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Late Cretaceous–Palaeogene nannofossil biostratigraphy of Challenger No. 1 well (Challenger Formation type section), offshore Perth Basin, Western Australia

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Late Cretaceous–Palaeogene calcareous nannofossil assemblages from the mainly carbonate section in Challenger No. 1 well, above the 780-m level, have some similarities with the recently described succession of carbonates in the Perth Canyon, south Perth Basin. The continuity of the marine Palaeogene in these two sections contrasts with the single marine unit (the hemipelagic Kings Park Formation) known in the onshore Perth Basin. In both offshore sections, it is impracticable to subdivide the Palaeogene carbonates into mappable lithostratigraphic units, and identification of known Paleocene and Eocene hemipelagic rock units is evidently not possible although their age equivalents (or partial equivalents) can be detected biostratigraphically.

Marine Oligocene sediments, recently identified (for the first time in the Perth Basin) in the Perth Canyon, are shown to occur in Challenger No. 1. The age of the type section of the Challenger Formation is revised (from Late Eocene) to Middle Eocene–Oligocene. Sediments immediately underlying the type Challenger Formation in Challenger No. 1 are Middle Eocene in age, and consequently are not the Kings Park Formation as previously reported. They probably equate with the basal type section of the hemipelagic Porpoise Bay Formation, suggesting a possibly significant age overlap between the type sections of the Challenger and Porpoise Bay Formations; the latter is probably a more terrigenous facies of part of the former. Lower Eocene beds similar to those discovered recently in the Perth Canyon also occur in Challenger No. 1. The Late Cretaceous assemblages identified in Challenger No. 1 are probably representatives of both the upper Campanian Lancelin beds (lower part) and the upper Santonian–lower Campanian Gingin Chalk.

Three major disconformities (or condensed sections) are detected in Challenger No. 1: at the Eocene/Oligocene boundary (lowermost Oligocene is missing) within the upper part of the Challenger Formation; at the Cretaceous/Tertiary boundary (Maastrichtian and Lower Paleocene are missing), and within the Campanian section. The Late Cretaceous–Palaeogene section in Challenger No. 1 is more complete than coeval sections at nearby Deep Sea Drilling Project sites in the Perth Abyssal Plain and on the Naturaliste Plateau.

Introduction

Challenger No. 1 well (lat. 32°25.3′S, long. 115°00.8′E) was drilled offshore in the Perth Basin (Fig. 1) during early 1975 by West Australian Petroleum Pty Ltd (WAPET). Quilty (1978) described its lithological and foraminiferal faunal successions above the 773-m level. Cockbain & Hocking (1989) nominated the 67-m-thick section in Challenger No. 1, between 530 and 597 m (Quilty's, 1978, 'Late Eocene unnamed formation'), as the type section of the Challenger Formation. Two foraminiferal assemblages were recorded from this section by Quilty (1978), who regarded them as Late Eocene in age. In a recent paper, I discussed these foraminiferal assemblages, and concluded that they suggest a Middle Eocene to (Early) Oligocene age (Shafik, 1991) .

Substantial new knowledge has been gained recently about the Palaeogene sequence in the Perth Basin. I have recorded several Paleocene, Eocene, and Oligocene marine levels in the Perth Canyon[2] (to the north of Challenger No. 1, Fig. 1) which were unknown previously in the Perth Basin (Shafik, 1991).

Because it has been long believed that the Oligocene corresponds to a period of erosion, with no marine record in the Perth Basin (Quilty, 1977; Quilty & others, in press), my interpretation of marine Oligocene in Challenger No. 1, and my record of a mid-Oligocene nannofossil assemblage from the Perth Canyon (Shafik, 1991), are highly significant. However, it was not possible to determine whether the mid-Oligocene beds in the Perth Canyon, and the suspected Oligocene (uppermost part of Challenger Formation) in Challenger No. 1, are parts of the same unit, without first examining material from Challenger No. 1 (see Shafik, 1991).

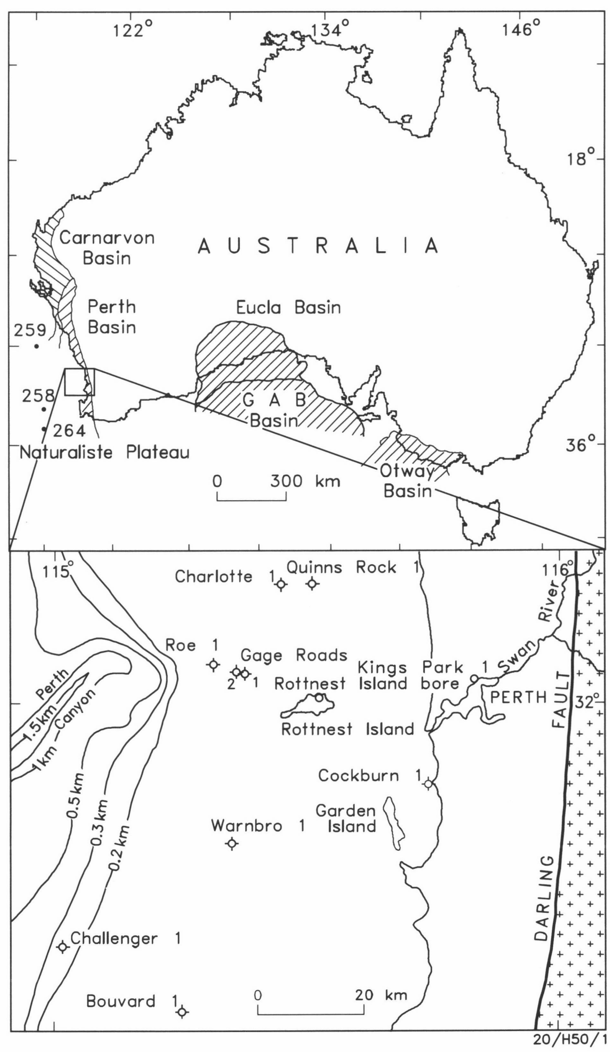

Figure 1. South Perth Basin, Western Australia, showing location of Challenger No. 1 well and other relevant localities.

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[2] Shafik (1991) used the name 'Fremantle Canyon' instead, following Marshall & others (1989) and Quilty & others (in press), but the Hydrographer of the Royal Australian Navy has informed BMR that the name 'Perth Canyon' has precedence.

The aim of this study is to document the calcareous nannofossil assemblages of the section above the 780-m level in Challenger No. 1 in order to: (1) test the assertion of the presence of an Oligocene section in the well; (2) date the type section of the Challenger Formation; and (3) elucidate and attempt to correlate the Upper Cretaceous–lower Tertiary stratigraphy in the well, below the Challenger Formation, with that which was recorded recently in the Perth Canyon and elsewhere in the Perth Basin (see Shafik, 1990a, 1991).

Nannofossil biostratigraphy

Forty-two samples of ditch cuttings, representing a continuous section between 460 and 780 m in Challenger No. 1, were examined for nannofossils. This enabled the establishment of a more detailed biostratigraphy than that previously outlined by Quilty (1978), who used 11 samples of ditch cuttings taken at 15-m intervals. Because I was examining cuttings, biostratigraphic events represented by the highest occurrence of key species are given more credence than those based on lowest occurrence, except for those of short-ranged species. In discussing the foraminiferal biostratigraphy of Challenger No. 1, Quilty (1978) recognised four disconformity-bounded units. Approximations of these units are discussed below, and the results are summarised in Figure 2.

Interval 460–530 m: undifferentiated Neogene and Oligocene carbonates

Quilty (1978) identified two lithological subunits in this interval. The upper subunit (465–498 m) is white chalk with minor pale brown chert and traces of glauconite, and the lower subunit (498–530 m) is white, friable calcarenite with abundant pale pink chert.

Assemblages are poorly preserved: effects of recrystallisation are evident, and the few specimens of *Discoaster* encountered are mostly overgrown with secondary calcite. The younger elements identified among these assemblages include *Calcidiscus leptoporus, C. macintyrei, Discoaster brouweri, D. exilis, D. variabilis, Helicosphaera kamptneri*, and *Reticulofenestra pseudoumbilicus* (Fig. 3). These elements collectively suggest a Middle Miocene to Early Pliocene age for the upper part of the interval (460–500 m). Quilty (1978) assigned the interval 465–530 m a Late Miocene age.

The assemblage from the base of the interval (sample 520–530 m) is similar to that from the uppermost part of the underlying type section of the Challenger Formation (sample 530–540 m). It includes *Braarudosphaera bigelowii, Chiasmolithus altus, Coccolithus pelagicus, Coronocyclus nitescens, Cyclicargolithus abisectus, C. floridanus, Helicosphaera compacta, H. euphratis, H. recta, Sphenolithus moriformis, S. predistentus, Reticulofenestra scissura*, and *Zygrhablithus bijugatus crassus*. The age is Oligocene owing to the presence of *S. predistentus, R. scissura, R. scrippsae, H. recta*, and *Z. bijugatus*, and the absence of the Eocene index species *Discoaster barbadiensis* and *D. saipanensis*; the latter two species occur abundantly in most samples from the underlying Challenger Formation up to the 540-m level. The key species *R. scissura, H. recta*, and *Z. bijugatus* disappear at 500 m (Figs. 2 and 3). Quilty (1978) regarded the lithological change at 498 m as a contact separating two lithological subunits.

The extinctions of *Reticulofenestra scissura, Helicosphaera recta*, and *Zygrhablithus bijugatus* have been used elsewhere to indicate levels at or near the top of the Oligocene (e.g., Edwards, 1971; Bukry, 1973), and the interval between 500 and 540 m is, therefore, Oligocene in age. This age assignment is supported by the occurrence of the species *Cyclicargolithus abisectus, Discoaster deflandrei*, and *Helicosphaera euphratis*, which were encountered occasionally in the interval (Fig. 3).

Cyclicargolithus abisectus, Helicosphaera euphratis, and *H. recta* co-occur elsewhere in sediments of middle to Late Oligocene age (see, for example, the distribution chart *in* Müller, 1979), and their presence in sample 520–530 suggests a maximum age of middle Oligocene.

The assemblages recovered from between 500 and 540 m in Challenger No. 1 lack the important low-latitude species *Sphenolithus distentus* and *S.* sp. aff. *S. ciperoensis*, which are prominent in a mid-Oligocene assemblage from the Perth Canyon (Shafik, 1991). The presence of these two species in the Perth Canyon section, and their absence from the Challenger No. 1 material, is accounted for by a significant change (or changes) in surface-water temperature during the (middle) Oligocene in the Perth Basin.

Interval 530–597 m: type section of the Challenger Formation

Quilty (1978) identified two lithological subunits in this interval. The upper subunit (530–567 m) consists of white chalk, changing to coarser friable bryozoan–echinoderm calcarenite towards the base, with abundant chert and traces of glauconite. The lower subunit (567–597 m) consists of white friable chalk and bryozoan–echinoderm calcarenite with dark grey chert.

Six samples were examined from the type section of the Challenger Formation. The assemblage from the top sample (530–540 m) is similar to that from the base of the overlying Oligocene unit, but lacks *Chiasmolithus altus* and *Helicosphaera recta* (Fig. 3). It is much less diversified than that from sample 540–550 m, which includes *Braarudosphaera bigelowii, Blackites vitreus, Chiasmolithus altus, C. oamaruensis, Clausicoccus cribellum, Coccolithus eopelagicus, C. formosus, Cyclicargolithus floridanus, Discoaster barbadiensis, D. deflandrei, D. saipanensis, D. tanii nodifer, Helicosphaera compacta, H. reticulata, H. seminulum, Isthmolithus recurvus, Lanternithus minutus, Pedinocyclus larvalis, Pontosphaera plana, Reticulofenestra hampdenensis, R. scissura, R. umbilicus, Sphenolithus predistentus*, and *Zygrhablithus bijugatus bijugatus*.

The association of *Chiasmolithus oamaruensis, Isthmolithus recurvus, Discoaster barbadiensis, and D. saipanensis* in the assemblage from sample 540–550 m indicates a Late Eocene age and a correlation with the foraminiferal late P16 Zone (Shafik, 1981). In the same assemblage, indicators of surface-water temperatures collectively suggest a mid-latitude water mass: the cool-water *C. oamaruensis* and *I. recurvus* are common, and are associated with the less frequently occurring warm-water *Helicosphaera reticulata, Sphenolithus predistentus, D. barbadiensis*, and *D. saipanensis*.

At the 540-m level, *Discoaster barbadiensis, D. saipanensis, Coccolithus formosus, Helicosphaera reticulata, Isthmolithus recurvus, Lanternithus minutus*, and *Reticulofenestra hampdenensis* disappear, marking the top of the Eocene (Fig. 3). Furthermore, these combined disappearances suggest either a condensed sequence at the base of the Oligocene, or a disconformity (missing lowermost Oligocene sediments) immediately above the 540-m level. The species *Coccolithus formosus*, which crosses the Eocene/Oligocene boundary and disappears within the Early Oligocene (e.g., Martini, 1971), reappears — together with *Reticulofenestra hampdenensis* — in sample 510–520 m (Fig. 3). I interpret these reappearances as a result of minor reworking within the Oligocene section.

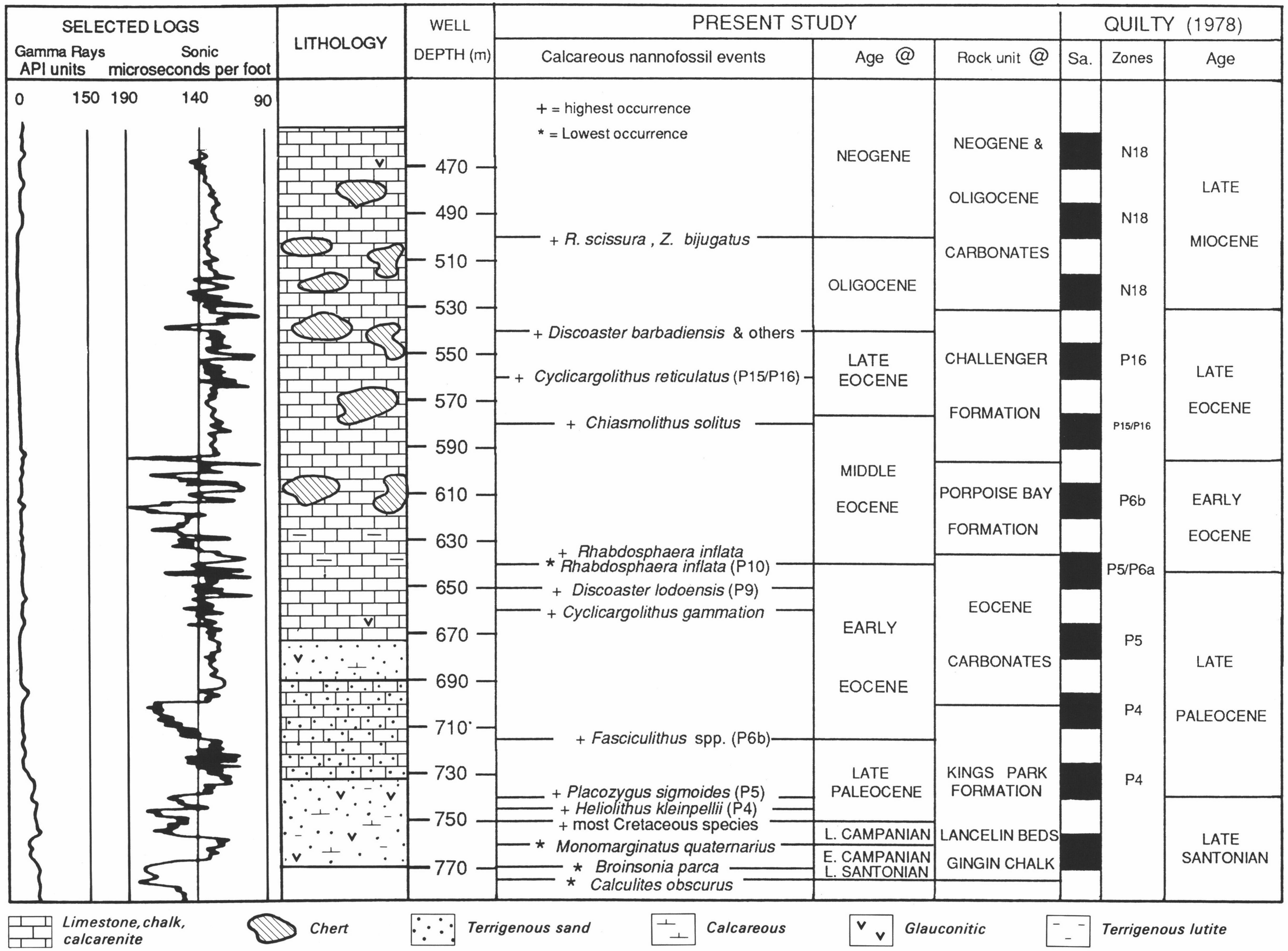

Figure 2. Summary of nannostratigraphy, lithostratigraphy, and previously determined foraminiferal (P and N) zones of Challenger No. 1.
@ most boundaries in these columns are tentatively placed, because the samples on which they are based are cuttings; Sa. sample.

NANNOFOSSIL SPECIES / SAMPLE LEVEL (m)	460-470	470-480	480-490	490-500	500-510	510-520	520-530	530-540	540-550	550-560	560-570	570-580	580-590	590-600	600-605	605-610	610-615	615-620	620-625	625-630	630-635	635-640	640-645	645-650	650-655	655-660	660-670	670-680	680-690	690-700	700-710	710-715	715-720	720-725	725-730	730-735	735-740	740-745	745-750
Calcidiscus leptoporus	X	X	X	X	X	X		X		X																													
Calcidiscus macintyrei	X	X		X		X				X																													
Campylosphaera dela																									X	X		X		X									
Campylosphaera eodela																															X	X	X	X					
Chiasmolithus altus					X	?	X		X					X	X	X																							
Chiasmolithus bidens															?		?	?											X				X	X	X	X	X	X	X
Chiasmolithus eograndis																													X	X	X	X			?		X		
Chiasmolithus grandis															?	X						X			X	X					X								
Chiasmolithus oamaruensis									X	X	X	X	X	X	X	X	X																						
Chiasmolithus solitus													X	X	X	X	X		X	X	X	X	X		X	X	X	X	X	X	X	?							
Chiphragmalithus calathus																							X		X	X								X					
Coccolithus formosus						X			X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X		X	X				
Coccolithus robustus																																							X
Coronocyclus nitescens	X			X	X	X	X	X					X																										
Cyclicargolithus abisectus				?	X		X								?																								
Cyclicargolithus floridanus				X	X		X	X	X				X		X				X	X			X														X		
Cyclicargolithus gammation																											X	X	X	X	X	X		X					
Cyclicargolithus reticulatus											X	X	X	X				X				?		X	X			?											
Discoaster barbadiensis									X		X	X	X			X				X		X	X		X	X	X	X	X	X	X				X				
Discoaster brouweri	X	X		X		X				X			X																										
Discoaster deflandrei					X	X			X					X		X																							
Discoaster lodoensis																								?	X	X	X	X	X	X		X		X					
Discoaster multiradiatus																													X		X	X	X	X	X	X	X		X
Discoaster saipanensis									?			X	X	X		X	X							X	X		X												
Discoaster sublodoensis																						X	X		X	X	X												
Discoaster tanii nodifer									X		X		X	X																									
Discoaster variabilis (group)	X	X	X																																				
Discoasteroides kuepperi																							?		?	?													
Ellipsolithus macellus																																			X	X	X		X
Fasciculithus involutus																																	X	X	X	X	X		
Fasciculithus tympaniformis																																		X	X	X		X	
Heliolithus kleinpellii																																							X
Helicosphaera compacta							X		X	X	X	X	X	X	X							X																	
Helicosphaera euphratis			X	X	X		X	X																															
Helicosphaera kamptneri	X	X	X	X	X	X	X			X																													
Helicosphaera recta					X	?	X																																
Helicosphaera reticulata									X				X	X																									
Isthmolithus recurvus									X			X	X	X		X																							
Lanternithus minutus									X	X	X	X	X	X		X			X			X	X		X	X		X											
Micrantholithus procerus																				X		X			X														
Nannotetrina cristata																							X																
Neochiastozygus perfectus																																	X		X			X	X
Neococcolithes dubius														X	X	X				X		X	X		X	X			X	X	X								
Pemma basquensis													X	X	X	X	X	X				X																	
Placozygus sigmoides																																						X	X
Pseudotriquetrorhabdulus inversus																									X	X													
Reticulofenestra hampdenensis						X			X	X			X	X									X				X												
Reticulofenestra pseudoumbilicus	X	X	X	?		?																																	
Reticulofenestra scissura				?	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X			X						X								X	
Reticulofenestra umbilicus						?			X	X	X	X	X	X	X	X	X		X	X				X											X				
Rhabdolithus gladius																X				X																			
Rhabdosphaera inflata																						X																	
Sphenolithus predistentus							X	X	X			X			X																								
Sphenolithus radians																				X			X		X	X													
Toweius eminens																																	X				X		X
Toweius pertusus																																X	X	X	X	X		X	X
Zygodiscus herlynii																																	X	X	X	X	X	X	
Zygrhablithus bijugatus					X		X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X		X		X		X				X	

NANNOFOSSIL EVENTS (┐ Highest occurr.; └ Lowest occurr.):

R. scissura, *H. recta* & *Z. bijugatus*

D. barbadiensis & others

C. reticulatus

C. solitus

R. inflata

D. lodoensis

C. gammation

Fasciculithus spp

P. sigmoides

H. kleinpellii

AGE:

PLIOCENE & MIOCENE

OLIGOCENE

LATE EOCENE

MIDDLE EOCENE

EARLY EOCENE

LATE PALEOCENE

Other important biostratigraphic events identified within the Challenger Formation (Fig. 2) are the highest occurrences of the key species *Cyclicargolithus reticulatus* (in sample 560–570 m, probably coinciding with the lithological change at 567 m) and *Chiasmolithus solitus* (in sample 580–590 m). In continuous sections, the highest occurrence of *C. reticulatus* is Late Eocene (Shafik, 1981), and that of *C. solitus* is Middle Eocene (Martini, 1971).

The assemblage from near the base of the formation (sample 580–590 m) includes *Braarudosphaera bigelowii, Blackites spinulus, B. vitreus, Chiasmolithus oamaruensis, C. solitus, Clausicoccus cribellum, Coccolithus eopelagicus, C. formosus, Coronocyclus nitescens, Cyclicargolithus floridanus, C. reticulatus, Discoaster barbadiensis, D. brouweri, D. saipanensis, D. tanii nodifer, Helicosphaera compacta, H. lophota, H. reticulata, H. seminulum, Holodiscolithus solidus, Isthmolithus recurvus, Lanternithus minutus, Lithostromation perdurum, Markalius inversus, Micrantholithus flos, Orthozygus aureus, Pedinocyclus larvalis, Pemma basquensis, P. rotundum, Pontosphaera multipora, Reticulofenestra hampdenensis, R. scissura, R. umbilicus, Sphenolithus stellatus, Syracosphaera labrosa, Transversopontis pulcheroides*, and *Zygrhablithus bijugatus crassus*.

The presence of *Discoaster saipanensis* and *Chiasmolithus solitus* in the assemblage from near the base of the type Challenger Formation indicates a Middle Eocene age. The younger species in the same assemblage, such as *Discoaster brouweri, Coronocyclus nitescens, Isthmolithus recurvus, Chiasmolithus oamaruensis*, and *Reticulofenestra scissura*, are probably a result of caving or downhole contamination.

Discussion. The nannofossil data presented above indicate that a substantial part of the type section of the Challenger Formation (540 to 575 m) is Late Eocene, confirming — in broad terms — the results of Quilty (1978). The same data also indicate that the uppermost part of the type Challenger Formation (530–540 m) is Oligocene, and its lower part (575–597 m) is Middle Eocene, agreeing well with previous views on the age of the formation (Shafik, 1991).

A disconformity or (more likely) a condensed section is suspected within the lower part of the type Challenger Formation, because it apparently lacks Middle Eocene nannofossil assemblages containing the key species *Cyclicargolithus reticulatus* in association with a large number of reworked Cretaceous species; such an association occurs widely near the level of extinction of *Chiasmolithus solitus* on the Australian western and southern margins (Shafik, 1985), including two locations in the Perth Basin (Shafik, 1978, 1991).

Cockbain & Hocking (1989) thought that the Challenger Formation in Challenger No. 1 rested disconformably on the Upper Paleocene to Lower Eocene Kings Park Formation, but the new nannofossil evidence presented below shows that the formation overlies much younger Middle and Lower Eocene sediments. As discussed below, the Middle Eocene sediments immediately beneath the Challenger Formation (Fig. 2) are probably equivalents of the basal part of the type Porpoise Bay Formation in Rottnest Island bore (Fig. 1), as defined by Cockbain & Hocking (1989).

Lithologically, the base of the type Challenger Formation is not distinguishable from the underlying Middle Eocene carbonates, although this base is clearly marked on the sonic and gamma logs (Fig. 2).

Interval 597–750 m: Middle Eocene–Upper Paleocene carbonates

Quilty (1978) identified three lithological subunits in the interval 597–740 m, but each of them is internally variable — especially the two subunits below 678 m.

The interval 597–750 m is bracketed by the Middle Eocene datum of highest occurrence of *Chiasmolithus solitus* (within the lower part of the overlying Challenger Formation) and the extinction level of most Cretaceous species, at 750 m (immediately below the base of the Paleocene). Biostratigraphic events identified within the interval (Fig. 2) include the up-sequence appearance of the short-ranged *Rhabdosphaera inflata* (at 640 m), and the up-sequence disappearance of species of *Fasciculithus* (at 715 m). The lowest-occurrence datum of *R. inflata* has been used elsewhere to indicate the Middle/Early Eocene boundary (Bukry, 1973), and the highest-occurrence datum of species of *Fasciculithus* has been used to approximate the base of the Eocene in the Perth Canyon succession (Shafik, 1991).

These two events are used to recognise three units within the interval 597–750 m, in the same way as they were used in the Perth Canyon succession (Shafik, 1991). The oldest unit, with the highest occurrence of *Fasciculithus* spp. near its top, correlates with the Kings Park Formation, which is known both onshore and offshore (including in the Perth Canyon). The overlying Eocene section, below the 635-m level, comprises thin Middle Eocene (with *Rhabdosphaera inflata*) and thick Lower Eocene segments. Coeval (Lower and Middle Eocene) beds have been discovered recently in the Perth Canyon (Shafik, 1991).

It is the Middle Eocene section (between 597 and 635 m), immediately underlying the type Challenger Formation, which is difficult to correlate with known stratigraphic successions in the basin, but I suggest that it is a partial equivalent of the type Porpoise Bay Formation. The difficulty reflects in part the lack of significant and reliable biostratigraphic events in the section 597–635 m (Fig. 2); biostratigraphic resolution in Challenger No. 1 is hampered by possible downhole contamination in the ditch cuttings, and most up-sequence appearances are deemed unusable. The difficulty also reflects the uncertainty of the precise age of the base of the type Porpoise Bay Formation (and its upper part); the age of its lower and middle parts is Middle Eocene, from nannofossil and foraminiferal assemblages (Shafik, 1978; Quilty, 1978).

Partial equivalent of the Porpoise Bay Formation (597–635 m). This section is white chalk with chert and traces of glauconite, grading into coarse, compact calcarenite with abundant chert below 615 m. It lacks any significant and reliable nannofossil biostratigraphic event, and its broad age of Middle Eocene (Fig. 2) can be only tentatively narrowed. *Rhabdolithus gladius*, a short-ranged species (confined to the mid-Middle Eocene NP15 Zone according to Martini, 1971), was encountered in two samples (605–610 m and 625–630 m) within this section (Fig. 3), suggesting a maximum age of mid-Middle Eocene and a correlation with the foraminiferal Zone P11 (according to data *in* Martini, 1971). This species has been recorded from near the base of the type section of the Porpoise Bay Formation in Rottnest Island bore (Shafik, 1978). Therefore, a possible correlation exists between the sediments underlying the type Challenger Formation and the basal part of the type Porpoise Bay Formation.

The Middle Eocene nannofossil assemblages from the middle part of the type section of the Porpoise Bay Formation include

Figure 3. Distribution of selected Cainozoic calcareous nannofossil species in cuttings from Challenger No. 1.

the key species *Cyclicargolithus reticulatus*, and correlate with the foraminiferal Zone P12 (Shafik, 1978); coeval assemblages containing *C. reticulatus* have been recorded from the Perth Canyon (Shafik, 1991). *C. reticulatus* is present at one level at least in the section 597–630 (Fig. 3), perhaps as a result of downhole contamination.

The assemblages with *Cyclicargolithus reticulatus* from the middle part of the type Porpoise Bay Formation and the Perth Canyon succession include large numbers of reworked Late Cretaceous calcareous nannofossil species, (Shafik, 1978, 1991). By contrast, the slightly older Middle Eocene assemblages from near the base of the type Porpoise Bay Formation (with the key species *Rhabdolithus gladius* and *Chiasmolithus solitus*) contain very few reworked Late Cretaceous nannofossils (Shafik, 1978). The apparent absence of Late Cretaceous nannofossils from the section 597–630 m in Challenger No. 1, together with the presence of *R. gladius* and *C. solitus*, strengthens further the correlation with the basal part of the type Porpoise Bay Formation.

Discussion. The stratigraphic relationship between the Porpoise Bay and Challenger Formations has never been established: the Porpoise Bay Formation, containing Middle Eocene assemblages, was interpreted to be older than the Challenger Formation, which was thought to be Late Eocene. My nannofossil biostratigraphic study of the Challenger No. 1 section — having shown that the lower part of the Challenger Formation is Middle Eocene — indicates that the two formations are probably partly coeval. The well dated parts of the type Porpoise Bay Formation (containing Middle Eocene assemblages with the key species *Cyclicargolithus reticulatus* and *Chiasmolithus grandis* without *C. solitus*; Shafik, 1978) fall within the suspected condensed section in the lower part of the type Challenger Formation. Indeed, the thick type section of the Porpoise Bay Formation (consisting of 382 m of brown calcareous shale and siltstone; Cockbain & Hocking, 1989) probably represents a more terrigenous facies of part (or less likely most) of the type Challenger Formation.

The key species *Chiasmolithus grandis* consistently ranges through the Eocene of Challenger No. 1 up to sample 635–640 m, and reappears briefly higher (sample 605–610 m). Elsewhere in Australia, this species ranges to the base of the Upper Eocene. It has been recorded, co-occurring with Late Eocene *Chiasmolithus oamaruensis*, in a core sample from the Lacepede Formation in the western Otway Basin (Shafik, 1983), and in association with late Middle Eocene nannofossils in dredges from the Great Australian Bight (Shafik, 1990b). The geographic distribution of *C. grandis* suggests that it disappeared earlier at higher latitudes or in cooler-water regimes. For example, this species persists up to the basal Upper Eocene (co-occurring with *C. oamaruensis*) at DSDP site 214, in the northern Indian Ocean (Shafik, 1983), and at DSDP site 360, south of Cape Town in the southeastern Atlantic Ocean (Bukry, 1978), but disappears much earlier, near the base of the Middle Eocene, in New Zealand (Edwards, 1971) and in the South Campbell Plateau (Edwards & Perch–Nielsen, 1975).

Unnamed Lower–Middle Eocene carbonates (635–700 m). The lithology of the thick section between equivalents of the Porpoise Bay and Kings Park Formations in Challenger No. 1 is variable, although dominantly carbonates. The upper part of the section (635–678 m) consists of compact calcarenite, sporadic limestone below 655 m, and some quartz sand at 660–670 m. The middle part is Quilty's 'subunit 678–694 m', which was described as medium to coarse quartz sandstone with varying amounts of bryozoan calcarenite locally recrystallised to compact limestone. The lower part (below 694 m) consists of chalk, grading into marl and predominating over quartz sand, with sporadic chert.

The key species *Rhabdosphaera inflata*, suggestive of an early Middle Eocene age, was encountered in a single sample (635–640 m) at the top of the section. Associated species in the same sample include *Blackites amplus, Braarudosphaera bigelowii, Chiasmolithus grandis, C. solitus, Coccolithus eopelagicus, C. pelagicus, ?Cyclicargolithus reticulatus, Discoaster barbadiensis, D. sublodoensis, Helicosphaera compacta, H. seminulum, Lanternithus minutus, Micrantholithus procerus, Neococcolithes dubius, Pemma basquensis, P. rotundum, Reticulofenestra samodurovii,* (reworked) *Tranolithus exiguus, Transversopontis fimbriatus, T. pulcher*, and *Zygrhablithus bijugatus crassus*. This assemblage is assignable to the early Middle Eocene *Rhabdosphaera inflata* Subzone of Bukry (1973), or the CP12b Subzone of Okada & Bukry (1980), on account of the existence of *Discoaster sublodoensis* and *Rhabdosphaera inflata*. A correlation with the foraminiferal Zone P10 is possible.

Three assemblages from the underlying section are listed below:

- Sample 640–645 m includes *Braarudosphaera bigelowii, Chiasmolithus solitus, Chiphragmalithus calathus, Clausicoccus cribellum, Coccolithus formosus, Cyclicargolithus floridanus, Daktylethra* sp., *Discoaster barbadiensis, D. sublodoensis, ?Discoasteroides kuepperi, Helicosphaera seminulum, Lanternithus minutus, Micrantholithus* spp., *Nannotetrina cristata, Neococcolithes dubius, Pemma rotundum, Pontosphaera multipora, Reticulofenestra hampdenensis, Sphenolithus radians, Transversopontis pulcher*, and *Zygrhablithus bijugatus bijugatus*.

- Sample 655–660 m contains short *Blackites spinulus, Calcidiscus protoannulus, Campylosphaera dela, Chiasmolithus grandis, C. solitus, Chiphragmalithus calathus, Coccolithus eopelagicus, C. formosus, Discoaster barbadiensis, D. lodoensis, D. saipanensis, D. sublodoensis, D. sublodoensis/D. saipanensis, ?Discoasteroides kuepperi, Helicosphaera lophota, Lanternithus minutus, Micrantholithus* spp., *Neococcolithes dubius, Pemma rotundum, Pontosphaera ocellata, P. pectinata, Pseudotriquetrorhabdulus inversus, Sphenolithus radians, Transversopontis* spp., *Zygrhablithus bijugatus bijugatus*, and *Zygrhablithus bijugatus crassus*.

- Sample 690–700 m includes *Braarudosphaera bigelowii, Campylosphaera dela, Chiasmolithus solitus, Coccolithus formosus, Cyclicargolithus gammation, Discoaster barbadiensis, D. lodoensis, Neococcolithes dubius, N. protenus, Pontosphaera pectinata, Reticulofenestra scissura*, and *Transversopontis* spp.; *R. scissura* is considered to be displaced from higher levels.

The distribution of *Discoaster lodoensis, Cyclicargolithus gammation, Discoaster sublodoensis*, and *Chiasmolithus eograndis* (Fig. 3) in these three assemblages is consistent with an Early Eocene age. Sample 690–700 represents the basal Eocene in Challenger No. 1.

Kings Park Formation equivalent (700–750 m). The up-sequence disappearance of *Fasciculithus* spp. at 715 m is a convenient event which can be used to separate the Kings Park Formation equivalent in Challenger No. 1 from the overlying Lower Eocene beds. However, both the gamma-ray and sonic logs suggest the 700-m level as a more realistic lithological boundary separating these two units, and it is adopted as such in Figure 2. The lithology of the section (700–750 m) is variable: chalk and quartz sand, and glauconitic sandstone near the base. The up-sequence disappearance of most Cretaceous species at 750 m conveniently separates the Upper Paleocene Kings Park Formation equivalent from the Upper Cretaceous Lancelin beds below.

In addition to several Eocene species (*Chiphragmalithus calathus, Coccolithus formosus, Cyclicargolithus gammation, Discoaster lodoensis*, and *Zygrhablithus bijugatus bijugatus*), a number of essentially Paleocene forms, including *Campylosphaera eodela, Campylosphaera* sp., *Chiasmolithus bidens, Discoaster multiradiatus, Fasciculithus involutus, F. tympaniformis, Micrantholithus* spp., *Neochiastozygus* spp., *Toweius pertusus*, and *Zygodiscus herlynii* are identified from 720–725 m in the upper part of the equivalent of the Kings Park Formation in Challenger No. 1; *Braarudosphaera bigelowii* is also noted. The Paleocene species indicate the latest Paleocene *Campylosphaera eodela* Subzone of Bukry (1973), or the CP8b Subzone of Okada & Bukry (1980).

The assemblage from the base of the Kings Park Formation equivalent in Challenger No. 1 (sample 745–750 m) includes several Late Cretaceous species (*Arkhangelskiella specillata, Cribrosphaerella ehrenbergii, Eiffellithus eximius, Gartnerago obliquum, Micula staurophora, Reinhardtites biperforatus, Tranolithus orionatus*, and *Watznaueria barnesae*) in association with *Braarudosphaera bigelowii, Chiasmolithus bidens, Coccolithus robustus, Discoaster multiradiatus, Ellipsolithus macellus, Heliolithus kleinpellii, Markalius apertus, Neochiastozygus perfectus, Placozygus sigmoides, Thoracosphaera operculata, Toweius eminens*, and *T. pertusus*. The co-occurrence of *Heliolithus kleinpellii* and *Placozygus sigmoides* suggests a position near the base of the range of the index species *Discoaster multiradiatus* (Varol, 1989), and an assignment to the Late Paleocene *Chiasmolithus bidens* Subzone of Bukry (1973), or CP8a Subzone of Okada & Bukry (1980).

Discussion. Levels above sample 745–750 m lack the Cretaceous component. Therefore, the base of the Tertiary in Challenger No. 1 could be placed immediately above sample 745–750 m. However, the occurrence of a large number of reworked Cretaceous nannofossils at the base of the Paleocene is not unusual on the Australian western margin (Shafik, unpublished data), and elements of the Tertiary component in sample 745–750 m — unlike those in the Cretaceous section below — are consistent with a Paleocene age. Admixtures of Paleocene, Eocene, and younger species are identified among the Cretaceous assemblages from the interval 750–780 m; these are considered to have resulted from downhole contamination by caving.

Interval 750–780 m: Lancelin beds and Gingin Chalk equivalents

This interval is a greyish green, richly glauconitic calcareous sandstone with rare *Inoceramus* prisms, and is interpreted as an equivalent of the Lancelin beds and Gingin Chalk (see below). The type Lancelin beds have been described as light grey marls, becoming slightly darker and glauconitic near the top, with fragments of *Inoceramus* throughout (Edgell, 1964). The Gingin Chalk (Glauert, 1910) in its type area is a unit of fine-grained chalks and marls sandwiched between two units of greensand (the Molecap and Poison Hill Greensands of Fairbridge, 1953). The Molecap Greensand, Gingin Chalk, and Poison Hill Greensand (arranged in ascending order) form a substantial part of the Coolyena Group of Cockbain & Playford (1973), but have been considered recently as members of the 'Lancelin Formation' by Davidson & Moncrieff (*in* Moncrieff, 1989); the concept of the 'Lancelin Formation' is not followed here, as it serves no useful purpose and mixes two distinctive units — namely the Gingin Chalk and the Lancelin beds.

Three samples were examined from the interval 750–780 m in Challenger No. 1. Their assemblages consist of abundant Late Cretaceous species in association with rare Tertiary (admixture of Paleocene, Eocene, and Oligocene) forms such as *Chiasmolithus edentulus, Coccolithus eopelagicus, Cyclicargolithus abisectus, Discoaster multiradiatus, Reticulofenestra scissura, Toweius eminens, Zygodiscus herlynii*, and *Zygrhablithus bijugatus crassus*. The Tertiary component decreases in number of species and specimens with depth, and is considered to have resulted from downhole contamination.

The Cretaceous component of the assemblage extracted from the highest sample (750–760 m) is similar to those which Shafik (1990a) recorded from the lower part (upper Campanian) of the Lancelin beds in onshore sections. This component includes *Ahmuellerella octoradiata, Arkhangelskiella specillata, Biscutum magnum, Broinsonia parca, Chiastozygus litterarius, Cretarhabdus conicus, Cribrosphaerella ehrenbergii, Eiffellithus eximius, E. turriseiffeli, Kamptnerius magnificus, Microrhabdulus decoratus, Micula concava, M. staurophora, Monomarginatus quaternarius, Prediscosphaera cretacea, Quadrum gothicum, Reinhardtites anthophorus, R. levis, Rhagodiscus reniformis, Tranolithus exiguus, Vekshinella elliptica, Watznaueria barnasae*, and *Zygodiscus bicrescenticus*.

Cretaceous elements of the assemblage from sample 760–770 m are similar to those from sample 750–760, but lack the key species *Biscutum magnum, Monomarginatus quaternarius*, and *Quadrum gothicum*. Instead, *Acuturris scotus, Biscutum coronum*, and *Lucianorhabdus cayeuxii* are present. *Broinsonia parca* is much smaller in this sample than in the one above it. These changes suggest that sample 760–770 m came from the top part (lower Campanian) of the Gingin Chalk equivalent (Shafik, 1990a).

In Challenger No. 1, either a condensed sequence or, more likely, a disconformity is suggested between the Gingin Chalk equivalent (sample 760–770 m) and the Lancelin beds equivalent (sample 750–760 m) by the apparent absence of mid-Campanian sediments. A similar disconformity occurs in onshore sections in the Perth Basin (Shafik, 1990a).

The assemblage from the lowest sample (770–780 m) in the Upper Cretaceous section of Challenger No. 1 includes *Acuturris scotus, Ahmuellerella octoradiata, Arkhangelskiella specillata, Broinsonia* sp. (similar to *B. parca* of Bukry, 1969, pl. 3, fig. 7), *B. dentata, Calculites obscurus, Chiastozygus litterarius, Corolithion exiguum, Cretarhabdus conicus, Cribrosphaerella ehrenbergii, Cylindralithus biarcus, Eiffellithus eximius, E. turriseiffeli, Gartnerago obliquum, Kamptnerius magnificus, Lucianorhabdus cayeuxii, Microrhabdulus decoratus, Micula concava, M. staurophora, Prediscosphaera cretacea, P. spinosa, Reinhardtites anthophorus, R. biperforatus, Tranolithus exiguus, Vekshinella elliptica, Watznaueria barnasae*, and *Zygodiscus bicrescenticus*. This assemblage is similar to those identified from outcrops of the upper Santonian Gingin Chalk in its type area (Shafik, 1990a).

Discussion. Quilty's (1978) assignment of a late Santonian age to the whole 740–770 m section was based on the foraminiferal assemblage in a single sample from its lower part (Fig. 2), and agrees with the nannofossil evidence presented above.

Sediments of Maastrichtian and Early Paleocene age seem to be missing at 750 m, indicating a major disconformity between the Cretaceous and Paleocene in Challenger No. 1. In the Perth

Canyon succession, the disconformity at the Cretaceous/Tertiary boundary is seemingly of much lesser magnitude, because of the occurrence of nannofossil assemblages indicative of late Maastrichtian and Early Paleocene ages (Shafik, 1991).

Discussion

The nannofossil biostratigraphic analysis outlined above indicates discontinuities at three levels within the Upper Cretaceous–Palaeogene section in Challenger No. 1; each of them probably corresponds to a major disconformity. They occur at the Eocene/Oligocene boundary within the upper part of the type Challenger Formation (540 m), at the Cretaceous/Tertiary boundary (750 m), and within the Campanian section between equivalents of the Lancelin beds and Gingin Chalk (760 m).

At the Eocene/Oligocene boundary, several key nannofossil species simultaneously disappear, suggesting a disconformity (missing lowermost Oligocene) and/or a condensed section. At the Cretaceous/Tertiary boundary, Maastrichtian and Lower Paleocene sediments (recorded in the Perth Canyon succession) are missing, suggesting a substantial disconformity. Within the Campanian section (750–770 m) a condensed section or a disconformity (missing mid-Campanian sediments) is suggested, similar to that onshore between the Gingin Chalk and the Lancelin beds (Shafik, 1990a); several key species, absent below 770 m, appear suddenly immediately above this level (at 760 m). These three interpreted major disconformities (or condensed sections) have distinct expressions on the sonic log (Fig. 2).

Middle Eocene assemblages containing the key species *Cyclicargolithus reticulatus*, and including a large number of reworked Cretaceous species, have been recorded from coeval levels in Rottnest Island bore and the Perth Canyon succession in the Perth Basin (Shafik, 1978, 1991), as well as in the Carnarvon Basin and basins on the Australian southern margin (Shafik, 1985). These widespread assemblages seem to be missing from the biostratigraphic sequence of Challenger No. 1, as no reworked Cretaceous species were identified in the Middle Eocene segment near the highest occurrence of *Chiasmolithus solitus*. A minor disconformity, or more likely a condensed section, is suspected in the lower part of the type Challenger Formation near the extinction level of the key species *Chiasmolithus solitus*.

The stratigraphy of the marine Upper Cretaceous–Palaeogene rock units in the south Perth Basin is summarised in Figure 4. Until recently, the Palaeogene sequence was poorly known. The recent discovery of Oligocene and Lower Eocene beds in the Perth Canyon (Shafik, 1991) and Challenger No. 1 (this study) has filled significant gaps in the stratigraphy of the basin. Marine Palaeogene sediments are limited to the Upper Paleocene Kings Park Formation in the onshore Perth Basin; age equivalents of this formation occur in offshore sections (e.g., Challenger No. 1), and in addition there are older Paleocene beds in the Perth Canyon succession (Shafik, 1991). Other Palaeogene rock units known in the Perth Basin are the offshore Porpoise Bay and Challenger Formations (Cockbain & Hocking, 1989).

Away from their type sections, the Kings Park, Porpoise Bay, and Challenger Formations seem to lose their lithostratigraphic identities in the more oceanic setting, for example, of the Perth Canyon. There they seem to overlap and merge into one large carbonate sequence (which includes Lower Paleocene levels as well) difficult to subdivide. Challenger No. 1 substantiates this conclusion to some extent, because the biostratigraphic bracket covering the larger part of the type Porpoise Bay Formation (which includes the extinction datum of *Chiasmolithus solitus*) coincides with the lower part of the type Challenger Formation.

Cockbain & Hocking's (1989) formal naming of the Porpoise Bay and Challenger Formations took into account age determinations obtained during the 1970s (Quilty, 1978), which were based on inadequately sampled material from two separate sections. The stratigraphic relationship between the Porpoise Bay and Challenger Formations was not known, except that the former was older and Middle Eocene; the age of the Challenger Formation was thought then to be Late Eocene. The present study has shown that the lower part of the Challenger Formation is Middle Eocene, and that the two formations are probably partly coeval. Indeed, the type Porpoise Bay Formation is probably a more terrigenous facies of part of the type Challenger Formation.

The Palaeogene marine stratigraphic succession in the Perth Basin is evidently more complete and more calcareous offshore. In the Perth Canyon, the Paleocene, Eocene, and Oligocene occur as a succession of carbonates that are difficult to differentiate lithostratigraphically from one another. In Challenger No. 1, the Paleocene and Eocene section, coeval with parts of the Perth Canyon succession, consists of carbonates with some terrigenous elements. Onshore, the Upper Paleocene–Lower Eocene Kings Park Formation is calcareous shale and siltstone in its type section below Perth.

This study stresses the contrast between the lithostratigraphic and biostratigraphic approaches in subdividing the offshore Palaeogene carbonates in the Perth Basin. In the Perth Canyon, it is probably impractical to subdivide the Palaeogene carbonates into mappable lithostratigraphic units. On the other hand, the several nannofossil events which are used to subdivide the Palaeogene carbonates of the canyon (Shafik, 1991), or of Challenger No. 1, can be identified elsewhere. The concept

AGE		ROCK UNIT	OCCURRENCE
OLIGOCENE		OLIGOCENE CARBONATES	Known only from the offshore, in the Perth Canyon and Challenger No. 1. Correlation between the Oligocene carbonates in the canyon and those in Challenger No. 1 has not been possible. Difficult to differentiate from overlying Miocene carbonates in Challenger No. 1 .
EOCENE	late – middle	CHALLENGER FORMATION	Lower part of type section in Challenger No.1 probably equates with most of the type section of the Porpoise Bay Formation in Rottnest Island bore. Difficult to differentiate from other Eocene carbonates in the Perth Canyon.
			Away from their type sections, the two formations lose their lithostratigraphic identities.
	middle	PORPOISE BAY FORMATION	Hemipelagic unit from the offshore: type section in Rottnest Island bore. Age equivalents of different parts of it are identifiable in the carbonate facies of the Perth Canyon and Challenger No. 1.
	early	EOCENE CARBONATES	Known only from the offshore, in the Perth Canyon and Challenger No. 1 successions.
PALEOCENE		KINGS PARK FORMATION	Hemipelagic unit: type section underneath Perth. Age equivalents are present in the more calcareous facies offshore.
		PALEOCENE CARBONATES	Lower Paleocene beds discovered recently in Perth Canyon. They are yet to be identified elsewhere.
LATE CRETACEOUS		BRETON MARL	Onshore in the Breton Bay and Lancelin areas; offshore in the Perth Canyon.
		LANCELIN BEDS	Onshore in the Lancelin area including Breton Bay; offshore in the Challenger No. 1 succession.
		GINGIN CHALK	Onshore at several localities; offshore in the Challenger No. 1 succession.

Figure 4. Late Cretaceous–Palaeogene stratigraphy of marine sedimentation in the south Perth Basin.

that the Challenger Formation in Challenger No. 1 is calcarenite, chalk, and chert (Cockbain & Hocking, 1989) is probably of limited use in studies of the Palaeogene carbonates of other offshore sections in the basin.

The Palaeogene sections at nearby DSDP sites (see Fig. 1 for location) are either seemingly missing (site 258) or largely reduced (sites 259 and 264), prominently lacking Oligocene sediments. Similarly, the Upper Cretaceous sections at the same sites are either barren or missing (site 259, in the Perth Abyssal Plain) or poorly represented. On the Naturaliste Plateau, the youngest Cretaceous is Santonian at site 258, and early Campanian at site 264. Sediments of late Campanian age, correlatable with the Lancelin beds equivalent in Challenger No. 1, have not been recorded at nearby DSDP sites.

Conclusions

Nannofossil dating of sediments in Challenger No. 1 has identified Oligocene beds overlying the type section of the Challenger Formation. This confirms the occurrence of marine Oligocene in the Perth Basin; the only other known such occurrence is the mid-Oligocene in the Perth Canyon.

The type Challenger Formation in Challenger No. 1 ranges in age from Middle Eocene to Oligocene, and is not just Late Eocene as previously thought. Its uppermost part (530–540 m) is Oligocene, its middle part (540–575 m) is Late Eocene, and its lower part (575–597 m) is Middle Eocene. The type Challenger Formation rests on Middle Eocene sediments — not the Upper Paleocene–Lower Eocene Kings Park Formation as previously reported.

The Middle Eocene sediments that underlie the Challenger Formation in Challenger No. 1 (between 597 and 635 m) are probably equivalent to the basal part of the type section of the Porpoise Bay Formation in the Rottnest Island bore. A significant overlap seemingly exists between the type sections of the Porpoise Bay and Challenger Formations; the type Porpoise Bay Formation is probably a more terrigenous facies of part of the type Challenger Formation.

In Challenger No. 1, a thick section (635–700 m) containing Early and Middle Eocene calcareous nannofossil assemblages extends the geographic limits of coeval beds recently discovered in the Perth Canyon succession.

Representatives of the Kings Park Formation, Lancelin beds, and Gingin Chalk are identified in Challenger No. 1 by their nannofossil assemblages.

Three major disconformities (or condensed sections) are identified from nannofossil evidence in the Challenger No. 1 section. These disconformities are at the Eocene/Oligocene boundary within the upper part of the type Challenger Formation; at the Cretaceous/Tertiary boundary between representatives of the Kings Park Formation and Lancelin beds; and within the Campanian section between representatives of the Lancelin beds and the Gingin Chalk. They have distinct expressions on the sonic log. Another disconformity, or more likely a condensed section, is suspected in the Middle Eocene part of the type Challenger Formation near the extinction level of *Chiasmolithus solitus*.

This and a previous study (Shafik, 1991) have demonstrated that subdividing offshore Palaeogene carbonate sections in the Perth Basin by biostratigraphic means is likely to be more successful than attempting to subdivide them lithostratigraphically (using units defined originally in hemipelagic sections). The Kings Park, Porpoise Bay, and Challenger Formations lose their lithostratigraphic identities away from their type sections; with the occurrence of Eocene beds (older than the type Porpoise Bay Formation) and Paleocene beds (older than the type Kings Park Formation) in the more oceanic sections in the Perth Canyon (see Shafik, 1991), the Palaeogene succession there becomes virtually one big carbonate unit. Subdividing this succession into rock units (which are unlikely to be mappable) seems pointless when microfossil biostratigraphy (e.g., using nannofossils) is likely to provide subdivisions that are identifiable elsewhere.

The Challenger No. 1 and Perth Canyon successions suggest that the Palaeogene in the Perth Basin is more complete and more calcareous offshore. However, at nearby DSDP sites, coeval Palaeogene successions are either seemingly missing (site 258, Perth Abyssal Plain) or largely reduced (sites 259 and 264 on the Naturaliste Plateau).

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List of calcareous nannofossil species mentioned in this paper

Cainozoic species

Blackites spinulus (Levin) Roth, 1970
Blackites vitreus (Deflandre) Shafik, 1981
Braarudosphaera bigelowii (Gran & Braarud) Deflandre, 1947
Calcidiscus leptoporus (Murray & Blackman) Loeblich & Tappan, 1978
Calcidiscus macintyrei (Bukry & Bramlette) 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 edentulus van Hek & Prins, 1987
Chiasmolithus eograndis Perch-Nielsen, 1971
Chiasmolithus grandis (Bramlette & Riedel) Radomski, 1968
Chiasmolithus oamaruensis (Deflandre) Hay, Mohler, & Wade, 1966
Chiasmolithus solitus (Bramlette & Sullivan) Locker, 1968
Chiphragmalithus calathus Bramlette & Sullivan, 1961
Clausicoccus cribellum (Bramlette & Sullivan) Prins, 1979
Coccolithus eopelagicus (Bramlette & Riedel) Bramlette & Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Coccolithus robustus (Bramlette & Sullivan) Shafik, 1991
Coronocyclus nitescens (Kamptner) Bramlette & Wilcoxon, 1967
Cyclicargolithus abisectus (Müller) Wise, 1973
Cyclicargolithus floridanus (Roth & Hay) Bukry, 1971
Cyclicargolithus gammation (Bramlette & Sullivan) Shafik, 1990b
Cyclicargolithus reticulatus (Gartner & Smith) Bukry, 1971
Discoaster barbadiensis Tan Sin Hok, 1929
Discoaster brouweri Tan Sin Hok, 1927 emend. Bramlette & Riedel, 1954
Discoaster deflandrei Bramlette & Riedel, 1964
Discoaster exilis Martini & Bramlette, 1963
Discoaster lodoensis Bramlette & Riedel, 1954
Discoaster multiradiatus Bramlette & Riedel, 1954
Discoaster saipanensis Bramlette & Riedel, 1954
Discoaster sublodoensis Bramlette & Sullivan, 1961
Discoaster tanii nodifer Bramlette & Riedel, 1954
Discoaster tanii tanii Bramlette & Riedel, 1954
Discoaster variabilis Martini & Riedel, 1963
Discoasteroides kuepperi Bramlette & Sullivan, 1961

Ellipsolithus macellus (Bramlette & Sullivan) Sullivan, 1964
Fasciculithus involutus Bramlette & Sullivan, 1961
Fasciculithus tympaniformis Hay & Mohler *in* Hay & others, 1967
Helicosphaera compacta Bramlette & Wilcoxon, 1967
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 kleinpellii Sullivan, 1964
Holodiscolithus solidus (Deflandre) Roth, 1970
Isthmolithus recurvus Deflandre *in* Deflandre & Fert, 1954
Lanternithus minutus Stradner, 1962
Lithostromation perdurum Deflandre, 1942
Markalius apertus Perch–Nielsen, 1979
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
Neochiastozygus chiastus (Bramlette & Sullivan) Perch–Nielsen, 1971
Neochiastozygus denticulatus (Perch–Nielsen) Perch–Nielsen, 1971
Neochiastozygus junctus (Bramlette & Sullivan) Perch–Nielsen, 1971
Neochiastozygus perfectus 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) Bldi–Beke, 1971
Pemma rotundum Klumpp, 1953
Placozygus sigmoides (Bramlette & Sullivan) Romein, 1979
Pontosphaera multipora (Kamptner) Roth, 1970
Pontosphaera ocellata (Bramlette & Sullivan) Perch–Nielsen, 1984
Pontosphaera pectinata (Bramlette & Sullivan) Sherwood, 1974
Pontosphaera plana (Bramlette & Sullivan) Haq, 1971
Pseudotriquetrorhabdulus inversus (Bukry & Bramlette) Wise *in* Wise & Constans, 1976
Reticulofenestra hampdenensis Edwards, 1973
Reticulofenestra pseudoumbilicus (Gartner) Gartner, 1969
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
Sphenolithus ciperoensis Bramlette & Wilcoxon, 1967
Sphenolithus distentus (Martini) Bramlette & Wilcoxon, 1967
Sphenolithus moriformis (Brnnimann & Stradner) Bramlette & Wilcoxon, 1967
Sphenolithus predistentus Bramlette & Wilcoxon, 1967
Sphenolithus radians Deflandre *in* Grass , 1952
Sphenolithus stellatus Gartner, 1971
Syracosphaera labrosa Bukry & Bramlette , 1969
Thoracosphaera operculata Bramlette & Martini, 1964
Toweius eminens (Bramlette & Sullivan) Perch–Nielsen, 1971
Toweius pertusus (Sullivan) Romein, 1979
Transversopontis fimbriatus (Bramlette & Sullivan) Locker, 1968
Transversopontis pulcher (Deflandre) Perch–Nielsen, 1967
Transversopontis pulcheroides (Sullivan) Bldi–Beke, 1971
Zygodiscus herlynii Sullivan, 1964
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959
Zygrhablithus bijugatus crassus Locker, 1967

Cretaceous species

Acuturris scotus Wind & Wise *in* Wise & Wind, 1977
Ahmuellerella octoradiata (Górka) Reinhardt, 1967
Arkhangelskiella specillata Vekshina, 1959
Biscutum coronum Wind & Wise *in* Wise & Wind, 1977
Biscutum magnum Wind & Wise *in* Wise & Wind, 1977
Broinsonia dentata Bukry, 1969
Broinsonia parca (Stradner) Bukry, 1969
Broinsonia sp. (similar to *B. parca* of Bukry, 1969, pl.3, fig.7)
Calculites obscurus (Deflandre) Prins & Sissingh *in* Sissingh, 1977
Chiastozygus litterarius (Górka) Manivit, 1971
Corollithion exiguum Stradner, 1961
Cretarhabdus conicus Bramlette & Martini, 1964
Cribrosphaerella ehrenbergii (Arkhangelsky) Deflandre *in* Deflandre & Fert, 1954
Cylindralithus biarcus Bukry, 1969
Eiffellithus eximius (Stover) Perch–Nielsen, 1968
Eiffellithus turriseiffeli (Deflandre) Reinhardt, 1965
Gartnergo obliquum (Stradner) Reinhardt, 1970
Kamptnerius magnificus Deflandre, 1959
Lucianorhabdus cayeuxii Deflandre, 1959
Microrhabdulus decoratus Deflandre, 1959
Micula concava (Stradner) Verbeek, 1976
Micula staurophora (Gardet) Stradner, 1963
Monomarginatus quaternarius Wind & Wise *in* Wise & Wind, 1977
Prediscosphaera cretacea (Arkhangelsky) Gartner, 1968
Prediscosphaera spinosa (Bramlette & Martini) Gartner, 1968
Quadrum gothicum (Deflandre) Prins & Perch–Nielsen *in* Manivit & others, 1977
Reinhardtites anthophorus (Deflandre) Perch–Nielsen, 1968
Reinhardtites biperforatus (Gartner) Shafik, 1979
Reinhardtites levis Prins & Sissingh *in* Sissingh, 1977
Rhagodiscus reniformis Perch–Nielsen, 1973
Tranolithus exiguus Stover, 1966
Tranolithus orionatus (Reinhardt) Reinhardt, 1966
Vekshinella elliptica Gartner, 1968
Watznaueria barnesae (Black) Perch–Nielsen, 1968
Zygodiscus bicrescenticus (Stover) Wind & Wise *in* Wise & Wind, 1977

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