Bureau of Mineral Resources, Geology & Geophysics

RECORD

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BMR Continental Margins Program

Hydrocarbon Prospectivity of the Offshore South Perth Basin

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SUMMARY

Some 5000 of multichannel and high-resolution seismic data, as well as an extensive suite of geological samples, were acquired by R.V *Rig Seismic* during the latter half of 1988. This data, coupled with results from previous exploration in the South Perth Basin, forms the basis for this interpretation of the stratigraphy and structure of the basin, as well as the assessment of the hydrocarbon potential of the offshore part of the basin.

Results from dredging the flanks of the Fremantle Canyon have refined the Tertiary stratigraphy of the basin, and has indicated the presence of Permian and Triassic rocks on the western margin of the Vlaming Sub-basin. Source rock analysis of relatively organic-rich dredge samples shows that Late Jurassic-Early Cretaceous and Permian rocks are immature in the vicinity of the canyon.

Interpretation of industry seismic data, coupled with the new BMR regional seismic lines, suggests that most faulting is strike-slip. This particularly applies to the basin-bounding faults along the western margin of the Vlaming Sub-basin and the large-scale arches within the sub-basin that have been produced by wrench faulting. The relatively thick sediment sequence in the sub-basin and the structuring mechanisms point to the Vlaming Sub-basin being a relatively large pull-apart basin. The type of structuring produced by strike-slip extension has resulted in a variety of structural plays within the Sub-basin, many of which are untested.

Geohistory and geochemical analysis indicate that the Vlaming Sub-basin subsided rapidly during the Jurassic and Early Cretaceous and that sediments of this age are mature throughout parts of the sub-basin. The

relatively complex tectonic history of the sub-basin, coupled with variations in sediment thickness and facies development, means that detailed analysis at both a regional and local level is required in order to determine the potential prospectivity of individual plays.

INTRODUCTION

From 9 July to 4 August and 15 September to 14 October 1988, the BMR research vessel *Rig Seismic* conducted two cruises in the region of the South Perth Basin (Plate 1). The aims and objectives of the cruise were:

(1) to develop an updated structural and stratigraphic framework for the Perth Basin.

(2) to collect a regional seismic grid to tie industry wells and previous seismic surveys, in order to produce a comprehensive assessment of the hydrocarbon potential of the South Perth Basin.

(3) sample the continental slope for stratigraphic control, source rock potential and palaeoceanography.

(4) develop models of basin evolution, particularly for small, deep sub-basins (e.g. Vlaming Sub-basin).

Approximately 4200 km of 96-channel and 72-channel (varying from 48-fold to 24-fold) seismic reflection profiles, using an airgun array system, and 860 km of 8-channel, high-resolution watergun seismic reflection data were acquired (Plate 1). The multichannel seismic data were tied to eleven exploration wells on the shelf. Underway gravity, magnetics and bathymetry were run in conjunction with the multichannel seismic profiling. An extensive geological sampling program, involving 23 dredges, 12 piston cores and 11 gravity cores, was undertaken, mainly in the vicinity of the Fremantle Canyon and submarine fan (Plate 1). Navigation was provided by a combination of satellite navigation (Transit Doppler System and Global Positioning System) and radio navigation (Hi-fix).

REGIONAL SETTING

The Perth Basin is a north-south trending elongate trough that extends for about 1000 km beneath the coastal region and continental margin of southwest Australia (Fig. 1). The basin covers an area of 45 000 km^2 offshore (Playford and others, 1976) and a similar area onshore. The basin is bounded to the east by the Darling Fault. This fault, which is considered to have been downthrown to the west by as much as 15 km since the Early Palaeozoic (Jones, 1976), separates the basin from the Archaean Yilgarn Block. The basin has a history of rifting and rift-fill since at least the Permian, which culminated in the complete separation of India from Australia during the Neocomian (Markl, 1974a,b, 1978a,b; Larson and others, 1979; Veevers and others, 1985). Seafloor spreading is thought to have occurred about a northeast trending ridge and along transform faults, such as the Wallaby Fracture Zone (Markl, 1974b).

BATHYMETRY

The continental margin offshore Perth (Plate 1) consists of a 40 to 100 km wide continental shelf, a fairly steep continental slope and a wide continental rise. The continental shelf, which in this region is known as the Rottnest Shelf (Carrigy and Fairbridge, 1954), consists of a relatively broad inner shelf plain and a narrower outer shelf slope. The depth of the shelf break varies between 163-175 m, and is characterized by a marked change in slope. The inner shelf (0-100 m), which widens from 30 km off Fremantle to over 70 km off Bunbury, has nearshore ridges of up to 60 m relief that consist of Pleistocene aeolian Tamala Limestone, followed by a smooth low gradient sea floor, and a seaward margin of low relief ridges (Collins, 1988). The outer shelf (100-170 m) is 11-17 km wide, and has a gentle slope (0.5°) and relatively smooth topography (Collins, op. cit.).

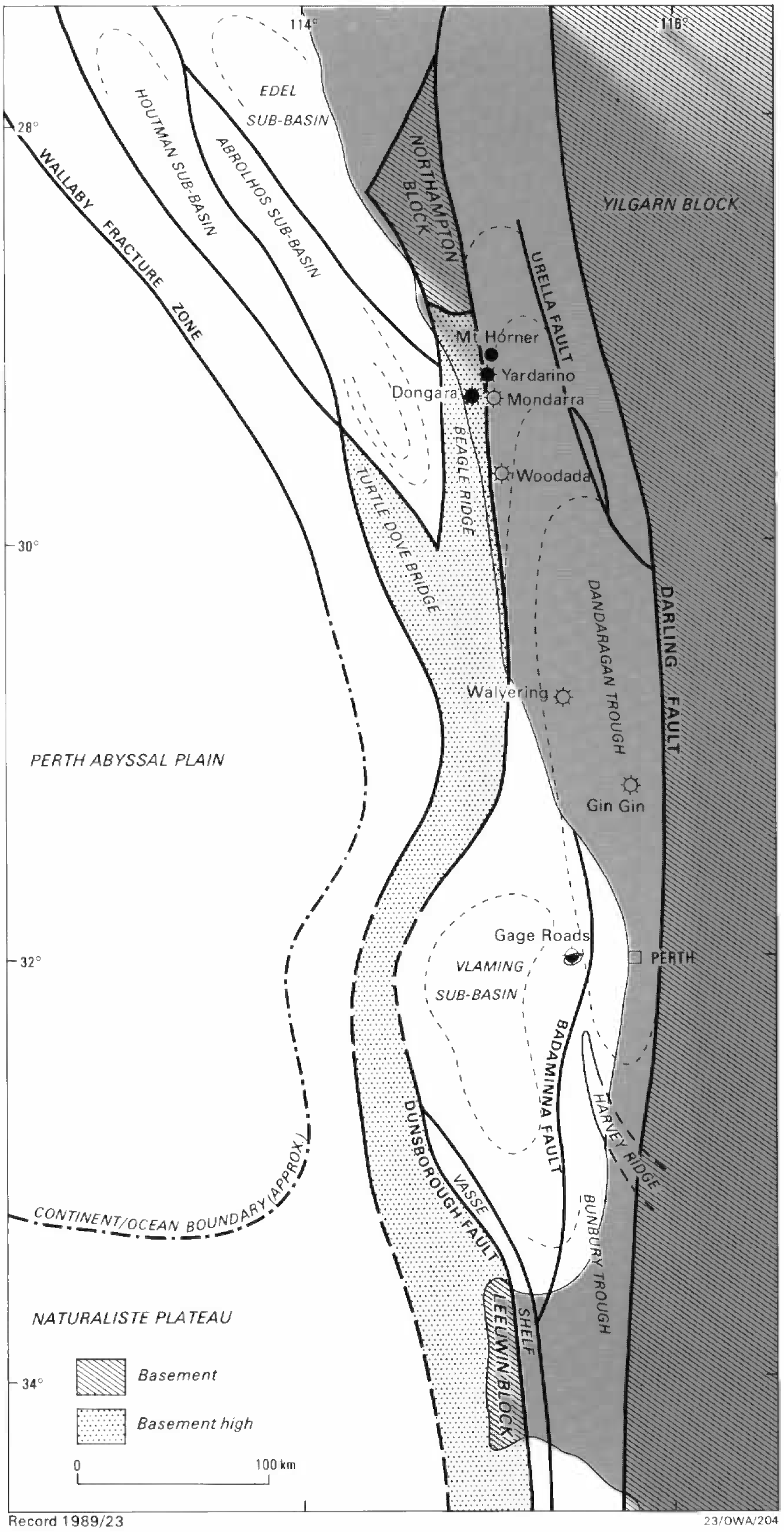

Figure 1. Tectonic map of the Perth Basin

The continental slope extends from the shelf break to about 4000 m. The slope is fairly smooth, but it is incised in places by submarine canyons and gullies, notably the Fremantle Canyon (Plate 1). The canyon is present on the continental slope directly off Perth. It heads somewhere near the shelf break and extends to about 4850 m depth (Quilty and others, in press).

The continental rise, between the 4000 and 5500 m isobaths, is over 100 km wide in places. At the base of the rise to the northwest is the Perth Abyssal Plain, whose depth is at about 5600 m.

PREVIOUS DATA

Offshore geophysical investigations by University of New South Wales and Lamont-Doherty Geological Observatory between 1960-1964 provided limited seismic refraction, magnetics and gravity data in the southwestern part of the basin (Hawkins and others, 1965). During 1971-1972, two reconnaissance surveys, one by BMR and the other by Shell Development Pty Ltd, over the continental margin of southwestern Australia obtained a broad seismic coverage (along with bathymetry, gravity and magnetics), mainly of the deeper parts of the margin. Results from these surveys (Shell, 1973; Branson, 1974; Petkovic, 1975; Symonds and Cameron, 1977) have provided a basic understanding of the structural setting of the region. Additional cruises by the Lamont-Doherty Geological Observatory and the Royal Australian Navy revealed the pattern of seafloor magnetic anomalies in the Perth Abyssal Plain and the tectonic style of the continent/ocean boundary (Markl, 1974a,b, 1978a,b; Larson and others, 1979; Veevers and others, 1985).

Offshore petroleum exploration in the Perth Basin began in 1965. A total of 21 wells have been drilled offshore, thirteen of which are located in the present area of interest (Plate 1; Appendix 1). Quinn's Rock 1 was the first well drilled offshore, by WAPET in 1968 (Bozanic, 1969a). It encountered Lower Cretaceous and Upper Jurassic sediments, similar to those encountered in wells onshore, and reached its total depth (TD) at 2185 m in the Yarragadee Formation. This well was followed immediately by Gage Roads 1 (TD 3639 m), which encountered hydrocarbon shows in the Gage Sandstone Member of the South Perth Shale (Bozanic, 1969b). Production tests indicated recovery rates of up to 500 barrels of 37.0-41.2° API oil per day. Between November 1970 and April 1971, WAPET drilled five wells in the Vlaming Sub-basin (Roe 1, Warnbro 1, Charlotte 1, Gage Roads 2, and Sugarloaf 1; Appendix 1). These wells indicated the complexity of the sub-basin, with large variations in the thickness of formations and even their complete absence in places. Bouvard 1 and Challenger 1 were drilled in the early part of 1975 by WAPET, followed by Peel 1, drilled by Phillips in late 1977. WAPET drilled their last offshore well in the South Perth Basin in 1981 (Parmelia 1). The last round of drilling took place in 1984 when Esso drilled Mullaloo 1 and Minder Reef 1.

In addition to the thirteen exploration wells, some 6000 km of seismic reflection profiles have been acquired in the offshore region of the South Perth Basin (Plate 1; Appendix 1).

A number of studies, involving geohistory analysis, source rock geochemistry and maturation patterns, have been published on the offshore Perth Basin using released oil company data (Kantsler and Cook, 1979; Thomas, 1979, 1984; Falvey and Deighton, 1982). In addition, a number of review studies of all or part of the Perth Basin detailing the structure, tectonics, and stratigraphy of the area, have been published (e.g. Jones and Pearson, 1972; Jones, 1976; Playford and others, 1976; Marshall and Lee, 1988; Marshall and others, 1989a,b; Hall, 1989).

REGIONAL GEOLOGY

STRATIGRAPHY OF THE SOUTH PERTH BASIN

Sediments ranging in age from Early Permian to Holocene are recognised in the major subdivisions of the South Perth Basin (Plate 2). The Dandaragan Trough is the deepest part of the basin, possibly containing more than 15 000 m of Phanerozoic Sediments (Playford and others, 1976). The known section is primarily of Permian, Triassic, Jurassic and Cretaceous age. Some Tertiary sediments occur in the Perth area and offshore. The Vlaming Sub-basin lies entirely offshore in a deep, fault bounded downwarp, and is considered to contain at least 15 000 m of Tertiary, Mesozoic and possibly Palaeozoic sediments (Playford and others, 1976). The Bunbury Trough is a deep graben which occurs between the Darling Fault on the east and the Busselton and Schroeder Faults on the west. The total thickness of sediments in the trough is at least 10 000 m (Playford and others, 1976), ranging in age from Permian to Early Cretaceous. Tertiary sediments are probably present in the offshore part of the Bunbury Trough.

Sue Coal Measures

The Sue Coal Measures are the oldest sediments recognised in the southern part of the Dandaragan Trough and Bunbury Trough (Plate 2). They were defined by Playford and Low (1972) for the sequence of interbedded sandstone, siltstone and coal that overlies Precambrian basement in Sue 1, the only well that has fully penetrated the formation. The upper part of the sequence was redefined as a separate unit, the Sabina Sandstone (Playford and others, 1975), which conformably overlies the Sue Coal Measures. The Sue Coal Measures has a maximum thickness of 1838 m in Sue 1 (Playford and others, 1976), and ranges in age from Late Sakmarian to Early Kazanian. It was deposited in a fluviatile to brackish water environment (Playford and others, 1976). It is probably equivalent to the mixed marine to continental sequence, from the Holmwood Shale at the base to the Wagina Sandstone at the top, that occurs in the North Perth Basin (Playford and Low 1972).

Sabina Sandstone

The Sabina Sandstone consists of a sequence of sandstones and shales that lies conformably between the Sue Coal Measures below and the Lesueur Sandstone above. The formation has been recognised in onshore wells in the southern part of the Dandaragan Trough and the Bunbury Trough (Plate 2). The maximum known thickness is 561 m in Lake Preston 1 in the Dandaragan Trough.

The Sabina Sandstone ranges in age from Late Kazanian to Early Scythian and is predominantly a fluviatile deposit, becoming paralic to the north. It represents a continuous period of sedimentation across the Permian-Triassic boundary, and it probably is equivalent to the time interval represented by the Wagina Sandstone and Kockatea Shale in the North Perth Basin (Playford and others, 1976).

Lesueur Sandstone

The Lesueur Sandstone consists of a sequence of fine- to very-coarse cross-bedded sandstones that conformably overlies the Sabina Sandstone, and is overlain conformably by the Cockleshell Gully Formation. It reaches a maximum thickness of 2201 m in Pinjarra 1 in the southern part of the Dandaragan Trough (Playford and others, 1976).

The Lesueur Sandstone ranges in age from Middle to Late Triassic in the Dandaragan Trough, but in the Bunbury Trough the lower part of the formation is of Early Triassic age (Playford and others, 1976), so that it is probably a time equivalent to the Woodada Formation and part of the Kockatea Shale in the North Perth Basin. The formation is predominantly a fluviatile, braided stream to fan delta sequence which is believed to have been deposited during a period of block faulting in the basin (Playford and others, 1976).

Cockleshell Gully Formation

The Cockleshell Gully Formation is defined as the sequence of interbedded sandstone, siltstone and claystone with beds of shale and coal that lies conformably between the Lesueur Sandstone below and the Cadda Formation or Yarragadee Formation above. Two members are distinguished in the Cockleshell Gully Formation, and have been formally defined by Playford and Low (1972). The lower, Eneabba Member, consists of multi-coloured sandstones with interbedded claystones and siltstones, and the upper Cattamarra Coal Measures Member consists of fine- to very-coarse sandstones, interbedded with siltstones, shales and seams of coal. The maximum known thickness of the Cockleshell Gully Formation is 2075 m in Pinjarra 1 in the southern part of the Dandaragan Trough.

Microflora from the Cockleshell Gully Formation is typical of the *Classopollis chateaunovi* Assemblage sub-zone of Filatoff (1975) and the *Corollina torosa* and *Callialasporites turbatus* zones of Helby, Morgan and Partridge (1987), which they consider to be Early Jurassic. The formation is largely a fluviatile deposit, laid down during a period of block faulting (Playford and others, 1976), although some sections indicate marginal marine conditions (Playford and others, 1975).

Cadda Formation

The Cadda Formation is a sequence of shales, siltstones, sandstones and limestones, lying conformably between, and probably interfingering with the Cockleshell Gully Formation below and the Yarragadee Formation above (Playford and others, 1976). The formation is recognised in some wells in the southern part of the Dandaragan Trough (Plate 2), but is probably equivalent to the basal part of the Yarragadee Formation elsewhere.

Microflora of the Cadda Formation belong to the *Dictyophyllidites harrisii* Assemblage sub-zone and *Dictosporites complex* Oppel-zone of Filatoff (1975) and the *Callialasporites turbatus* and *D. complex* Oppel-zones of Helby, Morgan and Partridge (1987), indicating an Early to Middle Bajocian age. The formation represents shallow marine to marginal marine deposition during a brief period of marine incursion (Playford and others, 1976).

Yarragadee Formation

The Yarragadee Formation is an interbedded sequence of sandstone and siltstone with thin shale beds and carbonaceous stringers, that conformably overlies the Cadda Formation or Cockleshell Gully Formation, and is conformably overlain by the Otorowiri Member of the Parmelia Formation (Playford and others, 1976; Backhouse, 1984). The formation may be up to 3000 m thick in the Dandaragan Trough and Vlaming Sub-basin, and up to 900 m thick in the Bunbury Trough (Backhouse, 1988).

Microflora of the Yarragadee Formation belong to the *Callialasporites dampieri* Assemblage-zone (*Dictyotosporites complex* Oppel-zone to *Murospora florida* Microflora) of Filatoff (1975) and Helby, Morgan and Partridge (1987), and the *Refitriletes watherooensis* and *Aequitriradites* *acusus* Zones of Backhouse (1988), indicating that the formation ranges in age from Late Bajocian to Late Tithonian. There is little lithologic variation in the Yarragadee Formation throughout the southern part of the Perth Basin, and the sequence appears to represent a period of widespread fluviatile sedimentation (Backhouse, 1988).

Parmelia Formation

Backhouse (1984) defined the Parmelia Formation as the sequence of sandstones, shales and siltstones that conformably overlies the Yarragadee Formation, and is unconformably overlain by the Warnbro Group. The formation is known in detail only from the sub-surface, and appears to be present in the Dandaragan Trough and Vlaming Sub-basin, although it may have been deposited in the Bunbury Trough, but subsequently removed by erosion (Backhouse, 1988).

The formation increases in thickness from east to west across the Vlaming Sub-basin where seismic evidence indicates that it reaches a maximum thickness of 8000 m below the continental slope west of Perth (Playford and others, 1976). It reaches a maximum drilled thickness of 1926 m in Peel 1 (Backhouse, 1984).

Two relatively fine-grained intervals are recognised within the Parmelia Formation. These are the basal Otorowiri Member and the much thicker Carnac Member in the middle of the formation (Backhouse, 1984). In the Vlaming Sub-basin, the Otorowiri and Carnac Members are separated by a sequence of fine- to coarse-grained sandstone and thin shale beds, and the Carnac Member is overlain by thick sandstone beds and infrequent thin shale beds (Backhouse, 1988). In the Dandaragan Trough, the Carnac Member either immediately overlies the Otorowiri Member (Plate 2), or is separated from it by a thin sequence of sandstone beds (Backhouse, 1988).

Within the Parmelia Formation, Backhouse (1988) defined the microflora into the *Biretisporites eneabbaensis* Zone and microplankton into the *Fusiformacysta tumida* Zone, which ranges from Late Tithonian to Berriasian. The sandstone sections of the formation probably represent braided channels and fluvio-deltaic deposits, whereas, on palynological evidence, the siltstone and shale beds of the Otorowiri and Carnac Members are considered to represent periods of uniform deposition in a series of large lakes (Backhouse, 1988), prior to the middle Neocomian phase of rifting.

Bunbury Basalt

The Bunbury Basalt consists of at least two tholeiitic basalt flows that appear to lie unconformably between the Yarragadee Formation below and the Leederville Formation above (Playford and others, 1976; Backhouse, 1988). The Bunbury Basalt is only known from several localities near Bunbury, reaching a maximum thickness of 85 metres (Playford and others, 1976).

Beds of siltstone and shale between the basalt flows contain microflora that belong to the *Biretisporites eneabbaensis* Zone of Backhouse (1988), suggesting that the Bunbury Basalt was extruded during or soon after the deposition of the Parmelia Formation (Plate 2). It was probably associated with a period of tectonism immediately prior to seafloor spreading. According to Backhouse (1988), the age of the Bunbury Basalt is most likely Late Berriasian to Early Valanginian.

Warnbro Group

Cockbain and Playford (1973) defined the Warnbro Group as the Early Cretaceous transgressive sequence that occurs between the top of the

Parmelia or Yarragadee Formation and the base of the Osborne Formation (Playford and others, 1976; Backhouse, 1988).

In the Vlaming Sub-basin and southern part of the Dandaragan Trough, the Warnbro Group overlies older sediments with a strongly unconformable contact of Middle Neocomian age, and can be subdivided into a lower, shale and claystone unit (the South Perth Shale), and an upper, sandstone unit (the Leederville Formation). A sandstone and shale unit (the Gage Sandstone Member) occurs locally at the base of the South Perth Shale (Backhouse, 1988). In the Bunbury Trough, only a thin sandstone and shale section, probably belonging to the Leederville Formation (Plate 2), unconformably overlies the Yarragadee Formation (Playford and others, 1976; Backhouse, 1988).

South Perth Shale

The South Perth Shale consists largely of shale and claystone, grading to siltstone, and containing some beds of sandstone. A sandstone unit, the Gage Sandstone Member, occurs locally at the base of the formation (Backhouse, 1988). The formation overlies the Parmelia Formation or Yarragadee Formation with a marked unconformity of variable relief (Playford and others, 1976), and is overlain conformably by the Leederville Formation. Excluding the Gage Sandstone Member, the South Perth Shale extends over the Dandaragan Trough and Vlaming Sub-basin, reaching a maximum thickness of 636 m in Mullaloo 1 in the Rottnest Trough, although seismic studies indicate the formation may be several thousand metres thick towards the edge of the continental shelf (Playford and others, 1976).

Microplankton of the South Perth Shale belong to Backhouse's (1987, 1988) *Kaiwaradinium scrutillinum*, *Phoberocysta lowryi* and *Aprobolocysta* *alata* Oppel-Zones, and microflora belong to the lower *Balmeiopsis limbata* Zone of Backhouse (1988), indicating a Late Valanginian to Hauterivian age. Backhouse (1987, 1988) regards the South Perth Shale as a shallow water, inner shelf deposit, formed as a result of a marine transgression following Middle Neocomian rifting and basin subsidence.

Gage Sandstone Member (Gage Formation of Davidson and Moncrieff, 1989)

The Gage Sandstone Member of the South Perth Shale consists of fine- to coarse-grained sandstones with rare siltstone and shale beds, that occur in localised areas at the base of the South Perth Shale (Backhouse, 1988). This basal sandstone member has been intersected by offshore wells drilled in the Vlaming Sub-basin, reaching a maximum thickness of 274 m in Warnbro 1, and probably extends onshore into part of the southern Dandaragan Trough (Backhouse, 1988). Davidson and Moncrieff (1989) have recently amended the Gage Sandstone Member to Gage Formation (Fig. 2), on the basis that it consists of interbedded sandstone, siltstone and shale, rather than just sandstone, and that the unit can be mapped at the base of the Warnbro Group over a large part of the central Perth Basin.

Microplankton belong to Backhouse's (1988) *Gagiella mutabilis* Oppel-zone, indicating a Valanginian age for the Gage Sandstone Member. The member appears to have been deposited in structurally low areas, in restricted marine to partly fluviatile conditions, as a result of erosion from newly formed fault blocks (Backhouse, 1988).

Leederville Formation

Cockbain and Playford (1973) defined the Leederville Formation as the sequence of interbedded sandstones, siltstones, shales and rare

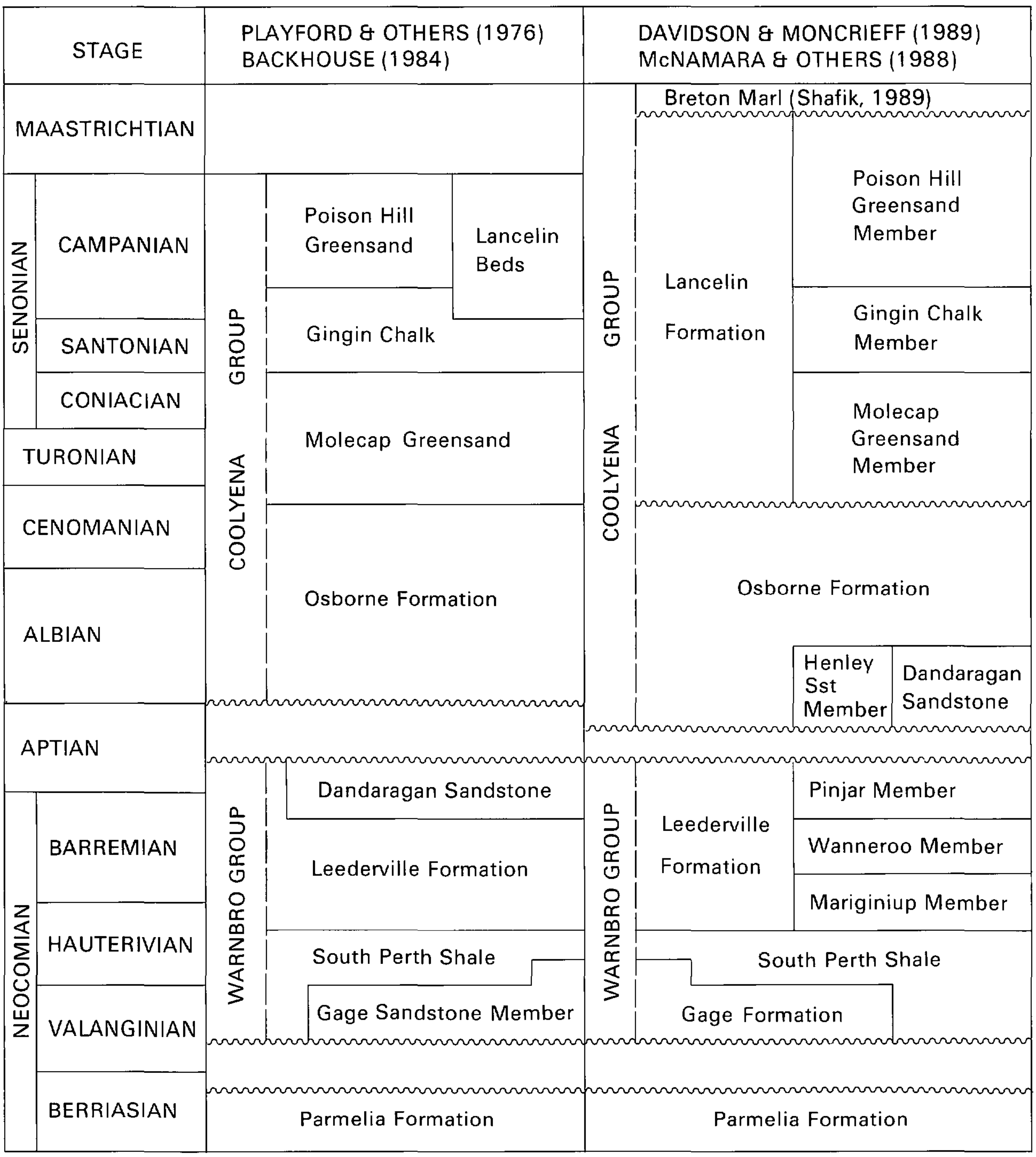

Figure 2. Revised stratigraphic nomenclature for the Cretaceous of the South Perth Basin.

conglomerates that conformably overlies or interfingers with the South Perth Shale or unconformably overlies the Parmelia Formation and older units, and is unconformably overlain by the Osborne Formation. The formation is widely distributed in the sub-surface throughout the South Perth Basin, thickening offshore to a known maximum of 662 m in Gage Roads 1.

Microplankton in the Leederville Formation belong to Backhouse's (1987, 1988) *Aprobolocysta alata, Batioladinium jaegeri* and *Fromea monilifera* Zones, and microflora belong to Backhouse's (1988) upper *Balmeiopsis limbata* Zone, indicating an age for the formation of Late Hauterivian to Early Aptian. The Leederville Formation appears to be of mixed origin, being a combination of fluvio-deltaic, shallow marine and paralic (Playford and others, 1976; Backhouse, 1988).

Coolyena Group

The Coolyena Group was defined by Cockbain and Playford (1973) for the marine sequence of glauconite bearing sediments and chalk of predominantly Late Cretaceous age that occurs in the central and southern parts of the Perth Basin, including the Dandaragan Trough and Vlaming Sub-basin. The sequence, as originally defined, consists of the Osborne Formation, Molecap Greensand, Gingin Chalk and Poison Hill Greensand in ascending order. However, the nomenclature has recently been revised by Davidson and Moncrieff (1989; see Fig. 2). Most of the revised units refer to the onshore equivalent of the Coolyena Group, whereas offshore in the Vlaming Sub-basin the upper units are usually difficult to distinguish. The Coolyena Group unconformably or disconformably overlies the Leederville Formation, and is disconformably overlain by the Early Tertiary Kings Park Formation.

Osborne Formation

The Osborne Formation consists of interbedded sandstones, siltstones, shales and claystones, and is characteristically glauconitic (Cockbain and Playford, 1973). The Osborne Formation unconformably or disconformably overlies the Leederville Formation, and is overlain, probably conformably, or interfingers with, the Molecap Greensand (Playford and others, 1976). The formation is recognised from bores in the Perth Metropolitan area, and offshore in wells in the southern part of the Vlaming Sub-basin, reaching a maximum known thickness of 259 m in Warnbro 1.

Spore and pollen assemblages from the Osborne Formation belong to the *Hoegisporis* Microflora Zone (Playford and others, 1976; Backhouse, 1988), and indicate an age range of Albian to Cenomanian. The Osborne Formation represents a shallow, transgressive marine sequence, probably laid down over an irregular topography (Playford and others, 1976).

Molecap Greensand

The Molecap Greensand consists of greensand and glauconitic quartz sandstone that probably conformably overlies the Osborne Formation, and is overlain conformably by the Gingin Chalk (Playford and others, 1976). Cockbain and Playford (1973) suggest that the Molecap Greensand may be equivalent to the upper part of the Osborne Formation, or may interfinger with it, in part. The formation is only recognised in discontinuous outcrops in the southern part of the Dandaragan Trough, where it reaches a thickness of 12 metres (Playford and others, 1976). Microplankton and microflora place the age of the Molecap Greensand from Late Cenomanian to Early Santonian (Playford and others, 1976). The formation represents a marine deposit laid down in a shallow sea.

Gingin Chalk

The Gingin Chalk is a unit of white, highly fossiliferous, slightly glauconitic chalk that lies with apparent conformity between the Molecap Greensand below and the Poison Hill Greensand above (Playford and others, 1976). The formation is only known in the Dandaragan Trough, where it reaches a thickness of about 18 metres. The abundant faunal assemblages in the Gingin Chalk indicate a Santonian to Campanian age (Playford and others, 1976), and that it was probably deposited in a warm, shallow sea, receiving very little terriginous detritus.

Poison Hill Greensand

The Poison Hill Greensand consists of greensand and glauconitic sandstone with thin shaly beds, conformably overlying the Gingin Chalk, and disconformably overlain by Tertiary or Quaternary sediments. The Poison Hill Greensand is only known with any certainty from the Dandaragan Trough, where the maximum thickness of the formation probably exceeds 45 m (Playford and others, 1976). Microflora and microplankton assemblages indicate a Campanian to Maastrichtian age for the Poison Hill Greensand (Playford and others, 1976), which is a marine sequence that may represent a regressive phase of the Late Cretaceous marine transgression (Playford and others, 1976).

Kings Park Formation

Quilty (1974 a,b) defined the Kings Park Formation as the sequence of slightly glauconitic calcarenites and calcilutites penetrated between 68 and 365 m in Quinns Rock 1 well. The formation disconformably overlies the Coolyena Group or older rocks, and is disconformably overlain by younger Tertiary or Quaternary deposits (Playford and others, 1976). The formation is only known in the Perth Metropolitan area and offshore adjacent to Perth, where it reaches a maximum thickness of 597 m in the Rottnest Island bore (Playford and others, 1976).

The age of the Kings Park Formation is Late Paleocene to Early Eocene based on faunal assemblages, and Quilty (1974 a,b) and Playford and others (1976) believe the formation represents a shallow marine to estuarine deposit that may be related to the now submerged drainage system of the old Swan River.

Revisions to the stratigraphic nomenclature by Cockbain and Hocking (1989) for the Tertiary of the Perth Basin include two new formations: the Middle Eocene Porpoise Bay Formation and the Upper Eocene Challenger Formation. Both formations are fine-grained bioclastics. The type section for the Porpoise Bay Formation is the Rottnest Island bore, between 285 and 667 m, whereas the type section for the Challenger Formation is the Challenger 1 well, between 530 and 597 m. Both formations are confined to the Vlaming Sub-basin.

Stark Bay Formation

The Stark Bay Formation was defined by Quilty (1974 a,b) for the sequence of calcarenites, dolomites and cherts encountered in Gage Roads 2 over the interval 362-577 m. The formation disconformably overlies the Kings Park Formation, and is overlain, probably unconformably, by an un-named red to brown carbonate unit. It is known only from wells in the Vlaming Sub-basin and has a maximum known thickness of 230 m in Gage Roads 1.

Planktonic foraminifera indicate that the formation is Early to Middle Miocene (Quilty, 1974 a,b), and the sedimentary sequence represents a marine carbonate depositional environment with almost no influx of terriginous material.

Ascot Beds

Playford and others (1976) proposed the Ascot Beds for a sequence of coarse-grained calcarenites known from the Perth metropolitan area. The areal extent of the Ascot Beds is unknown, and they have been dated as Pliocene.

Un-named Carbonate Unit

Quilty (1974 a,b) recognised a unit of red to brown limestone or dolomitic limestone which overlies the Stark Bay Formation in Gage Roads 1 and 2. Little is known of the age, lithology and stratigraphic relationships of this unit because of poor recovery whilst drilling. Quilty (1974 a,b) and Playford and others (1976) place the age of the unit as Late Miocene to Pliocene.

Kwinana Group and Equivalent Units

Much of the southern Perth Basin is covered by a mantle of Pleistocene and Holocene coastal-dune, beach and shallow marine carbonates and sands, with associated lake, swamp and alluvial deposits . This sequence has been defined as the Kwinana Group by Playford and others (1976), and consists of the Ridge Hill Sandstone, Yoganup Formation, Bassendean Sand, Tamala Limestone, Safety Bay Sand, Peppermint Grove Limestone and Rottnest Limestone. Additional Quaternary units have been only poorly defined, and have not been studied in any detail.

The present shelf is covered by a very thin veneer of Holocene carbonate sediments, with very little terrigenous influx, which disconformably overlie Pleistocene limestone. The nearshore zone has tabular sediment accumulations that vary from a few metres to 40 m in thickness. Collins (1988) has divided the blanket-like deposits on the shelf into three units: the Fremantle Blanket, Coventry Algal Veneer, and the Rottnest Blanket.

OFFSHORE WELL STRATIGRAPHY AND CORRELATIONS

Thirteen petroleum exploration wells have been drilled offshore in the Vlaming Sub-basin (Plate 1; Appendix 1). Exploration has been directed mainly at the Early Cretaceous Gage Sandstone Member of the South Perth Shale and the Late Jurassic to Early Cretaceous Parmelia Formation (Jones, 1976; Hall, 1989), where they are sealed by the South Perth Shale (Jones, 1976). A secondary objective has been the Late Jurassic Yarragadee Formation, overlain and sealed by the Otorowiri Member (Jones, 1976; Hall, 1989).

Seven of the thirteen wells were studied in detail by Backhouse (1984, 1988) to develop a revised Late Jurassic and Early Cretaceous biostratigraphy of the Perth Basin. Results from Backhouse, together with basic data available from the thirteen wells, have been used to compile a stratigraphic analysis of each well (Plates 3-15), together with correlations between the various wells of the Vlaming Sub-basin (Plates 16-18). The post-Cretaceous sequence has limited prospectivity for petroleum and it has not been correlated in detail.

Yarragadee Formation

The oldest unit penetrated is the Late Jurassic Yarragadee Formation, which is present in seven of the thirteen wells (Plates 3, 4, 6, 8, 9, 11, 12). The complete sequence has not been intersected offshore, but it is estimated to be over 3000 m thick (Playford and others, 1976; Backhouse, 1988). The Yarragadee Formation is widespread throughout the Vlaming Sub-basin. Where the formation has been intersected by wells, its top lies directly beneath the Otorowiri Member, and it has normally been correlated on this basis. The top of the sequence in well sections varies in depth from 1646 m in Quinns Rock 1 (Plate 3) to 3521 m at Peel 1 (Plate 12) near the centre of the sub-basin.

The formation has little regional lithological variation (Backhouse, 1988) and is typified by a serrated, blocky or cylindrical log pattern. It may have some source potential, but is regarded as having poor reservoir properties, with porosities averaging 7 percent (Hall, 1989).

Parmelia Formation

The Parmelia Formation conformably overlies the Yarragadee Formation, and has been intersected by all of the offshore wells drilled in the Vlaming Sub-basin (Plates 3-18). The depth to the top of the formation ranges from 610 m in Sugarloaf 1 (Plate 9) to 2179 m in Warnbro 1 (Plate 6), located near the southern end of the Rottnest Trough. The formation increases in thickness from east to west across the Vlaming Sub-basin (Backhouse, 1988), and the most complete sequence is intersected by Peel 1 (Plate 12) over the interval 1595 m to 3521 m; the section in Peel 1 has been used to formally define the formation (Backhouse, 1984).

The formation consists of a fine to coarse sandstone unit with two predominantly shale to siltstone members, the Otorowiri Member at the base and the much thicker Carnac Member in the middle. The Otorowiri Member is widespread over the Vlaming Sub-basin and has a distinct log character that can be identified in all wells that have intersected it. It is also a diagnostic seismic horizon (Hall, 1989). The Otorowiri Member varies in thickness from 27 to 84 m in well sections, and it provides a regional seal across the sub-basin. The Otorowiri Member is also considered to be oil prone (Hall, 1989).

The Carnac Member in the middle of the formation is lithologically similar to the Otorowiri Member (Backhouse, 1984, 1988), but has a more subtle log character, making it difficult to identify from the surrounding Parmelia Formation sandstones. It varies in thickness from 655 to 1262 m in the well sections, and may have some source potential (Hall, 1989). In some well sections, the Carnac Member has been partly or completely removed during the Middle Neocomian period of uplift and erosion, but, where preserved, it provides an intra-formational seal within the Parmelia Formation. The sandstones of the Parmelia Formation have porosities ranging from 10 to 35 percent, and permeabilities ranging from 11 to 2031 millidarcies (Hall, 1989), and produced 60 kilolitres per day of oil on test in Gage Roads 1 (Jones, 1976).

The top of the Parmelia Formation can be correlated with the Neocomian unconformity, which can be traced over the entire Vlaming Sub-basin. The base of the formation is correlated with the Otorowiri Member, which is widespread also, and extends as a continuous unit over most of the sub-basin. Well sections in the northern part of the Vlaming Sub-basin correlate with the upper part of the Parmelia Formation (Plate 16), including the upper part of the Carnac Member. The majority of wells in the central and southern parts of the sub-basin have intersected sections that correlate with the lower part of the Parmelia Formation

(Plates 17, 18), including the lower part of the Carnac Member and the Otorowiri Member. Only two wells, Peel 1 on the eastern margin of the sub-basin and Sugarloaf 1 in the south, have intersected the complete sequence of the Parmelia Formation.

Warnbro Group

The Warnbro Group overlies the Parmelia Formation with a strongly unconformable contact of Middle Neocomian age (Playford and others, 1976) in all well sections in the Vlaming Sub-basin. The contact is easily identifiable on wireline logs. In well sections, the Warnbro Group can be subdivided into three units on the basis of palynology (Backhouse, 1988) and wireline log character. The basal sandstone unit (the Gage Sandstone Member) and a lower shale-claystone unit (the South Perth Shale) occur only in wells in the central axis or flanks of the Rottnest Trough (Plates 16-18), whereas the upper sandstone unit, the Leederville Formation, is more widespread throughout the Vlaming Sub-basin. The most complete section occurs in Warnbro 1 (Plate 6) where the Warnbro Group attains a thickness of 1137 m.

The Gage Sandstone Member is areally more restricted than either the South Perth Shale or the Leederville Sandstone, but is a good reservoir, with porosities ranging from 10 to 31 percent, and permeabilities up to 1340 millidarcies (Hall, 1989). Two metres of oil saturated sand were reported in Gage Roads 2, but the sand was thin and tight (Jones, 1976). The South Perth Shale provides the seal for the Gage Sandstone Member reservoir.

The top of the Warnbro Group has been correlated with the Albian-Aptian unconformity, which can be identified in wireline logs and traced over the entire Vlaming Sub-basin. The base of the Warnbro Group correlates with the Neocomian unconformity. Of the three sub-units of the Warnbro Group, only the upper one, the Leederville Formation, can be correlated over the whole sub-basin (Plates 16-18). The South Perth Shale and Gage Sandstone Member are restricted, in general, to wells in the deeper, central axis of the sub-basin and along their flanks.

Coolyena Group

The Coolyena Group is only recognised in well sections in the southern half of the Vlaming Sub-basin, where it disconformably overlies the Warnbro Group (Playford and others, 1976). The Coolyena Group is composed of four sub-units: the Osborne Formation, Molecap Greensand, Gingin Chalk and Poison Hill Greensand (Cockbain and Playford, 1973), but it is only possible to differentiate the Osborne Formation in the offshore well sections.

Tertiary and Quaternary

All of the offshore wells in the Vlaming Sub-basin have intersected Tertiary and Quaternary sandstones and carbonates ranging in thickness from 179 m in Sugarloaf 1 (Plate 9) in the south to 610 m in Parmelia 1 (Plate 13) on the western flank of the sub-basin. Generally, the sequence thickens towards the north and west of the Vlaming Sub-basin. The Tertiary and Quaternary sediments have limited potential for petroleum and, consequently, they have not been sub-divided in the construction of the cross sections.

STRUCTURAL ELEMENTS

The Perth Basin consists of a series of extensionally formed sub-basins, separated by block-faulted structural highs. Structural analysis of the offshore North Perth Basin suggests that the basin was formed predominantly by strike-slip extensional tectonics (Marshall and others 1989a, b). The basin is considered to have developed as one arm of a rift system that is analogous to the present Red Sea-Dead Sea tectonic setting (Marshall and others, 1989a). Basin development has been closely tied to movement on the Darling Fault (Jones, 1976; Playford and others, 1976). The Darling Fault is the major bounding structure along the eastern margin of the Perth Basin (Fig. 1). Movement on the fault has led to shedding of large volumes of sediment from the adjacent Precambrian shield into the subsiding depocentres of the rift system.

The major structural elements of the Perth Basin are shown in Figure 1. The onshore part of the basin is dominated by the Dandaragan Trough, a major depocentre that is believed to contain up to 15 km of Permian to Cretaceous sediments, mainly as clastic piedmont wedges that were deposited during periods of movement on the Darling and Urella Faults. (Playford and others, 1976). The Dandaragan Trough is bounded on the east by the Darling Fault and to the west by the Beagle Ridge (Fig. 1). To the north it shallows onto the Precambrian basement of the Northampton Block, whereas to the south it is separated, to some extent, from the Bunbury Trough by the Harvey Ridge. The Bunbury Trough is a major onshore depocentre in the South Perth Basin, and contains a maximum of 10 000 m of Permian and Mesozoic sediments.

The series of troughs and highs extends offshore. In the north a series of narrow, elongate sub-basins, the Edel, Abrolhos and Houtman Sub-basins (Fig. 1), make up the offshore depocentres. These sub-basins are considered to be the product of three distinct rifting episodes in the Early Permian, Late Permian and Early Cretaceous (Marshall and Lee, 1988; Marshall and others, 1989a, b). The boundaries of these sub-basins are formed either by fault-bounded basement highs, such as the Beagle and Turtle Dove Ridge (Fig. 1), or by strike-slip faults. In the south, the Vlaming Sub-basin contains an extremely thick Late Jurassic-Early Cretaceous sequence. Since the Vlaming Sub-basin is the major structural feature of the offshore South Perth Basin it is dealt with in more detail below.

Structural Elements of the Vlaming Sub-basin

The Vlaming Sub-basin occupies the region beneath the shelf and upper slope offshore from Perth (Fig. 3), and it forms the major depocentre offshore in the South Perth Basin. The sub-basin covers an area of some 10 000 sq. km between latitudes 31° 30' and 33° 30'S. It is about 100 km wide at its widest point, off Perth. To the west it appears that the sub-basin is bounded by a basement high that forms a continuation of the Beagle and Turtle Dove Ridges to the north (Edwards Island Block of Jones, 1976) and the Leeuwin Block to the south (Fig. 3). To the east, the Vlaming Sub-basin is separated from the southern Dandaragan Trough and the Bunbury Trough by the Badaminna Fault system (Fig. 3), but the boundary with the central Dandaragan Trough is less well defined. The Dandaragan Trough is believed to extend beneath the inner shelf to the south of the junction between the Beagle Ridge and the Turtle Dove Ridge, but its boundary with the Vlaming Sub-basin offshore, and the nature of that boundary, remains unresolved.

The thickness of sediments in the Vlaming Sub-basin has not been determined, either by seismic techniques or from drilling. The sedimentary sequence is anomalously thick, compared to other

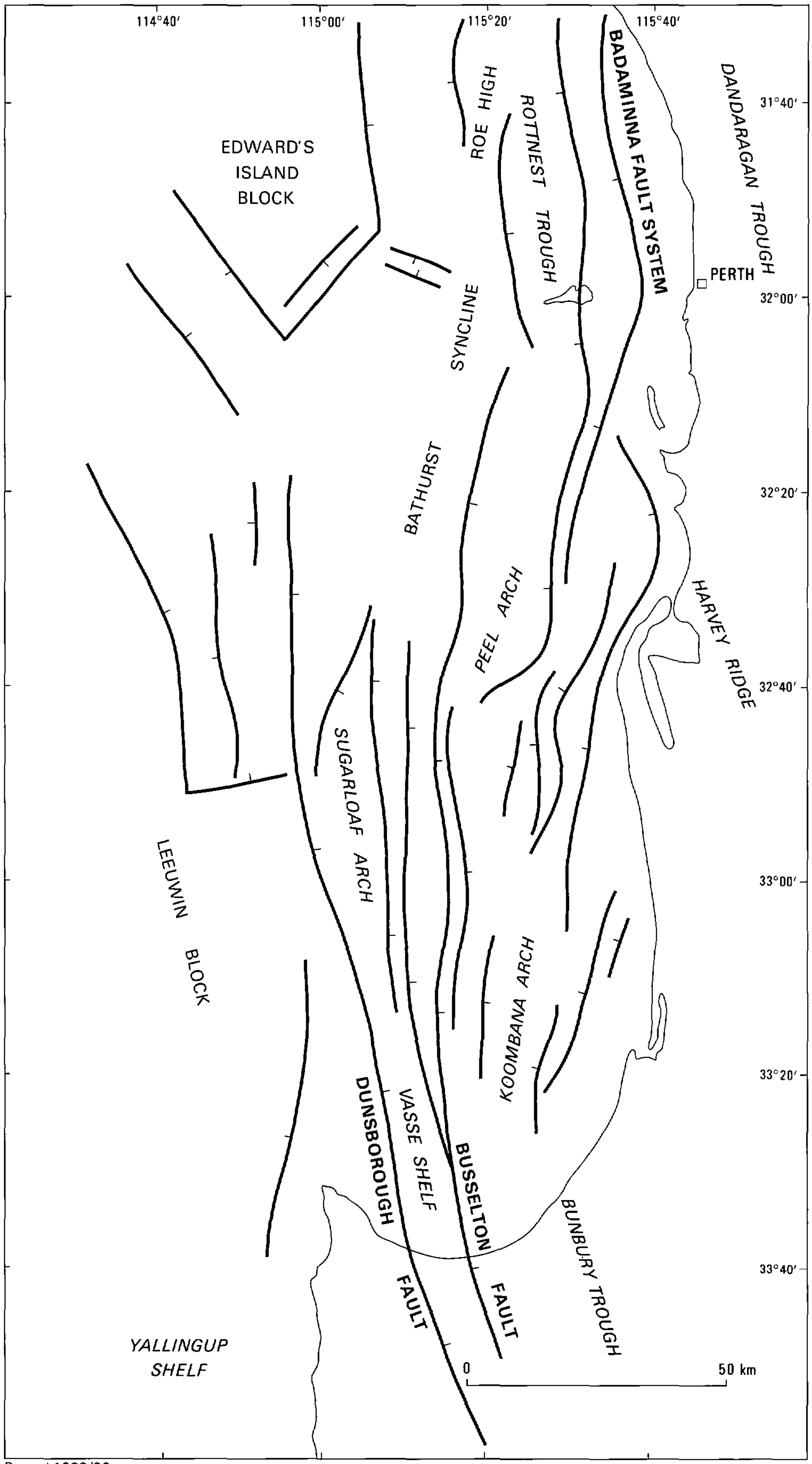

Figure 3. Structural elements of the South Perth Basin

parts of the Perth Basin, with estimates of up to 15 km (e.g. Jones, 1976). The only comparable region is the Houtman Sub-basin in the north, but even here the depth to the Middle Jurassic can be resolved by seismic and drill data, whereas in the Vlaming Sub-basin it remains beyond the limits of resolution of the techniques employed so far.

The margins of the Vlaming Sub-basin are dominated by relatively steep faults that are laterally persistent along the margins, although they do tend to be offset in places. The Dunsborough Fault (Fig. 3) is the major bounding fault to the southwest, where it separates the Vasse Shelf from the basement high which is an extension of the Leeuwin Block. The Vasse Shelf is, in turn, separated from the deeper part of the Vlaming Sub-basin by the Busselton Fault. The eastern margin of the sub-basin is dominated by the Badaminna Fault, which is probably several sub-parallel bounding faults along parts of its length. This fault separates the Vlaming Sub-basin from the Bunbury Trough and the southern part of the Dandaragan Trough.

The northern, and deepest, part of the Vlaming Sub-basin is dominated by the Bathurst Syncline, a broad downwarp that trends SSW, and the Rottnest Trough, a major graben feature to the east (Fig. 3). These two features are separated by the Roe High, a tilt block, faulted along its eastern boundary, that extends roughly from Minder Reef 1 to Warnbro 1 (Plate 1). Further to the south are several broad, faulted arches, such as the Peel Arch, which roughly follow the predominant N-S trend within the Vlaming Sub-basin.

Many of the faults within the Vlaming Sub-basin are persistent and, while sinuous in nature, can be traced for fairly large distances (Fig. 3). The arches, such as the Peel Arch, are widespread and of varying size, and they are indicative of large-scale compressive stresses within the

Sub-basin. They tend to coincide with points where the major faults diverge from their previous trends. The large degree of local faulting and folding at these localities can make the arches very complex structures.

TECTONIC AND DEPOSITIONAL HISTORY

The Perth Basin appears to have been largely non-depositional during the Early Palaeozoic, even though the initial stages of rifting probably began during the Silurian. Earliest tectonic movement appears to have been restricted to the Darling Fault and possibly along the edges of the Northampton Block (Jones, 1976; Playford and others, 1976). The initiation of the Dandaragan Trough could have been related to this earlier period of faulting. Offshore, the initial phase of rifting took place in the northern part of the basin during the Early Permian where a series of half-grabens was produced by displacement along low angle faults in the Edel Sub-basin (Marshall and Lee, 1988). The axis of rifting shifted during the Late Permian to the Abrolhos Sub-basin.

These initial phases of rifting in the Permian produced predominantly marine sediments in the north, whereas in the south there was deposition of an essentially non-marine sequence (Sue Coal Measures) that persisted into the Early Triassic (Sabina Sandstone). Whereas rifting episodes in the Late Permian are evident in the north, and there are several unconformity-bound sequences, deposition in the south appears to have been continuous. From the Late Triassic to the Late Jurassic, a prolonged 'rift-phase' ensued, resulting in large volumes of alluvial and fluvial sediments being deposited throughout the basin (Lesueur Sandstone, Cockleshell Gully Formation, Yarragadee Formation). A marine incursion took place during the Middle Jurassic (Cadda Formation), but this does not appear to have penetrated into the southernmost part of the basin.

In the Vlaming Sub-basin there was a distinct subsidence phase in the Late Jurassic, during which large volumes of sediment were deposited (Yarragadee Formation). This thick sequence of predominantly alluvial fans and fluvial sediments show little thinning or onlap onto the edges of the sub-basin, suggesting that they were deposited rapidly into an equally rapidly subsiding depocentre. The sedimentation style changed somewhat at the beginning of the Cretaceous, possibly indicating a more mature phase of rift-fill. It seems that the Vlaming Sub-basin was bounded on all sides by structural highs, and that there was damming of the previous fluvial system to some extent, resulting in the development of a lacustrine depositional environment during the late Tithonian and middle Berriasian (Backhouse, 1988). The first lacustrine phase (Otorowiri Member) was a widespread, but relatively short-lived event. The second phase (Carnac Member) saw more localised lake environments, but they appear to have been more permanent features, and resulted in relatively thick fine-grained sequences, such as seen in Peel 1 (Plate 12). This second phase of lake development was accompanied by a fluvio-deltaic depositional regime, that gradually encroached and eventually covered the lake system.

The final phase of rifting, accompanied by tectonism associated with breakup and the onset of seafloor spreading, took place during the Neocomian, during which many of the structural features in the Vlaming Sub-basin (e.g. Bathurst Syncline and Rottnest Trough) were formed. The breakup unconformity developed in the sub-basin towards the end of the Berriasian, and at least one flow of tholeiitic basalt (Bunbury Basalt) extended from the adjoining Bunbury Trough into the sub-basin along a valley floor that was eroded at around this time. While sedimentation was partly controlled by thermally-induced subsidence at this stage, there appears to have been a markedly higher degree of subsidence in the Vlaming Sub-basin than elsewhere in the South Perth Basin, possibly an effect of sediment loading. This relatively greater subsidence is evident from the geometry of the breakup unconformity, which shows a relatively planar attitude around the margins of the sub-basin, as opposed to a deeper unconformity, with substantially more relief, within the sub-basin, and a much thicker post-rift sequence above.

The exact nature of the faulting during this final rifting phase is difficult to assess. Major movement occurred along previous fault zones, such as the previous basin-bounding faults, and more notably on the Dunsborough Fault to the west (Fig. 3). The oblique nature of the final rift, in relation to the pre-existing faults, meant that there was a large degree of strike-slip movement. Accompanying this, there were areas of local compression which resulted in uplift and folding. The tilted fault blocks seen throughout the sub-basin originated at this time. Some post-rift faulting is evident in the sub-basin, but this has produced relatively little offset.

While the sub-basin margins remained relatively high, there was a rapid phase of fluvial and alluvial sedimentation (Gage Sandstone Member), produced by erosion of the recently uplifted scarps around the margins, into structurally low features, such as the Rottnest Trough. It is quite conceivable that, as the Perth Basin began to subside from decay of the thermal anomaly, the deeper parts of the Vlaming Sub-basin were actually below sea level at some stage, but were still depocentres for alluvial/fluvial sediments.

As the newly-formed continental margin subsided relatively rapidly during the early phase of drift, during the Early Cretaceous, there was flooding of the region that includes the present-day shelf, and incursion of the sea into the Vlaming Sub-basin and southern Dandaragan Trough. Continued greater subsidence of the Vlaming Sub-basin, relative to its margins, probably resulted in a relatively deep, low energy, possibly restricted marine depositional environment, that accumulated a large volume of fine-grained sediments (South Perth Shale). As sedimentation began to outstrip the ever-waning subsidence, there was a change to more shallow water, higher energy, marine conditions, and transgressive sandstones (Leederville Formation) began to blanket the South Perth Basin (Backhouse, 1988). These sandstones developed into a non-marine fluvio-deltaic system, as a regressive sequence began to build back out across the basin.

As subsidence, from both thermal decay and sediment loading, waned further, a widespread marine transgression during the latter part of the Early Cretaceous saw the transition from terrigenous-dominated marine sediments to carbonates (Coolyena Group). These carbonates are considered to have developed on a temperate continental margin, with condensed sequences, in the form of glauconitic greensands, indicating prolonged periods of non-deposition.

The present configuration of the continental margin was probably largely achieved by the beginning of the Tertiary, with fine-grained carbonates, containing minor amounts of glauconite, indicating a predominantly outer shelf/upper slope environment of deposition beneath the present shelf. Development of the Fremantle Canyon would have meant that most terrigenous sediment would have by-passed the shelf, and would have been deposited as part of the submarine fan at the base of the slope. Although the margin by this stage was essentially starved of terrigenous sediment, major eustatic cycles did result in some mixed carbonate/siliciclastic deposits, but, overall, the shelf remained a carbonate province.

FREMANTLE CANYON

INTRODUCTION

A large submarine canyon dissects the continental slope west of Perth (Plate 1). The canyon is about 120 km in length, but it consists of three discrete segments, each about 40 km in length (Plate 19). At the base of the canyon is a large submarine fan. The canyon has previously been referred to as the 'Swan Canyon' and the 'Perth Canyon', but it is now officially known as the Fremantle Canyon (Quilty and others, in press).

Methods

During BMR Cruise 80, the submarine canyon and its fan were investigated using a combination of seismic reflection profiling, dredging and coring. A total of 860 km of high-resolution seismic reflection profiles (Plate 20) were acquired using an 80 cubic inch watergun source and a short 8-channel streamer with group length of 12.5 m. Maximum offset was about 140 m and near offset was 53 m. The cable was towed at a nominal depth of 5 m, at a speed of 5 knots. The record length was 2.5 seconds, with a sampling rate of 1 millisecond (ms). A simple processing scheme was adopted, whereby the data was initially reformatted, resampled and sorted, and a static correction applied. The data was deconvolved, using a 150-point filter with a 20 ms gap. A 4-fold stacking procedure was applied, using a stacking velocity of 1500 m/sec. This was followed by an FK migration using the same velocity. The data was frequency filtered, both pre-stack and post-migration, using a 20-90 Hz bandpass filter. The data is displayed with a trace density of 19.7 traces/cm corresponding to a horizontal scale of 1:12303, and with a vertical exaggeration of 3.3:1.

A total of 20 dredge sites were occupied on the walls of the canyon. Of these 17 recovered rocks of varying lithology, mainly sandstones, shale/mudstones and limestones. The location of the successful dredge sites are shown in Plate 21. The dredges were run in as close proximity as possible to those seismic lines which indicated the best outcrops. Attempts were made to sample over as small a depth range as possible, so as to have greater control on the position of the dredged samples. At some sites, up to three dredges were cast in order to sample the entire canyon wall (Plate 21).

Six piston core sites were occupied on the fan at the base of the canyon, four of which were successful. A further three sites on the distal part of the fan were occupied during Cruise 81.

Bathymetry

The bathymetry of the Fremantle Canyon is shown in Plate 19. The head of the canyon occurs at about the depth of the shelf break (average depth of 170 m; Collins, 1988). The bathymetry indicates that there is no channel extending back across the shelf, even though the canyon is directly opposite to the Swan River. This is similar to many of the submarine canyons around the continental margin of Australia, whose heads are normally located at or directly below the shelf break, and have not incised the shelf (Von der Borch, 1968; Davies, 1973; Marshall, 1980). On seismic line 80/06 (Plate 23), there are two distinct canyon heads, whereas deeper they have merged to form a single, deeply incised channel.

Initially, the canyon trends southwesterly, but at an axial depth of about 1700 m it suddenly changes direction. Here, the canyon forms a junction with a northwesterly trending arm, which heads at a depth of around 600 m (Plate 19). This arm of the canyon extends for 60 km, to an axial depth of 3000 m, before suddenly changing direction again to a westerly orientation (Plate 19). The canyon extends in this direction to a depth of about 4400 m, after which it opens out onto the submarine fan. Near the canyon mouth, the southern levee of the fan is considerably higher than the northern levee, and it tends to form an extension of the canyon wall. The axial channel of the canyon divides into at least two channel valleys on the proximal part of the fan.

SEISMIC RESULTS

Ten of the 25 high-resolution seismic lines (Plates 22-31) have been processed to date, and the following is an interpretation of these lines. Most of them are situated on the upper two-thirds of the canyon. Watergun line 80/05 (Plate 22) was run in about 150 m water depth; i.e. above the shelf break. The section shows no indication of the canyon, either at the seafloor or in the subsurface. What is interpreted as the Neocomian unconformity reflection has some relief, but this is not related to canyon processes. Above the unconformity, there is some downlap and channeling at about the level of the South Perth Shale, whereas what is interpreted as top Leederville is relatively planar.

The next line (80/06; Plate 23) coincides with MCS line 81/32. The shelf is about 150-180 m, but the canyon has cut down to 300 m. Two distinct canyon heads are apparent on this line. In the subsurface there is some channeling and infill at shallow depths, but only beneath the southern canyon head; the strata beneath the northern head are relatively undisturbed. In line 80/08 (Plate 24) the axial depth of the canyon is at 1275 m, and the canyon has incised what appear to be Tertiary sediments.

As the canyon deepens along that NE-SW trending arm there is a marked change in the structure. In lines 80/10, 11 and 12 (Plates 25-27) there is a distinct difference in the seismic character on either side of the canyon. What can be considered the northern side of the canyon shows tilted fault blocks that have been planated by the Neocomian unconformity. The unconformity is very shallow, and it commonly crops out on the upper part of the canyon wall. The tilted fault blocks show strata dipping in either direction, and in line 80/12 they appear to crop out on the canyon wall (Plate 27). On the southern wall of the canyon, the unconformity is relatively deep and there is a much greater thickness of post-breakup sediments on this side. The shallow nature of the Neocomian unconformity on the northern side of the canyon is similar to its attitude in the Bunbury Trough and Vasse Shelf, which in turn suggests that the canyon forms the boundary of the Vlaming Sub-basin in this vicinity. However, the canyon arm itself is not the actual boundary, as might be assumed. This is evident in line 80/14 (Plate 29) which shows tilted fault blocks beneath the southern side of the canyon as well as the northern side, indicating that the sub-basin boundary is further to the east.

Along the NW-SE trending arm of the canyon the Neocomian unconformity is generally at about the same level on both sides of the canyon. In line 80/19 (Plate 30) the canyon is about 1500 m deeper than the surrounding seafloor. Dredging of Permian and Triassic rocks on both sides of the canyon (see Biostratigraphy) on this transect indicates that in this vicinity the canyon is cutting through a structurally higher block than the Vlaming Sub-basin.

At the location of line 80/23 (Plate 31), the canyon is about 20 km wide and it has a broad floor at an axial depth of 3075 m. The seismic section shows a prominent reflection between 3.6 and 4.1 seconds (TWT), which is interpreted as the Neocomian unconformity. This age pick appears to be verified from the palynology (see later).

DREDGE RESULTS

A total of some 450 kg of rocks were recovered from the flanks of the Fremantle Canyon during the sampling phase of operations. Most of these rocks were limestones, but some dredge samples consist of sandstones, shales and mudstones. A full description of the dredge hauls and their locations is given in Appendix 2. The dredge targets were picked from the watergun monitor sections on board ship, and the stations roughly coincide with the selected seismic lines (Plate 21).

Apart from station 80DR/002, on the lower continental slope north of the canyon, only three dredge hauls recovered sandstones. At station 80DR/013 (Plate 21) the dredge recovered medium to coarse grained, friable quartzose sandstones, some of which show cross-bedding and others show iron-staining. At station 80DR/014 one sample of a silty sandstone was recovered. This sample consists of 1-4 cm thick sandstone layers interbedded with finely laminated silty sandstone. The laminae consist of alternating light and dark grey layers, which define small-scale trough cross-bedding, with a later generation of cross-beds cutting into part of the previous one. A finely laminated (2-5 mm) shaley sandstone was recovered at 80DR/015 (Plate 21). Dark (silty or carbonaceous) laminae between the predominantly sandy layers define a series of cross-beds and climbing ripples. Individual cross-bedded units are of the order of 3-5 cm thick.

Shale samples recovered from several dredges (Appendix 2) are mainly dark brown or grey and finely laminated. Some consist of alternating light and dark layers, with laminae of 1-10 mm in thickness. X-ray diffraction analysis (Appendix 3) indicates that the shales often contain a relatively high amount of feldspar. Other dominant minerals are quartz and kaolinite, while mica and montmorillonite are present in trace amounts.

Mainly softish, but fissile, mudstones recovered from the dredge hauls vary in colour from dark grey to pale chocolate brown to black. Some mudstones are finely laminated, whereas others are more massive. Quite often, the carbonised remains of plant fragments can be discerned under the low power microscope. XRD results (Appendix 3) indicate that quartz and kaolinite are the dominant minerals, while feldspar is fairly common, and mica and montmorillonite occur in trace amounts.

The limestones, the major lithology dredged from the canyon walls, all appear to be relatively similar, although there are distinct differences in colour, texture and the degree of diagenesis. The colour of the limestones varies from white to medium grey. Dirty grey-coloured limestones generally contain a fair amount of glauconite, while some variegated limestones reflect either differences in the degree of diagenesis within the rock or the presence of cherty layers. The limestones are calcilutites and calcarenites, and they range in texture from grainstone to mudstone. Mudstones and wackestones are the more common types, whereas packstones and grainstones make up about 25 percent of the recovered limestones.

The limestones are bioclastics, and common skeletal components include foraminifera, nannofossils, sponges, radiolaria, diatoms, echinoids and bryozoans. XRD results (Appendix 3) show that low Mg calcite is the only carbonate mineral present. Dolomite has been suspected in several samples, but so far this has not been verified. Silica is fairly common in these limestones, and in a few samples it predominates. The silica is present mainly in the form of sponge spicules. Quite frequently, casts of spicules can be discerned under the microscope, indicating that in some limestones there has been dissolution of silica. Siliceous moulds of radiolaria can be fairly common in some samples as well. Glauconite is a common accessory mineral in the limestones. The glauconite varies from yellowish green to greenish black in colour, indicating that it is relatively mature, and it is present as discrete pellets, 0.1-1.0 mm in diameter. Fine-medium size quartz grains are usually present in trace amounts, but the occasional sample has a fair amount of quartz, that commonly is much coarser than the others. Dissolution in dilute hydrochloric acid sometimes released a very fine residue that is considered to be clay minerals. XRD results (Appendix 3) have verified this to some extent.

While there is some variety in texture and mineralogy, the limestones are considered to have been deposited in fairly similar environments. The dilution in the amount of terrigenous material and the predominance of relatively fine-grained skeletal material points to a fairly deep marine environment. The presence of relatively mature glauconite pellets as an accessory mineral in these limestones suggests an outer shelf to upper slope environment.

BIOSTRATIGRAPHY

Calcareous Nannofossils

With the exception of the Upper Paleocene-Lower Eocene Kings Park Formation, the onshore Upper Cretaceous-Lower Tertiary marine sequence in the Perth Basin has been poorly defined until fairly recently when two unnamed Eocene units, containing calcareous nannofossils and/or planktic foraminiferids, were discovered: a Middle Eocene unit investigated by Shafik (1978) who recorded its calcareous nannofossils, and an Upper Eocene unit investigated by Quilty (1978) who documented its planktic foraminiferids. More recently, Shafik (1989) described an Upper Maastrichtian unit, with abundant calcareous nannofossils, which he informally referred to as the Breton Marl. Cockbain and Hocking (1989) have proposed the names Porpoise Bay and Challenger Formations respectively for the two previously unnamed Eocene units .

Material examined in the present study, from the Fremantle Canyon and the continental slope north of Perth, fills most of the nannofossil biostratigraphic gap between the Kings Park and the Porpoise Bay Formations. In addition, records of several new nannofossil-bearing levels within the Paleocene, Eocene and Oligocene are documented (Appendix 4). Furthermore, nannofossils from a Lower Miocene horizon in the southeastern wall of the canyon are recorded.

Onshore Maastrichtian and Early Tertiary Nannofossil Biostratigraphic Sequence

In an unpublished report, Shafik (1989) detailed the Late Cretaceous nannofossil biostratigraphy of onshore parts of the Perth Basin. Relevant to the present study is the documentation of Late Maastrichtian assemblages from what has informally been named the Breton Marl (Shafik, 1989). These assemblages can be characterised by the occurrence of *Nephrolithus frequens*, *Lithraphidites quadratus* and *Cribrosphaerella daniae*. The type section of the Breton Marl is in Breton Bay corehole 1 (Lat. 31°10' 36" S - Long. 115° 24' 06" E), consisting of an approximately six-metre thick section of soft marl. The underlying Lancelin Formation in Breton Bay corehole 1 is about 60 metres thick, and is separated from the Breton Marl by an intra-Maastrichtian disconformity (Shafik, 1989; Fig. 2).

The Kings Park Formation (Fairbridge *in* Coleman, 1952; amended Quilty, 1974a, b) represents the oldest Tertiary marine sediments in the onshore Perth Basin. Its type section is 275-metres thick in the Kings Park 2 bore (Perth Metropolitan area), but a thickness of more than 500 metres has been reported elsewhere in the Perth area. The formation consists of grey calcareous, mostly glauconitic shale and siltstone, containing bryozoans, foraminiferids, calcareous nannofossils, molluscs, ostracods and sponge spicules (McWhae and 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 the foraminiferids recovered from offshore are younger than Late Paleocene. Shafik (1978) recorded the nannofossils of the Kings Park Formation in several boreholes as well as its type section. Except for those nannofossils in the Rottnest Island Bore, Shafik (1978) correlated the other nannofossil assemblages of the Kings Park Formation with the Late Paleocene foraminiferal late P4 and P5 zones, 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*, *Cyclococcolithus* sp. cf. *C. formosus*, *Discoaster* sp. cf. *D. diastypus*, *D. multiradiatus* and *Transversopntis* sp. aff. *T. pulcher*, whereas those from the upper Paleocene levels lack discoasters, but include the index species, *Heliolithus kleinpellii* and *H. riedeli*, in addition to several species of *Fasciculithus*. Shafik (1978) dated the nannofossils in Rottnest Island Bore as Middle Eocene in age, and recommended that this unit be given separate lithostratigraphic status; being deposited during a separate sedimentary cycle other than that for the other occurrences of the Kings Park Formation, including its type section. Subsequently, Cockbain and Hocking (1989) have named the middle unit in the Rottnest Island Bore as the Porpoise Bay Formation. The type section of the Porpoise Bay Formation consists of 382 metres of brown calcareous shale and siltstone, unconformably overlying the 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*, *Cyclococcolithus formosus*, *Daktylethra punctulata*, *Discoaster nodifer*, *Helicosphaera lophota*, *Lanternithus minutus*, *Micrantholithus procerus*, *Pemma basquensis*, *P. papillatum*, *P. rotundum*, *Pontosphaera multipora*, *P. ocellata*, *Reticulofenestra dictyoda*, *R. scrippsae*, *R. umbilica* and *Zygrahblithus bijugatus*. The key species *Chiasmolithus solitus*, *Cyclicargolithus reticulatus* and *Helicosphaera reticulata* are also present, suggesting correlation with the Middle Eocene foraminiferal zone P12.

Quilty (1978) has described an Upper Eocene unnamed unit from the offshore region south of Perth (in Challenger 1), which subsequently has been named the Challenger Formation by Cockbain and Hocking (1989). The type section of the Challenger Formation consists of 67 metres of chalk, calcarenite and chert, disconformably overlying the Kings Park Formation. According to data in Quilty (1978), the Challenger Formation contains several important foraminiferal zonal species such as *Hantkenina primitiva*, *H. alabamensis*, *Globigerinatheka index index*, *G. subconglobata* and *Globorotalia cerrozulensis* subspp., referable to zone P16.

Late Cretaceous to Early Oligocene Nannofossil Assemblages from the Fremantle Canyon and their Significance

The distribution of the calcareous nannofossils recovered from most of the Fremantle Canyon dredges is given in Plates 32 and 33. In the more detailed discussion in Appendix 4, the assemblages are arranged in a chronologic order, rather than according to the order of the dredge stations, to easily relate them to the sequence of the onshore Perth Basin. Nannofossil biostratigraphic assignments (Tables 1 and 2) are to datum intervals (DI) rather than zones, in order to avoid difficulties inherent in the usage of formally defined zonations. However, correlation with the foraminiferal P zones are made when possible.

From the results discussed here and in Appendix 4, the following conclusions can be made:

(1) Important calcareous nannofossil biostratigraphic events within the interval from the Late Maastrichtian to Early Miocene are indicated from dredge results from the Fremantle Canyon. These are correlated with the low-latitude foraminiferal P and N zones, and are used to elucidate the lithostratigraphic succession of the canyon.

(2) The Upper Maastrichtian Breton Marl, described by Shafik (1989) from onshore material, is recognised as occurring in the northeastern wall of

Table 1. Nannofossil biostratigraphic assignment of Fremantle Canyon dredges--Late Cretaceous to Early Eocene.

Age	Calcareous nannofossil biostratigraphic events	(Foraminiferal P zones)	Dredges	
EARLY EOCENE	+*Fasciculithus* spp.	(early P6b)	←80DR/020-6	KINGS PARK FORMATION EQUIVALENT
	**Tribrachiatus bramlettei; Discoaster diastypus*			
LATE PALEOCENE			80DR/021-5	
	**Campylosphaera eodela*	(P5/P6 boundary)	80DR/017-3	
	**Discoaster multiradiatus*	(late P4)	80DR/014-12 80DR/014-13	
	**Discoaster nobilis*; **Heliolithus riedeli*	(mid P4)	80DR/005-8 80DR/005-9 80DR/014-3 80DR/016-2 80DR/016-3 80DR/022-3	
	**Discoaster mohleri*	(early P4)	80DR/004-2 80DR/014-8	
	**Toweius pertusus*	(early P4)		
EARLY PALEOCENE	+*Cruciplacolithus frequens*	(late P3b)		UNNAMED NEW UNIT(S) OR OLD PHASE OF K P F
	**Heliolithus kleinpellii*	(mid P3b)		
	**Fasciculithus tympaniformis*	(P3a/P3b boundary)	80DR/020-8	
	**Chiasmolithus bidens*	(P2)		
	**Ellipsolithus distichus*	(P1c)		
	+*Ellipdolithus macellus*	(mid P1c)	80DR/014-10	
	+*Cruciplacolithus tenuis*	(earliest P1c)	80DR/014-5	
	**Chiasmolithus danicus*	(late P1b)		
	**Cruciplacolithus primus*	(early P1b)		
	**Biantholithus sparsus*			
LATE MAASTRICHTIAN			80DR/020-9 80DR/020-10 80DR/020-11	BRETON MARL EQUIVALENT
	**Nephrolithus frequens*			
MIDDLE MAASTRICHTIAN: A disconformity in the onshore sequence (Shafik, 1989).				

*Lowest occurrence +Highest occurrence

Table 2. Nannofossil biostratigraphic assignment of Fremantle Canyon dredges--Early Eocene to Early Oligocene.

Age	Calcareous nannofossil biostratigraphic events	(Foraminiferal P zones)	Dredges	
EARLY	+*Cyclococcolithus formosus*	(mid P18)		?
OLIGOCENE	+*Reticulofenestra hampdenensis*	(?early P18)	← 80DR/014-4	CHALLENGER FORMATION EQUIVALENT
	+*Discoaster saipanensis*	(P17)		
LATE	+*Cyclicargolithus reticulatus*	(P16)		
	**Isthmolithus recurvus*	(mid P16)	← 80DR/014-11	
EOCENE	+*Neococcolithes dubius*	(early P16)		
	**Chiasmolithus oamaruensis*	(early P15)		
	+*Chismolithus grandis*			
	+*Daktylethra punctulata*	(P13)		PORPOISE BAY FORMATION EQUIVALENT
	**Reticulofenestra scissura*	(P13)		
MIDDLE			80DR/008-2 80DR/013-1 80DR/009-1	
	**Cyclicargolithus reticulatus*	(P12)	?80DR/018-2 ?80DR/019-3	
	**Reticulofenestra umbilica*	(late P12)		
	+*Chiasmolithus gigas*	(late P11)	← 80DR/019-1	?
EOCENE	**Chiasmolithus gigas*	(early P11)		?
	**Nannotetrina fulgens*	(late P10)	80DR/019-4	
	**Rhabdosphaera inflata*	(P9/P10 boundary)		
			80DR/023-1C 80DR/021-11 80DR/022-1 80DR/003-8 80DR/003-7 80DR/003-3	UNNAMED NEW UNIT
	**Discoaster sublodoensis*	(late P9)		
EARLY	**Toweius? crassus*	(late P8)	80DR/003-2	
	**Discoaster lodoensis*	(latest P7)	?80DR/003-1 ?80DR/003-9 80DR/003-6 80DR/017-1 80DR/020-5	
EOCENE	+*Tribrachiatus contortus*	(late P6b)		
	**Tribrachiatus orthostylus*	(late P6b)	80DR/020-7 80DR/014-14 80DR/018-1	
	+*Fasciculithus* spp.	(early P6b)		
	**Tribrachiatus bramlettei;Discoaster diastypus*	(P6a/P6b boundary)		
PALEOCENE	:Table 1.			

the Fremantle Canyon. The nannofossil evidence from the canyon material, suggesting that surface waters were cold during the Late Maastrichtian, matches the evidence derived from the onshore material.

(3) At least two new horizons in the Lower Paleocene are present offshore. These are thought either to form previously unknown unit(s) or are a part of the younger Kings Park Formation. A consequence of the latter option is that the lower boundary of the Kings Park Formation becomes older offshore, suggesting that the formation is transgressive.

(4) An hiatus seems to exist between the Cretaceous and Tertiary in the Fremantle Canyon. The Uppermost Maastrichtian and Lowermost Paleocene seem to be missing from the canyon sequence. In the onshore sequence, the hiatus between the Cretaceous and Tertiary is more substantial with the absence of the Lower Paleocene as well as the uppermost Maastrichtian.

(5) The Kings Park Formation occurs widely along the walls of the Fremantle Canyon, but mainly as calcilutites. Thus, the terrigenous components, thought to have been contributed to the formation in the Perth Metropolitan area by a river system (Shafik, 1978), evidently did not reach the depositional sites presently occupied by the Fremantle Canyon.

(6) The Early to early Middle Eocene nannofossil biostratigraphic sequence indicated has no counterpart in onshore sections. It is regarded as being based on a new unit yet to be named. This (mainly Lower Eocene) unit apparently consists of a succession of calcilutites and calcarenites. It is widely occurring, being exposed at many locations along the walls of the Fremantle Canyon and also on the continental slope north of Perth.

(7) Evidence of a significant reworking episode during the Middle Eocene occurs in the offshore equivalent of the Middle Eocene Porpoise Bay Formation, confirming Shafik's (1985) similar findings at contemporaneous levels in the onshore sections of the Perth, Carnarvon, Eucla and Otway Basins.

(8) The offshore equivalent of the Porpoise Bay Formation, being shelf carbonates (calcarenites and calcilutites), is probably difficult to distinguish from the similar shelf carbonates of the Upper Eocene Challenger Formation. It is thought that these two formations merge into one unit along the walls of the canyon.

(9) An unnamed Mid (upper Lower) Oligocene unit is discovered, based on a nannofossil assemblage containing the index species *Sphenolithus distentus* which indicates a correlation with the foraminiferal zone P21a.

(10) The key species *Sphenolithus heteromorphus*, found in a dolomitic calcilutite sample, was used to suggest indirectly the presence of the foraminiferal zone N7 - a level known from the bottom of the Stark Bay Formation.

Foraminifera

A total of 61 samples were submitted for foraminiferal age determination and interpretation of the depositional environment, and almost all samples yielded foraminifera. The youngest samples submitted are of Early Miocene age and the oldest of Early Cretaceous age. Three samples are of Late Maastrichtian age. The great majority of samples fall into the age range Middle Eocene to Late Paleocene (Appendix 5).

The samples are dated nominally using the tropical "N" and "P" zonation established for low latitude foraminiferal assemblages by Blow (1969, 1979), and by Berggren (1969) and Berggren and Miller (1988). However, since virtually none of the zone index species are present in the temperate offshore Perth Basin assemblages, the actual zonation used is a combination of McGowran's foraminiferal "datums" for the southern Australian region (McGowran 1978 etc.), and the North West Shelf zonation developed by Woodside Offshore Petroleum (Wright, 1973 a,b; Heath and Apthorpe, 1981, 1984). Both these dating schemes are correlated approximately with the "P" zonation, but the precision of this correlation varies greatly from one part of the zonation to another, and in many cases the two sets of zonal boundaries do not correspond. The designation in terms of "P" zones is therefore used for ease of communication and correlation, and does not imply that these zones as defined by their authors are actually being used here. The notation "(T--)" which follows some of the "P" zone assignments refers to the North West Shelf zonation. It has the great disadvantage of being a regional, and still formally unpublished, zonation.

Distribution charts of all species identified are presented in Plates 34-36. The interpretation of environment given for some samples is necessarily vague. Many samples yielded almost entirely planktonic foraminiferal assemblages. While this suggests an oceanic setting and deeper than continental shelf water depths, the lack of benthonic species has hindered attempts to estimate water depths.

The lithostratigraphy and biostratigraphy of the offshore South Perth Basin has been briefly described by Quilty (1974 a,b, 1978) from subsurface sections both onshore and offshore. Other relevant papers include McGowran (1964, 1965) on the Kings Park Formation and McNamara and others (1988) on the Lancelin Formation. The lithostratigraphic nomenclature of the Tertiary and Cretaceous sequences has been revised recently (Cockbain and Hocking, 1989; Davidson and Moncrieff, 1989).

The sequence represented by the present set of dredge samples will be discussed from oldest strata to youngest. The oldest sample submitted is a light grey, glauconitic mudstone of Early Cretaceous age (80DR/023-2). The entirely arenaceous foraminiferal assemblage is long-ranging in time and does not enable any more precise age estimate. Foraminifera have been reported previously from the Early Cretaceous of the Perth Basin; most occurrences have been from the South Perth Shale. None of the assemblages have been of age-diagnostic value (J. Backhouse, pers. comm.). The assemblage found here suggests epicontinental shelf sea depths, being dominated by species of *Trochammina* and *Haplophragmoides*.

The Late Cretaceous is represented by three samples (80DR/020-9, 10, 11); all appearing to be very close together in stratigraphic position. These Late Maastrichtian samples are from the uppermost unit of the Lancelin Formation (McNamara and others, 1988), which has informally been named the Breton Marl (Shafik, 1989; see Fig. 2). The presence of a new species of *Heterohelix* (to be described by Rexilius) suggests large-scale reworking from the Late Campanian (see Rexilius, 1984). This, in turn suggests that the Late Maastrichtian may be resting unconformably on the Late Campanian or Earliest Maastrichtian in the Fremantle Canyon area, a situation shown diagrammatically in Plate 37.

No samples equivalent in age to the Santonian Gingin Chalk Member of the Lancelin Formation have been found in the present suite of samples. Quilty (1978) reported a Late Santonian age from a glauconitic sandstone in the Challenger 1 well, apparently basing the age determination on the occurrence of similar species in the Gingin Chalk, north of Perth. However, the species listed by Quilty (1978, p.111) are long-ranging, and a younger age for the assemblage is possible.

A new unit, of Early Paleocene age, is seen in two samples from dredge 80DR/014 (Samples 10 and 12) on the north wall in mid-canyon (Plate 37). The fauna, which is dominated by *Globoconusa daubjergensis*, is assignable to the North West Shelf zone T1 (=late P1 to early P2). Sediments of this age are widespread on the north west margin of Australia, but have not been reported previously from the southern or southwestern margin. A new formation name is required because the unit appears to lie disconformably beneath the Kings Park Formation. The interpretation of a disconformable contact is based on the presence, in sample 80DR/014-8, of an abundance of reworked Early Paleocene fauna in a sparse Late Paleocene assemblage. Both this sample and the two Early Paleocene samples also contain Late Cretaceous reworking.

The Late Paleocene to Basal Eocene Kings Park Formation is represented by a number of samples (Plate 37). Quilty (1978, Fig.3) shows the facies distribution of the formation south and east of Rottnest Island. The occurrence of numerous carbonate samples of outer shelf or deeper facies in the Fremantle Canyon suggests that the zero-edge contour for the formation turns north between the canyon and the Roe 1 well, west of Rottnest Island. The dredge 80DR/003 on the continental slope north of the canyon (Plate 37) did not recover any samples which could be assigned to the Kings Park Formation with any confidence, and it is possible that the formation is absent in this area. The base of the Kings Park Formation may be as old as late zone P3 (T3), based on somewhat questionable determinations for samples 80DR/017-3 and 80DR/020-8. There are a number of samples within the two-fold subdivision of zone P4, and there is one definite and one possible sample determination within zone P5 (T6). There is no definite sample assignment to zone P6a (T7), and an hiatus at this level is known to be widely present on the North West Shelf. A questionable brief hiatus is inserted in Plate 37 because of the absence of T7 samples. Several samples are assigned to the Basal Eocene zone P6b (T8). There are no samples assignable to zones P7-8. The top of the Kings Park Formation has therefore been drawn at the base of this interval in Plate 37. The facies distribution in the Kings Park Formation suggests outer shelf conditions in zones T3 and T4, deepening to probably upper bathyal depths by zone P6b time.

Three and possibly four samples, from four separate dredge hauls, are dated as Early Eocene zone P9 (Plate 37). This may be a separate marine interval, not reported previously in the Perth Basin. Whether this should be considered as the uppermost part of the Kings Park Formation depends on whether a continuous sequence can be demonstrated to be present through the interval of zones P7 and P8. There is no evidence in the present set of samples for such a continuous sequence. If the unit is indeed separate from the Kings Park Formation, it should be given a new formation name, and it is informally named here as the Fremantle Canyon Limestone. The chalky porous white limestones contain a foraminiferal fauna that is approximately 99 percent planktonic in composition, suggesting bathyal water depths. There is nothing in the very rare benthonic assemblages to contradict this interpretation.

The next episode of sedimentation is of Middle Eocene age. It appears to span the equivalent time interval of zones P11 to P14, although neither these zones, nor the North West Shelf equivalents, are precisely recognisable in the sequence. The correlation to these zonations is taken from McGowran (1978) and McGowran and Beecroft (1985), with some reservations, as the species associations they report for southern Australia do not agree with those seen here in all instances. The zonal labels used here are, at best, a guide, rather than a definitive statement on the precise level within the Middle Eocene. This Middle Eocene episode is referred to as the Porpoise Bay Formation (Plate 37). The name is from Cockbain and Hocking (1989), taken from Quilty (1978), who described, but did not name, a shallow marine clastic unit of this age in the Rottnest Island bore. The samples from the Fremantle Canyon are siliceous limestones of bathyal aspect. They appear to span a longer time interval than that ascribed to the shallow-water Rottnest Island section by Quilty (1978). The youngest Middle Eocene samples seen in the Fremantle canyon sequence, in dredge hauls 80DR/008 and 80DR/014, are of latest Middle Eocene age. The faunas correspond with those described from Challenger 1 from 567-597 m by Quilty (1978), which he at that time labeled "Late Eocene". The highest occurrence of *Acarinina primitiva* is taken by McGowran (1978) as marking the top of the Middle Eocene Zone P14, an occurrence which appears to be in agreement with distributions on the North West Shelf. Thus, as the basal part of the Challenger Formation is represented in the Fremantle Canyon sequence, along with the Porpoise Bay Formation, there is a distinct possibility that the two units are in fact one continuous sequence. Quilty (1978, p. 115) referred to this possibility. Without study of closely sampled sequences over this interval, it seems unlikely that the question of the relationship between the units will be resolved. Faunas of Late Eocene age have not been found in the present set of samples. It would be helpful to reexamine the Challenger 1 well section to clarify the correlations.

Three samples from the shallowest dredge haul near the eastern end of the canyon (80DR/007) are of Early Miocene age (Plate 37). The oldest sample, of zone N5 age, contains an abundant and diverse assemblage with upper to middle bathyal benthonic species. Two younger samples of zone N6-7 age are of outer shelf facies. These samples are slightly older than the Stark Bay Formation, which Quilty (1978, Fig.6) shows as Middle

Miocene (Zones N8 to N9), with a possible base as old as N7. The depositional environment of the canyon samples is much deeper than that inferred for the Stark Bay Formation, in which Quilty (1974 a,b) records the inner to middle shelf genus *Lepidocyclina*. Whether the canyon sequence is continuous with the Stark Bay Formation is unknown. The distribution of the Stark Bay Formation appears to be discontinuous in the wells reported on by Quilty (1978, Fig.5).

Sediments of post-Early Miocene age were not identified in the samples submitted. Three limestone samples were barren of identifiable foraminifera. The Late Miocene - Early Pliocene sequence recorded by Quilty in Challenger 1 is definitely not present in this sample set.

One feature of the Cainozoic sequence in this sample set is that lithologically many of the carbonates appear very similar. Without age dating it would not be possible to separate the sequence into discrete units.

Palynology

Twenty-one shale/mudstone samples dredged from the Fremantle Canyon were examined for their content of palynomorphs. The location of the dredge samples are shown in Plate 21 and Appendix 2. The samples, averaging about 500 gm in weight, were cleaned and subjected to a standard and common extraction procedure. The following notes summarise observations made to date.

Samples 1 to 5 from dredge 80DR/005 (see Appendix 2 and Plate 21 for location) contain common forms of *Bisaccates*, *Araucariacites*, *Corollina*, *and Trisaccites*. *Contignisporites* spp. and *Murospora florida* are among the less common spores. Extremely rare specimens of *Cicatricosisporites* *australiensis* were found in several samples. Plant leaf cuticle is common, and very rare acanthomorph acritarchs are present. No dinoflagellates have been identified. Rare, reworked and well preserved specimens of Permian spores and pollen are present in every sample.

Samples from 80DR/005 are assigned an Early Cretaceous age, most likely Berriasian *B. eneabbaensis* Zone (Backhouse, 1987), or *C. australiensis* Zone (Helby and others, 1987). This indicates that the rocks are from the Carnac Member of the Parmelia Formation. They are from a lacustrine facies, with possible occasional brackish influence.

Samples 1 to 5 from dredge 80DR/013 from the north wall of the Fremantle Canyon (see Appendix 2 and Plate 21 for location) contain common forms of *Vittatina, Striatiti* and *Marsupipollenites. Monosaccates* are present, but comprise a very low percentage of the whole. Rare specimens of *D. ericianus, P. gretensis, A ramosus*, acanthomorph acritarchs and one specimen of *D. parvitholus* were observed. Preservation is poor to good. Assemblages in this group of samples are all relatively similar, but show variability in percentage content. The environment and age of these samples are interpreted as being a non-marine equivalent of Permian Upper Stage 5 (Kemp and others, 1977; Price, 1983).

Sample 1 from dredge 80DR/014 (Plate 21) had a sparse yield, and at this stage it can only be determined as undifferentiated Upper Mesozoic.

One sample (Sample 2) of dredge 80DR/015 (Plate 21), from the southern side of the canyon had relatively pale specimens and a sparse yield when compared to Cretaceous and Permian samples listed above, but it includes relatively common *Striatiti* (with *L. noviaulensis*), *Discisporites psilatus* and rare *Falcisporites australis, Punctatisporites, Lundbladispora* sp. and *Kraeuselisporites cuspidus*. No acritarchs were observed. The interpretation of this sample is that it belongs to the

Lower Triassic, Dienerian - Smithian *P. samoilovichii* Zone (Helby and others, 1987); a non-marine equivalent of the Kockatea Shale (Balme, 1963), which in the South Perth Basin would be equivalent to the upper part of the Sabina Sandstone.

One sample (Sample 1) from dredge 80DR/016 (Plate 21), higher up the southern side of the canyon wall than 80DR/015 contains a very sparse assemblage of colourless fossils. This assemblage is similar to that in Sample 2 from 80DR/015, and is assigned a Triassic age.

Four samples (Samples 1-4; Appendix 2 from dredge 80DR/020 gave fairly mixed results. The samples from this locality are of mixed ages and could be regarded as allochthonous. However, it could be that the dredge managed to sample all these particular horizons in outcrop. Sample 1 gave a small, but diverse yield, which indicates that it is a non-marine equivalent of the Lower Cretaceous *B. enabbaensis* Zone of Backhouse (1988). This would indicate that this sample is from the Carnac Member. However, the seismic profile that is coincident with this dredge station, line 80/23 (Plate 31), shows what is considered to be the Neocomian unconformity below the deepest part of the canyon. In the absence of any Gage Sandstone Member, it is possible that this sample belongs to the South Perth Shale. At this point, it is tentatively assigned to the Carnac Member.

Sample 2 gave a small yield, mainly of dinoflagellates; including *Hoegisporis uniforma, Ascodinium parvum, Fromea amphora, Diconodiniim multispinum, D. psilatum, Litosphaeridium siphonophorum* and *Microdinium ornatum*. Rare pollen include *P. pannosus*. This sample can be accorded a Middle Cretaceous (Albian/Vraconian-Cenomanian), Upper *P. ludbrookiae* - *D. multispinum* Zones (Helby and others, 1987) age, and is regarded as marine. On the basis of this age determination, Sample 2 can be considered as part of the Osborne Formation. Sample 3 gave a very small yield and its age cannot be determined.

Sample 4 contains a mixed assemblage of spores/pollen and dinoflagellates. The spore/pollen assemblage includes common *Callialasporites* spp., *Bisaccates, Trisaccites*, and *Corollina*. The dinoflagellate assemblage is not very diverse, but includes fairly common *Gardodinium lowii*. This sample should be referred to the Lower Cretaceous (Hauterivian) *G. lowii* Zone (Backhouse, 1987), which would indicate that it is part of the South Perth Shale.

Sample 1 from dredge 80DR/023 is virtually barren of fossils. There are some plant fragments, but the age cannot be determined. Similarly, Sample 4 from dredge 80DR/002 from the continental slope north of Perth is barren of fossils.

One of the unexpected results from the palynological examination of the dredge samples is the presence of a Permian (80DR/013) and Triassic (80DR/015) flora in several samples. From the general stratigraphy of the Vlaming Sub-basin, with predominantly Late Mesozoic rocks, it is conceivable that these are recycled forms. Other (Upper Mesozoic) samples in the dredge hauls contain well preserved, recycled Permian spores and pollen (the most readily identified forms), but always in quantities much less than 1 percent of the total yield. This is a common feature of much of the Australian Mesozoic; much of it evidently derived from widespread Permian deposits. However, the assemblages in question from the Fremantle Canyon appear to be true to the quoted ages. In each case, the assemblages are internally consistent, and would have to be 100 percent reworked into otherwise barren material. The Permian assemblages are of consistent composition and state of preservation and it must be strongly suggested that they are indeed of Permian age.

There are only two samples with assemblages of Triassic aspect, each from a separate locality, and the same argument cannot be so firmly applied. Even so, two separate localities bearing 100 percent Triassic, if they were reworked, would be a very remarkable happening and requires explanation. The indications from the watergun data that the Fremantle Canyon forms part of the boundary of the Vlaming Sub-basin substantiates these seemingly anomalous ages. West of line 80/14 the canyon cuts through strata that cannot be related to the Vlaming Sub-basin. Similarly, that part of the northern wall of the canyon crossed by lines 80/10 to 80/12 is bounded by tilted fault blocks, some of which appear to be basement. This suggests that, in the vicinity of the canyon, remnants of an earlier basin occur around the western flanks of the Vlaming Sub-basin. This is somewhat analogous to the boundary between the sub-basin and the Vasse Shelf and the Bunbury Trough.

ORGANIC GEOCHEMISTRY

Samples and Methods

Eleven samples from three dredge sites on the flanks of the submarine canyon were analysed by Rock Eval pyrolysis, and total organic carbon was determined using a Leco carbon analyser (Table 3). The rocks were dark grey to black mudstones in which the carbonised remains of plant material could often be discerned under the low power microscope (Appendix 2). The age range of the samples is variable. One sample (4921) from dredge 80DR/020 is considered to be equivalent to the late Early Cretaceous Osborne Formation. One sample (4920) from 80DR/020 and all four samples from 80DR/005 are considered to belong to the Carnac Member of the Parmelia Formation (Berriasian). All four samples from 80DR/013 are Late Permian. From the Rock Eval analyses, the Tmax value and production index (PI) were not considered reliable unless the pyrolysis yield (S2) value was greater than 0.2 kg/MT. PI values greater than 0.3 were considered to indicate staining due to migrated hydrocarbons.

Subsequently, with the intention of obtaining further information about the nature and maturity of the organic matter, three samples from the Carnac Member (4927, 4928 and 4920) and one from the Late Permian (4925) were selected for solvent extraction. The resulting saturated hydrocarbons were analysed by gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS).

Results and Discussion

Total organic carbon (TOC) contents were within the range 1.1-3.5 percent (Table 3). Although a value of 0.5% TOC has been used as the lower limit for sediments to be considered as potential source rocks, known source horizons usually have TOC contents greater than 1 percent. On this basis alone, the dredge samples have some potential for sourcing hydrocarbons.

Figure 4 is a cross-plot of hydrogen index (HI) versus Tmax. Considering the relatively low TOC values for these samples, HI is probably artificially depressed due to the mineral matrix effect. Generally the mineral matrix effect occurs in sediments with TOC values less than 3-4 percent. It is due, essentially, to retention of the pyrolysate on the clay mineral matrix; resulting in an artificially low S2, and hence HI value. The isolated kerogen would be expected to have a higher HI than the corresponding rock. However, a Type III character for the kerogen would still be expected for those samples showing HI < 100 mg hydrocarbons/g TOC. Four samples have moderately high HI values in the

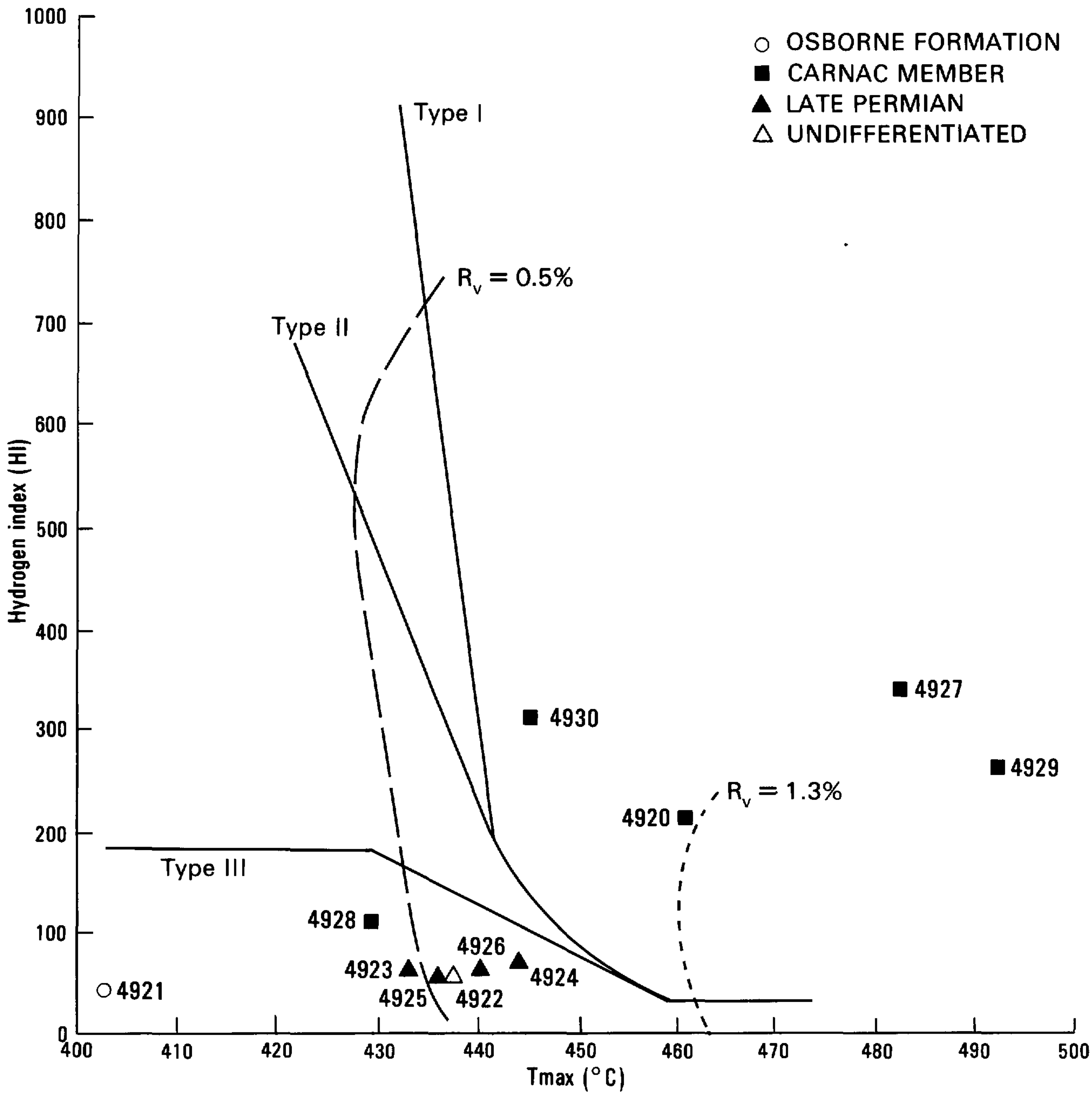

Figure 4. HI/Tmax plot of dredge samples from the Fremantle Canyon.

range 220-350 mg hydrocarbons/g TOC (Table 3), indicating some residual hydrocarbon potential even for the presumably overmature samples (Fig. 4).

One caution with respect to the above interpretation is the complex nature of the S2 peak derived from the Rock Eval analyses. The 'multiple peak' nature of S2 for most samples suggests an admixture of different kerogen types. The most obvious sources are due to weathering/oxidation of the original kerogen or the presence of residual asphaltenic-like material (under Rock Eval conditions, evolution of hydrocarbons from this high molecular weight material would occur over a similar temperature range as kerogen breakdown).

Table 3: Total organic carbon and Rock Eval data from dredge samples

Dredge No. Lab. No.		Depth (m)	TOC (%)	S1	S2	TMAX	PI	HI	GP
80DR/020		2420-3000							
4920	1		1.33	0.37	2.81	461	0.12	211	3.18
4921	2		1.16	0.24	0.47	402	0.34	41	0.71
4922	3		1.06	0.24	0.62	437	0.28	58	0.86
80DR/013		1940-2500							
4924	1		1.70	0.05	1.19	444	0.04	70	1.24
4923	2		2.27	0.11	1.42	434	0.07	63	1.53
4925	3		2.84	0.02	1.61	436	0.01	57	1.63
4926	5		2.32	0.05	1.45	440	0.03	63	1.50
80DR/005		730-1350							
4927	1		1.10	0.29	3.73	482	0.07	339	4.02
4928	2		3.52	0.47	3.98	429	0.11	113	4.45
4929	4		1.18	0.22	3.15	492	0.07	267	3.37
4930	6		1.13	0.41	3.55	445	0.10	314	3.96

The youngest sample (4921) from the late Early Cretaceous Osborne Formation is reasonably high in TOC content, but the Rock Eval data (Table 3; Fig. 4) shows that this sample is extremely immature. Rock Eval data from those samples from the Early Cretaceous Carnac Member indicate that they range from immature to overmature (Fig. 4). However the biomarker analyses (see below) suggests that they are all immature.

The Rock Eval data indicate that the Permian samples are immature to marginally mature, even though the TOC values are marginally higher than the other samples (Table 3; Fig. 4). The HI values are all less than 70, indicating that they have poor source characteristics. The data suggests that Late Permian sediments in the vicinity of the canyon have not been buried to any great extent (probably less than 2000 m). This, in turn, suggests that these sediments are from the margin of the Vlaming Sub-basin, whereas any Permian sediments within the sub-basin would have to be so deeply buried as to be overmature.

Gas chromatography shows that the saturated hydrocarbons for those selected samples are dominated by a homologous series of n-alkanes with a marked odd-to-even predominance, and with a high wax content (n-alkanes greater than C_{22}). The waxy hydrocarbons are most likely derived from land plant residues, consistent with the observation of carbonised plant fragments under the microscope. However, the high odd-to-even predominance is at odds with the high Tmax values in samples 4927 and 4930 (Table 3; Fig. 4). The possibility exists that weathering/biodegradation has occurred to a greater degree in the Carnac Member samples than the Late Permian example. This is indicated by a lower content of low molecular weight ($<C_{20}$) n-alkanes and isoprenoids. The Late Permian sample (4925) contains the isoprenoids, pristane (pr) and phytane (ph) in relatively high abundance, and the moderately high pr/ph value of 2.8 suggests an oxygen-rich water column.

Results from the GC-MS analyses show that the Late Permian sample contains relatively low amounts of C_{30} desmethylsteranes, possibly indicating a slight marine influence. By comparison, the Carnac Member samples contain no detectable C_{30} desmethylsteranes, suggesting a non-marine depositional environment. Furthermore, those biomarkers which are generally associated with marine or carbonate environments, e.g. bisnor-hopanes and 3-methylhopanes, are only minor components in these sediments.

Information regarding source type can sometimes be obtained from the relative abundance of C_{27}:C_{28}:C_{29} desmethylsteranes (Haung and Meinschein, 1979). Land plant input usually results in a dominance of C_{29} desmethylsteranes, whereas algae possess a wide range of desmethylsteranes (C_{26}-C_{29}). The C_{29}/C_{27} desmethylsterane is in the range 2.3-6.6, indicating a large plant input to all samples.

In the Late Permian example, C_{30} methylsteranes are in 10 percent relative abundance to C_{29} desmethylsterane. To date, only 2-, 3-, and 4-methylsteranes have been characterised in sediments and petroleum. The predominance of 4-methylsteranes closely parallels the evolution of dinoflagellates from the Triassic to the present time. Only 2- and 3-methylsteranes are found in the Late Permian sample, consistent with its inferred Late Palaeozoic age. For the Early Cretaceous samples, C_{30} methylsteranes are in much lower relative abundance, being only 1 percent that of the C_{29} desmethylsterane. As well as containing 2- and 3-methylsterane, other methylsteranes are present in similar abundance. These are possibly 4-methylsteranes. However, this needs to be confirmed by coinjection of authentic standards.

In contrast to the Rock Eval analyses, the four GC and GC-MS extracts are considered to be immature with respect to oil generation, in that all the common indicators (20S/20R desmethylsteranes and 22S/22R hopanes) are far from equilibrium. Furthermore, the Carnac Member extracts show some hopanes that still retain the biological configuration. Only hopanes with the geological configuration are present in the Late Permian sample, reflecting its slightly higher maturation.

Because of the lack of exploration wells in the western part of the Vlaming Sub-basin, most reports on the maturation trends in this part of the sub-basin have been speculative (e.g. Hall, 1989). The geochemical results from the dredge data help to fill in this gap. While the Rock Eval analyses indicate that samples range from immature to overmature, the biomarker results suggest that the Early Cretaceous and Late Permian rocks in the vicinity of the canyon are immature. This implies that sediments of this age on the western margin of the Vlaming Sub-basin have limited source rock potential.

STRUCTURAL ANALYSIS OF THE SOUTH PERTH BASIN

PREVIOUS INTERPRETATION

Previously, industry exploration requirements in the South Perth Basin have meant that only the eastern side of the offshore part of the basin has had sufficient seismic coverage for a detailed analysis of the basin's structure (Plate 1). The main structural trends that have been delineated from the existing industry seismic reflection data set show that the region is predominantly downfaulted to the west, with grabens and half grabens being developed as a consequence of this faulting. Onshore, the Darling Fault is seen as a key element in the basin's development (Playford and others, 1976). The trend of most of the major faults offshore is parallel to the Darling Fault (i.e. north-south), and most seismic surveys have been designed to cross these faults orthogonally. This has tended to make the interpretation of the strike lines difficult, especially if the faults actually plunge NNW, and if there is a large degree of strike-slip movement along the major faults.

A large number of arches have previously been interpreted from the seismic data (Fig. 3). However, from mapping on a basin-wide scale it is evident that the arches, which are predominant on the eastern side of the Vlaming Sub-basin, are often continuous features. Since the Neocomian unconformity and younger horizons are generally only one second TWT or less, this has allowed the recognition and definition of the basin forming faults relatively easily. However, the orientation of the seismic grids and the lack of seismic data in the western side of the sub-basin has meant that the overall interpretation of the basin-forming processes has been incomplete and somewhat ambiguous.

The seismic interpretation for the region has also been hampered by the generally poor quality of the seismic data. This is largely due to the widespread occurrence of surface limestones that cause ringing and diffraction, and hampers penetration of the seismic signal to great depths. This has made the resolution of the deeper horizons in these localities difficult and sometimes impossible. Most of the major stratigraphic units of the sub-basin have been mapped to some degree by previous permit holders. These horizons have frequently been tied to wells, and their areal distribution and isopachs, especially in the northern part of the sub-basin, are well defined. There is, however, a paucity of well data in the west and the south (Plate 1). This is not especially critical for horizons above the Neocomian unconformity, where little, if any, structuring exists. However, the interpretation of the deeper horizons has been difficult as a result of severe disruption by faulting, folding and erosion .

INTERPRETATION AND MAPPING

Reinterpretation of industry data and the interpretation of the new BMR seismic reflection data was undertaken in order to better define the structural style and occurrence of key seismic horizons. The seismic interpretation was based on a grid of open file company seismic reflection data and the regional lines recorded on the recent BMR surveys in the region. Due to the generally poor quality of the early data only post-1980 data was incorporated in the grid. Only in those areas where no post-1980 data existed was older data interpreted.

The major horizons that were interpreted and mapped include: top Leederville Formation, the Neocomian unconformity and the top Otorowiri Member. Other horizons, that were mapped to less extent and could not be defined basin-wide, include top South Perth Shale, an intra-Warnbro Group seismic marker, base Carnac Member. Three preliminary maps from this interpretative exercise have been reproduced. The first of these is a time structure contour map of the Neocomian unconformity (Plate 38), the second is a time structure contour map of the Otorowiri Member (Plate 39) and the third is a structural elements map for the region (Plate 40). Note that on the structure contour maps, the horizons have been extrapolated across the Fremantle Canyon, whereas,in reality, they are commonly truncated at this locality.

There is very little faulting that penetrates beyond the Neocomian unconformity. Where it does occur, it is minor in nature, and so it is not displayed on the structure contour map (Plate 38). On the other hand, faulting at the top Otorowiri Member level (Plate 39) is so severe and chaotic that a large degree of smoothing has been undertaken to produce the time structure contour map for this horizon. Not all the faults have been mapped, but all the major highs and lows are present.

The structural attitude of the Neocomian unconformity indicates that the general phase of basin-wide subsidence was replaced by rapid, local uplift and erosion, associated with the drift-onset phase of continental breakup. The uplift was caused by local compression along strike-slip faults, and it is not thought to be associated with any thermal event. The fact that the major uplift is associated with the sub-basin margins and not the centre of the sub-basin is further evidence of a local compressional regime and not a regional thermal uplift. Accompanying the uplift around the basin rim was erosion and planation. However,in the centre of the basin, the amount of relief on the unconformity surface indicates that the subsidence rate was greater. In the depressions formed on the unconformity surface there are indications of possible lacustrine, fluvio-deltaic and marine deposits. These depressions tend to be bounded by at least one fault scarp, and, from the evidence of erosion on these scarps, it is thought that faulting was contemporaneous with deposition and that these faults controlled the location of the depocentres. Following the formation of the Neocomian unconformity, there is some evidence of arch collapse in local regions, such as that which formed the Rottnest Trough. Above the Neocomian unconformity, there is evidence of marine transgression, with prograding sediments onlapping the erosion surface over a wide area.

A STRIKE-SLIP INTERPRETATION FOR THE SOUTH PERTH BASIN

It can be recognised from the regional seismic data that there is a large component of normal faulting and associated half-graben and graben development in the South Perth Basin. There are, however, some features in evidence in the structural configuration of the Vlaming Sub-basin that clearly indicate that there is a substantial strike-slip component to the basin-bounding faults and to faults within the sub-basin.

The strongest indication of a strike-slip movement along the major faults is the large number of arches in the pre-Neocomian section that are considered to have been produced by wrench faulting. If the basin underwent a regional compressional episode, faulting and folding would have occurred on a regional scale. Instead, the arches are local and highly variable in size and degree of complexity. Coupled with this is the coincidence of the arches at localities where there is a marked change in the trend of the major faults, and nearly always in areas where the faults converge to some degree. This suggests that at the final stage of rifting there were regions of local compression and uplift, centred on fault bends or junctions, such as would occur and be created in a strike-slip regime.

The presence of the Leeuwin and Edward Island Blocks forming the major western boundary of the Vlaming Sub-basin is an indication that movement on the major faults during the rifting phase was not purely dip-slip. If this were the case, it would be expected that these basement highs would be downfaulted beneath the western edge of the sub-basin. Instead, the sub-basin tends to be bounded by a single fault along its western margin, and this fault is near vertical. Sediments along the margin do not show any signs of onlap onto the basement high. Rather, the sediments are relatively unstructured and they abut directly against the high. This can be contrasted to the post-breakup sediments, which in the vicinity of the basement high form distinct alluvial fan deposits. The geometrical relationships and style of contact between the sub-basin and the basement high point to this major basin-bounding fault being strike-slip in nature.

Most of the major faults in the sub-basin plunge in a NNW direction and they shallow markedly to the south. Coupled with these major faults are several small, shallow detachment faults which dip in a NNW direction and numerous transfer faults which trend WSW.

The indication of basin-bounding strike-slip faults and large-scale wrench faults within the sub-basin suggests that the Vlaming Sub-basin is an example of a relatively large pull-apart basin. The actual sediment thickness in the Vlaming Sub-basin has not been resolved as yet, but various suggestions (e.g. Playford and others, 1976) indicate possibly as much as 15 km. Large thicknesses of sediment indicative of rapid deposition in a rapidly subsiding depocentre is a common attribute of pull-apart basins. Coupled with this is the fact that the sedimentary thickness of the basin increases to the NNW, indicating that the Vlaming Sub-basin is possibly a detached pull-apart basin. From the Bunbury Trough in the south, it appears that the major depocentre has migrated northward through time. As most of the basin forming faults trend northward also, there would have been a large degree of strike-slip movement on these faults as the basin opened. It is interesting to note that the Dunsborough Fault ceases to be the major fault defining the western limit of the Leeuwin Block in the locality of the Sugarloaf Arch, and at this point there is a large offset in the basement block (Plate 40). In proximity to this offset is a large depression in the Neocomian unconformity (Plate 38). The offset between the Dunsborough Fault and the new northerly-trending fault is considered to be the expression of a transfer fault at this point.

The Fremantle Canyon has long been an enigma in the structural analysis of the Vlaming Sub-basin. However structural analysis of the BMR watergun data shows that at the head of the canyon there is a small graben that trends WNW. Along the NNE-trending arm of the canyon there is an offset in the sub-basin boundary, possibly produced by a transfer fault that strikes in the same direction as the canyon. In the deeper NNW-trending part of the canyon there is another offset to the sub-basin boundary, again possibly being accommodated by a similar trending transfer fault (Plate 40).

STRUCTURE IN RELATION TO HYDROCARBON ACCUMULATION

There appears to be three main types of structural plays within the Vlaming Sub-basin. The most common structural plays are the arches that have been developed in the central and southern parts of the sub-basin (Plate 40). These arches are essentially positive flower structures that have been produced during wrenching of the basin. These structures tend to be large and, structurally, fairly complex. To date, the only well that appears to have been drilled on one of these structures is Sugarloaf 1 (Plate 39). The broader feature to the east of Sugarloaf 1 remains untested, as do some other arches in deeper water to the west. While these structures are generally large, they are heavily faulted, and possibly they lack closure within individual fault blocks. However, there is potential for trapping at the Neocomian unconformity or possibly deeper along the axis of the arch.

Another potential structural trap are closures associated with the upthrown blocks along faults. A typical example is the Roe High (Plate 40) where there is closure against the major western bounding fault of the Rottnest Trough. In some examples, there is rollover on the downthrown block as well. However, the closure on the Roe High is narrow and elongate, and wells sited on this feature, such as Roe 1, Gage Roads 1 and 2, and Warnbro 1 have relatively small closures. Bouvard 1 and

Challenger 1 have been drilled on similar structures, and the time structure contour map of the Otorowiri Member (Plate 39) show comparable structures to the southwest of these wells that remain undrilled to date.

An untested structural play in the Vlaming Sub-basin consists of a series of relatively large compressional features along the western margin of the sub-basin. These structures are considered to have developed as a result of strike-slip movement along the sub-basin bounding faults, particularly where there are bends or offsets in the major fault. In the northern part of the Vlaming Sub-basin, the western limb of the Bathurst Syncline forms a broad compressional structure along the margin of the sub-basin. This has been offset by a series of NNW-trending transfer faults to form several individual structures. A similar feature occurs where there is a large offset of the Dunsborough Fault, just to the north of 33°S. Unlike the broad structures to the north, this feature is cut by several N-S trending faults (Plate 39), and it is possibly more related to the arches described previously.

One of the major reservoirs in the Vlaming Sub-basin is the Gage Sandstone Member, particularly where it has been sealed by the South Perth Shale. This sandstone tends to occupy lows in the Neocomian unconformity. The time structure map of the unconformity (Plate 38) shows that the largest depressions, and potentially the thickest sequence of the Gage Sanstone Member, occurs along the western boundary of the sub-basin. This depression, or series of depressions are related to continued offset along the major bounding fault in this region, with draping and thickening of sediments over this feature. While the absence of Gage Sanstone Member in Challenger 1 could indicate an overall absence of this unit in the western part of the sub-basin, its distribution is known to be patchy, and it possibly does occupy several of these depressions. The relatively deep depression to the northwest of Sugarloaf 1 (Plate 38) occurs at the corner of the offset in the Dunsborough Fault (Plate 39). If the Gage Sandstone Member is present and is sealed by the South Perth Shale, then the coincidence of this depression with the underlying structure could present a potentially significant play in the sub-basin.

The structural analysis of the Vlaming Sub-basin indicates that several potential structural plays exist within the sub-basin. These play types have developed as a result of strike-slip extension, mainly from localised compressional events during the latter part of the sub-basin's formation. Many potential structures exist along the relatively untested western margin of the sub-basin. The limited amount of industry and BMR data in this region requires to be significantly augmented by additional closely-spaced seismic lines to better realise the potential of this part of the Vlaming Sub-basin.

SEDIMENTARY ENVIRONMENTS

YARRAGADEE FORMATION

The Yarragadee Formation comprises a major alluvial fan-delta system, the total thickness of which is not known in the offshore South Perth Basin. Over 90 percent of the formation consists of sandstones, which were deposited as alluvial-fan and braided-channel units. Wireline-log data from offshore wells show channel sandstone units 10 to 40 m thick with less common, swamp, marsh and overbank sequences, 2 to 3 m thick, separating each channel unit. At the top of the formation, where it is overlain by the Otorwiri Member of the Parmelia Formation, a sand-rich deltaic sequence is evident.

Backhouse (1988) considers that the Yarragadee Formation is a fluvial sequence, comprising sandstone units with minor shale beds and some carbonaceous stringers. The sandstone is medium- to coarse-grained, poorly-sorted and kaolinitic, and the sequence exhibits little regional lithologic variation. The appearance of reworked Permian palynomorphs in the formation indicates that a major part of the sequence was derived from recycling of older sequences which probably extended over the Yilgarn Block during the Late Jurassic (Backhouse, 1988; p.37). Thin, discontinuous beds of coal and shale present in the Yarragadee Formation in Warnbro 1 and Sugarloaf 1 are considered to have been deposited in lacustrine and abandoned-channel systems (Kantsler and Cook, 1979).

PARMELIA FORMATION

The presence of two shale-dominated units, each overlain by fine- to coarse-grained sandstone units, which form the bulk of this formation, indicates repetition of a major cycle. The deposition of lacustrine sediments over a large area, in the form of the Otorowiri Member, was marked by the first occurrence of a distinctive suite of non-marine dinoflagellates and acritarchs (Backhouse, 1988; p.18).

A cycle of deltaic sediment influx is evident in the central part of the Otorowiri Member in Quinns Rock 1, but, in general, the member comprises lacustrine micaceous siltstone, shale and claystone, which is up to 99 m thick. A regressive cycle in the upper part of the Otorowiri Member is in the form of a sandy delta which led to infilling of the Otorowiri lake system. The sandy delta was fed by fluvial channels, evident in that part of the lower Parmelia Formation which directly overlies the Otorowiri Member. The fluvial channel system deposited fine- to coarse-grained sandstone units interspersed with thin shale beds. In the sequence penetrated by Gage Roads 2, the fluvial channel complex (Fig. 5) passes into a sandy delta which has at least four coarsening-upwards cycles. These cycles consist of delta-plain and delta-front sediments.

The Carnac Member comprises further lacustrine siltstone, shale and claystone as well as deltaic sandstone, siltstone and shale. The delta-front cycles are evident in the upper part of the Carnac Member in Gage Roads 2 (Fig. 5). Thick deposits of Carnac deltaic and lacustrine sediments are typified in the sequence penetrated by Peel 1 (Plate 12). In areas where delta-front and delta-plain sediments did not extend, such as Minder Reef 1 (Plate 15) and Roe 1 (Plate 5), the sequence is largely shale and siltstone, deposited as lacustrine or pro-delta sediments (Fig. 5).

The upper part of the Parmelia Formation is marked by a return to fluvio-deltaic conditions; sand-rich parts of this unit comprise fluvial and delta-plain sequences, whereas the delta-front sequence, such as that evident in Minder Reef 1, comprises shale, siltstone and fine sandstone. Thin discontinuous beds of coal and shale present throughout various parts of the Parmelia Formation were deposited either in marsh, abandoned-channel or deltaic settings.

GAGE SANDSTONE MEMBER

The Gage Sandstone Member is a restricted alluvial-fan to fan-delta sequence which was deposited on the flanks and axis of the Rottnest Trough. In the central axis of the trough, the unit comprises coalescing fan-deltas which have formed down-slope of the adjacent eroding fault scarps and uplifted blocks of Parmelia Formation. Between 65 and 100 percent of the sequence comprises channel sandstone units from 5 to 30 m

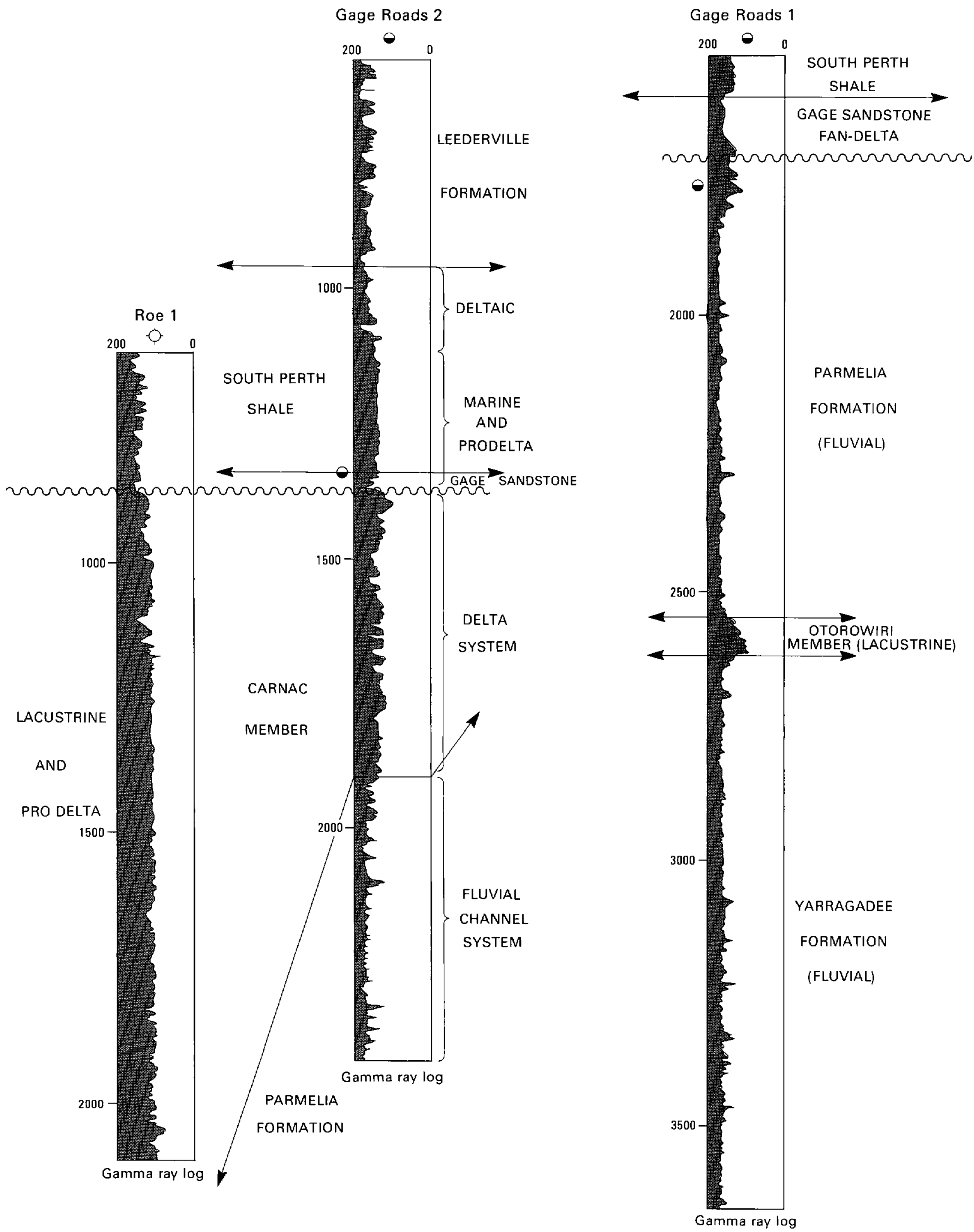

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Figure 5. Log characteristics and environmental interpretation of units intersected in wells from the north Vlaming Sub-basin.

thick (Fig. 5).

Seismic data in the central part of the Rottnest Trough indicate that reflections in the Gage Sandstone Member are concordant with the underlying Neocomian unconformity and overlying sequences of the South Perth Shale. Close to fault-scarps and the limbs of the trough, the sequence downlaps onto the unconformity surface. Internally, within the Gage Sandstone Member, reflectors are generally parallel, although some mounding is apparent where localised fan systems have built up.

Fan-deltas are interpreted from the downlap and onlap of Gage Sandstone Member reflectors onto the Neocomian unconformity surface. Backhouse (1988; p.6) identifies part of the Gage Sandstone Member cored in Warnbro 1 (Plate 6) as comprising turbidite beds in cycles 2 m thick. He considers that the entire Gage Sequence in the offshore Perth Basin was deposited in marine or restricted marine waters. In contrast, he considers that the Gage Sandstone Member in the onshore southern Dandaragan Trough is fluviatile. In view of the above interpretation, the suggested presence of turbidite beds is confusing. It could be that they represent fining upward sequences. While it may be difficult to establish from cores and cuttings whether or not the unit in the Vlaming Sub-basin is a fan-delta system or a submarine fan, from the seismic and well data available we prefer the interpretation of an alluvial fan-delta system for the majority of the Gage Sandstone Member.

SOUTH PERTH SHALE

This sequence tends to be thicker and relatively shale-dominated in the centre of the Rottnest Trough, whereas it is absent from crestal areas, such as the Roe High (Roe 1). Sandstone comprises from 1 to 30 percent of the sequence, and sand units are up to 25 m thick, although in most wells they tend to be less than 7 m thick. Although largely marine, shale-rich sequences towards the top of the South Perth Shale are considered to reflect possible pro-delta conditions.

The South Perth Shale attains a total thickness of between 200 and 700 m in the axis and flanks of the Rottnest Trough. Where the Gage Sandstone Member is absent, there tends to be considerable relief exhibited on the unconformity surface on which the South Perth Shale is deposited, suggesting more prolonged or relatively intense erosion in these areas.

Localised submarine lobes and fan systems have been developed in parts of the South Perth Shale sequence where the depositional gradient has allowed. Shallow dips characterise the upper part of the sequence, whereas in the lower part of the sequence reflectors have downlapped over the Gage Sandstone Member and, where that is absent, older sediments of the Parmelia Foundation.

A shallow-water, inner shelf marine environment is postulated for the South Perth Shale by Backhouse (1988; p.6). Marine bivalves, ostracods and rare benthonic forams, as well as spores, are present in the sequence. Localised bar sandstone units are evident on wireline-log patterns in most wells; prominent examples include the sequences in Mullaloo 1, Minder Reef 1 and Quinns Rock 1.

LEEDERVILLE FORMATION

This sequence which overlies the South Perth Shale, is marked by a predominance of sandstones deposited under shallow-marine shelf conditions. Seismic reflections within the sequence are generally parallel or shingled, although the upper boundary of the sequence has indications of erosional truncation. Sandstones at the base of the sequence in Gage Roads 1 are identified by Backhouse (1988) as successive marine transgressive and regressive phases, although this could be interpreted as alternating fining upward sequences on a slowly subsiding shelf. Much of the upper part of the Leederville Formation may be fluvio-deltaic, but some minor marine intervals are present (Backhouse, 1988).

COOLYENA GROUP

The Osborne Formation comprises a marine sequence of glauconite, claystone and sandstone which transgressed over the eroded surface on the upper part of the Leederville Formation (Backhouse, 1988).

TERTIARY

The Tertiary sequence is commonly subdivided into glaucontic shale, sandstone and limestone (Kings Park Formation - deposited in a restricted marine embayment), overlain by bryozoal calcarenite, dolomite and chert of the Stark Bay Formation (inner continental shelf sequence).

QUATERNARY

Quaternary sediments comprise calcified marine-shelf sequences with some beach and dune sediments deposited in nearshore and coastal areas.

HYDROCARBON POTENTIAL

RESERVOIR POTENTIAL

Yarragadee Formation

The oldest sequence intersected by petroleum exploration wells in the Vlaming Sub-basin is the Late Jurassic Yarragadee Formation, which has been intersected during drilling at depths of approximately 1600 m to 3550 m subsea. The complete sequence has not been penetrated in any of the offshore wells, but over 2700 m of the sequence is evident onshore in Cockburn 1 (Backhouse, 1988).

Sandstone comprises approximately 80 to 90 percent of the vertical thickness of the sequence and wireline-log data indicates that it was deposited as massive channel units 10-40 m thick. Composition of the sandstone ranges from arkose to sub-arkose, and although the major mineral present is quartz (over 60%), and the other grain type is feldspar (10%), kaolinite (10-20%) takes up some of the intergranular pore space (Arditto, 1982).

Core data shows that porosity of the sandstone units of the Yarragadee Formation decreases from 25 to 30 percent at depths of approximately 1700 m to 10 to 15 percent at depths in excess of 3000 m. Over the same depth range, permeability readings are, at best, up to 900 millidarcies, but are generally less than 200 m.d. below 2000 m.

Petrographic data indicates that the Yarragadee sandstone units are derived from a largely granitic source. Authigenic clays have formed from feldspar components, and although the clay matrix has considerable microporosity, its presence increases the irreducible water saturation of sands, and, as a result, permeability is reduced. The sequence should, however, be more than adequate as a reservoir for gas over much of the Vlaming Sub-basin; less so for oil because of the diminution of permeability with depth (Arditto, 1982).

Parmelia Formation

The Parmelia Formation, as shown in Figure 5, comprises deltaic sandstones and shales as well as fluvial to lacustrine sediments. Lacustrine, and to some extent deltaic conditions, are evident in the Otorowiri and Carnac Members. These units are separated by a middle sequence of fluvial channel to lacustrine sandstone and shale. The uppermost unit of the formation, sometimes referred to informally as the Charlotte Sandstone, is also fluvial to deltaic. In total, the Parmelia Formation ranges in thickness from about 750 to 2750 m. Sandstone comprises from 20 to 80 percent of the sequence, and individual sandstone units are from 7 to 30 m thick.

The formation has been intersected in offshore wells at depths ranging from 900 to 3000 m. Core analysis of samples from depths of 2000 to 3000 m show that porosities of 16 to 28 percent and permeabilities of 100 to 2000 millidarcies are present in the fluvial channel units. In fluvial sandstone units of the formation, porosity readings range from 23 to 28 percent and permeability is of the order of one to two darcies. Lower readings can be expected in deltaic sandstones which, in general, are less well sorted. According to Arditto (1982), the more mature sandstone units in the formation are subarkosic in composition but range from lithic arkose to feldspathic litharenites. The main sandstone grain type is quartz (60%) and feldspar (15%), while the matrix is largely kaolinite (15%).

Gage Sandstone Member

Where it has been intersected, the Gage Sandstone Member ranges from 31 to 214 m in thickness, 70 to 95 percent of which is sandstone. It is present throughout the Rottnest Trough, but pinches out onto the eastern and western highs surrounding the trough. The average thickness of sandstone units in the sequence varies from 6 to 31 m.

Porosity readings of 23 to 30 percent are evident from core samples of the sequence, while permeability ranges from 200 to 1800 millidarcies. The sequence has been intersected at depths of between 1400 and 2000 m and the sediments are arkosic in composition. The main grain types are quartz (45%), feldspar (20%), with kaolinite (15%) and calcite (20%) as matrix and cement respectively (Arditto, 1982).

South Perth Shale

The limited amount of sandstone in this unit is a major constraint with respect to its potential as a reservoir; it is more likely to be either a source for hydrocarbons, where the sequence has attained sufficient maturity, or a seal to the Gage Sandstone Member or other underlying units of the Parmelia Formation.

Leederville Formation

Between 350 and 500 m of this sequence has been intersected by petroleum exploration wells in the Vlaming Sub-basin, and it comprises from 25 to 90 percent sandstone; individual sandstone units are 6 to 18 m thick. The sandstones generally have excellent porosity and permeability and are unlikely to have been buried at depths greater than 2000 m.

SOURCE POTENTIAL

Yarragadee Formation

Potential source rocks in the Yarragadee Formation consist of thin shaley sequences, inter-bedded between the major channel sandstone units. Geochemical analysis (Appendix 6) indicates that the shaley units commonly contain in excess of 1.5 percent total organic carbon (TOC) and, in some wells, such as Sugarloaf 1 and Warnbro 1, TOC values in excess of 2.5 percent are not uncommon (Appendix 6; Plates 6, 9). The presence of such concentrations of organic matter in this dominantly fluviatile sequence is likely to provide a source for both oil and gas, although Burns (1982) considers that much of the Vlaming Sub-basin sequence is likely to be gas prone. A lack of thick shale units in the Yarragadee Formation downgrades the possibility of any seal for hydrocarbons within the sequence, but top seal of the formation is possible from the overlying Otorowiri Member of the Parmelia Formation.

Parmelia Formation

Geochemical results from the Parmelia Formation (Appendix 6) show that, overall, the fluvial sandstones contain less organic source material than the deltaic and lacustrine shale units. Total organic carbon (TOC) content ranges from less than 1 percent in the fluvial sandstones to over 2 to 3 percent in shale-rich parts of the sequence. Pyrolysis data (Appendix 6) suggest that there is potential for mixed oil and gas source material in the formation. The greater vertical thickness of fine-grained sediments in the Parmelia Formation, compared to the underlying Yarragadee Formation, makes it more likely to be a potential source where it is mature enough to generate hydrocarbons. Adequate sealing potential is evident in the shale-rich units of the formation.

The Otorowiri Member seals a gas-bearing interval in Gage Roads 1, but the sandstone from the underlying Yarragadee Formation is poor in terms of reservoir quality.

Gage Sandstone Member

Analytical results from two wells show that between 1 and 3 percent TOC is present in shale units within the Gage Sandstone Member (Appendix 6). Although this may be adequate, the sequence is considered more likely to represent a potential reservoir target around the flanks of major highs and along the axis of the Rottnest Trough. Limited thickness, areal extent and the sand-rich nature of the Gage Sandstone Member make it more likely to be a reservoir target for hydrocarbons generated from older underlying sequences rather than a major source rock unit itself. Lack of major shale units and proximity to the overlying South Perth Shale indicate that top seal by younger or lateral seal by shale-rich sequences is the most likely mechanism for sealing of the Gage Sandstone Member.

South Perth Shale

Total organic carbon (TOC) in the South Perth Shale commonly ranges from 1 to 2.9 percent, but values as high as 70 percent are evident (Appendix 6). At best, a mixed oil and gas product is expected from this sequence where it is oil mature.

Leederville Formation

The amount of organic material evident in the formation appears, from current data, to be generally less than 1 percent, although shale units do tend to have relatively high TOC (Appendix 6). It is likely to be a reservoir with some potential for internal seal rather than a major potential source sequence.

Coolyena Group/Tertiary Sequences

Limited source potential is apparent in these sequences due to their relative immaturity. Migrated hydrocarbons generated from deeper parts of the sequence could, however, be trapped in this part of the geological succession.

MATURATION TRENDS

The amount of vitrinite reflectance data for the South Perth Basin is relatively limited, and because most of the existing wells intersect the crestal parts of structural highs, maturation trends evident in Figures 6 and 7 may not be representative of the more deeply buried parts of the basin. In addition, some of the data show that differing values, due to contamination or recycling of vitrinite from other parts of the sequence, can detract from maturation trends. Another possible reason for the spread of readings is the presence of differing maceral types (Thomas, 1984; p.396).

Allowing for such problems, the pattern evident from wells in the Vlaming Sub-basin is shown in Figure 8. If the level of 0.65 percent to 0.8 percent R_o max is taken as the stage of oil generation, it is evident in Figures 8 and 9 that only some wells intersect oil-mature sequences.

Wells such as Sugarloaf 1, Warnbro 1 and Gage Roads 1 show that the onset of early oil generation is likely to be at depths from 1500 m (Sugarloaf 1; Fig. 8) to 3000 m (Gage Roads 1; Fig. 8). Reflectance values for samples in the Yarragadee Formation are depressed by the

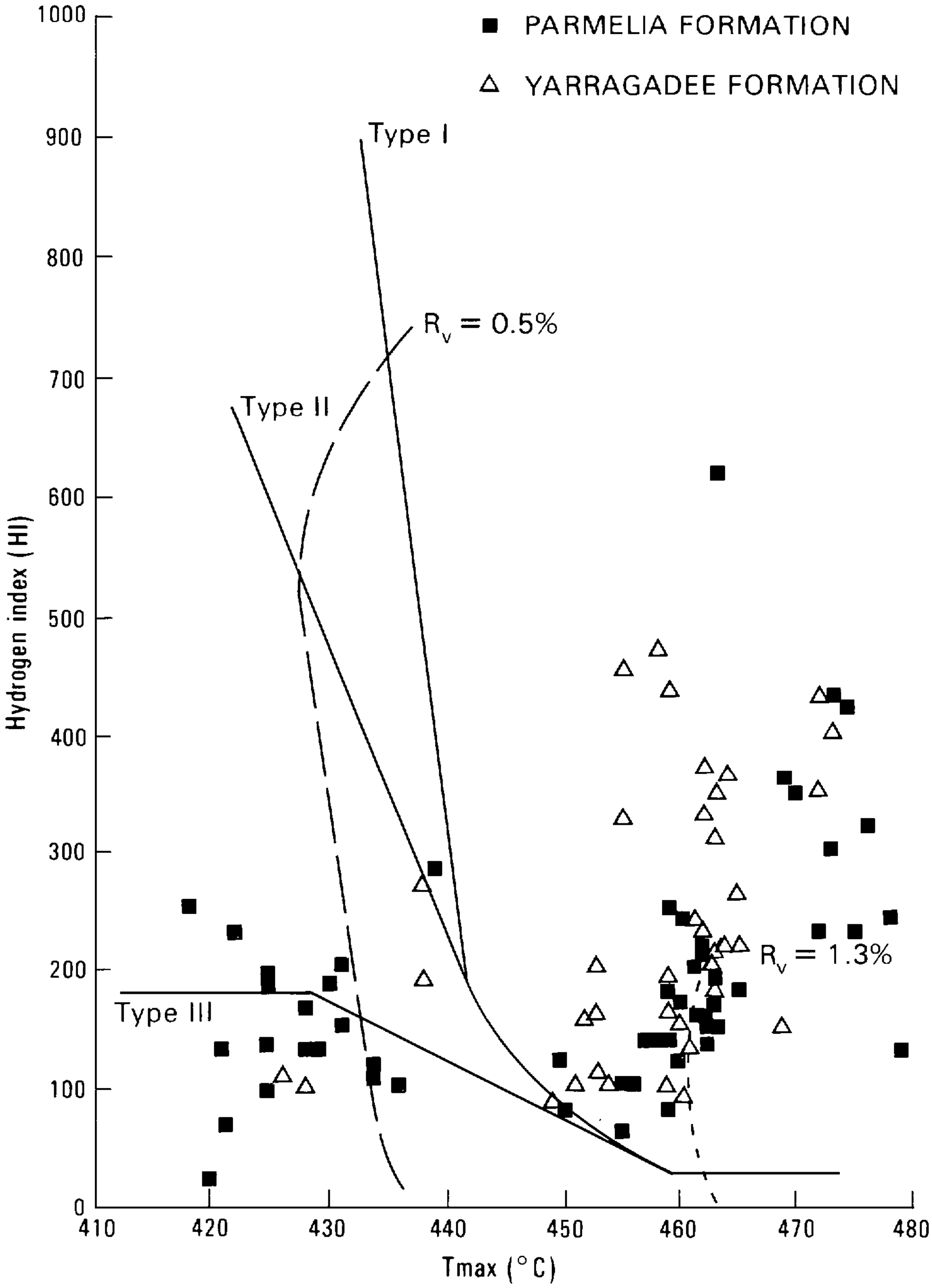

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Figure 6. HI/Tmax plot of well samples from the Yarragadee and Parmelia Formations.

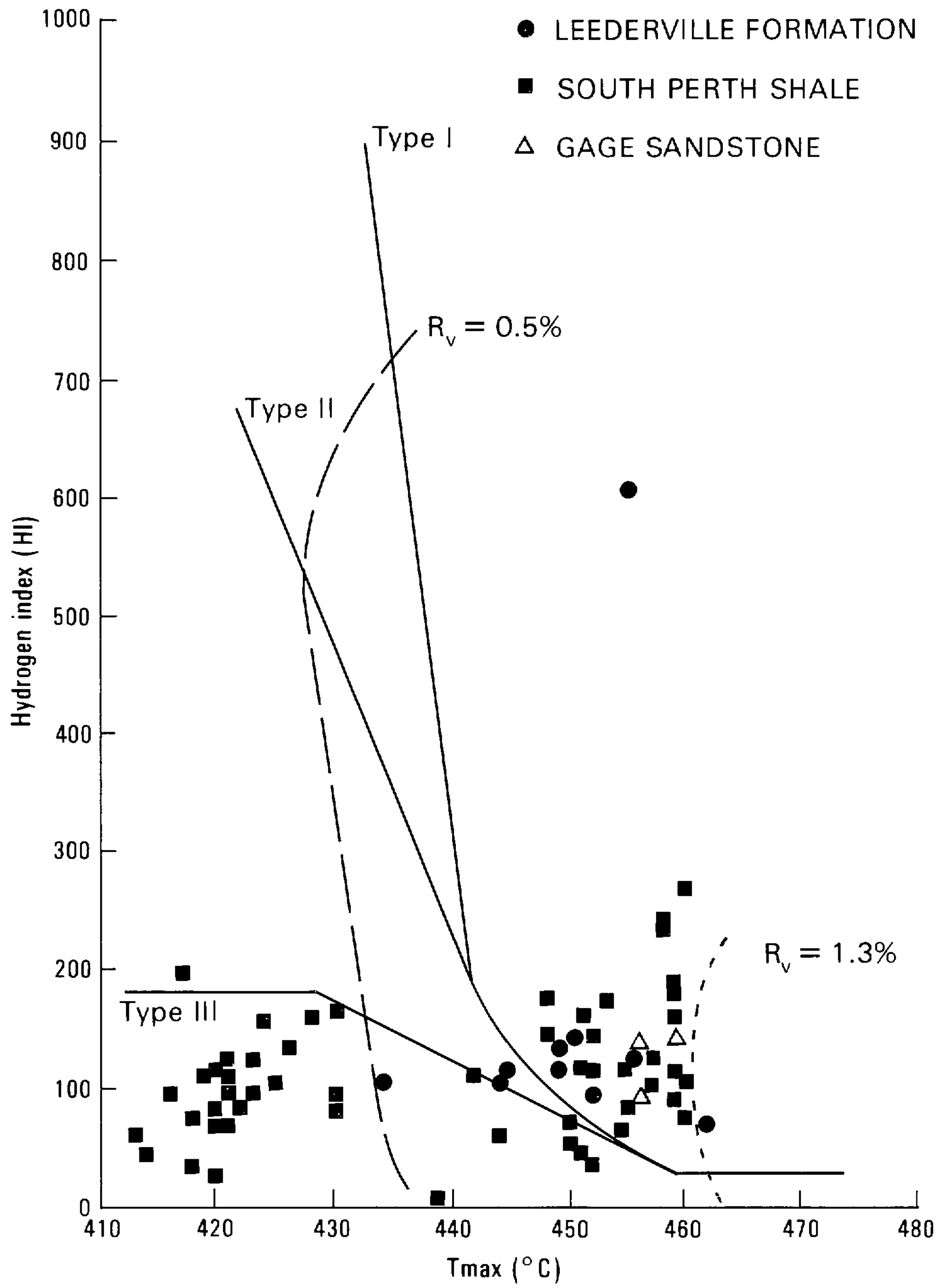

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Figure 7. HI/Tmax plot of well samples from the Warnbro Group.

presence of cell wall material and bitumens (Kantsler and Cook, 1979; p.98).

In terms of the basin-wide pattern of maturation, Kantsler and Cook (1979) suggest that data from the four wells they sampled in the Vlaming Sub-basin show an average reflectance gradient of 0.14 percent R_o/km. Few of their well plots show evidence of a change of reflectance gradient with depth; Gage Roads 1 being one exception. Their overall assessment was that the Vlaming Sub-basin showed low rank gradients in the Cretaceous section (0.11% R_o/km) and higher rank gradients (up to 0.34% R_o/km) in the Jurassic section.

Rock Eval results compiled by Surdan (1982) suggest that parts of the Parmelia and Yarragadee Formations contain organic matter which is mature and may be gas-prone sources (Appendix 6). Other samples from the same sequences contain mature organic matter likely to generate both oil and gaseous hydrocarbons (Figure 6).

Over much of the Vlaming Sub-basin the Upper Jurassic sequence that was tested by Kantsler and Cook (1979; p.105) has been, or is in, the zone of oil generation. Early Jurassic sediments, not intersected by existing wells, are almost certain to be mature, if not overmature, for oil generation. They consider that the rank gradients of 0.20 percent to 0.34 percent R_o/km evident in the Jurassic sequence indicate that oil generation may have begun during the Early Cretaceous. Their assessment of the high wax paraffinic oil recovered from Gage Roads 1 is that it is consistent with a source from the Yarragadee and Parmelia Formations. The coaly horizons in these sequences contain up to 30 percent exinite and 50 percent subertinite which Kantsler and Cook (1979) suggest must be considered as a potentially good source rock.

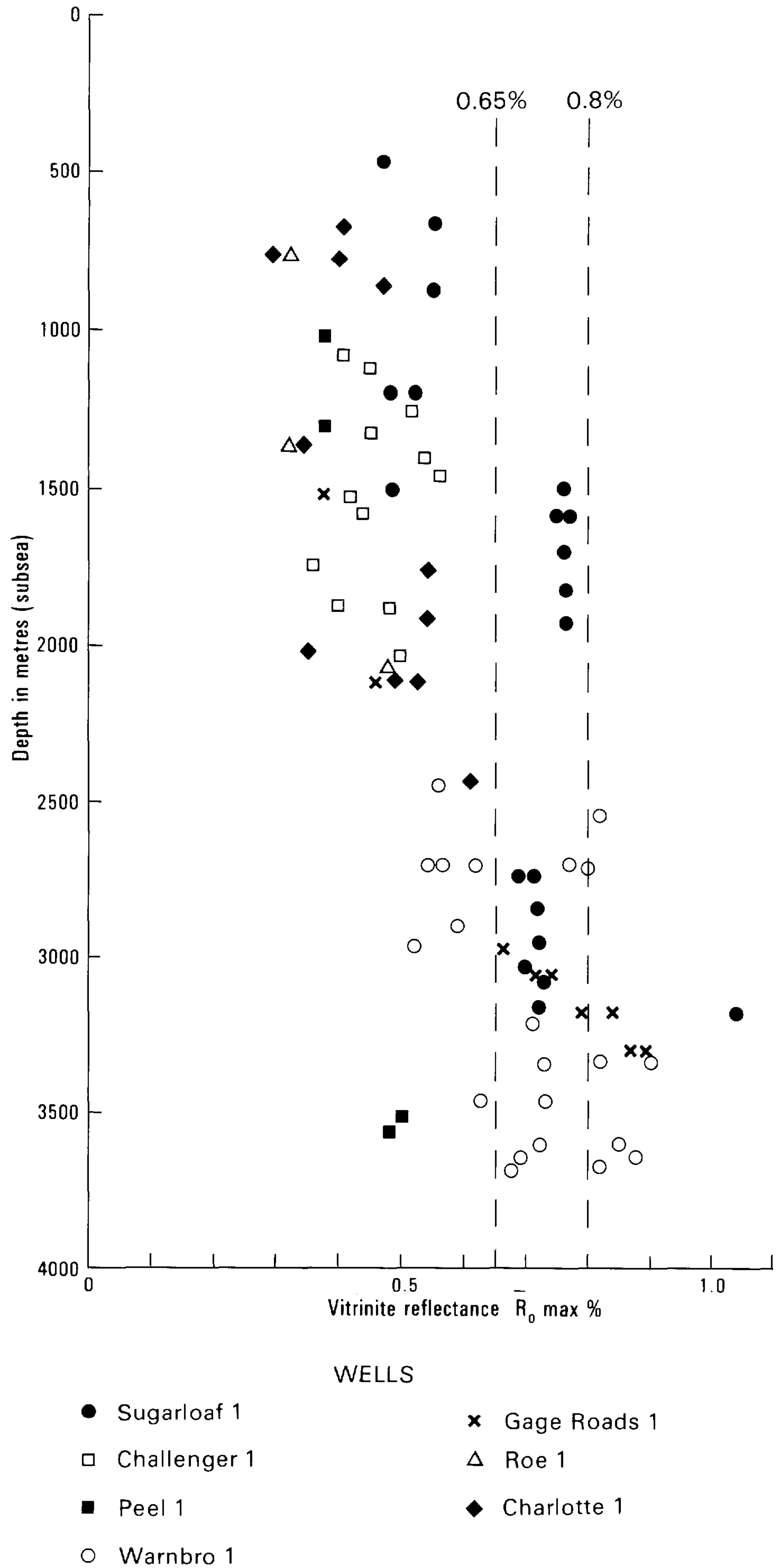

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Figure 8. Vitrinite reflectance vs depth plot for the Vlaming Sub-basin wells.

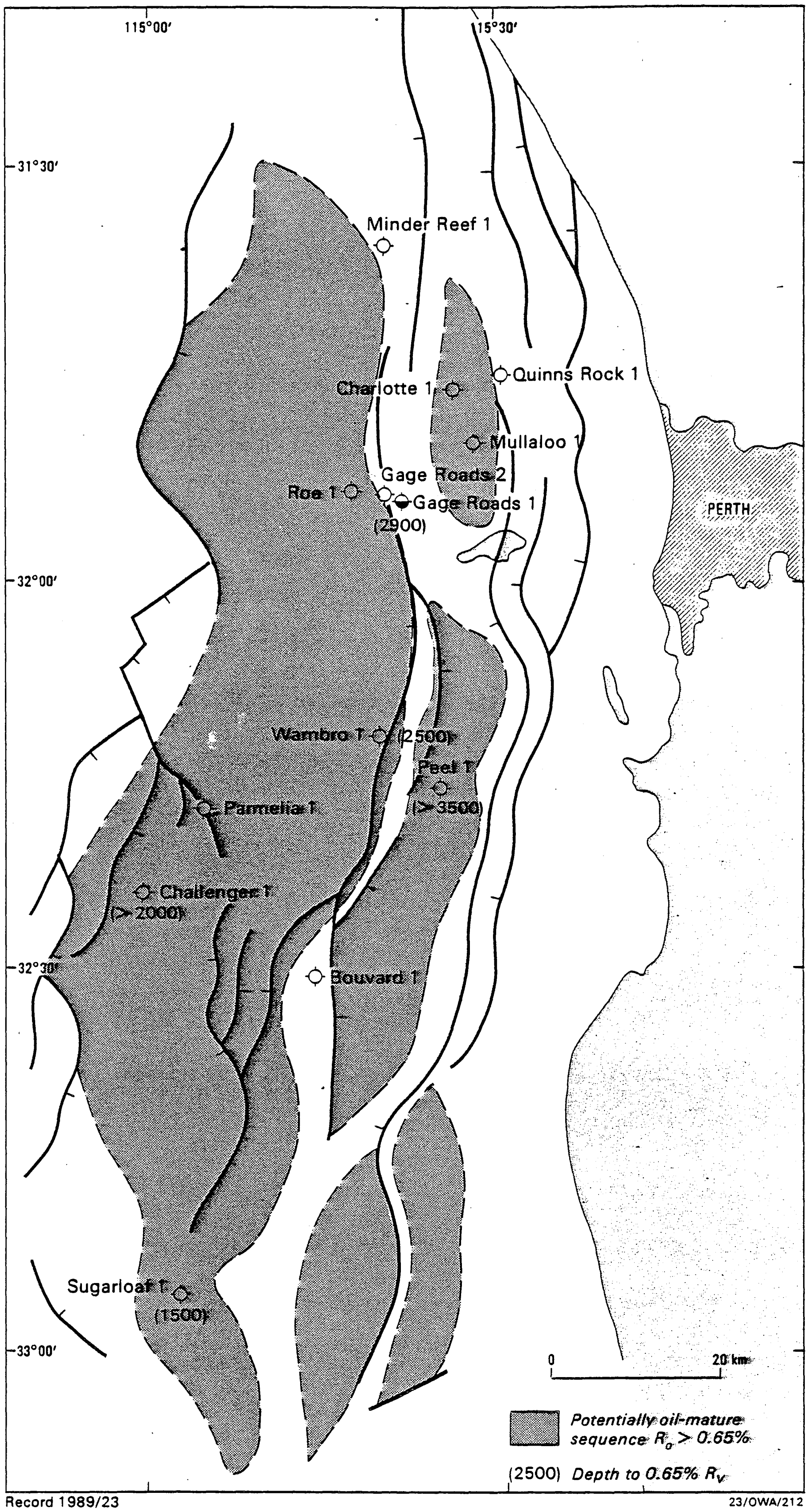

Figure 9. Distribution of potentially oil-mature sequences in the Vlaming Sub-basin.

The Otorowiri Member of the Parmelia Formation is oil mature over more deeply buried parts of the Vlaming Sub-basin, as is the underlying upper part of the Yarragadee Formation. The upper part of the Parmelia Formation should be mature in the deepest parts of the basin (Hall, 1989; p.445). The Gage Sandstone Member and South Perth Shale are likely to be mature in the deepest part of the Rottnest Trough and the Bathurst Syncline. Younger parts of the sequence may be marginally mature in some parts of the Vlaming Sub-basin.

Rock Eval results compiled by Surdan (1982) suggest that part of the Leederville Formation and Warnbro Group contain organic matter which appears to be immature, gas-prone source material (Appendix 6). Other samples from the same units consist of mature organic matter likely to generate both oil and gaseous hydrocarbons (Figure 7).

GEOHISTORY ANALYSIS

Geohistory analyses for all the offshore oil exploration wells in the South Perth Basin (Plates 41-53) were undertaken using the method described by Falvey and Deighton (1982). This method models subsidence and thermal maturation from data extracted from exploration wells. The reliability of the modelling is largely dependent on the quantity and quality of the input data, which is largely derived from well completion reports. In the South Perth Basin the thirteen wells that have been drilled, with the exception of Mullaloo 1 and Minder Reef 1, are relatively old wells (Appendix 1), and so there is a general paucity of data, notably vitrinite reflectance data, by which the thermal geohistory models can be constrained. Further, the lack of adequate porosity and thermal conductivity data has required that the analyses depend on models for these parameters. As thermal conductivity is a major parameter, the model results can only be interpreted loosely. However, the results do have some implications for the oil prospectivity of the region and provide a good basis for an analysis on the relative prospectivity within the basin.

The heat flow values derived from the well analyses are the only reliable means from which to determine the thermal state of the region; the use of thermal gradient maps like those derived by Kantsler and Cook (1979) and Thomas (1984) is fraught with problems because of the dependence of temperature, and hence temperature gradient, on thermal conductivity. The heat flow map for the South Perth Basin (Figure 10) shows an average value for the region of 63 mW/m^2; on a world-wide scale this heat flow value is moderately high. From the heat flow map it can be seen that there is little variation in heat flow on a basin wide scale. The only notable exceptions are Bouvard 1 with a lower heat flow of 46 mW/m^2 and the contrast between the proximal wells of Gage Roads 1, with heat flow of 55 mW/m^2, and Gage Roads 2 with a heat flow of 71 mW/m^2. However, the overall error on the absolute values is such that these differences can be ignored. The relative error is also small and has little influence on the overall maturation levels.

Palaeoheat flow was derived from the tectonic subsidence curves for the geohistory analyses. The shape of the curves was matched with a least squares fit to the subsidence model of Sleep (1971). It must be pointed out that Sleep's model is for the classic rifted margin, and it may not be directly applicable to the Vlaming Sub-basin because of its presumed dominant strike-slip component. However, the tectonic subsidence curves do show a strong thermal decay component which would indicate that Sleep's (1971) model is the most appropriate available for the sub-basin. Pitman and Andrews (1985) developed a thermal and subsidence model for small pull apart basins that would seem to be more

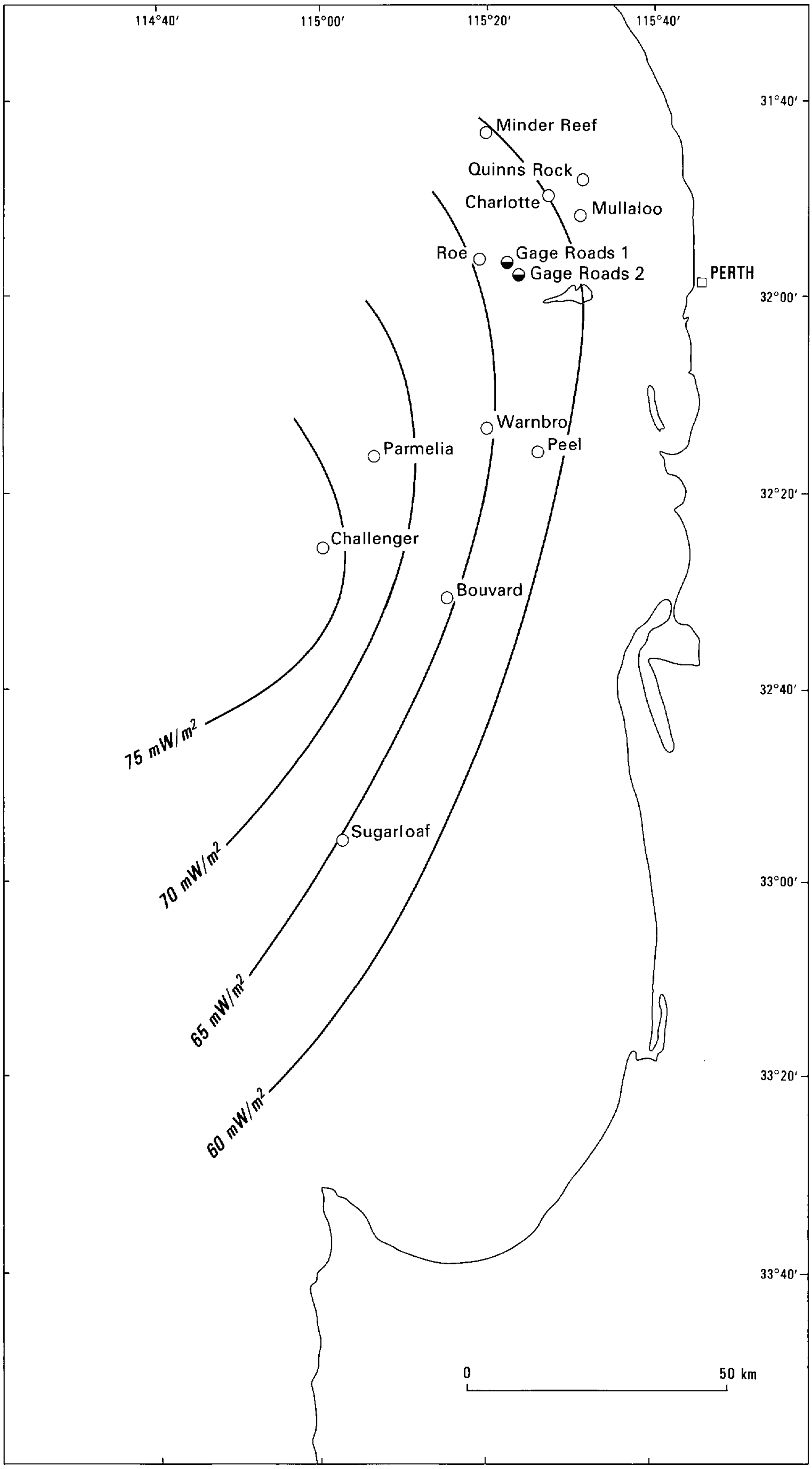

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Figure 10. Heat flow map of the offshore South Perth Basin.

applicable to our model of the Vlaming Sub-basin's evolution. However, the lack of reliable data for the initial rapid subsidence phase in the sub-basin's history and the considerable difference in scale, preclude this model from being used for the Vlaming Sub-basin.

Heat flow levels at the time of basin initiation are thought to be generally 80-90 mW/m^2 higher than they are today. However, this anomaly had essentially disappeared by the time of major tectonism in the basin in the Early Cretaceous. The palaeo-heatflow modelled in this manner is generally higher than that calculated by Falvey and Deighton (1982). Heatflow levels have been relatively constant since the Early Cretaceous to the present day. This relatively constant heat flow, with little variation in lateral heat flow, means that the modelled vitrinite reflectance with depth relationships are remarkably similar, basin-wide, especially with respect to the zone of peak oil generation and above. The calculated oil window is relatively shallow and uniform across the basin. It suggests that the onset of oil generation (R_V=0.5 to 0.7) is at depths of 2600 to 3000 m; peak oil generation (R_V=0.7 to 1.1) is between 2600 and 4500 m; peak wet gas generation (R_V=1.1 to 1.3) is between 4500 and 5400 m; and the base of the oil window at the end of dry gas generation (R_V=2.0) is at a depth of 6500 m.

One aspect of geohistory analysis is that assumptions are required to be made in order to carry out the modelling. A critical factor, in this regard, is the depth to basement. The depth to basement defines the lower boundary, which is important in determining subsidence rate, total subsidence, palaeo-heatflow and, therefore, maturation levels. The lack of wide aperture common depth point seismic reflection lines and high quality deeply penetrating seismic refraction data means that the depth to basement for the offshore region, and any lateral variation in basement depth, is difficult to quantify. The BMR lines show shallow basement to the west, helping to define the western limit of the Vlaming Sub-basin. However, as all of the wells are in the deeper, central parts of the sub-basin, and these wells do not penetrate basement, it has been assumed that the basement depth is 6000 m. This figure, while at odds with estimates of actual sediment thickness in the Vlaming Sub-basin (e.g. Jones, 1976; Hall, 1989), is, from a modelling viewpoint, adequate for the geohistory analyses. For instance, the calculated and measured vitrinite reflectance values roughly correspond if this assumed depth is used. Similarly, the total subsidence curve for basement at a depth of 6000 m at an age of 286 Ma B.P. (Early Permian) describes an arcuate curve that is near that described by Sleep (1971). The effect of increasing the basement depth, to say 10 000 or 15 000 m is to increase the value of the calculated vitrinite reflectance at any depth to unreasonable levels.

The most notable result from the tectonic subsidence curves is the sharp and relatively short lived structural anomalies contained within it. The geohistory plots indicate that the sub-basin was subsiding rapidly in the Late Jurassic. Subsidence had presumably started earlier, but as no wells have penetrated the Yarragadee Formation fully, it is difficult to quantify beyond this time. The structural anomalies in the subsidence curves manifest themselves as either periods of rapid subsidence, presumably structurally controlled, or periods of uplift during the onset of breakup and drift. The unconformities have been modelled as being produced by erosion as a result of uplift of only 100 m. There is a problem in deriving the amount of uplift and erosion; the figure of 100 m is a moderate amount and is used mainly to flag the periods of erosion.

The marked similarity between the geohistories of all the wells in the Vlaming Sub-basin makes it relatively simple to make basin-wide extrapolations. A brief description of the salient points of each of the geohistory diagrams shown in Plates 41-53 follows. The geohistory diagrams are made up of six individual plots. The most important of these is the geohistory plot. The vertical line at time 0.0 corresponds to the stratigraphy encountered by the well. The TD. of the well is the last horizon before basement; the latter assumed to be at 6000 m at an age of 286 Ma B.P. for reasons discussed above. The geohistory plot maps the horizon depth through time. As an aid to the interpretation of the geohistory plot are the subsidence histograms, which graph the rate of matrix fill (i.e. the volume of sediment less the porosity volume), the rate of fill (or sedimentation rate), the stripped basement subsidence rate (i.e. the rate of change of the basement subsidence derived from the palaeo-heatflow and tectonic subsidence plot, discussed later) and the basement subsidence rate (the rate of change in the basement depth derived from the basement plot within the geohistory plot). Associated with the subsidence histograms is the palaeo-heatflow and subsidence plot. One curve plots the stripped basement (i.e. subsidence with the sediment load component removed) through time. This curve is often referred to as the tectonic subsidence curve. There are two components which make up this curve; (i) subsidence/uplift due to thermal effects and (ii) subsidence/uplift due tectonic factors, like faulting or compression. From this curve it is possible to extract the overall thermal decay of the heat anomaly that is coincident with the basin formation. This palaeo-heatflow is expressed by the second line within the plot. It is constrained by the heat flow value derived from the thermal characteristic of the sedimentary section and the bottom hole temperature (BHT) of the well. The palaeo-heatflow curve constitutes the primary thermal signature from which the palaeo temperatures and vitrinite reflectance values are calculated. Each of these two thermal features are also plotted. The calculated vitrinite reflectance values are also overlain on the primary geohistory plot. From this it is possible to ascertain when a particular horizon entered into a particular iso-vitrinite zone.

Bouvard 1

The tectonic subsidence plot for the Bouvard 1 well describes a rather smooth deepening of the basement through time (Plate 41). Even though the data from this well extends only to the Early Cretaceous, only half the inferred life of the basin, there has been only minor subsidence since this time. The leveling off of the tectonic (largely thermal) subsidence from this time to the present supports the assumption that the thermal anomaly associated with basin formation had substantially dissipated by the time of breakup. Subsequent subsidence of the basin has been largely driven by sediment loading. There are three marked phases of rapid subsidence, at about 140, 132 and 65 Ma B.P. There was a period of erosion immediately after these periods of high sedimentation. This can be seen in the subsidence histogram plots (Plate 41).

The thermal calculations show a smooth rise in the vitrinite reflectance values through time. There is also a regular rise in the bed temperature with time. There are some periods of rapid rise, corresponding to times of rapid sedimentation and consequent deepening. The fall in basement temperature in the Late Jurassic is due to a fall in the background heat flow, and the other relative bed temperature falls correspond to periods of uplift. The lack of maturity data for this well means that it is not possible to corroborate the calculated vitrinite reflectance values. However, as can be seen by other geohistory analyses, the calculated vitrinite values do not differ greatly from other wells where measured vitrinite reflectance does support the calculated results.

Challenger 1

This well (Plate 42) shows the same features as those discussed for Bouvard 1. Both sites contain approximately the same amount of post-Jurrasic sediment. However, at the Challenger location the sedimentation rate was somewhat lower, but sedimentation was sustained over a longer period of time. The periods of rapid subsidence followed by erosion are not so evident, but they do still correspond roughly to those from Bouvard 1. The subsidence anomalies, non-thermal for both locations, are remarkably similar. The vitrinite versus depth plot is similar also, and at this location the measured vitrinite reflectance values fall evenly about the calculated values.

Charlotte 1

The Charlotte 1 well varies from the two previous wells in one important respect. There is a large tectonic subsidence anomaly in the Early Cretaceous (Plate 43). Nearly all the basement subsidence from then to the present day can be accounted for in one phase of downwarp. It can be seen from the plots of the other wells that this time marks a period of rapid subsidence for the whole sub-basin, and it constitutes varying total proportions of post-Jurassic subsidence. In general, this period of subsidence represents a major phase in the basin's development, and in Charlotte 1 it accounts for approximately 80 percent of the post-Jurassic subsidence. This anomaly on the subsidence plot is interpreted as tectonic and not thermal, as thermal anomalies, whilst they can be large in depth magnitude, are rarely short in time magnitude. Thus the anomaly is interpreted as being associated with a pull apart phase.

Gage Roads 1 & 2

Due to their proximity, Gage Roads 1 and Gage Roads 2 will be discussed collectively. Firstly, they both have the same major features that would be expected from wells drilled close together. The only minor difference that is apparent is the sedimentation rates. Again, both wells illustrate rapid tectonic subsidence in the Early Cretaceous, and very little subsidence thereafter (Plates 44, 45). One feature that begins to emerge from both these wells, and those previously discussed, is the increase in subsidence since the Early Tertiary. This may be an anomaly due to aliasing, in that there are very few age picks from the shallow section of the wells. Another alternative is that the basin is still undergoing some adjustment, possibly connected with movement on the Darling Fault. The measured and calculated vitrinite reflectance values, at depth, show fairly good agreement in Gage Roads 1.

Minder Reef 1

This is a shallow well that penetrated only to the very top of the Late Jurassic (Plate 46). Consequently, the geohistory plot lacks some of the detail shown by other wells. It does, however, exhibit the same characteristic subsidence history as those wells discussed previously.

Mullaloo 1

The Mullaloo 1 well geohistory plot (Plate 47) shows little detail that varies from the previous discussion. It can be seen, however, that there is a long period of uplift and erosion from the Early Cretaceous to the early Tertiary at this location.

Parmelia 1

This well shows a similar geohistory plot to that of Bouvard 1. There appears to be a much smoother basement subsidence than most other wells, and a noticeable lack of substantial tectonic subsidence anomalies (Plate 48). Other features of some consequence are the subdued sedimentation rates and the basement subsidence rates.

Peel 1

The Peel 1 well tectonic subsidence plot (Plate 49) illustrates most clearly the rapid basement subsidence that took place in the Vlaming Sub-basin during the Early Cretaceous. Another feature illustrated in this well is the period of erosion, related to breakup and drift, that followed this subsidence phase. The arcuate nature of the tectonic subsidence plot is the best indication so far that the sub-basin can be modelled as a pull-apart basin.

Quinn's Rock 1

This well is similar to Peel 1, in that there are few anomalies on the tectonic subsidence plot (Plate 50). It must be pointed out that the tectonic subsidence plot is the most important signature of the basin, and hence there is a need to consider it carefully.

Roe 1

The geohistory of the Roe 1 well (Plate 51) requires some care. There are few time picks, and, overall, the data is sparse. The paucity of stratigraphic data means that there is a certain amount of averaging of the data, and any detailed interpretation is not possible. Roe 1 does, however, exhibit the general thermal and subsidence characteristics of the sub-basin.

Sugarloaf 1

The Sugarloaf 1 well is the deepest well in the basin, and so it is critical for the overall interpretation of the geohistory plots for the whole sub-basin. Its geohistory plot (Plate 52) does support the findings from the previous wells, and, while deep, it does not provide any differences in the interpretation of the basin as a whole. Sugarloaf 1 is similar to Peel 1.

Warnbro 1

The Warnbro 1 geohistory plot (Plate 53) shows a classic basin development pattern. The calculated and measured vitrinite values show a good agreement.

PETROLEUM PLAYS

The major petroleum plays most apparent in the South Perth Basin (Vlaming Sub-basin) are those that have been investigated by previous exploration drilling. Each of the major sedimentary units from the Yarragadee Formation up to, and including, the South Perth Shale and overlying Coolyena Group has, to varying degrees, the major elements required for the generation, migration, entrapment and preservation of petroleum. Previous drilling shows that much of the Jurassic and Cretaceous sequence is mature or marginally mature for petroleum generation, and in the case of the Gage Roads 1 well, oil has been entrapped and preserved in a possible stratigraphic trap.

Yarragadee Formation

Current indications are that this sequence is mature for hydrocarbon generation over much of the Vlaming Sub-basin and is possibly overmature for oil generation in deeper parts of the sub-basin. Adequate source material is present, and the sequence could possibly source both oil and gas, depending on the level of maturation and the type of source material. Reservoir quality is adequate in shallower parts of the basin but is greatly reduced at depths of over 3000 m.

The best potential seal for the Yarragadee Formation is provided by the overlying shales of the Otorowiri Member. Some potential exists for internal seal within the Yarragadee Formation, but as shale units between channel sandstones are relatively thin and discontinuous, they are unlikely to have the capacity to seal significant volumes of hydrocarbons.

Parmelia Formation

Adequate source, reservoir and seal are evident within the Parmelia Formation. The shale-rich Otorowiri and Carnac Members should be adequate as source and seal units. Sandstone-rich parts of the formation underlying the Carnac and Otorowiri Members are likely to be the major potential reservoirs, although there is some possibility for petroleum to be reservoired in deltaic sandstones of the Carnac Member by internal sealing.

Gage Sandstone Member

The recovery of hydrocarbons from this unit in the Gage Roads 1 and 2 wells is a major feature of the petroleum prospectivity of the Vlaming Sub-basin. In most cases it should have good reservoir potential and be sealed by the overlying South Perth Shale sequence. It has the potential to be a significant stratigraphic play where it pinches out along the flanks of the Rottnest Trough and other troughs of the Vlaming Sub-basin. Some potential for internal sealing within the sequence is also possible.

South Perth Shale

As a seal this sequence is of critical importance to older underlying units. Firstly, as a seal for possible pinchouts of the Gage Sandstone Member, but also for the Parmelia Formation where it subcrops beneath the South Perth Shale on the crestal parts of major structural highs. However, in some instances the South Perth Shale pinches out on the flanks of such highs and adequate sealing would most probably be absent.

Leederville Formation

As a possible reservoir sequence with few extensive shale units, this sequence is unlikely to act as a major seal for underlying units. It is possibly sealed by the overlying Coolyena Group and could provide a secondary trap for any hydrocarbons escaping from mature underlying sequences.

DISCUSSION

Previous exploration drilling in the Vlaming Sub-basin has tested a variety of potential petroleum traps including such features as potential faulted anticlines, fault and stratigraphic traps. The major features which previous exploration has regarded as possible leads or prospects are illustrated schematically in Figure 11. The major features

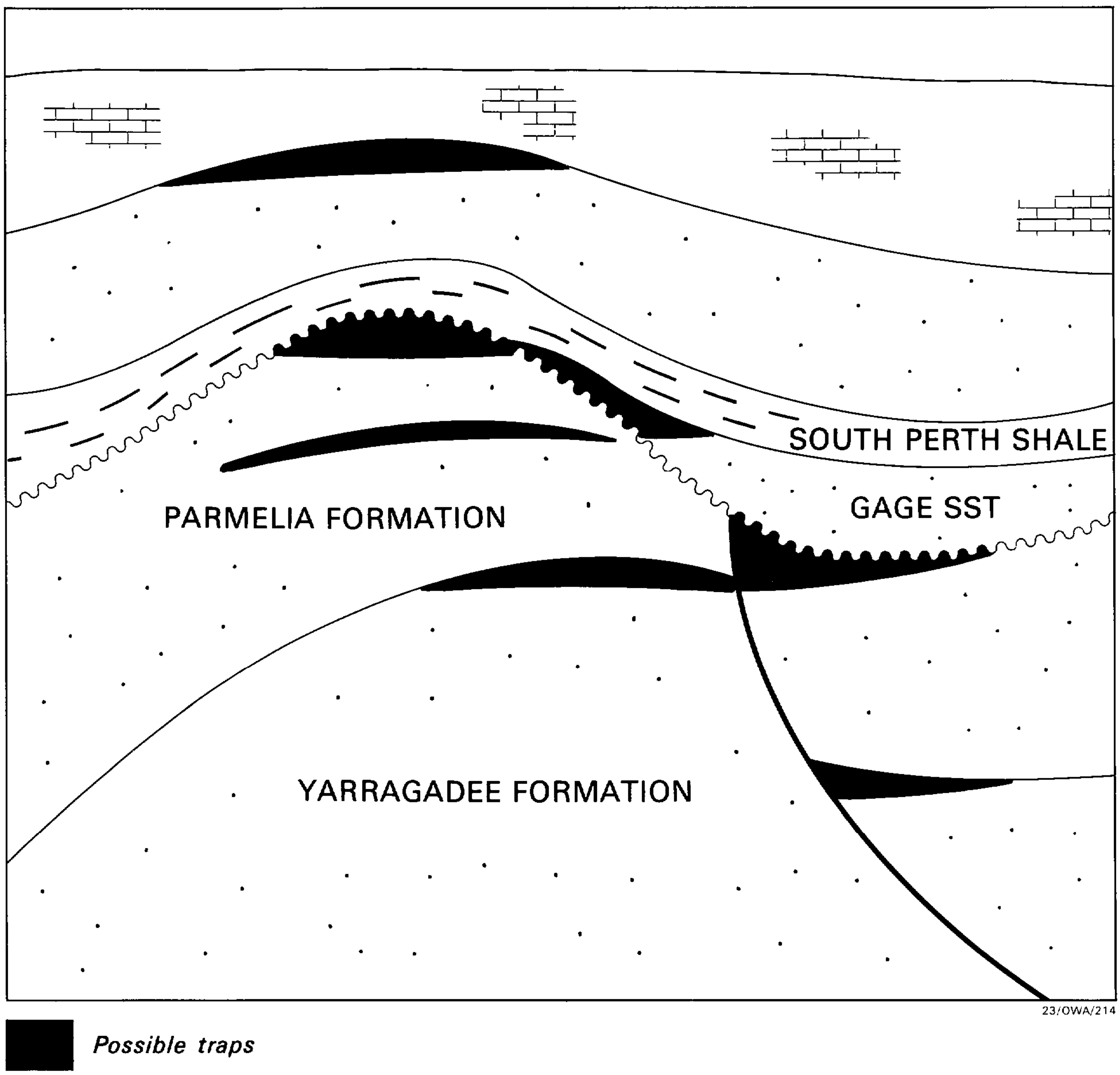

Figure 11. Potential hydrocarbon plays in the Vlaming Sub-basin.

include such play elements as stratigraphic pinchouts of the Gage Sandstone Member, faulted anticline closures in the Yarragadee and Parmelia Formations and fault block features underlying the major Cretaceous unconformity surface.

Additional potential leads of these types may be present in the Vlaming Sub-basin. In addition, other less likely features may also be present, including dip-closed anticlines in the relatively immature Leederville Formation, Coolyena Group and younger carbonate sequence. The ultimate petroleum prospectivity of the region remains to be determined by additional exploration.

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Appendix 1. Offshore South Perth Basin database - wells and seismic surveys.

Exploration Wells

Well	Operator	Completion Date	W.D. (m)	T.D. (m)
Quinn's Rock 1	WAPET	Nov. 1968	40	2185
Gage Roads 1	WAPET	Jan. 1969	58	3639
Roe 1	WAPET	Dec. 1970	104	2104
Warnbro 1	WAPET	Jan. 1971	47	3635
Charlotte 1	WAPET	Jan. 1971	42	2405
Gage Roads 2	WAPET	Feb. 1971	30	2942
Sugarloaf 1	WAPET	April 1971	45	3627
Bouvard 1	WAPET	Jan. 1975	51	1968
Challenger 1	WAPET	March 1975	212	2238
Peel 1	Phillips	Dec. 1977	42	3684
Parmelia 1	WAPET	May 1981	242	1749
Mullaloo 1	Esso	May 1984	43	2000
Minder Reef 1	Esso	June 1984	43	1500

Seismic Surveys

Year	Operator	Survey Name	Km
1980	Geometals	Green Head	170
1980	Haoma	Seabird 1	133
1980	Wainoco	Cape Leeuwin	783
1981	Mesa	Rhonda	408
1981	Strata	Seabird 2	467
1982	BP	1982-WA-174	1632
1982	Alberta	South Turtle Dove	1095
1982	Esso	Vlaming (V82A)	2506
1983	Balmoral	Cervantes	362
1983	BP	1983-WA-174	381
1983	Esso	Vlaming (V83A)	973
1985	BHP	HV85A	551

Appendix 2. Description of dredge samples from the Fremantle Canyon

80DR/002

Latitude: 30° 06.98'S
Longitude: 113° 44.64'E
Water Depth: 4075 m
Site Description: Lower continental slope
Recovery: 11 kg of sandstone and some shale

Sample 1 Somewhat iron stained, friable to fairly well cemented, coarse grained, poorly sorted, quartz sandstone. The degree of cementation appears to be variable. Both angular quartz grains and rounded, up to pebble-size, rock fragments are apparent under the binocular microscope. There appears to be very little fine-grained matrix in the sandstones. Their texture implies a fluviatile depositional environment.................T/S (x3)

Sample 2 Medium to coarse grained, moderately sorted, friable, quartz sandstone.....................T/S

Sample 3 Fairly clean looking, medium grained, moderately to poorly sorted, quartz sandstone that varies from friable to fairly well cemented..........T/S

Sample 4 Medium to dark grey, soft, sandy siltstone containing what appear to be plant fragments.....P

80DR/003

Latitude: 31° 13.64'S
Longitude: 114° 35.96'E
Water Depth: 2415 m
Site Description: Continental slope north of Perth
Recovery: 35 kg of limestone

Sample 1 Light to medium grey, fairly well cemented calcarenite (packstone), with a reasonably high siliceous content............................N, F

Sample 2 Slightly greenish grey, crumbly (moderately cemented) calcarenite (packstone). The greenish tinge is probably due to the presence of glauconite, which is evident in the acid insoluble (10% HCl) fraction, along with fairly abundant siliceous material (sponge spicules, internal moulds of radiolaria and fine sand-size quartz grains................................N, F, T/S

Sample 3 Light grey, well cemented, foram-rich calcarenite (packstone). The foraminifera appear to be mainly planktonic varieties........................N, F

Sample 4 Light to medium grey, friably cemented calcilutite (wackestone). The acid insoluble fraction contains minor glauconite and rounded quartz grains, but no apparent sponge spicules. The remainder of the insoluble residue is almost colloidal (possibly either clay minerals or finely amorphous silica).......................................N, F

Sample 5 — Fawnish medium grey, fairly well cemented calcarenite (packstone) that superficially appears similar to Sample 1. However, the acid insoluble fraction shows fairly abundant glauconite and possibly oxidised glauconite, but no apparent spicules or silica moulds................N, F, T/S

Sample 6 — Light grey, soft to friably cemented chalky to marly calcilutite (wackestone). The acid insoluble residue contains a small amount of glauconite and quartz.......................................N, F

Sample 7 — Pale grey, fairly well cemented calcarenite (packstone) that contains a fair amount of pale yellowish to dark green glauconite. Planktonic foraminifera are obvious under low magnification. On treatment with dilute (10% v.v) HCl there was hardly any effervescence, which suggests that the sample may be predominantly dolomite.....N, F, T/S

Sample 8 — White to pale grey, soft (virtually uncemented), chalky calcarenite (grainstone) with very little acid insoluble residue.......................N, F

Sample 9 — Medium grey, fairly well cemented calcarenite (packstone).................................N, F

<u>80DR/004</u>

Latitude: 32° 00.20'S
Longitude: 114° 57.50'E
Water Depth: 950-970 m
Site Description: NW wall of Fremantle Canyon
Recovery: 60 kg of limestone

Sample 1 — Slightly dirty looking pale to medium grey, friably to fairly well cemented calcarenite (grainstone). The acid insoluble fraction shows a fair amount of glauconite, plus quartz grains and possibly clay minerals......................N, F

Sample 2 — Slightly dirty looking pale to medium grey, fairly well cemented calcarenite (grainstone), somewhat similar to Sample 1. However, the acid insoluble fraction contains a fair amount of sponge spicules, plus minor glauconite and quartz....N, F

Sample 3 — Pale to medium grey, fairly well cemented calcarenite (grainstone). This sample has a relatively large acid insoluble residue than the other two, indicating that it is possibly dolomitic..................................N, F

80DR/005

Latitude: 32° 00.70'S
Longitude: 114° 58.00'E
Water Depth: 730-1350 m
Site Description: NW wall of Fremantle Canyon, but more towards the base than 80DR/004
Recovery: Shales, mudstones and limestones

Sample 1 — Pale chocolate brown, finely laminated (2-5 mm in places) mudstone. Cleavage faces of mica are prominent, and what appears to be finely disseminated organic material can be discerned under the microscope......................P, G, X

Sample 2 — Pale to medium brown, unlaminated, but fissile, mudstone. This rock is relatively soft and can be broken by hand. Fairly well rounded, fine sand- and silt-size quartz, mica and plant fragments are visible under the microscope...............P, G, X

Sample 3 — Dark brownish grey, finely laminated shale.......P

Sample 4 — Pale chocolate brown, finely laminated mudstone. The rock is soft enough to have been bored by marine organisms, presumably polychaetes, and these borings have been filled by pelagic ooze. Fine quartz and mica are evident under the microscope................................P, G, X

Sample 5 — Dark grey, fissile, but fairly hard, mudstone. The rock consists of fine quartz, mica and fairly abundant fragments of carbonised plant material, plus fines...................................P, X

Sample 6 — Dark grey, fairly soft mudstone that is relatively finer than the previous samples. Fine silt-size quartz and mica are the most obvious minerals in the coarse fraction.......................P, G, X

Sample 7 — Slightly dirty pale to medium grey, friably cemented calcarenite (packstone). The minor amount of acid insoluble residue consists of quartz and glauconite.............................N, F, T/S

Sample 8 — Medium to slightly darkish grey, well cemented calcarenite (grainstone). There is a fair amount of acid insoluble residue which consists of quartz, sponge spicules and glauconite...N, F, T/S

Sample 9 — Medium grey, soft, foram-rich calcilutite (wackestone) with minor quartz and glauconite..................................N, F

80DR/006

Latitude: 32° 01.67'S
Longitude: 114° 59.61'E
Water Depth: 1250-1620 m
Site Description: NW wall of Fremantle Canyon
Recovery: Mildly consolidated ooze

80DR/007

Latitude: 32° 03.30'S
Longitude: 115° 01.13'E
Water Depth: 650 - 850 m
Site Description: SE wall of Fremantle Canyon above 80DR/008
Recovery: 60 kg of limestone

Sample 1 White to light grey, friable to fairly well cemented, chalky calcilutite (wackestone). Very little acid insoluble residue, except for some sponge spicules..............................N, F

Sample 2 Light grey, friable calcilutite (wackestone) with a somewhat sucrosic texture and abundant spicule-like material. XRD results indicate that calcite is the only mineral present................N, F, X

Sample 3 White to light grey, soft to friably cemented (chalky) calcilutite (wackestone) that contains abundant spicules............................N, F

80DR/008

Latitude: 32° 02.50'S
Longitude: 115° 00.30'E
Water Depth: 850-1150 m
Site Description: SE wall of Fremantle Canyon below 80DR/007
Recovery: 20 kg of limestone

Sample 1 Light to medium fawnish grey and fairly well cemented calcilutite (wackestone). The acid insoluble fraction contains a fair amount of green glauconite pellets plus siliceous material, mainly in the form of sponge spicules and internal moulds of radiolaria. Some fine sand-size quartz is present as well......................N, F, T/S

Sample 2 Medium grey, well cemented calcarenite (grainstone) with skeletal material prominent. The acid insoluble residue is fairly small, with minor sponge spicules, quartz and glauconite........N, F

80DR/009

Latitude: 32° 01.70'S
Longitude: 114° 58.60'E
Water Depth: 1200-1650 m
Site Description: SE wall of Fremantle Canyon below 80DR/008
Recovery: 5 kg of limestone

Sample 1 Medium grey, fairly well cemented calcilutite (mudstone). The acid insoluble fraction is fairly large, which suggests that the sample is partly dolomitic..............................N, F, T/S

Sample 2 ....Pt

80DR/010

Latitude: 31° 59.35'S
Longitude: 115° 01.50'E
Water Depth: 1591 m
Site Description: NW wall of Fremantle Canyon
Recovery: Grey ooze

80DR/011

Latitude: 31° 58.80'S
Longitude: 115° 01.60'E
Water Depth: 1300 m
Site Description: NW wall of Fremantle Canyon
Recovery: No recovery

80DR/012

Latitude: 31° 57.70'S
Longitude: 115° 04.50'E
Water Depth: 1381 m
Site Description: From base of canyon wall to two-thirds up the NW wall of Fremantle Canyon
Recovery: Mildly consolidated oozes

80DR/013

Latitude: 32° 03.60'S
Longitude: 114° 45.00'E
Water Depth: 1940-2500 m
Site Description: Northern wall of Fremantle Canyon
Recovery: 20 kg of shales, sandstones and limestone

Sample 1 Very dark grey, siliceous and fairly well cemented, massive mudstone with very little indication of bedding. The coarse fraction consists of fine sand- to silt-size quartz and mica in a darkish matrix and possibly a siliceous cement.............................P, G, X, T/S

Sample 1C — This was the only limestone in the dredge haul, and it consisted of a well-rounded, cobble-size rock. Light to medium grey, well cemented calcilutite (mudstone). The sample is highly siliceous, and there is some glauconite..N, F, T/S

Sample 2 — Dark grey, finely laminated shale consisting of silt-size quartz grains, mica and clays with a siliceous cement. Some possible carbonised plant fragments are present.....................P, G, X

Sample 3 — Dark grey, fairly well cemented mudstone with possibly a siliceous cement..................P, G

Sample 4 — Variegated, light grey to black, well cemented shale. The colour variety is due to interbedding of quartz-rich, siliceous bands, about 1-3 cm thick, that alternate with finely laminated carbonaceous (?) layers that contain fine quartz, mica and clays in what is probably a siliceous cement. The interbeds tend to be discontinuous; this is apparent, even in hand specimen..P, X, T/S

Sample 5 — Dark grey, well cemented shale................P, G

Sample 6 — Medium to coarse, iron-stained, friable quartz sandstone. The quartz grains are thinly coated by iron oxides, and it appears that hematite is partly cementing the grains...................T/S

Sample 7 — Medium, clean, friable, quartz sandstone which shows more resistant siliceous bands, which appear also to define cross-bedding trends...........T/S

Sample 8 — Fine-medium, clean, fairly well sorted, friable quartzose sandstone with thin (2 mm) clay (?) partings that appear to define cross-bedding...T/S

<u>80DR/014</u>

Latitude: 32° 03.10'S
Longitude: 114° 45.50'E
Water Depth: 1135-1965 m
Site Description: Northern wall of Fremantle Canyon
Recovery: Limestones and sandy shales

Sample 1 — Pale grey to dark grey silty sandstone consisting of 1-4 cm thick sandstone layers, interbedded with finely laminated silty sandstones. These laminae are alternating light and dark grey layers which define small-scale trough cross-bedding with a later generation cutting into part of a previous trough..................................P, T/S

Sample 2 — White to light grey, well cemented, porcellanous calcilutite (mudstone) containing planktonic foraminifera. Sample has been diagenetically altered, and treatment with dilute (10% v.v) HCl suggests that it is mainly dolomite......N, F, T/S

Sample 3	Light to medium grey, soft to friably cemented, but somewhat chalky calcilutite (mudstone). Minor acid insoluble residue.......................N, F
Sample 4	White, moderately cemented, chalky calcilutite (mudstone) ....N, F
Sample 5	Medium grey, friable to fairly well cemented, glauconitic calcilutite (wackestone). The acid insoluble fraction consists of abundant glauconite pellets, plus a fair amount of fine sand-size quartz and some very fine material (clay minerals?)............................N, F, T/S
Sample 6	White, well cemented, foram-rich calcilutite (wackestone)................................N, F
Sample 7	Off-white, friable to fairly well cemented calcilutite (wackestone) ....N, F
Sample 8	Light to medium grey, soft calcilutite (mudstone). The acid insoluble fraction is small, but it contains some glauconite and minor quartz. XRD results indicate that calcite is the major mineral, with some quartz. A small peak at 8.9Å could be glauconite......................N, F, X
Sample 9	White, porcellanous, well cemented calcilutite (mudstone) that exhibits some planktonic foraminifera on polished surfaces. The sample has undergone a fair amount of diagenesis and possibly there has been some dolomitisation ....N, F
Sample 10	Light to medium grey, soft calcilutite (mudstone). XRD analysis indicates that calcite is the major mineral, with a trace of quartz and the 8.9Å mineral.................................N, F, X
Sample 11	Light grey, friable to fairly well cemented, somewhat bedded calcilutite (mudstone)..N, F, T/S
Sample 12	Light to medium grey, diagenetically altered and well cemented calcilutite (mudstone)......N, F
Sample 13	Light to medium grey, soft calcilutite (mudstone) that is slightly chalky....................N, F
Sample 14	Light to medium grey, soft to friably cemented calcilutite (mudstone). XRD analysis shows calcite to be the major mineral, with a trace of quartz and the 8.9Å mineral.....................N, F, X

80DR/015

Latitude: 32° 06.00'S
Longitude: 114° 43.00'E
Water Depth: 2380-2460 m
Site Description: Southern wall of canyon
Recovery: 5 kg of shales

Sample 1 Finely laminated (2-5 mm) shaley sandstone. Dark (silty or carbonaceous) laminae between the predominantly sandy layers define the cross-bedded characteristics of the sample. A slabbed and polished part of the rock shows this extremely well..P

Sample 2 Finely laminated, alternating light and dark shale. Laminae are of the order of 1-10 mm in thickness, with dark olive grey laminae being more predominant and thicker compared to pale yellowish grey laminae. Parting surfaces show abundant mica.......................................P, X

80DR/016

Latitude: 32° 06.05'S
Longitude: 114° 43.00'E
Water Depth: 1750-2470 m
Site Description: Higher up the southern side of the canyon wall than 80DR/015
Recovery: 40 kg of shales, limestones and ooze

Sample 1 Fawnish grey, well-bedded shale with partings of the order of 0.4-1.5 cm. This shale is much lighter in colour than many of the previous examples...................................P, X

Sample 2 Light to medium grey, fissile (moderately cemented) calcarenite (packstone). The acid insoluble fraction shows some green, greenish black and yellowish green glauconite, plus fairly abundant siliceous material, mainly sponge spicules, and internal moulds of radiolaria. Some rounded quartz grains also are present...N, F, T/S

Sample 3 Medium grey, well cemented calcilutite (mudstone) with minor glauconite..................N, F, T/S

80DR/017

Latitude: 31° 57.40'S
Longitude: 114° 44.20'E
Water Depth: 1800-2814 m
Site Description: Northeastern wall of Fremantle Canyon
Recovery: 10 kg of limestone

Sample 1 Light to medium grey, friably cemented calcilutite (wackestone). XRD results indicate that the only carbonate mineral present is calcite, with a trace of montmorillonite, mica(?) and probably some glauconite........................N, F, S, X, Pt

Sample 2 ....Pt

Sample 3 Light grey, soft to friably cemented calcilutite (wackestone). The acid insoluble residue is minor, but it includes some glauconite...........N, F, S

80DR/018

Latitude: 31° 59.80'S
Longitude: 114° 39.50'E
Water Depth: 2400-2810 m
Site Description: Southern wall of Fremantle Canyon
Recovery: 2 kg of limestone and ooze

Sample 1 Light grey, friably cemented calcilutite (mudstone) that shows vague bedding on a centimetre scale. Some acid insoluble material is present in the form of fine material (clay minerals?) and minor glauconite........N, F, S, Pt

Sample 2 Medium grey, well cemented calcilutite (mudstone).................................N, F

80DR/019

Latitude: 32° 00.00'S
Longitude: 114° 38.00'E
Water Depth: 1600-2700 m
Site Description: Upper part of the SW wall of Fremantle Canyon
Recovery: Limestones and ooze

Sample 1 Light fawnish grey, very soft calcilutite (wackestone). There is a fair amount of acid insoluble residue, including sponge spicules, radiolaria and quartz grains. Some fine material (clay minerals?) is present also.............N, F

Sample 2 Medium grey, well cemented calcarenite (packstone)...........................N, F, T/S

Sample 3 Light to medium grey, friable to fairly well cemented calcilutite (mudstone). Minor, but very fine (clay mineral?) acid insoluble residue...N, F

Sample 4 Light grey, soft to slightly friable calcilutite (mudstone) with only minor acid insoluble residue....................................N, F

80DR/020

Latitude: 31° 50.05'S
Longitude: 114° 37.60'E
Water Depth: 2420-3000 m
Site Description: NE wall of Fremantle Canyon
Recovery: 15 kg of dark grey shales and light to medium grey limestones

Sample 1	Very dark grey, soft, but fissile, mudstone. Coarser fraction includes silt-size quartz and mica in a fine silt- to clay-size matrix. The sample appears to be organic-rich, but plant material appears to be scarce and finely disseminated..............................P, G, X
Sample 2	Dark grey to black, organic-rich, fairly soft mudstone..................................P, G, X
Sample 3	Black, organic-rich, fissile mudstone.........P, G
Sample 4	Medium to dark grey, massive, but fissile, mudstone.....................................P, X
Sample 5	Medium grey, very friable calcilutite (wackestone) consisting of fine-medium sand-size skeletal fragments and minor glauconite in a fine-medium silt-size matrix. Some fine (clay mineral?) insoluble residue (10% HCl)..................N, F
Sample 6	Light-medium grey, friably cemented calcilutite (mudstone) with some fine insoluble residue...N, F
Sample 7	Medium grey, very friable to soft calcilutite (wackestone) with some coarser skeletons and minor glauconite. Some fine insoluble residue.......N, F
Sample 8	Medium grey, very friable calcilutite (mudstone) with some coarser skeletons..................N, F
Sample 9	Light to medium grey and fairly soft calcilutite (mudstone) with some coarser skeletons (forams). A fair amount of acid insoluble residue suggests that the sample is partly dolomitic...........N, F
Sample 10	Light to medium grey, fairly soft, and finely laminated calcilutite (mudstone). The bedding laminations are reasonably uniform, about 2-5 mm thick. Some insoluble residue is present......N, F
Sample 11	Light to medium grey, fairly soft, laminated calcilutite (mudstone). The laminations are less distinct than Sample 10, but they appear to be of similar thickness...........................N, F

80DR/021

Latitude: 31° 48.00'S
Longitude: 114° 39.00'E
Water Depth: 1420-2650 m
Site Description: NE wall of Fremantle Canyon
Recovery: 80 kg of limestone

Sample 1 Variegated, white to grey well cemented cherty limestone. XRD analysis indicates that chert and calcite are the major minerals present.....N, F, X

Sample 5 Light grey, soft to friably cemented calcilutite (mudstone) that has a chalky texture. XRD analysis indicates that some chert is present.......N, F, X

Sample 11 White, soft to friably cemented chalky calcilutite (mudstone). This is a fairly pure limestone, with only minor glauconite........................N, F

80DR/022

Latitude: 31° 51.80'S
Longitude: 114° 36.30'E
Water Depth: 2310-2970 m
Site Description: Base of southern wall of Fremantle Canyon
Recovery: 3 kg of limestone

Sample 1 Variegated, white to grey, well cemented cherty limestone.............................N, F, S, T/S

Sample 2 Very pale grey, chalky calcilutite (mudstone) that is soft, but remains friably cemented. Almost no insoluble residue is present..........N, F, S, SEM

Sample 3 Very pale grey, slightly more indurated calcilutite (mudstone). The acid insoluble residue contains some fine material (clay minerals?) and minor glauconite......................N, F, S, Pt

Sample 4 Whitish, soft calcilutite (mudstone) that contains abundant siliceous spicules diatoms and radiolaria, plus some fine material as acid insoluble residue.........................N, F, S

80DR/023

Latitude: 31° 53.40'S
Longitude: 114° 34.50'E
Water Depth: 1920-2520 m
Site Description: Higher up the southern wall of Fremantle Canyon than 80DR/022
Recovery: One piece each of shale, sandstone and limestone

Sample 1 Light olive grey (externally, but possibly darker inside), reasonably consolidated mudstone.....P, X

Sample 1C — Whitish, fairly well cemented, but chalky, calcarenite (packstone)..................N, F, T/S

Sample 2 — This sample was originally thought to be a limestone, but XRD analysis indicates that it is a mudstone containing quartz, kaolinite, montmorillonite and mica...................N, F, X

<u>Key</u>: Samples were prepared and submitted for the following:-

P palynological analysis
N nannofossil analysis
F foraminiferal analysis
G organic geochemical analysis
T/S thin section
X XRD analysis
Pt photography
SEM scanning electron microscope examination

Appendix 3: X-Ray Diffraction Results from Dredge Samples

80DR/005

Sample 1	Kaolinite (major), quartz (minor), mica and montmorillonite (tr.)
Sample 2A	Kaolinite, quartz (major), feldspar, mica and montmorillonite (tr.)
Sample 2B	Kaolinite, quartz (major), feldspar, mica and montmorillonite (tr.)
Sample 4	Quartz, kaolinite (major), feldspar, mica and montmorillonite (tr.)
Sample 5	Quartz, kaolinite (major), feldspar (minor), mica and montmorillonite (tr.)
Sample 6	Quartz, kaolinite (major), feldspar (minor), mica and montmorillonite (tr.)

80DR/007

Sample 2	Calcite (major), halite (tr.)

80DR/013

Sample 1	Quartz, kaolinite, plagioclase (major), mica and montmorillonite (tr.)
Sample 2	Quartz, feldspar (major), kaolinite (minor), mica and montmorillonite (tr.)
Sample 4	Quartz, feldspar, calcite, kaolinite (major), mica and montmorillonite (tr.)

80DR/014

Sample 8	Calcite (major), quartz and glauconite (tr.)
Sample 10	Calcite (major), quartz and glauconite (tr.)
Sample 14	Calcite (major), quartz and glauconite (tr.)

80DR/015

Sample 2	Quartz, feldspar, kaolinite (major), mica (minor)

80DR/016

Sample 1	Quartz, kaolinite (major), mica (minor)

80DR/017

Sample 1	Calcite (major), montmorillonite and glauconite (tr.)

80DR/020

Sample 1	Quartz, kaolinite (major), feldspar, mica and

	montmorillonite (tr.)
Sample 2	Quartz, kaolinite (major), feldspar, mica and montmorillonite (tr.)
Sample 4	Quartz, kaolinite (major), feldspar and mica (tr.)

80DR/021

Sample 1	Silica, calcite (major), clay minerals(?) (tr.)
Sample 5	Calcite (major), siica, clay minerals(?) (tr.)

80DR/023

Sample 1	Quartz, kaolinite (major), feldspar, mica (tr.)
Sample 2	Quartz (major), kaolinite, montmorillonite (minor), mica (tr.)

Appendix 4: Age determinations and description of calcareous nannofossil assemblages

An Upper Maastrichtian to Lower Miocene stratigraphy of the Fremantle Canyon has been delineated as a result of studying the calcareous nannofossils in dredge samples from the Fremantle Canyon and the continental slope north of Perth. Two unnamed new units have been discovered as a result of this study: a Lower Eocene and a Mid Oligocene unit, in addition to a possible new Lower Paleocene unit(s). The question of whether the newly discovered Lower Paleocene levels represent the lower part of the offshore equivalent of the Kings Park Formation or not is left open pending further work. With regard to the Lower Tertiary marine succession of the onshore Perth Basin, the unnamed new Lower Eocene unit fills the stratigraphic gap between the mainly 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, apparently leaving the stratigraphic gap between these two formations largely unfilled. An hiatus between the Cretaceous and Tertiary seems to exist in the canyon, between the Upper Maastrichtian Breton Marl or equivalent (name informally introduced by Shafik, 1989) and the Lower Paleocene levels. The lithological evidence from the canyon material seems to suggest that the Middle Eocene Porpoise Bay Formation and the Upper Eocene Challenger Formation merge, forming one unit; the palaeontological evidence does not negate this conclusion.

Late Maastrichtian (Breton Marl equivalent)

Three samples 80DR/020-9, -10 and -11 of light to medium grey, fairly soft calcilutite, which were dredged from the northeastern wall of the Fremantle Canyon were found to contain rich nannofossil assemblages (see Plate 32). The presence of the age-diagnostic species *Nephrolithus frequens*, *Cribrosphaerella daniae* and *Lithraphidites quadratus* in all three samples suggests a Late Maastrichtian age and also that these samples are from the same stratigraphic unit. This is not inconsistent with the fact that these samples came from the same dredge haul. The overall composition of the assemblages suggests cold surface waters, and deposition on the shelf and/or in a nearshore environment.

The evidence of age and depositional palaeoenvironment derived form the Fremantle Canyon samples matches similar evidence based on onshore assemblages studied from the Breton Marl by Shafik (1989). This suggests that the canyon samples represent the offshore equivalent of the Breton Marl. The lithological evidence from these samples does not negate this conclusion.

It is worth noting that the nannofossil key species for the Latest Maastrichtian, *Micula prinsii*, was not found in either the onshore Breton Marl (Shafik, 1989) or its offshore equivalent in the Fremantle Canyon. This evidence suggests the existence of an hiatus between the Cretaceous and Tertiary in the canyon (Table 1).

Early Paleocene (no known onshore equivalent)

Three levels are described below.
Sample 80DR/014-5, a grey friable to well cemented glauconitic calcilutite, which was dredged from the northern wall of the canyon,

yielded a fairly well-preserved nannofossil assemblage which is an admixture of Late Cretaceous and Early Paleocene forms (Plate 32). The Late Cretaceous forms are diversified, being dominated by those indicating Late Maastrichtian, including the key species *Nephrolithus frequens*. The Paleocene forms are fewer in number of species. They include *Cruciplacolithus edwardsii*, *Markalius astroporus* and *Cyclococcolithus robustus*. *Thoracosphaera operculata* is also present.

The assemblage is assigned to the basal Paleocene biostratigraphic interval immediately below the lowest occurence of *Cruciplacolithus tenuis* (see Table 1). A correlation with the foraminiferal zone late Plb is indicated.

Sample 80DR/014-10, a grey soft calcilutite, was found to contain a very rich moderately well preserved nannofossil assemblage dominated by species of *Cruciplacolithus*, but includes a large number of rare reworked Late Cretaceous species. The assemblage is assigned to the Early Paleocene biostratigraphic DI:**Cruciplacolithus tenuis*/**Ellipsolithus macellus* (see Table 1) on account of the presence of *C. tenuis*. This assignment suggests a correlation with the foraminiferal zone early Plc.

Sample 80DR/020-08, a grey, friable calcilutite that was dredged from the northeastern wall of the canyon, was found to contain a moderately well preserved assemblage with *Chiasmolithus bidens*, but without species of *Fasciculithus* and *Sphenolithus*. Reworked Upper Cretaceous forms are very rare and apparently confined to a few species. The assemblage is assigned to the Early Paleocene biostratigraphic DI:**Chiasmolithus bidens*/**Fasciculithus tympaniformis* which correlates mainly with the forminiferal zone P2.

The three samples examined above are thought to represent a unit (or possibly two) 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 possibilities regarding this Lower Paleocene unit(s): (a) being a new unit(s) separate from the Kings Park Formation, or (b) being 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.

<u>Late Paleocene-Early Eocene</u> (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 (Plate 32) are assignable to at least five nannofossil biostratigraphic datum intervals, being bracketed by the lowest occurrence of *Toweius pertusus* and highest occurrence of species of *Fasciculithus*. Table 1 shows that these assemblages seem to represent a continuous nannofossil biostratigraphic sequence which may be equated with the foraminiferal zonal interval P4 - early P6b. Consequently, they are regarded as being from the offshore equivalent of the Kings Park Formation, notwithstanding that some of these assemblages are slightly older than those recorded by Shafik (1978) from occurrences of the formation onshore. Reworking from Cretaceous sources is minimal, and only a few samples were found to contain evidence for it. The assemblage from sample 80DR/014-8 includes a few reworked Upper Cretaceous species, but the exceptionally high abundance of *Placozygus sigmoides* in this assemblage suggests a possible reworking from a Lower

Paleocene source as well.

Only one assemblage is possibly Early Eocene in age. This was recovered from sample 80DR/020-6 and is assigned to the (broad) Late Paleocene - Early Eocene DI:**Campylosphaera eodela/+Fasciculithus* spp. (Table 1), on account of uncertainty regarding the presence of typical *Discoaster diastypus*. However, the occurrence of *Fasciculithus involutus* and *Transversopontis pulcher* in the presence of *Discoaster multiradiatus* and *Campylosphaera eodela* suggests a very close level to the base of the Eocene. The assemblages of the other samples are Late Paleocene in age (see, Table 1).

The warm-water species of the genus *Discoaster* are either rare or absent below sample 80DR/017-3, which marks the lowest occurrence of *Discoaster multiradiatus* in Table 1. Individual specimens of the species of the genera *Chiasmolithus* and *Cruciplacolithus*, which are thought as more suited to cold surface waters, are abundant in most of the assemblages below sample 80DR/017-3, as stacked in Table 1. These two observations suggest that for most of the Late Paleocene, surface waters were cold in the Perth Basin. On the other hand, 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. Based on evidence from the onshore Kings Park Formation, Shafik (1978) reached a similar conclusion: surface waters in the Perth Basin were cold during most of the Late Paleocene, becoming warmer during the Latest Paleocene to Earliest Eocene interval.

Pentaliths (such as *Braarudosphaera bigelowii* and *Micrantholithus* spp.) and other hemipelagic species (such as *Hemiholithus kerabyi* or *Zygrhablithus bijugatus*) are common in most of the assemblages, suggesting that the offshore equivalent of the Kings Park Formation was deposited on the shelf and/or in a nearshore environment; this is consistent with the conclusion reached by Shafik (1978) based on evidence from onshore occurrences of the formation. Possible present-day minimum and maximum water depths from which the sediments bearing these assemblages could have been recovered are 730 and 3000 metres.

Most of the samples, referred to in Table 1 as representing the offshore equivalent of the Kings Park Formation, are grey calcilutites, varying mainly in their degree of induration. The remainder are grey calcarenites. Thus the Kings Park Formation becomes much more calcareous offshore, as would be expected. It should be noted that the three samples from the Lower Paleocene unit (discussed above) are grey calcilutites, thus favouring the option that it is an older phase of the Kings Park Formation.

The terrigenous aspect of the type section of the Kings Park Formation was viewed by Shafik (1978) as a result of a high rate of sedimentation, the supply being a highland close by. This also explains the uniformity of the microfauna and microflora and the great thickness of the formation in the Perth Metropolitan area. Evidently, the terrigenous components, thought to be contributed by a river system (Shafik, 1978), did not reach the depositional sites occupied presently by the Fremantle Canyon, where the formation is highly calcareous.

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

In this report, the disappearance (highest occurrence) of species of the genus *Fasciculithus* is taken as a good working criterion for the base of the Eocene in the absence of *Tribrachiatus bramlettei* and typical *Discoaster diastypus*. Nannofossil assemblages, representing the Early to (early) Middle Eocene time slice, are based on a large number of samples which were collected from nine dredge stations; the youngest sample being 80DR/019-4 (see Table 2). These seem to form a continuous nannofossil biostratigraphic sequence consisting of five biostratigraphic units. The sequence is bracketed by the disappearance of *Fasciculithus* spp. and the appearance of *Nannotetrina fulgens* (see, Table 2). This nannofossil biostratigraphic sequence may be correlated with the foraminiferal zonal interval P6b - P10.

The oldest unit in the sequence is based on three samples (80DR/018-1, 80DR/014-14 and 80DR/020-7) of grey, soft to fariably cemented calcilutite, which were collected from the northern, southern and northeastern walls of the Fremantle Canyon. This unit predates the lowest occurrence of the index species *Tribrachiatus orthostylus* (see Table 2), and may be characterised by the presence of several Eocene-originated species (such as *Chiasmolithus eograndis*, *C. grandis*, *Cyclococcolithus formosus*) among a suite of Paleocene-originated species (such as *Ellipsolithus macellus*, *Toweius pertusus* and *T. magnicrassus*). The presence of forms transitional between *Discoaster multiradiatus* and *D. barbadiensis* is noted in this unit. A correlation with the foraminiferal zone P6b is indicated (see table 2). Very scarce reworked Cretaceous forms were noted among the assemblages of this unit (Plate 33)

The next higher biostratigraphic unit in the sequence, also based on three samples (80DR/020-5, 80DR/017-1 and 80DR/003-6), consist of chalky and friably cemented calcilutites which were dredged from the continental slope north of Perth and from the northeastern wall of the Fremantle Canyon. Two other samples (80DR/003-1 and -9) of fairly well cemented calcarenite, which were obtained from the continental slope north of Perth, are questionably included in this unit. The reason for the uncertainty is the poor preservation of the already rare fossils in these two samples; signs of recrystalization are evident by the presence of abundant calcite rhombs in the preparations examined. Assemblages of this biostratigraphic unit predate the lowest occurrence of *Discoaster lodoensis*, and is characterised by the presence of the index species *Tribrachiatus orthostylus* (Table 2). Forms transitional between *Discoaster multiradiatus* and *D. barbadiensis* persist in this unit. Specimens of the genus *Discoaster* are appreciably more than those of the genera *Chiasmolithus* and *Cruciplacolithus*, particularly in sample 80DR/017-1, suggesting some warming during the Early Eocene time slice of the 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.

The next biostratigraphically higher unit in the sequence is an assemblage recovered from sample 80DR/003-2, a greenish grey, glauconitic calcarenite, which was dredged from the continental slope north of Perth. This assemblage was found to contain the index species *Discoaster lodoensis*, without *D. sublodoensis*.

Based on the available data, it may be concluded that by far the most widespread nannofossil biostratigraphic Eocene part of the offshore Perth Basin's Lower to basal Middle Eocene sequence is that based on the many assemblages containing *Discoaster sublodoensis*. This key species was found in the two highest biostratigraphic units of the sequence. The youngest of these units, being discriminated by containing *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. The nannofossil assemblage of 80DR/019-4 can be correlated with the Middle Eocene foraminiferal zone P10, whereas the assemblages from the older biostratigraphic unit (with *Discoaster sublodoensis*) is correlated with the Early Eocene foraminiferal zone P9.

The biostratigraphic unit with *Discoaster sublodoensis* and without *Rhabdosphaera inflata* is based on assemblages in six samples of grey calcarenite and calcilutite which were dredged from the southern and northeastern wall of the Fremantle Canyon and from the continental slope north of Perth. Of these, the assemblage in sample 80DR/023-1C is of particular interest as 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* are not known to overlap. Other members of the assemblage in sample 80DR/023-1C (such as *Cyclicargolithus gammtion*, *Camylosphaera dela*, *Discoasteroides kuepperi*, *Discoaster lodoensis*, *Lophodolithus* and *Reticulofenestra dictyoda*) are those which are usually present in the biostratigraphic DI:**D.sublodoensis/*Rhabdosphaera inflata*.

The Early to early Middle Eocene biostratigraphic sequence discussed above evidently has no counterpart in known onshore sections. Assemblages from the basal part of the Porpoise Bay Formation in the onshore sequence (data *in* Shafik, 1978) is referable to the biostratigraphic DI:**Reticulofenestra umbilica/*Cyclicargolithus reticulatus* and the slightly younger DI:**Cyclicargolithus reticulatus/*Reticulofenestra scissura*, both correlate with the foraminiferal zonal interval late P12 - early P13 (see Table 2). These levels are substantially younger than the youngest level in the Lower-Middle Eocene sequence discussed above. This sequence, therefore, is considered to represent a new unit yet to be named. Seemingly, this unnamed new unit, consisting of calcilutites and calcarenites, is widely occurring. The evidence suggests that it is exposed at many locations along the walls of the Fremantle Canyon and also on the continental slope north of Perth.

Middle Eocene (Porpoise Bay Formation equivalent)

Several Middle Eocene assemblages were extracted from samples obtained from four dredge stations along the walls of the Fremantle Canyon.

Sample 80DR/019-1, a grey, soft calcilutite from the southwestern wall of the canyon yielded a particularly well preserved assemblage. This included the key Middle Eocene species *Nannotetrina fulgens* and abundant *Chiasmolithus* spp. but not *C. gigas*. Table 2 shows that the vertical range of *C. gigas*, being short, is used to subdivide the biostratigraphic interval between the lowest occurrence of *Nannotetrina fulgens* and *Reticulofenestra umbilica* into three biostratigraphic divisions. It is difficult to determine whether the assemblage of 80DR/019-1 belongs to the biostratigraphic division below or above the range of *Chiasmolithus gigas*. However, this assemblage can be correlated with the foraminiferal zone P11.

Samples 80DR/019-3 and 80DR/018-2, grey, well cemented calcilutites from the southwestern and southern walls of the canyon, yielded moderately well preserved assemblages which include species of the Middle Eocene *Nannotetrina* and forms of *Reticulofenestra* approaching the typical *R. umbilica*. These assemblages are tentatively placed in the biostratigraphic DI:**Reticulofenestra umbilica/*Cyclicargolithus reticulatus* (foraminiferal zone P12). Deposition was on the shelf as indicated by the presence of several species including *Zygrhablithus bijugatus crassus*.

Specimens of *Chiasmolithus solitus* are abundant in the assemblage of 80DR/019-3, exceeding those of species of *Discoaster*. This suggests conditions for cold surface-waters.

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, are diversified containing the index species *Cyclicargolithus reticulatus* (Plate33). These assemblages are assigned to the biostratigraphic DI:**Cyclicargolithus reticulatus/*Reticulofenestra scissura* and a correlation with the foraminiferal zonal interval late P12 - early P13 can be made (see Table 2). A large number of Upper Cretaceous nannofossil species were found among these assemblages, suggesting a substantial reworking episode from a Cretaceous source. This contrasts with the levels above and below where reworked nannofossils are either non-existent to very minor or from Paleocene rather than Upper Cretaceous sources.

Species indicative of deposition on the shelf or in a nearshore environment, being usually restricted to hemipelagic sediments, are common in the assemblages of 80DR/008-2, 80DR/013-1 and 80DR/09-1. These include *Braarudosphaera bigelowii*, *Daktylethra punctulata*, *Lanternithus minutus*, *Micrantholithus procerus*, *Pemma papillatum*, *Pontosphaera plana* and *Zygrhablithus bijugatus crassus*.

With the exception of the basal one metre, nannofossil content of the lower part of the type section of the Porpoise Bay Formation is known (data *in* Shafik, 1978). It equates well with the assemblages of samples 80DR/008-2, 80DR/013-1 and 80DR/009-1. The older Middle Eocene assemblages of samples 80DR/019-1, 80DR/019-3 and 80DR/018-2 either equate with the basal one metre, or have no counterparts in the type section of the Porpoise Bay Formation, being older. The assemblage of sample 80DR/019-4, dated as earliest Middle Eocene, is still older than the assemblage of sample 80DR/019-1. It is thought that the assemblage of sample 80DR/019-4 represents the upper part of an unnamed (mainly Lower Eocene) unit, underlying the offshore equivalent of the Porpoise Bay Formation.

The the type section of the Porpoise Bay Formation is a brown calcareous shale and siltstone, whereas the offshore equivalent of the formation (samples 80DR/008-2, 80DR/013-1 and 80DR/009-1) apparently is a sequence of calcarenites and calcilutites. Evidently, the formation becomes more calcareous offshore, and probably cannot be discriminated from the overlying carbonates (the chalk and calcarenite of the type section) of the Challenger Formation.

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, Shafik (1985) indicated a significant reworking episode which was linked to some important events such as a major acceleration in the spreading rate south of Australia. The occurrence of a large number of reworked Upper Cretaceous nannofossils in the offshore equivalent of the Porpoise Bay Formation (samples 80DR/008-2, 80DR/013-1 and 80DR/009-1) confirms the wide geographic evidence of that reworking episode.

Late Eocene (Challenger Formation equivalent)

Sample 80DR/014-11, a grey, fairly well cemented calcilutite, which was dredged from the northern wall of the Fremantle Canyon, yielded a poorly preserved Late Eocene nanofossil assemblage. The age of Late Eocene is based on the co-occurrence of the index species *Chiasmolithus oamaruensis* and *Cyclicargolithus reticulatus*. Signs of dissolution abound in several preparations examined from the sample, and some reworking from Paleocene sources was detected. Neither *Neococcolithes dubius* nor the index species *Isthmolithus recurvus* was encountered. The 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 assumes the absence of *Neococcolithes dubius* as due to preservational factors, whereas the latter assumes the absence of *I. recurvus* as an exclusion due to ecological factor, such as a possible warming. The presence of *Sphenolithus pseudoradians*, although somewhat tenuous as evidence for a warming, is undeniable. Specimens of *Discoaster saipanensis* exceed in number those of *Chiasmolithus oamaruensis* favouring a possible warming. It must be noted, however, that heavily-calcified *Isthmolithus recurvus* was encountered frequently in a seemingly younger assemblage from another sample (80DR/014-4) which came from the same dredge haul.

The nannofossil assemblage of 80DR/014-11 can be correlated with the foraminiferal zone P16, nevertheless (see Table 2). This correlation indicates that sample 80DR/014-11 came from the Challenger Formation.

The presence of *Lanternithus minutus*, *Pontosphaera plana* and *Zygrhablithus bijugatus* suggests that deposition was on the shelf and/or in a nearshore environment. 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, seemingly did not occur uniformly throughout this sample which shows some bedding.

Latest Eocene-Early Oligocene (?Challenger Formation equivalent)

Sample 80DR/014-4, a white, moderately cemented and partly dolomitic chalky calcilutite which was dredged from the northern wall of the canyon, yielded a moderately to poorly preserved nannofossil assemblage (Plate 33). Discoasters are relatively rare and mostly heavily calcified. The assemblage is dominated by *Reticulofenestra scissura* and *R. umbilica*. The holococcolith taxa *Zygrablithus bijugatus* and *Lanternithus minutus* are fairly common. The key species *Isthmolithus recurvus* is frequent, but all specimens encountered are heavily calcified. The absence of the rosette-shaped discoasters (*Discoaster* *barbadiensis* and *D. saipanensis*) and the index species *Cyclicargolithus reticulatus*, in the presence of others key species such as *Reticulofenestra hampdenensis*, *Isthmolithus recurvus* and *Cyclococcolithus 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 may be assigned to the biostratigraphic DI: *+Cyclicargolithus reticulatus/+Reticulofenestra hampdenensis*, which spans the Latest Eocene and Earliest Oligocene (see Table 2).

The depositional environment is similar to that deduced for the Upper Eocene sample 80DR/014-11, based on a similar evidence of *Lanternithus minutus* and *Zygrhablithus bijuatus*.

Data in Quilty (1978) and in Shafik (1978) suggests that the foraminiferal and/or nannofossil content of the lower part of the type sections of both the Challenger and Porpoise Bay Formations is known, but not so for the upper parts of either formations. It is worth noting that more than 100 metres of sediment in the upper part of the type section of the Porpoise Bay Formation has not been studied, and their calcareous microfossil content is unknown. In Table 2, the Middle/Upper Eocene boundary is arbitrarily used as the demarcation between equivalents of the Porpoise Bay and Challenger Formations. However, the lithological evidence suggests that the two formations merge into one unit offshore. Sample 80DR/014-4 is likely to have come from the upper part of this (combined Porpoise Bay and Challenger Formations) unit.

<u>"Mid" Oligocene</u> (no known onshore equivalent)

Sample 80DR/022-4, a whitish soft calcilutite with abundant siliceous spicules, which was dredged from the base of the southern wall of the canyon, yielded a rich moderately well-preserved nannofossil assemblage; some signs of partial dissolution are evident and discoasters are overgrown with secondary calcite. Some reworking from Eocene source(s) is detected. The assemblage includes *Chiasmolithus altus*, (reworked) *C. eograndis*, *Coccolithus eopelagicus*, *Cyclicargolithus abisectus*, *C. floridanus*, (reworked) *Cyclococcolithus 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 *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 Berggren and others (1985), this association of key species may be correlated with the foraminiferal zone P21a. Deposition was on the shelf and/or in a nearshore environment, as evidenced by the presence of *Zygrhablithus bijugatus*.

Biostratigraphic studies on the Tertiary of the Perth Basin (e.g. Quilty, 1974a, b) suggest a significant biostratigraphic gap in the onshore marine record, between the Upper Eocene Challenger Formation and the Lower to Middle Miocene Stark Bay Formation. Sediments of Oligocene age are missing. Sample 80DR/22-4, containing late Early Oligocene nannofossil assemblage, can be regarded as representing an unnamed new unit.

Early Miocene (Stark Bay Formation)

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

Sample 80DR/007-3, a slightly dolomitic, friably 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 procerus* and *Sphenolithus moriformis*. Severely etched specimens of *Pontosphaera* were also noted.

The association of *Calcidiscus leptoporus*, *Helicophaera kamptneri*, *H. euphratis*, *Cyclicargolithus abisectus* and *C. floridanus* in the 80DR/007-3 assemblage 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 dominantly dolomitic 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 with the foraminiferal zone N7 according to data in Berggren and others (1985). Other nannofossils identified in 80DR/007-2 are *Braarudosphaera bigelowii*, *Calcidiscus leptopora* and *Cyclicargolithus floridanus*. Deposition was on the continental shelf and/or in a nearshore environment as evidenced by the presence of *Braarudosphaera bigelowii*.

Quilty (1974b) introduced the Lower to Middle Miocene Stark Bay Formation based on material from several offshore wells. The type section of this formation is in Gage Roads 2, consisting of 215 metres of white, bryozoan and echinodermal calcarenite becoming brown dolomite and chert in places,particularly near the base. It unconformably overlies either Cretaceous sediments or the Kings Park Formation (Quilty, 1974b). Diagnostic foraminiferal species are abundant in places, mostly indicating zones N8 and N9, but based on *Globorotalia barisanensis* and *Globigerina woodi woodi* at the bottom of the formation in one section, zone N7 was suspected (Quilty, 1974b).

As indicated above the nannofossil assemblage of sample 80DR/007-2 may be correlated with the foraminiferal zone N7, and therefore can be roughly equated with the bottom of the Stark Bay Formation in Gage Roads 1, which was studied by Quilty (1974b). The other two Lower Miocene samples are probably older than sample 80DR/007-2, but lithologically similar to the Stark Bay Formation.

Appendix 5: Age determinations and description of foraminiferal assemblages

80DR/003

Sample 1.
Age: Indeterminable (no foraminifera seen)
Comments: Hard recrystallised limestone, with trace quantities of radiolaria (recrystallised). No foraminifera released from matrix or seen on rock faces, although some possibly recrystallised tests are relic fauna.

Sample 2.
Zone: Lower P11 to P10 (lower T11-upper T10)
Age: Middle Eocene
Environment: possibly outer shelf
Comments: Siliceous calcisiltite with recrystallised spicules and radiolaria. The sparse, dominantly planktonic foraminiferal fauna are mostly long-ranging species. Benthos is rare, thus hindering an environmental interpretation. Age determined on the basis of the overlap of *Morozovella bullbrooki*, *Planorotalites australiformis*, *P. planoconica*, and *Subbotina frontosa*.

Sample 3.
Zone: P11 (T11a)
Age: Middle Eocene
Environment: questionable outer shelf to upper bathyal
Comments: White limestone with patches of hard grey chert(?). Only a small part of the sample has broken down, but this yielded a moderate number of planktonic foraminifera; also sponge spicules and rare bone chips. Age based on overlapping ranges of *Truncorotaloides* spp., *Planorotalites australiformis*, abundant *Morozovella bullbrooki*, and a single specimen of *Morozovella aragonensis*. Based on McGowran's work on the Ninety East Ridge, the assemblage can be assigned to P11. The environment is questionable only because virtually no benthonic species were found; the planktonic abundance suggests relatively deep water.

Sample 4.
Zone: P11?
Age: Middle Eocene?
Comments: Hard cream-grey calcilutite with saccharoidal dolomite? crystals disseminated throughout. Almost no foraminifera present, even in broken down portion of processed sample. Specimens are very poorly preserved, with crystal overgrowths that make identification very dubious. Age determination was based on single specimens of *?Turborotalia cerroazulensis pomeroli* and *?Planorotalites planoconica*. The situation is complicated by contamination from Pleistocene to Recent faunas.

Sample 5.
Age: Indeterminable
Comments: Lithology similar to that of Sample 4, but it contains only a handful of very poorly preserved foraminifera; all indeterminable.

Sample 6.
Zone: P6b (T8)
Age: Earliest Eocene
Environment: outer shelf to ?upper bathyal; warm water interval

Formation: Kings Park Fm
Comments: Chalky calcilutite with small foraminiferal residue, but well-preserved specimens. The assemblage consists predominantly of *Acarinina* spp. and *Subbotina* spp., with a moderate number of keeled *Morozovella* spp. suggesting warmish water. Age based on the presence of *Morozovella aequa*, *M. marginodentata*, *M.* cf. *lensiformis*, *M.* cf. *wilcoxensis*, *Planorotalites australiformis* and *Acarinina collactea*, and the absence of Paleocene indicator species. Benthonic species are extremely rare, and the environment is difficult to determine.

Sample 7.
Zone: undifferentiated P12 to P10
Age: Middle Eocene
Environment: outer shelf (at least)
Formation: Porpoise Bay Formation equivalent
Comments: White calcisiltite, moderately hard and recrystallised, with sponge spicules and recrystallised radiolaria; rare foraminifera, all planktonic, mostly *Acarinina* and *Subbotina*. The overlap of rare *Planorotalites australiformis* and ?*Truncorotaloides* cf. *topilensis* make a Zone P11 age most likely, but the preservation is extremely poor and the identification of *T.* cf. *topilensis* cannot be confirmed. An age as old as Early Eocene is not out of the question.

Sample 8.
Zone: P11 (T11a)
Age: Middle Eocene
Environment: ?outer shelf to ?uppermost slope
Formation: Porpoise Bay Formation equivalent
Comments: The small washed residue consists mostly of foraminifera, with rare sponge spicules, sparse bryozoan and echinoderm fragments, rare mollusc fragments and a little glauconite. The foraminiferal assemblage is totally dominated by *Acarinina* and *Subbotina*, with index species extremely rare. The age is based on the overlap of *Morozovella aragonensis* and *Truncorotaloides topilensis*, following McGowran (1978) and North West Shelf distributions. The presence of extremely rare specimens, identified as *Morozovella lensiformis* and *M.* cf. *formosa* (?*spinulosa*) gives an Early Eocene aspect to the *Morozovella* assemblage which is at odds with the presence of definite *Truncorotaloides*. The Middle Eocene age is, however, felt to be reliable.

Sample 9.
Zone: undifferentiated P11-P6b
Age: undifferentiated early Middle Eocene to Early Eocene
Comments: Hard white limestone with traces of recrystallised radiolaria and glauconite. Almost no foraminifera present, and these are poorly preserved. No short-ranging index species.

<u>80DR/004</u>
Fremantle Canyon

Sample 1.
Zone: P4 (probably T4)
Age: Late Paleocene
Environment: Shelf, probably middle to outer
Formation: Kings Park Formation
Comments: Calcarenite, skeletal and bioclastic, heavily recrystallised and cemented. Moderately common, but poorly preserved foraminiferal fauna, mostly juvenile *Acarinina*. Benthonic species are moderately

common; *Cibicides* and other shelf genera dominate. Rare miliolids. Age is based on *Planorotalites chapmani, P. pseudomenardii,* and *P. imitata.*

Sample 2.
Zone: P4 (T4)
Age: Late Paleocene
Environment: Shelf, probably outer
Formation: Kings Park Formation
Comments: Siliceous calcarenite composed of siliceous sponge spicules, radiolaria, diatoms, calcareous foraminifera and fine sand-size bioclasts. Planktonic foraminifera are abundant, but only *P. chapmani*, which is common, approaches the normal size for adult specimens; other species are diminutive. No keeled *Morozovella* sp. are present. Benthonic assemblages are diverse, but most specimens are small; many small *Cibicides*-like forms. Preservation is very good.

Sample 3.
Zone: P4
Age: Late Paleocene
Environment: Shelf, probably outer
Formation: Kings Park Formation
Comments: Calcarenite, moderately cemented, but porous. Planktonic foraminifera are poorly preserved, being heavily overgrown with drusy calcite(?) cement. Assemblage is not particularly diverse, except with respect to diminutive *Cibicides* among the benthos. Age is based on *Planorotalites chapmani* and *P. pseudomenardii.*

<u>80DR/005</u>

Sample 7.
Zone: P4
Age: Late Paleocene
Environment: probably upper bathyal, based on high planktonic percentage
Formation: Kings Park Formation
Comments: Indurated light grey calcarenite with glauconite and trace sponge spicules. Most of the rock is composed of planktonic foraminifera (*Subbotina* and *Acarinina*) in a very poorly preserved condition, heavily encrusted. Few specimens can be definitely identified. Age is based on *Planorotalites chapmani* and *P. pseudomenardii.*

Sample 8.
Zone: P4
Age: Late Paleocene
Environment: outer shelf to upper bathyal
Formation: Kings Park Formation
Comments: Age based on *P. chapmani* and *P. pseudomenardii.*

Sample 9.
Zone: P4 (T4)
Age: Late Paleocene
Environment: outer shelf to upper bathyal
Formation: Kings Park Formation
Comments: Chalky calcilutite, glauconitic, richly foraminiferal. There is a diverse and well preserved benthonic assemblage, but the fauna as a whole is dominated by planktonic species, largely *Subbotina* and *Acarinina*. Age is based on *Planorotalites chapmani* and *P. pseudomenardii.*

80DR/007
Fremantle Canyon, eastern end

Sample 1.
Zone: *Globigerinoides trilobus* of Jenkins (1986) - N5-N7
Age: Early Miocene
Environment: outer shelf
Formation: possibly an older extension of the Stark Bay Formation, or else a new unit
Comments: Chalky calcisiltite with some siliceous spicules. Calcareous clasts have a heavy drusy overgrowth. There is a very sparse, badly preserved planktonic foraminiferal assemblage that is almost entirely *Globigerinoides* (mostly *G. trilobus*). Of note is the presence of *Globorotalia zealandica* in this sample. The environment is based partly on a high planktonic percentage, and partly on the presence of *Cibicides* spp. in association with *Karreriella* sp. and *Melonis pompilioides*.

Sample 2.
Zone: probably G. trilobus (N5-N7)
Age: probably Early Miocene
Environment: shelf, middle to outer
Formation: ?Stark Bay Formation
Comments: Indurated limestone, but with high porosity; abundant sponge spicules. Foraminifera are sparse and badly preserved; the fauna consists almost entirely of *Globigerinoides*, mostly *G. trilobus*. Presence of *Globorotalia conica* (Middle Miocene according to Jenkins (1986)) is anomalous. There is no other indication of Middle Miocene species or of *Praeorbulina bioseries*, so an Early Miocene age is preferred.

Sample 3.
Zone: N5
Age: Early Miocene
Environment: upper bathyal, with possible downslope movement of shelf species
Formation: Samples from this dredge are somewhat older than the Stark Bay Formation, and could possibly represent a new unit. There is insufficient evidence to indicate whether a conformable sequence is developed from the Early Miocene (N5) present here, to the Mid-Miocene (N8-9) Stark Bay Formation documented by Quilty (1974 a,b, 1978).
Comments: A richly foraminiferal sample with diverse planktonic and benthonic species, but they are not very well preserved. The diversity is in strong contrast to the other two samples in this dredge haul. Deep-water species present here include *Laticarinina pauperata*, *Planulina* cf. *ariminensis*, *Melonis pomilioides*, *Karreriella* cf. *bradyi* and *Martinotiella* cf. *communis*. *Laticarinina* is a bathyal-abyssal species, not found above 300 m; the other species are found in outer neritic to upper/middle bathyal depths. Additionally, many small shelf rotalids are present, which have possibly moved downslope. The age is based on the overlapping ranges of *Globigerina binaiensis*, *Globigerinoides altiaperturus*, *G. quadrilobatus*, and *Turborotalia peripheroronda* var.

80DR/008

Sample 1.
Zone: approx. P14 (*T. rohri* zone of Beckmann and others, 1981)
Age: latest Middle Eocene
Environment: upper bathyal
Formation: Challenger Formation
Comments: Siliceous calcilutite, with a trace of glauconite. Abundant, somewhat recrystallised siliceous spines, spicules and radiolaria. The abundant and well-preserved foraminifera consist of relatively common *Acarinina primitiva* and *Globigerinatheka index* in a *Subbotina/Acarinina*-dominated assemblage. The co-occurrence of *A. primitiva*, *Turborotalia cerroazulensis cocaensis*, and *T. cerroazulensis* defines the age as approximately P14. One specimen of *Planorotalites australiformis* is anomalously young. This is an important sample for zonal purposes and for filling one of the 'gaps' in the sequence as reported by Quilty (op. cit.). There is a very sparse benthonic assemblage, but *Vulvulina pennatula* is significant.

Sample 2.
Zone: probably P12 (probably T11b)
Age: Middle Eocene
Environment: undifferentiated outer shelf to upper bathyal
Formation: Porpoise Bay Formation equivalent
Comments: Indurated calcisiltite with common siliceous spicules and a trace of glauconite. The very sparse foraminiferal assemblage when released from the hard matrix is almost all planktonic. The age is based on *Acarinina primitiva*, *Globigerinatheka* cf. *kugleri*, *Morozovella bullbrooki*, *Truncorotaloides* cf. *topilensis* (= *?pre-topilensis* of McGowran), *Turborotalia cerroazulensis pomeroli*, *Planorotalites pseudoscitula*, and *Morozovella spinulosa*. The occurrence of one specimen of *Hantkenina primitiva* in this Middle Eocene sample is at variance with its Late Eocene occurrence recorded elsewhere in southern Australia by McGowran. There are very few benthonic foraminifera on which to base an environmental interpretation.

80DR/009

Sample 1.
Zone: P12 (T11b)
Age: Middle Eocene
Environment: probably outer shelf to uppermost bathyal
Formation: Porpoise Bay Formation equivalent
Comments: Chalky calcilutite with some coarse quartz grains and siliceous spines. The age is based on overlapping ranges of *Morozovella bullbrooki*, *Subbotina frontosa*, *Turborotalia cerroazulensis pomeroli*, *Globigerinatheka* cf. *index*, common *Acarinina primitiva*, and the absdiolaria. Sparse and poorly preserved foraminiferal fauna, consisting mostly of *Cibicides* spp. and *Pseudohastigerina micra*.

80DR/014

Sample 2.
Age: indeterminable
Comments: Hard light grey calcilutite with some sponge spicules and rare planktonic foraminifera visible on broken rock surfaces. The sample has not broken down in processing and no age determination is possible.

Sample 3.
Zone P4
Age: Late Paleocene
Environment: probably upper bathyal?
Formation: Kings Park Formation
Comments: Moderately hard chalky calcilutite, little broken down in processing, and only a small amount of fauna was recovered. Foraminiferal assemblage is dominated by *Subbotina triloculinoides* and *Planorotalites pseudomenardii*. Almost no benthonic specimens seen, and the environmental interpretation is based solely on the high planktonic percentage.

Sample 4.
Zone:??
Age: ?very late Middle Eocene
Environment: possibly upper bathyal?
Formation: This appears to fall in the 'gap' between the Late Eocene Challenger Fm and the Middle Eocene Porpoise Bay Fm (see also 80DR/008-1). However, the age needs to be verified by further work before this sample could be assigned to a formation.
Comments: A hard calcilutite which has yielded only a small amount of disaggregated foraminiferal fauna. The assemblage is of low diversity and significant index species are lacking. The assemblage is dominated by "Globigerinids", specifically *Globigerina ampliapertura* and *Turborotalia increbescens*, normally seen only in Late Eocene and younger assemblages. Against this evidence is the presence of very rare *Acarinina primitiva* and *A. pseudotopilensis*, which have their range tops in the Middle Eocene. No specimens of *Globigerinatheka* spp. or the *Turborotalia cerroazulensis* group (other than cf. *pomeroli*) were found, so that a zonal assignment is extremely difficult. An age just below the Late/Middle Eocene boundary seems most likely. However, confirmation from nannoplankton is really required. Because of the uncertainty of the present age determination, the sample cannot be assigned to a formation with any certainty. The environmental interpretation is based on the overwhelmingly planktonic nature of the foraminiferal assemblage; only four benthonic specimens were found.

Sample 5
Age: ?Late Campanian-?Maastrichtian (definitely Late Cretaceous)
Environment: probably shelf.
Formation: probably Lancelin Formation.
Comments: Glauconitic white limestone with quartz silt and recrystallised ?radiolaria. Extremely rare foraminifera, very badly preserved, broken, and replaced by diagenesis. Two hours' picking yielded only some 30 specimens, most indeterminable. One *Gublerina cuvillieri* suggests an age of Late Campanian to Maastrichtian. A moderate number of benthonic specimens (about equal to planktonic ones) suggest shelf water depths. Trace of probable Recent contamination.

Sample 6
Zone: P12 - P14
Age: Middle Eocene
Environment: ?deep (bathyal?)
Formation: Challenger or Porpoise Bay Formation
Comments: Much the same fauna as Sample 9, but foraminifera are even rarer. No benthonic specimens seen.

Sample 7
Zone: P14 equivalent
Age: topmost Middle Eocene
Environment: upper bathyal
Formation: Challenger Formation
Comments: Rich foraminiferal fauna in chalky white limestone, dominated by large *Globigerinatheka index*; also a moderate number of large *Hantkenina*. *Globigerina ampliapertura* common. Essentially a Late Eocene-looking fauna, with very rare angular-truncate *Acarinina*, indicating topmost Middle Eocene. This fauna appears to be almost identical to Quilty's (1978) Challenger 1 sample at 567-597 m, which he labelled "Late Eocene, P15/16". There appears to be no foraminiferal basis for this age, as the species present range from the Late Eocene into the Middle Eocene (see for example, Beckmann and others, 1981). Most authors now place the top of the Middle Eocene at the top of zone P14, at the extinction of angular-truncate Acarininids. Of these, *Acarinina (Pseudogloboquadrina) primitiva* is listed by Quilty, and *A. pseudotopilensis* is present here. Thus it would appear that the section in Challenger 1 well ranges down into the Middle Eocene. As this is the type section for the Challenger Formation (Cockbain and Hocking, 1989), it follows that the Challenger Formation ranges at least from latest Middle Eocene to Late Eocene in age.

Sample 8
Zone: probably very low P4 (low T4) with reworking
Age: probably Late Paleocene
Environment: probably outer shelf
Formation: Kings Park Formation
Comments: The age is based on very rare Late Paleocene species: one *Planorotalites pseudomenardii*, one *Morozovella angulata*, and rare *Acarinina conicotruncata*. The bulk of the assemblage is *Subbotina pseudobulloides*, *Globoconusa daubjergensis*, and *S. triloculinoides*. This sample is interpreted as having undergone massive reworking from the Early Paleocene; also rare reworking from Late Cretaceous. See sample 10.

Sample 9
Zone: P14 equivalent
Age: topmost Middle Eocene
Environment: ??bathyal
Formation: Challenger Formation
Comments: Hard limestone which has released few foraminifera. Essentially the same fauna and comments as for sample 7.

Sample 10
Zone: T1 (=latest P1 to earliest P2)
Age: Early Paleocene
Environment: bathyal
Formation: new unit
Comments: Well-preserved assemblage, mostly less than 100 microns in size, containing around 50 percent *Globoconusa daubjergensis*, on which the zone is based. Next in abundance are *Subbotina pseudobulloides*; other species including *Subbotina triloculinoides* are uncommon. This sample level may well the the source of the reworking seen in Sample 8. Sparse Late Cretaceous specimens indicate reworking. *Nuttallides truempyi*, plus a high planktonic percentage, indicate bathyal water depths.

Sample 11
Zone: P14 equivalent
Age: latest Middle Eocene
Environment: probably deep
Formation: Challenger Formation
Comments: Chalky white limestone with common *Subbotina* and *Globigerinatheka*. Same assemblage as sample 7; see comments that sample.

Sample 12
Zone: T1 (=late P1 - early P2)
Age: Early Paleocene
Environment: probably deep
Formation: new unit
Comments: Hard white siliceous calcilutite, containing a very rare foraminiferal assemblage of diminutive specimens. Rock fractured, with crystalline healing of fractures. Age based on *Globoconusa daubjergensis* and *Planorotalites compressa*. No evidence for water depth, but all specimens recovered are planktonic. Formation is a new unit, not reported before from the Perth Basin.

Sample 13
Age: ?possibly Early Eocene
Environment: middle to outer shelf
Comments: Washed residue of sample consists of diminutive foraminifera, silt-sized glauconite, and some echinoderm spines. All foram specimens are tiny, and size sorting seems likely. The abundance of *Acarinina collactea*, *Morozovella convexa* and *Planorotalites pseudoscitula* suggests an Early Eocene age, but no zonal index species were found. Possible reworking from Paleocene and Late Cretaceous. Moderately diverse benthonic assemblage.

Sample 14
Zone: probably P6b
Age: probably Basal Eocene
Environment: bathyal
Formation: Kings Park Formation
Comments: Abundant, well-preserved foraminiferal assemblage in a chalky, porous calcilutite. Dominantly *Acarinina* and *Subbotina*, with *A. collactea* common. Age based on common *A. collactea*, rare *Morozovella formosa gracilis*, *M. lensiformis*, *M. cf. subbotinae*, *M. cf. aequa*. Needs more work to be certain of zonal assignment. Environment based on diverse assemblage, of which *Nuttallides truempyi* is the most common form.

<u>80DR/016</u>

Sample 2
Zone: lower P4 (T4)
Age: Late Paleocene
Environment: upper bathyal?
Formation: Kings Park Formation
Comments: Indurated calcisiltite with abundant siliceous spicules and radiolaria, and very sparse, badly preserved planktonic foraminifera. Almost no benthonic specimens seen, hence questionable environmental determination. Age based on presence of *Planorotalites chapmani P. pseudomenardii* and *P. ehrenbergi*. Most of the fauna is so badly recrystallised and overgrown with calcite as to be unidentifiable.

Sample 3
Age: Middle to ?Early Eocene
Environment: ?
Comments: A white limestone which has released almost no foraminifera. Very large *Planorotalites australiformis* and small *Acarinina pseudotopilensis* indicate a generalised age. Virtually no benthonic specimens seen.

<u>80DR/017</u>

Sample 1
Zone: probably P6b
Age: probably Basal Eocene
Environment: outer shelf to uppermost bathyal
Formation: Kings Park Formation
Comments: Calcilutite with sparse foraminiferal fauna dominated by *Acarinina mckannai*. Very few *Morozovella* spp; no *Pseudohastigerina*. The presence of *M. aequa* plus *Planorotalites planoconica* suggest Basal Eocene or very late Paleocene. *P. chapmani* s.s. is absent. The zonal determination is somewhat tentative, but the age certainly lies between P4 and P6b. The environmental determination is based on the rare benthic assemblage dominated by *Bulimina* and *Cibicides* spp.

Sample 3
Zone: probably late P3 (probably T3)
Age: Early Paleocene on scheme used here (see Fig.); but some authors include P3 as the lowest zone of the Late Paleocene
Environment: outer shelf
Formation: older than previously recorded for the Kings Park Formation, but possibly the basal part of the offshore extension of the formation.
Comments: Calcilutite with a *Subbotina/Morozovella pusilla* fauna. No *Planorotalites* found, but fine fraction of sample needs more work. Age based on *Acarinina mckannai*, *A. conicotruncata*, *Subbotina pseudobulloides*, *Morozovella pusilla*, *M.* cf. *angulata* and *M.* cf. *uncinata*. Early Pleistocene contamination.

<u>80DR/018</u>

Sample 1
Zone: tentatively P9
Age: tentatively Early Eocene (definitely within Early to Middle Eocene)
Environment: moderately deep (?upper bathyal); but almost no benthonic fauna
Formation: ?new unit; occurs in the gap between the Porpoise Bay Formation and the Kings Park Formation
Comments: Calcisiltite which has released a moderate number of planktonic foraminifera, common spherical recrystallised radiolaria, and rare branching siliceous spines. Foraminiferal assemblage is dominated by large *Subbotina* spp. Very rare index species. Age interpreted from one specimen each of *Morozovella cf. caucasica*, *M. lensiformis*; rare *Morozovella spinulosa/formosa*, *Planorotalites australiformis*, and *?Truncorotaloides* sp. Almost no benthonic specimens found.

Sample 2
Zone: P10-P12 (upper T10-T11b)
Age: Middle Eocene
Environment: outer shelf or upper bathyal
Formation: Porpoise Bay Formation equivalent
Comments: Calcilutite with sparse low diversity *Acarinina/ Subbotina*-dominated fauna. There are very rare specimens of any age significance; the age is interpreted from one specimen of *Subbotina frontosa*, rare *Morozovella bullbrooki*, *M. convexa*, *Planorotalites planoconica*; common *Acarinina primitiva* and *A. pseudotopilensis*. Some Plio-Pleistocene contamination.

80DR/019

Sample 1
Zone: P11
Age: Middle Eocene
Environment: outer shelf or shelf edge
Formation: Porpoise Bay Formation equivalent
Comments: This soft chalky sample has produced a small but superbly preserved residue of sponge spicules, radiolaria, rare diatoms and foraminifera. The foraminiferal assemblage is dominated by planktonic specimens; mostly *Acarinina collactea*, *A. primitiva* and *Subbotina* spp. Virtually no *Morozovella*; very rare specimens of other species. Age defined from overlap of *A. primitiva*, *Planorotalites australiformis*, *Globigerinatheka kugleri* (one specimen) and *G. cf. senni*. Benthonic specimens are rare; dominantly *Bulimina esnaensis*, *Eponides umbonatus*.

Sample 2
Age: probably Eocene
Environment: indeterminable
Comments: Very hard limestone, possibly partly replaced by chert. Almost no fauna released. Age interpreted from 4 specimens of *Pseudohastigerina micra* (Early Oligocene to Eocene).

Sample 3
Zone: probably P11
Age: Middle Eocene
Environment: outer shelf to upper bathyal
Formation: Porpoise Bay Formation equivalent
Comments: Chalky calcilutite, with siliceous spicules leached out; very few foraminifera in a large amount of matrix. Age based on abundant *Acarinina primitiva*, rare *Globigerinatheka senni*, *Planorotalites australiformis*, *P. pseudoscitula* and *Subbotina frontosa*. There are almost no benthonic fauna from which to interpret the environment.

Sample 4
Zone: P9 (T10)
Age: Early Eocene
Environment: probably upper bathyal
Formation: ?new unit (see other samples this age)
Comments: Chalky calcilutite with leached spicules. Sparse but well-preserved foraminiferal fauna, over 99 percent planktonic specimens, largely *Subbotina* and *Acarinina*. There are almost no *Planorotalites*, including *P. australiformis*. Age is based on the presence of *Morozovella caucasica* plus *M. aragonensis*. *M.* "*rex*" morphotypes are anomalous. In DSDP Site 264 on the Naturaliste Plateau, McGowran (1977, p.433) reports similar assemblages between 155 and 163 m.

80DR/020

Sample 5
Zone: P5 to possibly P6b (T6 to possible T8)
Age: Late Paleocene (to possibly Basal Eocene)
Environment: bathyal
Formation: Kings Park Formation
Comments: Moderately indurated chalky calcilutite with well preserved foraminiferal fauna. Abundant small *Planorotalites*, including very rare *P. simplex*, the index species for the top of zone T6, and principal evidence, here, for the Paleocene age preferred for the sample. The planktonic assemblage is diverse. Both the benthonic and planktonic assemblage are very similar to Sample 7, which is definitely Zone T6. Both samples may be from virtually the same level in the sequence.

Sample 6
Zone: P6b - ?P6a (T8 - ?T7)
Age: Basal Eocene (to possibly Uppermost Paleocene?)
Environment: outer shelf to ?uppermost bathyal
Formation: Kings Park Formation
Comments: Indurated chalky limestone with siliceous spicules partly leached out. Very sparse fauna released from matrix. Not as diverse as other samples in this haul; benthos lacks the deep water species seen in Samples 5 and 7. Age interpreted from presence of *Morozovella aequa, M. bullbrooki, M. wilcoxensis, M. convexa, Planorotalites planoconica* and the absence of any Paleocene indicators. Basal Eocene age definitely preferred, but would need more sample processed to completely eliminate possibility of latest Paleocene.

Sample 7
Zone: P5 (T6)
Age: Latest Paleocene
Environment: bathyal (below 500m)
Formation: Kings Park Formation
Comments: Indurated chalky limestone, somewhat leached, but with a well-preserved, diverse foraminiferal fauna. Planktonic forms are dominant, with *Subbotina* very abundant; other species are rare. *P. australiformis* is relatively common. Age is based on the presence of three specimens of *Planorotalites simplex* and the absence of older Paleocene indicators: the zonal definition for N.W. Shelf Zone T6. Diverse assemblage of small *Planorotalites*; rare *Morozovella*, including *M. aequa*. The most common benthonic species is *Eponides umbonatus*, followed by *Osangularia lens, Nuttallides truempyi* and *Lenticulina* spp. *N. truempyi* has an upper depth limit of 500-600m (van Morkhoven and others, 1986). Also present is the bathyal species *Vulvulina pennatula*.

Sample 8
Zone: tentative P3b (?T3)
Age: tentative latest Early Paleocene
Environment: bathyal (below 500m)
Formation: basal Kings Park Formation
Comments: Chalky, indurated limestone, poorly broken down. The sparse, dominantly planktonic fauna are very poorly preserved. The assemblage is dominantly *Subbotina pseudobulloides* and *S. triloculinoides*, but lacking both *Acarinina* and *Morozovella*. There are a moderate number of specimens with large bullas, resembling *Catapsydrax stainforthi*. Since *Catapsydrax* morphotypes generally do not appear before the Middle

Eocene, this is a peculiar assemblage. A search for Neogene forms yielded nothing to suggest contamination by younger faunas. Benthonic fauna is sparse, but of same Paleocene-Early Eocene species as seen in Samples 5, 6 and 7. A difficult sample that definitely requires more work.

Sample 9
Zone: Abathomphalus mayaroensis (C13)
Age: Late Maastrichtian
Environment: ?middle to outer shelf
Formation: Breton Marl, after Shafik (1989)
Comments: Silty, glauconitic soft chalk with abundant spherical radiolaria (recrystallised), and sparse foraminifera in a very small residue. Age indicated by presence of *Abathomphalus mayaroensis*, but the presence of *Heterohelix praesemicostata* (Rexilius, informal name) suggests possible reworking of older (Late Campanian) strata across the mid-Maastrichtian disconformity (see McNamara and others, 1988). There is contamination from Holocene and Early Tertiary forams in the residue. Needs more sample processed to clarify the problem of possible massive reworking. Benthos a normal shelf assemblage for the Late Cretaceous.

Sample 10
Zone: *Abathomphalus mayaroensis* (C13)
Age: Late Maastrichtian
Environment: ?middle to ?outer shelf
Formation: Breton Marl
Comments: Very small residue, mostly spherical radiolaria and fine glauconite; foraminiferal assemblage sparse and benthonic dominated; most specimens diminutive. Very sparse planktonic assemblage contains same key species as sample above: *A. mayaroensis* and *H. praesemicostata*; so same question of reworking arises. Large number of arenaceous benthonic specimens gives assemblage a shallower water aspect than Sample 9, but sample needs more work.

Sample 11
Zone: Abathomphalus mayaroensis (C13)
Age: Late Maastrichtian
Environment: middle to outer shelf
Formation: Breton Marl
Comments: As for Sample 9, but with fewer radiolaria and more planktonic foraminifera. The same index species are present, indicating possible reworking as for 9 and 10. Diverse benthos which could use more work and a full description.

<u>80DR/021</u>

Sample 1
Zone: ?P10 - ?P14
Age: probably Middle Eocene
Environment: ?deep
Formation: ?Porpoise Bay Formation equivalent
Comments: Hard, partly chert-replaced limestone which has released only a handful of planktonic foraminifera. No index species found. Long-ranging species common in the Middle Eocene are present. No benthonic fauna released.

Sample 5
Zone: upper P4 (T5)
Age: Late Paleocene.
Environment: outer shelf to upper bathyal
Formation: Kings Park Formation
Comments: Indurated limestone with sparse foraminiferal assemblage. Almost all specimens are *Subbotina*; index species very rare to absent. Age based on two specimens of *Planorotalites pseudomenardii* and two broken specimens of *P.* cf. *simplex* (both zonal index forms). Benthonic assemblage dominated by *Gavelinella beccariformis*; others are very rare.

Sample 11
Zone: P9 (T10)
Age: Early Eocene
Environment: ?upper bathyal
Formation: ?new unit
Comments: Chalky porous calcilutite with many leached out spicule impressions; moderately hard and only a little of the sample has broken down. Very sparse foraminifera, virtually all planktonic specimens. *Morozovella caucasica* and *M. aragonensis* are present, and define the age in the absence of *M. aequa*. The problem of the homeomorphy of *M. caucasica* and *M. velascoensis* arises in isolated samples such as this; the age really depends on the presence of *M. aragonensis* and the absence of older species. Little benthonic fauna, on which to interpret the water depth, are present.

<u>80DR/022</u>

Sample 1
Age: ?Basal Eocene (to possibly Middle Eocene?)
Environment: probably outer shelf to uppermost bathyal
Formation: Kings Park Formation
Comments: Indurated calcilutite which has released only a small number of foraminifera. Although all the planktonic species are long-ranging, the presence of rare *Acarinina mckannai* with *Planorotalites australiformis* and *Pseudohastigerina wilcoxensis* makes a Basal Eocene age the most likely choice. Almost no benthonic fauna.

Sample 2
Zone: ?P6b
Age: ?Basal Eocene
Environment: probably upper bathyal
Formation: ?Kings Park Formation
Comments: Recrystallised calcarenite/calcisiltite with very sparse, very badly preserved foraminifera, almost all planktonic species. Age based on two specimens of *Morozovella subbotinae*, and one of *M. cf. lensiformis*; remainder of assemblage is Early to Middle Eocene in species ranges. Environment based on one specimen close to *Nuttalides truempyi*; almost no other benthic forms seems.

Sample 3
Zone: part P4 (T4b)
Age: Late Paleocene
Environment: outer shelf to upper bathyal
Formation: Kings Park Formation
Comments: Processed residue is entirely well-preserved foraminifera. There is considerable Pleistocene-Holocene contamination. Age based on *Planorotalites chapmani*, *P. pseudomenardii*, *Subbotina pseudobulloides*, *Morozovella* cf. *uncinata*, abundant *M. pusilla*, and *Acarinina*

conicotruncata: a good T4b assemblage. Moderately diverse benthos.

Sample 4
Age: ?Late Middle Eocene
Environment: outer shelf - upper bathyal "spongiolite" facies
Formation: ?Porpoise Bay Formation equivalent
Comments: The washed residue forms a remarkable sample composed almost entirely of siliceous spicules, spines, diatoms and radiolaria. Foraminifera are rare, but beautifully preserved. The evidence for foraminiferal age is complicated by the presence of substantial Plio-Pleistocene contamination. Thus there is a real problem in sorting out variants of the *Turborotalia inflata* group from *Turborotalia cerroazulensis cerroazulensis* in this assemblage. The presence of *Acarinina primitiva* indicates an age at least as old as Middle Eocene. The sample needs repreparation from a thoroughly cleaned rock specimen; then prolonged picking to isolate the rare foraminifera from other microfossils. Needs a nannoplankton determination for purposes of present study.

80DR/023

Sample 1C
Zone: probably P9
Age: probably Early Eocene
Environment: ?upper bathyal
Formation: ?new unit
Comments: Indurated calcisiltite, releasing very sparse foraminiferal fauna, virtually all planktonic specimens. Similar fauna and problem to 80DR/021-11: *Morozovella caucasica* could equally well be *M. velascoensis* (Paleocene). *Morozovella* cf. *aragonensis* here tends towards a *M. formosa gracilis* morphotype. The younger age (P9) is suggested by *Subbotina* cf. *frontosa* and a single specimen of *Pseudohastigerina* cf. *micra*; but the age cannot be regarded as completely definite.

Sample 2
Age: ?Aptian or older
Environment: epicontinental marine shelf
Formation: unknown; presumably part of the Warnbro Group.
Comments: Lithology is a light grey, silty, glauconitic mudstone with an entirely arenaceous benthonic foraminiferal fauna. Species identified have been recorded from the Early Cretaceous of the Great Artesian Basin by Crespin (1963), Ludbrook (1966) and Haig (1980); but the assemblage also contains other species not described by those authors. Needs taxonomic study. Sample should be palynologically datable on dinoflagellates. Assignment to a formation would depend on the dinoflagellate dating.

Appendix 6: Geochemical data from offshore wells in the South Perth Basin (compiled from Burns (1982) and Surdan (1982))

Key:

TOC:	Total organic carbon in sample, (%)
S1:	Pyrolysis free - hydrocarbon signal (mg hydrocarbons/g rock)
S2:	Pyrolysis kerogen signal (mg S2 hydrocarbons/g rock)
TMAX:	Temperature at which S2 signal is a maximum (degrees celsius)
PI:	Production Index [S1(S1+S2)]
HI:	Hydrogen Index (mg hydrocarbons/g organic carbon)
GP:	Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)

1. Leederville Formation

Well	Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Sugarloaf 1								
	640	59.83	5.60	363	455	0.02	607	368
Bouvard 1								
	795	0.39	-	-	-	-	-	-
Challenger 1								
	905	0.07	-	-	-	-	-	-
	1045	0.17	-	-	-	-	-	-
Warnbro 1								
	1131	1.26	0.57	1.8	451	0.24	143	204
	1189	1.38	0.90	1.8	449	0.33	133	2.7
	1259	1.28	0.65	1.1	452	0.36	93	1.8
	1308	1.13	1.00	1.4	456	0.41	128	2.4
	1309	2.34	0.97	2.4	444	0.29	103	3.4
	1448	2.38	0.59	2.7	445	0.18	115	3.3
Gage Roads 1								
	869	0.16	0.09	-	-	-	-	0.3
	1034	0.19	0.08	0.2	-	0.28	108	0.3
Roe 1								
	716	-	0.06	-	-	-	-	0.1
	802	0.06	0.07	-	-	-	-	0.2
Quinns Rock 1								
	384	0.32	-	-	-	-	-	-
	582	0.64	0.05	0.7	449	0.06	114	0.8
Charlotte 1								
	674	51.63	1.41	53.7	434	0.03	104	55.1
	814	6.25	0.14	4.3	462	0.03	69	4.5

2. <u>South Perth Shale</u>

Well	Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Sugarloaf 1								
	805	1.07	0.08	1.3	459	0.06	123	1.4
	881	0.97	0.06	0	460	0.08	75	0.8
	1189	0.37	0.10	0	430	0.14	168	0.7
	1521	1.69	0.18	3.1	459	0.05	185	3.3
	1595	70.29	7.79	189.4	460	0.04	269	197.1
Bouvard 1								
	855	0.96	-	-	-	-	-	-
	1060	0.19	-	-	-	-	-	-
	1110	0.16	-	-	-	-	-	-
Challenger 1								
	1008	1.32	0.77	2.59	417	-	196	1.08
	1060	0.25	-	-	-	-	-	-
	1075	3.84	9.25	25.45	325	-	662	1.02
	1115	1.14	0.16	1.10	416	-	96	0.66
	1155	0.75	0.06	0.53	420	-	70	0.37
	1205	2.96	0.15	3.5	455	0.04	119	3.9
	1285	1.03	0.05	0.5	449	0.09	52	0.6
	1298	3.30	0.07	3.68	419	-	111	1.06
	1300	2.58	0.29	3.7	454	0.07	143	4.0
	1320	2.99	0.09	1.8	444	0.05	60	1.9
	1392	3.83	0.09	4.71	421	-	122	1.22
	1481	1.87	0.08	2.11	421	-	112	0.59
Warnbro 1								
	1435	2.12	0.10	1.57	418	-	74	0.86
	1509	2.23	0.70	3.9	453	0.15	173	4.6
	1557	2.26	0.32	2.67	420	-	118	1.02
	1613	2.96	1.04	5.2	458	0.17	175	6.2
	1679	2.42	0.35	3.28	426	-	135	0.93
	1686	2.85	0.83	6.6	458	0.11	231	7.4
	1753	2.8	0.76	6.7	457	0.10	240	7.5
	1801	2.9	0.33	4.66	428	-	160	0.98
	1811	2.92	0.57	4.6	451	0.11	159	5.2
	1890	3.12	0.32	4.7	456	0.06	134	5.0
	1923	3.06	0.18	2.89	430	-	94	0.83
Gage Roads 1								
	1152	0.16	0.14	0.3	-	0.34	166	0.4
	1232	1.01	0.10	0.6	455	0.14	59	0.7
	1311	2.67	0.16	2.9	460	0.05	108	3.1
	1375	2.54	0.19	3.3	457	0.05	129	3.5
	1389	3.47	0.6	2.55	421	-	73	1.79
	1405	3.19	0.20	5.0	459	0.04	158	5.2
	1436	3.08	0.21	5.8	459	0.04	188	6.0
	1466	3.54	0.5	3.44	423	-	97	1.71
	1521	3.84	0.5	3.82	421	-	99	1.27
	1524	2.98	0.22	3.5	451	0.06	119	3.8
	1579	3.06	0.24	3.4	452	0.07	112	3.7
	1618	2.51	0.6	2.44	423	-	97	0.96

Well	Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Quinns Rock 1								
	665	0.60	-	0.2	452	-	37	0.2
	713	0.16	0	0	439	-	0	0.06
	720	1.50	0.06	1.9	457	0.03	129	2.0
	734	0.89	0.02	0.28	418	-	31	0.38
	762	1.01	0.10	0.4	451	0.19	43	0.5
	765	1.08	-	-	-	-	-	-
	770	2.73	0.02	0.29	420	-	26	0.42
	841	0.53	0.04	0.44	430	-	83	0.35
	845	0.69	1.11	0.6	459	0.64	92	1.7
Charlotte 1								
	1008	1.32	0.77	2.59	417	-	196	1.08
	1046	1.13	0.17	1.3	442	0.12	112	1.4
	1075	3.84	9.25	25.45	325	-	662	1.02
	1101	1.39	0.23	2.0	448	0.10	145	2.2
	1115	1.14	0.16	1.10	416	-	96	0.66
	1155	0.75	0.06	0.53	420	-	70	0.37
	1195	0.90	0.03	0.8	455	0.09	86	0.9
	1247	2.55	0.12	2.7	457	0.04	105	2.8
	1298	3.30	0.07	3.68	419	-	111	1.06
	1357	3.51	0.09	2.6	450	0.03	73	2.7
	1392	3.83	0.09	4.71	421	-	122	1.22
	1421	3.74	0.24	5.6	451	0.04	149	5.8
	1481	1.87	0.08	2.11	421	-	112	0.59
Gage Roads 2								
	1203	2.27	0.08	1.43	420	-	62	0.89
	1258	2.68	0.11	2.98	421	-	111	1.51
	1341	2.64	0.05	2.15	420	-	81	2.15
Peel 1								
	1090	0.59	0.02	0.26	414	-	44	0.11
	1240	1.68	0.02	1.01	413	-	60	0.87
	1330	2.15	0.07	1.43	420	-	66	0.85
	1410	1.70	0.07	1.46	422	-	85	0.69
	1490	2.76	0.12	3.49	423	-	126	0.88
	1550	2.33	0.10	2.44	425	-	104	0.86

3. Gage Sandstone Member

Well	Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Warnbro 1								
	2058	2.99	0.22	4.3	459	0.05	144	4.5
Gage Roads 1								
	1622	3.05	0.21	2.8	456	0.07	91	3.0
	1680	1.01	0.14	1.4	456	0.09	136	1.5
	1726	2.72	0.30	3.6	459	0.03	131	3.9

4. Parmelia Formation

Well	Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Challenger 1								
	1435	1.11	0.09	1.4	450	0.06	125	1.5
	1500	0.74	0.05	0.6	450	0.07	88	0.7
	1590	0.40	0.05	0.4	455	0.11	104	0.5
	1660	0.39	0.06	0.3	455	0.19	65	0.3
	1770	0.49	0.06	0.5	455	0.10	107	0.6
Warnbro 1								
	2213	3.33	0.51	6.2	465	0.08	186	6.7
	2305	3.47	0.28	5.2	462	0.05	151	5.5
	2436	2.41	0.45	3.8	463	0.11	159	4.3
	2482	3.33	0.21	4.6	462	0.04	140	4.8
	2546	3.41	0.36	5.6	461	0.06	164	5.9
	2598	2.53	0.28	3.6	463	0.07	144	3.9
	2720	3.50	0.55	7.5	462	0.07	215	8.1
	2750	3.28	0.33	6.3	463	0.05	191	6.6
	2811	3.61	0.46	6.4	463	0.07	176	6.8
	2905	3.68	0.68	8.3	462	0.08	225	9.0
Gage Roads 1								
	1519	3.05	0.11	4.1	453	0.03	133	4.2
	1857	3.10	0.19	6.3	461	0.03	202	6.5
	1945	3.15	0.22	5.4	460	0.04	172	5.6
	2021	3.0	0.21	4.8	459	0.04	159	5.0
	2104	3.14	0.18	5.0	458	0.03	160	5.2
	2229	3.00	0.20	4.3	457	0.04	142	4.4
	2320	2.33	0.15	2.4	459	0.06	86	2.6
	2430	3.39	0.21	4.3	453	0.05	127	4.5
	2518	3.57	0.14	3.3	456	0.04	106	3.9
Quinns Rock 1								
	951	1.08	1.12	1.9	460	0.38	172	3.0
	1012	0.26	0.11	0.3	449	0.30	99	0.4
	1113	1.69	0.40	4.3	459	0.09	253	4.7
	1168	0.74	0.20	1.1	458	0.15	149	1.3
	1280	0.46	0.12	0.7	458	0.15	148	0.9
	1392	0.69	1.07	1.9	439	0.35	281	3.0
	1491	1.55	0.81	2.9	459	0.10	185	3.2
Charlotte 1								
	2127	0.89	0.04	1.52	428	-	170	0.21

5. Carnac Member

Well	Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Roe No 1								
	979	1.49	0.35	2.0	479	0.15	136	2.4
	1145	0.32	0.69	1.4	474	0.34	428	2.0
	1192	0.27	0.45	0.4	-	0.52	153	0.9
	1317	0.22	0.11	0.2	-	0.34	95	0.3
	1350	1.70	0.54	4.35	418	-	255	0.84
	1357	1.75	2.52	6.1	471	0.29	351	8.7
	1360	1.41	0.15	3.3	475	0.04	232	3.4
	1490	0.43	0.08	0.14	408	-	32	0.14
	1503	1.36	1.45	5.1	469	0.22	372	6.5
	1527	1.53	2.24	4.36	380	-	284	0.56
	1548	0.99	0.03	0.06	369	-	6	0.16
	1572	0.72	1.32	2.83	319	-	393	0.43
	1618	0.70	0.06	0.18	420	-	25	0.13
	1680	1.51	5.07	4.6	473	0.52	306	9.7
	1755	0.54	0.10	0.17	409	-	31	0.17
	1793	6.06	43.41	37.9	463	0.53	625	81.3
	2012	1.24	1.19	5.4	473	0.18	436	6.6
	2020	0.70	0.31	1.38	425	-	197	0.37
	2098	1.84	0.11	3.75	431	-	203	0.55
	2101	1.97	0.22	4.9	478	0.04	249	5.1
	2104	1.38	0.30	4.5	476	0.06	327	4.8
	2122	0.51	0.33	1.1	472	0.23	232	1.5
	2124	0.47	0.18	0.47	425	-	100	0.21
Charlotte 1								
	2179	1.29	0.18	2.45	425	-	189	0.35
	2292	1.03	0.05	1.96	430	-	190	0.35
	2386	1.88	0.20	2.64	425	-	140	0.58
	2433	1.22	0.07	1.48	434	-	121	0.24
Gage Roads 2								
	1697	2.27	0.07	1.65	421	-	72	0.97
	1770	1.44	0.17	1.94	428	-	134	0.42

6. Otorowiri Member

Well	Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Challenger 1								
	1865	2.09	0.10	2.7	460	0.04	127	2.8
Gage Roads 1								
	2555	2.72	0.24	3.9	458	0.06	142	4.1
	2593	1.83	0.11	2.86	433	-	156	0.55
	2615	1.71	0.11	2.50	433	-	146	0.45
	2621	1.51	0.12	2.43	430	-	160	0.50
	2626	0.60	0.15	1.1	473	0.13	183	1.3
Quinn's Rock 1								
	1606	1.14	0.44	2.66	422	-	233	0.51
	1622	1.11	0.17	2.7	460	0.06	241	2.8
	1639	2.17	0.13	2.93	421	-	135	0.72
	1664	1.40	0.08	2.23	431	-	159	0.34
Peel 1								
	3502	0.46	0.09	0.53	434	-	115	0.13
	3505	0.38	0.06	0.39	436	-	102	0.09

7. Yarragadee Formation

Quinn's Rock 1								
	1677	1.48	0.14	2.8	463	0.05	188	2.9
	1720	1.74	0.22	3.6	462	0.06	206	3.8
	1765	1.73	0.11	3.1	463	0.03	178	3.2
	1826	1.75	0.15	3.4	462	0.04	196	3.6
	1902	1.59	0.16	2.7	463	0.06	170	2.9
	1932	1.05	0.14	1.7	452	0.08	157	1.8
	1976	1.70	0.19	3.7	464	0.05	220	3.9
	2085	1.59	0.11	2.5	462	0.04	160	2.6
	2125	0.6	0.05	1.6	461	0.05	135	1.6
	2128	1.69	0.14	3.1	463	0.04	184	3.3
	2171	1.05	0.23	2.2	453	0.10	205	2.4
	2177	1.74	0.17	4.0	462	0.04	232	4.2
	2201	1.68	0.46	4.1	461	0.10	245	4.6
	2323	2.57	0.13	2.7	454	0.05	107	2.9
	2360	3.00	0.39	4.9	453	0.07	163	5.3
	2421	3.31	0.19	3.4	51	0.05	106	3.7
	2434	1.15	0.08	1.6	461	0.05	135	1.6
Sugarloaf No 1								
	2220	2.14	0.42	7.9	464	0.05	369	8.3
	2305	1.74	0.52	4.7	465	0.10	267	5.2
	2549	2.21	2.19	10.5	458	0.17	474	12.7
	2802	2.83	0.62	1.0	455	0.05	459	13.6
	3037	6.41	1.74	2.2	459	0.06	440	29.9
	3162	19.76	4.01	7.8	462	0.05	333	79.8
	3250	4.05	0.61	1.1	462	0.04	374	15.8
	3366	2.15	0.50	4.3	465	0.10	221	5.3
	3448	5.23	1.03	1.3	463	0.06	312	17.3
	3655	11.67	3.73	4.4	455	0.16	330	53.1

Well	Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Gage Roads 1								
	2649	2.11	0.16	3.9	468	0.04	186	4.1
	2771	2.35	0.18	4.4	465	0.04	187	4.6
	2899	2.13	0.17	3.3	466	0.04	176	3.9
	2963	2.29	0.20	4.4	465	0.04	192	4.6
	3006	2.44	0.16	3.7	462	0.04	151	3.8
	3076	2.09	0.17	3.9	465	0.04	186	4.1
	3162	1.89	0.13	3.0	468	0.04	177	3.5
	3280	2.19	0.22	4.3	465	0.05	195	4.5
	3328	1.69	0.18	2.2	476	0.03	129	2.4
	3366	2.18	0.26	4.3	463	0.06	196	4.5
	3476	2.25	0.28	3.4	464	0.08	151	3.7
	3555	0.35	0.11	0.8	456	0.18	129	0.9
	3649	0.58	0.17	0.8	456	0.18	129	0.9
Bouvard No 1								
	1305	0.50	0.07	0.8	459	0.03	167	0.9
	1400	1.05	0.14	2.0	459	0.06	196	2.2
	1475	0.36	-	0.2	453	-	61	0.3
	1625	0.31	0.06	0.3	459	0.16	103	0.4
	1725	0.19	-	0.2	453	-	127	0.3
	1875	0.29	-	0.3	460	-	98	0.3
	1975	0.08	-	-	-	-	-	-
Warnbro 1								
	2913	2.64	0.12	2.95	426	-	111	0.92
	2951	3.33	0.32	7.1	463	0.04	212	7.
	2953	2.86	0.09	2.92	428	-	102	0.74
	2982	3.47	0.37	5.4	460	0.06	157	5.8
	3009	3.12	0.25	5.3	465	0.04	170	5.6
	3131	0.90	0.20	1.4	469	0.12	156	1.6
	3229	3.04	0.34	4.9	461	0.06	163	5.3
	3287	3.30	0.27	5.6	463	0.05	171	5.9
	3345	3.15	0.49	5.5	463	0.03	175	6.0
	3433	60.99	16.40	14.0	472	0.07	351	230.3
	3581	10.01	1.92	30.9	473	0.07	438	102.4
	3610	21.84	6.8	95.6	472	0.07	438	102.4
	3635	10.47	2.07	36.8	463	0.05	351	38.8
Peel 1								
	3535	1.37	0.31	3.72	438	-	271	0.26
	3545	1.41	0.19	2.79	438	-	197	0.24
Challenger 1								
	2030	1.85	0.18	3.1	459	0.06	165	3.2
	2245	2.45	0.40	3.6	458	0.10	148	4.0