008–02	80DR/014–11	80DR/014–04
Micrantholithus crenulatus				+		+			+				+	+										
Micrantholithus entaster	+	+		+	+	+			+			+	+											
Micrantholithus flos						+																		
Micrantholithus procerus																				+	+	+		
Micrantholithus vesper						+																		
Nannifula sp. 1						+																		
Nannotetrina cristata																	+							
Nannotetrina fulgens																	+							
Neochiastozygus chiastus				+	+	+																		
Neochiastozygus concinnus						+																		
Neochiastozygus distentus						+																		
Neochiastozygus junctus				+																				
Neococcolithes dubius		+	+	+	+						+	+	+	+	+	+	+	+	+			+		
Neococcolithes protenus				+		+			?	+	?	?												
Orthozygus aureus																	+		+					
Pedinocyclus larvalis																				+				
Pemma basquensis																				+				
Pemma papillatum																				+	+			
Pemma rotundum																		+	+	+	+	+		
Placozygus sigmoides	+					+																		
Pontosphaera multipora																+	+		+	+		+		
Pontosphaera ocellata	+		+	+									+		+		+	+						
Pontosphaera panarium				+			+										+							
Pontosphaera pectinata	+																							
Pontosphaera plana	+	+	+	+	+	+			+	+		+	+				+	+	+	+	+	+	+	
Reticulofenestra dictyoda										+	+	+	+	+	+	+	+	+	+					
Reticulofenestra hampdenensis																				+	+	+	+	+
Reticulofenestra samodurovii														+		+	+	+	+			+		
Reticulofenestra scissura																						+	+	+
Reticulofenestra scrippsae																							+	
Reticulofenestra sp. (*praescrippsae*)														+	+									
Reticulofenestra umbilicus																		+		+	+	+	+	+
Rhabdosphaera gladius			+							+					+	+	+			+				
Rhabdosphaera sp.																	+	+						
Rhabdosphaera inflata																+								
Rhabdosphaera perlongus	+	+		+	+			+	+			+	+				+							
Rhabdosphaera pseudomorionum																	+							
Rhabdosphaera solus										+														
Rhabdosphaera pseudomorionum																	+							
Scapholithus fossilis										+		+												
Sphenolithus anarrhopus			+																					
Sphenolithus moriformis			+	+	+	+											+	+			+	+	+	+
Sphenolithus pseudoradians																							+	
Sphenolithus radians	+				+	+	+		+	+	+	+	+	+		+	+	+		+				
Striatococcolithus pacificanus										+		+												
Toweius eminens				+																				
Toweius pertusus	+	+	+	+	+	+	+	+	+	+	+	+	+		+								+	
Toweius? crassus	+	+	+	+	+	+	+	+	+	+	+	+	+		+									
Transversopontis fimbriatus										+							+							
Transversopontis pulcher	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	+			?		
Transversopontis pulcheroides										+			+						+					
Tribrachiatus orthostylus				+	+	+				+	+	+	+											
Zygodiscus adamas				+						+														
Zygodiscus herlynii	+	+	+	+		+	+	+				+							+				+	
Zygrhablithus bijugatus bijugatus	+	+	+	+	+	+			+						+	+	+				+		+	+
Zygrhablithus bijugatus crassus		+			+	+	+		+	+	+	+	+	+	+	+		+			+	+		
Arkhangelskiella orthocancellata			+																					
Arkhangelskiella specillata																	+					+		
Broinsonia bukryi		+																						
Chiastozygus litterarius				+																+	+	+		
Eiffellithus eximius						+							+							+	+			
Eiffelithus turriseiffeli				+		+																		
Gartnergo obliquum																				+	+			
Kampterius magnificus																				+				
Micula staurophora																				+				
Prediscosphaera cretacea																						+		
Reinhardtites biperforatus																				+	+	+		
Tranolithus orionatus			+		+																+			
Vekshinella elliptica					+																+			
Watznaria barnesae	+	+	+																	+	+	+		
Zygodiscus bicrescenticus			+																		+	+		
Zygodiscus deflandrei	+		+																	+	+			