THE VLAMING SUB-BASIN

OFFSHORE SOUTH PERTH BASIN

CONTINENTAL MARGINS PROGRAM
FOLIO 7

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Marine Geosciences and Petroleum Geology Program

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SUMMARY

Some 3000 km of multichannel and high-resolution seismic reflection profiles, plus an extensive suite of geological samples, were acquired by the AGSO's research vessel *Rig Seismic* from the Vlaming Sub-basin in the latter part of 1988. These data, coupled with results from previous company seismic and well data in the offshore South Perth Basin, form the basis for this interpretation of the stratigraphy, structure and hydrocarbon potential of the sub-basin.

Predominantly non-marine sediments, ranging in age from Early Permian to Early Cretaceous, have been deposited within the major depocentres of the South Perth Basin. The Dandaragan Trough, one of the deepest onshore depocentres is considered to contain in excess of 15 000 m of Phanerozoic sediments. The Bunbury Trough, a deep graben which occurs to the south between the Darling and Busselton Faults, contains at least 10 000 m of Permian to Early Cretaceous sediments (Playford and others, 1976). While the onshore section is primarily of Permian, Triassic, Jurassic and Cretaceous age, Tertiary sediments are known to occur in the Perth area and also offshore.

The Vlaming Sub-basin occupies the region beneath the shelf and upper slope offshore from Perth and it forms the major depocentre of the offshore South Perth Basin. The sub-basin covers an area of some 10 000 km^2 between latitudes 31° 30' and 33° 30'S. It is about 100 km wide at its widest point, off Perth. It appears that the sub-basin is bounded to the west by Permo-Triassic equivalents of the Bunbury Trough and possibly a basement high that forms a continuation of the Beagle and Turtle Dove Ridges to the north (Edwards Island Block of Jones, 1976), and by the Leeuwin Block to the south. To the east, the Vlaming Sub-basin is separated from the southern Dandaragan Trough and the Bunbury Trough by the Badaminna Fault System.

Fourteen petroleum exploration wells have been drilled offshore in the Vlaming Sub-basin. 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).

Previous structural interpretations of the Vlaming Sub-basin (e.g. Jones, 1976) have suggested that the margins are dominated by north-south trending, relatively steep

faults that are considered to be laterally persistent, although there are indications of numerous offsets in places. The Dunsborough and Busselton Faults are the major bounding faults to the southwest, where they separate, respectively, the Vasse Shelf from the basement high which is an extension of the Leeuwin Block, and the Bunbury Trough from the Vlaming Sub-basin. The Vasse Shelf consists of Permo-Triassic rocks similar to those in the Bunbury Trough, but with a much reduced sedimentary thickness (Iasky and others, 1991). The eastern margin of the sub-basin is dominated by the Badaminna Fault System, which normally consists of several sub-parallel faults, but with the easternmost one usually acting as the major down-to-the-basin fault.

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

The overall impression of the previous structural interpretation and mapping is the disjointed nature of the major faults throughout the Vlaming Sub-basin. This haphazard arrangement is seen as a result of not taking into account large horizontal offsets between faults, which are related to primary basement structures that are too deep to be imaged by conventional seismic surveys. The structural interpretation in this report is based on the premise that the faults within the sub-basin form a linked system, commonly with large offsets on individual fault traces. These offsets are, in general, related to pre-existing structures, most of which are transfer faults. Offsets of the bounding faults and frequent reversals in fault plane orientation indicate that the sub-basin is cut by a series of NW-SE trending transfer faults. These transfer faults have resulted in the compartmentalisation of many structures within the basin, although major structures, despite being significantly offset, do persist throughout the sub-basin. For instance, the sudden termination of the Badaminna Fault Zone at 33°S can be explained by a 25 km offset of the basin boundary by a major transfer fault. This particular transfer fault is significant because it appears to form an extension of the onshore Harvey Ridge - the boundary between the Southern Dandaragan Trough and the Bunbury Trough. Another major transfer fault occurs to the south of Rottnest Island. Here, there is a marked change in the orientation of the normal faults from a NNE direction to a more northerly trend north of Rottnest Island.

Because of the large thickness of sediment, basin-forming structures are obscured and the timing of the initiation of the Vlaming Sub-basin is unknown; the only major rifting event in the Perth Basin prior to the Early Cretaceous was during the Permian. Virtually all of the structures seen on the seismic sections were produced in the Early Cretaceous and have been superimposed on a thick, previously unstructured basin fill. The seismic reflection profiles indicate that the sub-basin progressively thickens and widens to the north, but no evidence of the principal basin-forming structures can be found, even in the south where Triassic or possibly even Late Permian sequences may be present. However, results from elsewhere in the Perth Basin (Marshall and others, 1989a, b) indicate highly oblique extension occurred during the Permian, resulting from the interaction between the Darling Fault system and a NW-SE tectonic transport direction. Reactivation of these structures in the Early Cretaceous would have resulted in the interaction between the NW-SE transfer faults and N-S oblique normal faults in the Vlaming Sub-basin to produce a transtensional result. While the structural style in the Early Cretaceous in the Vlaming Sub-basin is both extensional and strike-slip, the amount of extension is small (<20%), and the principal fault displacement is strike-slip: up to 5km of horizontal displacement has been measured in the Bathurst Syncline. This style of extension has resulted in a complex basinal structure, where the tectonic elements seen in one part of the basin appear to be totally unrelated to other parts of the basin. Consequently, this has produced a variety of structural plays within the sub-basin that are not only a departure from the typical style of play produced within basins dominated by normal extension, but which may only exist in one part of the basin and not in others. Many of these plays remain untested.

The results of geohistory modelling of thirteen of the wells in the Vlaming Sub-basin indicate that the sub-basin subsided rapidly during the Late Jurassic/Early Cretaceous. Sedimentation rates suggest that the sub-basin was also filling rapidly at this time. The subsidence/fill characteristics of the basin, which accord with a transtensional origin for the sub-basin, suggest that pre-Late Jurassic sediments have been rapidly buried and are now overmature. From an analysis of their porosity and permeability, potentially the best reservoirs are, in order: the Gage Sandstone Member, the un-named sandstone units immediately above and below the Carnac Member, and the sandstone units within the upper part of the Yarragadee Formation.

Potential source rocks in the Yarragadee Formation consist of thin shaly sequences, inter-bedded between the major channel sandstone units. Geochemical analysis indicates that the shaly 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% are not uncommon. 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. Geochemical results from the Parmelia Formation show that, overall, the fluvial sandstones contain less organic source material than the deltaic and lacustrine shale units. TOC content ranges from less than 1% in the fluvial sandstones to up to 2-3% in shale-rich parts of the sequence. Pyrolysis data suggest that there is potential for mixed oil and gas source material in the formation. 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 to 3000 m. The amount of vitrinite reflectance data for the South Perth Basin is limited, and because most of the existing wells intersect the crestal parts of structural highs, maturation trends may not be representative of the more deeply buried parts of the basin.

The pre-breakup Late Jurassic Yarragadee Formation and the Early Cretaceous Parmelia Formation are considered to be mature for hydrocarbon generation, particularly in the Bathurst Syncline. Adequate source material is present, mainly in the form of exinite and subinertinite, and the sequence could source both oil and gas. The shale-rich Otorowiri and Carnac Members of the Parmelia Formation are potentially the best source rocks in the sub-basin. These units are deep in the Bathurst Syncline and are likely to be oil-mature. Migration pathways exist for oil generated in the syncline to be delivered and trapped at higher levels in the Roe High region and in structures on the western margin of the sub-basin, to the north of the syncline.

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INTRODUCTION

From 9 July to 4 August and 15 September to 14 October 1988, the AGSO (formerly BMR) research vessel *Rig Seismic* conducted two cruises in the offshore South Perth Basin region (Plate 1). 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, magnetic and bathymetric data were acquired 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 Perth 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).

The aims and objectives of the cruises were:

(1) to develop an updated structural and stratigraphic framework for the offshore South 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 Vlaming Sub-basin

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

(4) to develop models of basin evolution, particularly for small, deep basins such as the Vlaming Sub-basin.

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 southwestern 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, a major, relatively linear geosuture that separates the basin from the Archaean Yilgarn Block. This fault, which is considered to have been downthrown to the west by as much as 15 km since the Early Palaeozoic (Jones, 1976), still manifests itself as a topographic feature along sections of its length (e.g. the Darling Scarp).

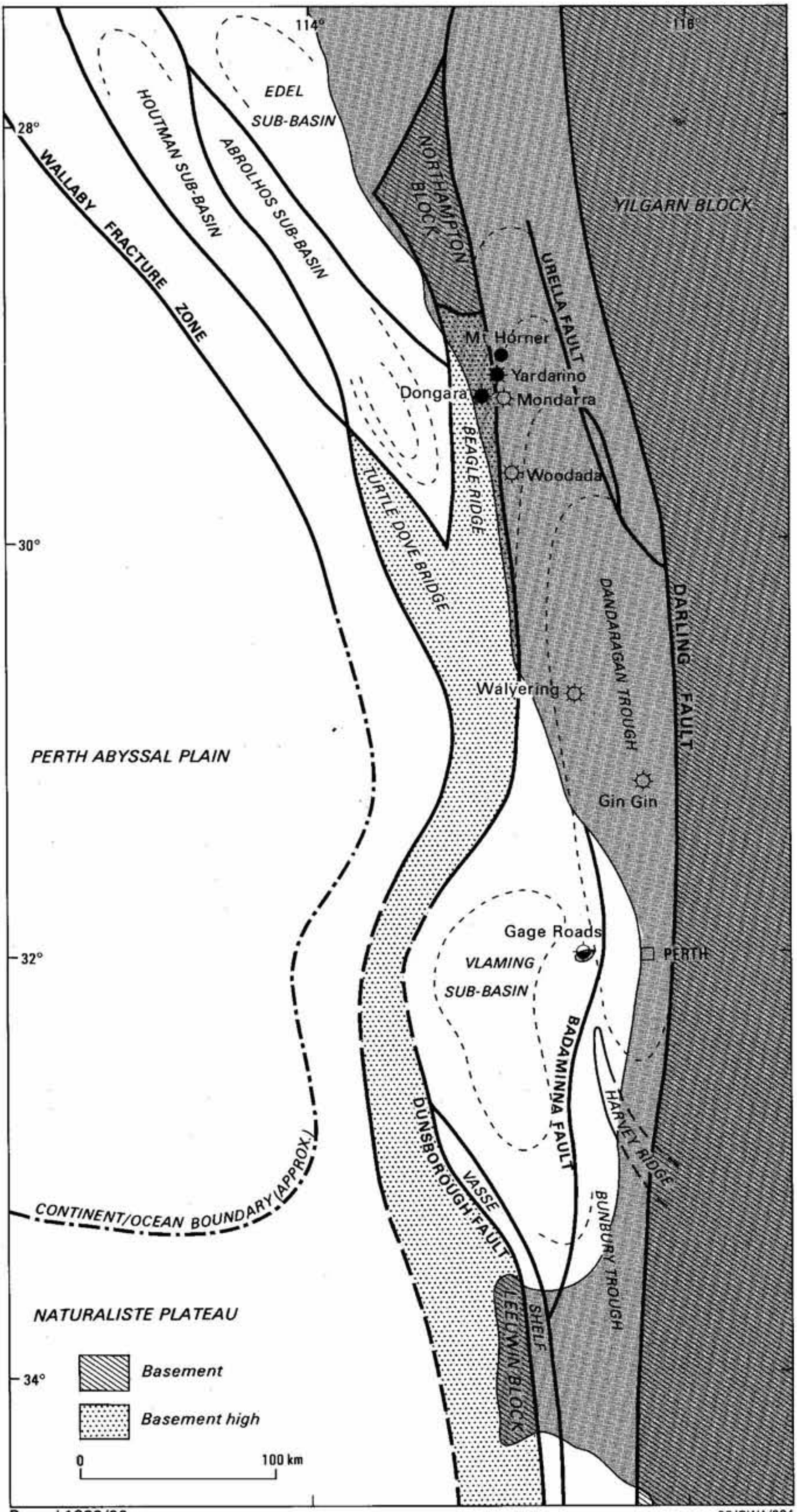

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Figure 1. Tectonic map of the Perth Basin

The basin has a history of rifting and rift-fill since at least the Permian, which culminated in the separation of Greater 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 between northwest trending transform faults, such as the Wallaby Fracture Zone (Markl, 1974b).

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 by oblique extension related to faults with a predominantly strike-slip component (Marshall and others 1989a, b). Basin development has been closely tied to movement on the Darling Fault throughout the Phanerozoic (Jones, 1976; Playford and others, 1976). 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 to 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), makes 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 Ridges (Fig. 1), or by strike-slip faults. In the south, the Vlaming Sub-basin contains an extremely thick Late Jurassic-Early Cretaceous sequence within an intracratonic setting.

BATHYMETRY

The continental margin offshore Perth consists of a 40 to 100 km wide continental shelf, a fairly steep continental slope and a broad continental rise (Plate 1). 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 (0-100 m) and a narrower outer shelf slope (100-170 m). The depth of the shelf break varies between 163-175 m, and is characterised by a marked change in slope. The inner shelf, 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 seafloor, and a seaward margin of low relief ridges (Collins, 1988). The outer shelf is 11-17 km wide, and has a gentle slope (0.5°) and relatively smooth topography (Collins, op. cit.).

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 Perth Canyon (Plate 1). The bathymetry of the Perth Canyon is shown in Plate 2. The head of the canyon occurs at about 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 west of the mouth of 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 surficially incised the shelf (Von der Borch, 1968; Davies, 1973; Marshall, 1980).

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 2). 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 2). The canyon extends in this direction to a depth of about 4400 m, after which it opens out onto a 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.

Elsewhere, the continental rise, which is usually present between the 4000 and 5500 m isobaths, is over 100 km wide in places. At the base of the rise to the northwest lies the Perth Abyssal Plain, with an average depth of about 5600 m.

PREVIOUS DATA

Offshore geophysical investigations by the 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 provided a regional seismic coverage (along with bathymetry, gravity and magnetics). 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. Twenty two wells have been drilled so far in the offshore part of the basin, fourteen 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 penetrated Lower Cretaceous and Upper Jurassic sediments, similar to equivalent age sediments in wells onshore, and reached a total depth (TD) of 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 revealed 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). In 1984 Esso drilled Mullaloo 1 and Minder Reef 1. The most recent well to be drilled in the Vlaming Sub-basin was Tuart 1, drilled by Ampolex in 1991 (Malcolm, 1992).

In addition to the fourteen exploration wells, some 6000 km of seismic reflection profiles have been acquired in the offshore region of the South Perth Basin prior to 1990 (Plate 1; Appendix 1). Since 1990, reprocessing of existing lines and acquisition of new seismic data have been conducted for Ampolex, Shell/Petrofina and Woodside.

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, c; Hall, 1989).

REGIONAL GEOLOGY

STRATIGRAPHY OF THE SOUTH PERTH BASIN

Sediments ranging in age from Early Permian to Holocene are recognised in the major depocentres of the South Perth Basin (Plate 3). 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.

Sue Coal Measures (Late Sakmarian-Early Kazanian)
The Sue Coal Measures are the oldest sediments recognised in the southern part of the Dandaragan Trough and Bunbury Trough (Plate 3). They were defined by Playford and Low (1972) as 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 reaches its maximum known thickness (1838 m) in Sue 1 (Playford and others, 1976). 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 (Late Kazanian-Early Scythian)

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 3). The maximum known thickness is 561 m in Lake Preston 1 in the Dandaragan Trough.

The Sabina Sandstone is a predominantly fluviatile deposit, becoming paralic to the north. It represents a continuous period of sedimentation across the Permian-Triassic boundary, and is probably the time equivalent of the Wagina Sandstone and Kockatea Shale in the North Perth Basin (Playford and others, 1976).

Lesueur Sandstone (Middle-Late Triassic)

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. In the South Perth Basin, it reaches a maximum known 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 (Early Jurassic)

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 are 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). 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 (Early to Middle Bajocian)
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 3), 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). The formation represents shallow marine to marginal marine deposition during a brief period of marine incursion (Playford and others, 1976).

Yarragadee Formation (Late Bajocian-Late Tithonian)
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). 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 (Late Tithonian-Berriasian)

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, and while Playford and others (1976) suggest that it reaches a maximum thickness of 8000 m below the continental slope west of Perth, the available seismic data suggests that it is of the order of 2000-2500 m; notwithstanding that the upper part of the formation has been substantially eroded. 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 3), or is separated from it by a thin sequence of sandstone beds (Backhouse, 1988).

Within the Parmelia Formation, Backhouse (1988) assigned the microflora to the *Biretisporites eneabbaensis* Zone and microplankton to the *Fusiformacysta tumida* Zone, which range 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 (Late Berriasian-Early Valanginian)

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 known 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 3). It was probably associated with a period of tectonism immediately prior to the initiation of seafloor spreading.

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 Valanginian 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 3), unconformably overlies the Yarragadee Formation (Playford and others, 1976; Backhouse, 1988).

South Perth Shale (Late Valanginian-Hauterivian)

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 known thickness of 636 m in Mullaloo 1 in the Rottnest Trough.

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 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 (Late Hauterivian-Early Aptian)
Cockbain and Playford (1973) defined the Leederville Formation as the sequence of interbedded sandstones, siltstones, shales and rare 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) as 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

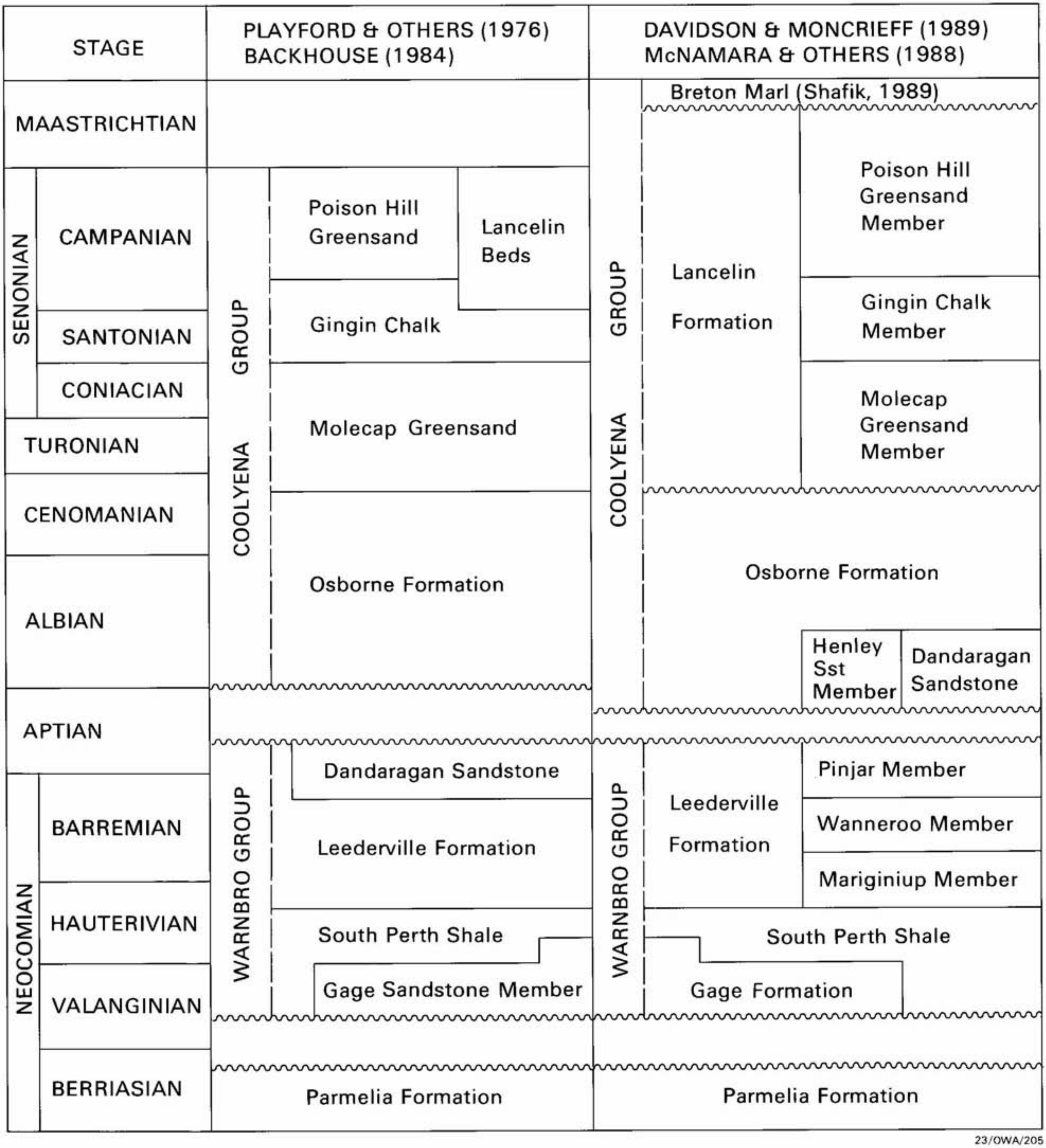


Figure 2. Revised stratigraphic nomenclature for the Cretaceous of the South Perth Basin.

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 (Albian-Cenomanian)

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 (Late Cenomanian-Early Santonian)

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). The formation represents a marine deposit laid down in a shallow sea.

Gingin Chalk (Santonian-Campanian)

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 terrigenous detritus.

Poison Hill Greensand (Campanian-Maastrichtian)
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). It is a marine sequence that may represent a regressive phase of the Late Cretaceous marine transgression (Playford and others, 1976).

Lancelin Beds (Late Campanian-Early Maastrichtian)
The type section in the Lancelin 2b borehole consists of 13.7 m of light grey marls with fragments of *Inoceramus*. In Breton Bay 1 borehole, the beds reach a thickness of more than 40 m. Here they overly the Gingin Chalk and are overlain by the Breton Marl. A Late Campanian equivalent has been recorded offshore in Challenger 1 (Shafik, 1992).

Breton Marl (Late Maastrichtian)
This unit is present in the Breton Bay 1 borehole, where it consists of a 6 m thick section of soft marl disconformably overlying the Lancelin Beds (Shafik, 1990). Both foraminiferal and nannofossil evidence indicate that age equivalent limestones occur in the Perth Canyon (Marshall and others, 1989c).

Kings Park Formation (Late Paleocene-Early Eocene)
The type section of the Kings Park Formation (Fairbridge *in* Coleman, 1952; amended Quilty, 1974a, b) is 275 m thick in the Kings Park No. 2 borehole. The formation is only known in the Perth metropolitan area and offshore adjacent to Perth, where the maximum known thickness is 597 m in the Rottnest Island borehole (Playford and others, 1976). 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). Quilty (1974a, b) defined the Kings Park Formation as the sequence of slightly glauconitic calcarenites and calcilutites penetrated between 68 and 365 m in Quinn's Rock 1 well. The formation disconformably overlies the Coolyena Group or older rocks, and onshore, it is disconformably overlain by younger Tertiary or Quaternary deposits (Playford and others, 1976). McGowran (1964, 1968) revised the age of the Kings Park Formation to Late Paleocene. Cockbain (1973) recorded a foraminiferal assemblage of Late Paleocene to Early Eocene age from the formation, and Quilty

(1974a, b) indicated that foraminiferids recovered from offshore are younger than Late Paleocene. Shafik (1978) recorded the nannofossil assemblages of the Kings Park Formation in several boreholes as well as in its type section, and correlated these assemblages with the Late Paleocene foraminiferal zones late P4 and P5, but also argued for an Early Eocene age (zone P6). The age of the Kings Park Formation is now considered to be Late Paleocene to Early Eocene, and while Quilty (1974a, b) and Playford and others (1976) believe that the formation represents a shallow marine to estuarine deposit that may be related to the now submerged drainage system of the old Swan River, it is apparent that extensive age equivalent limestones occur offshore.

<u>Porpoise Bay and Challenger Formations</u> (Middle Eocene-Early Oligocene)
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 (Cockbain and Hocking, 1989) consists of 382 m of brown calcareous shale and siltstone, between 285 and 667 m in the Rottnest Island bore, where it unconformably overlies the Lower Cretaceous Leederville Formation. Originally, this section was referred to as part of the Kings Park Formation, but having recorded Middle Eocene nannofossils from the section, Shafik (1978) recommended that it be given a separate lithostratigraphic status.

The type section of the Challenger Formation (Cockbain and Hocking, 1989) consists of 67 m of chalk, calcarenite and chert, between 530 and 597 m in Challenger 1 (see also Cockbain, 1990). Quilty (1978) described its lithological succession and foraminiferal fauna, and Shafik (1992) has given a detailed account of its nannofossil assemblages. Two lithological sub-units have been identified within this section. The upper sub-unit (530-567 m) consists of white chalk, changing to coarser, friable, bryozoan-echinoderm calcarenite towards the base, with abundant chert and traces of glauconite. The lower sub-unit (567-597 m) consists of white friable chalk and bryozoan-echinoderm calcarenite with dark grey chert. Originally, it was thought that the Challenger Formation was Late Eocene (Quilty, 1978; Cockbain and Hocking, 1989; Cockbain, 1990). Recently, Shafik (1992) revised the age of the type Challenger Formation, indicating a range from Middle Eocene to Early Oligocene. Shafik (1992) indicated that the type sections of the Porpoise Bay and Challenger Formations are partly coeval. Most of the biostratigraphic bracket comprising the type Porpoise Bay Formation coincides with the lower part of that comprising the type Challenger Formation in the Challenger 1 well.

Stark Bay Formation (Early to Middle Miocene)
This formation was defined by Quilty (1974a, b) as 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.

Diagnostic foraminiferal species are abundant in places, mostly indicating zones N8 and N9 (Quilty, 1974 a,b). Shafik (1991) identified Miocene carbonates in the Perth Canyon older than the type Stark Bay Formation. This suggests that the formation is a time transgressive unit, having an older base in the canyon succession than in its type section. Alternatively, the formation is probably indistinguishable from older carbonates in the canyon, the Tertiary record in the canyon being more complete than in the Gage Roads wells. The sedimentary sequence represents a marine carbonate depositional environment with almost no influx of terrigenous material.

Wadjemup Formation
The type section of the Wadjemup Formation (Cockbain and Hocking, 1989) is 289 m of yellow to red, well-sorted medium- to coarse-grained calcarenite with some limestone and dolomite in Gage Roads 1 well, between 100 and 389 m. Foraminiferids from this section suggest a Late Miocene to Recent age (Quilty, 1978). Originally, this section was proposed as the reference section for the "Rottnest Formation" of Quilty (1978).

Ascot Formation
Playford and others (1976) proposed the Ascot Beds for a sequence of coarse-grained calcarenites known from the Perth metropolitan area. The Ascot Formation was redefined by Cockbain and Hocking (1989), and consists of grey, medium- to coarse-grained sandy calcarenite. It has been dated as Pliocene, but its areal extent is unknown.

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, that disconformably overlies 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

Fourteen 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 fourteen wells have been 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 used in this study, have been used to compile a stratigraphic analysis of each well (Plates 4-16), together with correlations between the various wells of the Vlaming Sub-basin (Plates 17-19). The post-Cretaceous sequence has limited prospectivity for petroleum and it has not been correlated in detail.

Yarragadee Formation

The oldest unit penetrated in the Vlaming Sub-basin to date is the Late Jurassic Yarragadee Formation, which is present in seven of the thirteen wells (Plates 4, 5, 7, 9, 10, 12, 13). The complete sequence has not been intersected offshore, the thickest section encountered so far being 1532 m in Sugarloaf 1 (Plate 10), but it is estimated to be of the order of 3000-4000 m thick (Playford and others, 1976; Birch, 1984; Backhouse, 1988). The Yarragadee Formation is widespread throughout the Vlaming Sub-basin, and it appears that it is also extremely uniform, with no indication of thinning at the margins. Where the formation has been intersected by wells, it immediately underlies the Otorowiri Member, and the top of the formation has normally been correlated on this basis. The top of the sequence in well sections varies in depth from 1646 m in Quinn's Rock 1 (Plate 4) to 3521 m in Peel 1 (Plate 13) .

The formation has little regional lithological variation (Backhouse, 1988) and is typified by a serrated, blocky or cylindrical log pattern. The sandstones are white to light grey in colour, medium grained and moderately to very poorly sorted. They have an arkosic to sub-arkosic composition with an average of 20 percent feldspar. The porosity of the sandstones has been reduced by the formation of quartz overgrowths and authigenic kaolinite (Arditto, 1982). The thin shale bands are grey-brown in colour and occasionally carbonaceous. Interspersed are thin coal seams, consisting of black, brittle subvitreous coal. The Yarragadee Formation may have some source potential, but, overall, it is regarded as having poor reservoir properties, with porosity 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 4-19). The depth to the top of the formation ranges from 610 m in Sugarloaf 1 (Plate 10) to 2179 m in Warnbro 1 (Plate 7). 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 13) 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 two sandstone units and two predominantly shale to siltstone members, the Otorowiri Member at the base and the much thicker Carnac Member in the middle. The Otorowiri Member, which consists predominantly of claystone, 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 appears also as a diagnostic high amplitude reflector on seismic sections. 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 section above the Otorowiri Member within the lower part of the Parmelia Formation is dominated by a relatively porous, medium-grained sandstone, that is possibly related to a fluvio-deltaic depositional environment.

The Carnac Member is lithologically similar to the Otorowiri Member (Backhouse, 1984, 1988). It consists of shales and some siltstone, interbedded with thin coarse-grained units. The Carnac Member 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 upper part of the Parmelia Formation, which has been informally referred to as the Charlotte Member, consists of relatively clean fluvio-deltaic sandstones of reasonable reservoir quality.

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 17), 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 18, 19), including the lower part of the Carnac Member and the Otorowiri Member. Only Peel 1, on the eastern margin of the sub-basin, has 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 quite often 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 (Gage Sandstone Member) and a lower shale-claystone unit (South Perth Shale) occur only in wells in the central axis or flanks of the Rottnest Trough and somewhat to the south, whereas the upper sandstone unit, the Leederville Formation, is more widespread throughout the Vlaming Sub-basin (Plates 17-19). The most complete section occurs in Warnbro 1 (Plate 7) where the Warnbro Group attains a thickness of 1137 m.

The Gage Sandstone Member is regionally more restricted than either the South Perth Shale or the Leederville Sandstone. Its maximum measured thickness, based on Backhouse's (1988) biostratigraphic zonation, is 448 m in Mullaloo 1, but in this well only the basal 156 m is sand; the rest being shale. Contrary to earlier opinion, the Gage Sandstone Member is not restricted to the Rottnest Trough. It does extend some way to the south of the trough, reaching thicknesses of 234 m in Parmelia 1 and 220 m in

Warnbro 1. In these two wells there are also shaly sections, which supports Davidson and Moncrieff's (1989) contention that this unit, if defined on a biostratigraphic rather than a lithologic basis, does consist of interbedded sandstone, siltstone and shale, and can be regarded as a separate formation.

The Gage Sandstone Member consists dominantly of medium- to coarse-grained sandstone, that is moderately to poorly sorted, with minor siltstones and shales. It has variable but generally good reservoir characteristics, 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 South Perth Shale consists predominantly of shale with generally minor interbedded sandstone units, which are of the order of 25 m in thickness. This unit appears to become sandier to the south; in Challenger 1 the upper part of the sequence tends to be coarser-grained, while in Bouvard 1 the entire sequence tends to be coarser.

The Leederville Formation, which consists predominantly of sandstones with some interbedded shales, conformably overlies the South Perth Shale. This unit represents a mainly regressive sequence of marine to marginal marine sandstones that covered the entire shelf at that time. 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.

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 10) in the south to 610 m in Parmelia 1 (Plate 14) on the western flank of the sub-basin. Nannostratigraphy of material dredged from the Perth Canyon and cuttings from Challenger 1 (Plate 12) indicate continuous deposition of relatively fine-grained limestones on the shelf and upper slope throughout most of the Paleocene and the Eocene (Shafik, 1991, 1992).

The Tertiary marine section in the offshore South Perth Basin is more complete than its counterpart onshore. The Kings Park Formation is the only Palaeogene marine unit known in the onshore Perth Basin. In contrast, several other marine Palaeogene units are known from the offshore Perth Basin (see below), but these apparently lose their lithostratigraphic identities away from their type sections. Oligocene marine sediments had not been identified in the Perth Basin until Shafik (1991) found mid to late Oligocene calcareous nannofossils in carbonates dredged from the Perth Canyon. Other marine Oligocene sediments were identified in Challenger 1 (Shafik, 1992). In addition, new marine Paleocene and Eocene units have been reported from the offshore South Perth Basin (Shafik, 1991, 1992).

Early Paleocene carbonates were recovered from dredge hauls from the Perth Canyon (Marshall and others, 1989c; Shafik, 1991), but, as yet, they have not been identified elsewhere in the basin. These early Paleocene calcilutites, sampled from the northern and northeastern walls of the canyon, are not dissimilar in texture and composition from Kings Park Formation age-equivalent carbonates in the canyon.

Equivalents of the Kings Park Formation in the Perth Canyon consist of calcilutites, with some calcarenites, occasionally siliceous but mostly glauconitic, and varying in their degree of induration. In Challenger 1, the Kings Park Formation is represented by a 50 m thick section of chalk and quartz sand, with glauconitic sandstone near its base.

Early and Middle Eocene calcareous nannofossil assemblages have been identified from carbonates sampled from the Perth Canyon and Challenger 1 (Shafik, 1991, 1992). In the canyon, these sediments consist of calcilutites and calcarenites, while their correlatives in Challenger 1 are an 65 m thick section of mainly carbonates, between 635 and 700 m. The basal part (below 694 m) consists of chalk, grading into marl with some quartz sand and sporadic chert. The middle part consists basically of medium to coarse quartz sandstone, with varying amounts of bryozoan calcarenite, in places recrystallised to compact limestone. The upper part of this section (635-678 m) consists of compact calcarenite, sporadic limestone below 655 m, and some quartz sand at 660-670 m.

The unnamed Eocene carbonates in Challenger 1 overlie other carbonates which equate with the type Kings Park Formation, and underlie the equivalent of the Porpoise Bay Formation.

Shafik (1991) recorded a mid to late Oligocene nannofossil assemblage in calcilutite with abundant siliceous spicules from the southern wall of the Perth Canyon. This is the first published marine Oligocene record in the Perth Basin. Subsequently, Shafik (1992) identified other nannofossil assemblages indicative of mid to late Oligocene age in a calcarenite unit with chert between 489 and 530 m in Challenger 1.

Prior to the discovery of the new marine Paleocene, Eocene and Oligocene units in the offshore Perth Basin, the three then known Palaeogene units (the Kings Park, Porpoise Bay, and Challenger Formations) were differentiated into two depositional sequences (Cz1 and Cz2) by Cockbain (1990). The younger depositional sequences in the basin, Cz3 and Cz4, comprise the Stark Bay, Wadjemup and Ascot Formations (Cockbain, 1990). Sequences Cz1 - Cz4 were considered to be separated by disconformities.

Offshore, it seems possible that sequence Cz1 includes the unnamed Paleocene carbonates and the younger Paleocene to basal Eocene carbonates which are equivalents of the Kings Park Formation. Cockbain (1990) stated that sequence Cz2 comprises the Porpoise Bay and Challenger Formations. The boundary separating sequences Cz2 and Cz3 in the offshore record is likely to fall within the upper part of the type Challenger Formation, where a disconformity at the Eocene/Oligocene boundary occurs (see Shafik, 1992).

Shafik (1991, 1992) maintains that subdividing offshore Palaeogene carbonate sequences in the Perth Basin by biostratigraphic means is likely to be more successful than attempting to subdivide these sequences lithostratigraphically. The Kings Park, Porpoise Bay and Challenger Formations appear to change their texture and composition away from their type sections. They typically become finer grained and relatively homogeneous beneath the outer shelf and slope, where they appear to overlap and merge into one apparently continuous carbonate sequence, including Eocene beds older than the type Porpoise Bay Formation, and Paleocene beds older than the type Kings Park Formation.

STRUCTURAL ELEMENTS OF THE VLAMING SUB-BASIN

The Vlaming Sub-basin occupies the region beneath the shelf and upper continental slope offshore from Perth (Plate 20), where it forms the major depocentre of the offshore South Perth Basin. The sub-basin covers an area of some 10 000 km^2 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 (Plate 20), although this has not as yet been confirmed from the available seismic and potential field data. To the east, the Vlaming Sub-basin is separated from the southern Dandaragan Trough and the Bunbury Trough by the Badaminna Fault System (Plate 20), 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, remain 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 parts of the Perth Basin, with estimates of up to 15 km (e.g. Jones, 1976). Apart from that part of the Dandaragan Trough adjacent to the Darling Fault, the only region with a comparable thickness is the Houtman Sub-basin in the north, but even there the depth to Middle Jurassic sediments 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.

Previous structural interpretations of the Vlaming Sub-basin (e.g. Jones, 1976) have suggested that the margins are dominated by north-south trending, relatively steep faults that are considered to be longitudinally persistent, although there are indications of several offsets in places. Southwest of the Vlaming Sub-basin, the Dunsborough Fault (Plate 20) forms a major boundary, separating the Vasse Shelf from the basement high which forms the Leeuwin Block. The Vasse Shelf is, in turn, separated from the Bunbury Trough by the Busselton Fault. The Vasse Shelf consists of Permo-Triassic rocks similar to those of the Bunbury Trough, but with a much reduced sedimentary thickness (Iasky and others, 1991).

The northern, and deepest, part of the Vlaming Sub-basin is dominated by the Bathurst Syncline, a broad SSW-trending downwarp, and the Rottnest Trough, a major graben feature to the east (Plate 20). 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.

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. The 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 when 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 shows little thinning or onlap onto the edges of the sub-basin, suggesting that it was deposited rapidly into an equally rapidly subsiding depocentre. The sedimentation style changed somewhat at the beginning of the Cretaceous, possibly reflecting a more mature phase of rift-fill. It appears 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 13). This second phase of lake development was accompanied by a fluvio-deltaic depositional regime, that gradually encroached upon 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 near 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 (Plate 20). 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 and relatively more movement on the bounding faults of the sub-basin. This greater degree of subsidence in the Vlaming Sub-basin relative to both its eastern and western marginal blocks 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 style of 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 (Plate 20). 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 vertical displacement.

While the sub-basin margins remained relatively high directly after breakup, 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 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 of alluvial-fan and fan-delta sedimentation.

As the newly-formed continental margin subsided relatively rapidly during the early phase of drift, throughout 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 large volumes of relatively fine-grained sediment (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 sandstones began to blanket the South Perth Basin (Backhouse, 1988). These sandstones (Leederville Formation) developed into a non-marine fluvio-deltaic system, as a regressive sequence began to build back out across the proto-shelf.

As subsidence 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 relatively 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 Perth 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 temperate carbonate province.

STRUCTURAL ANALYSIS OF THE VLAMING SUB-BASIN

PREVIOUS INTERPRETATION

Industry exploration requirements in the Vlaming Sub-basin have meant that only the eastern side of the sub-basin has had sufficient seismic coverage for a detailed analysis of the basin's structure (Plates 1 and 21). 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 on the eastern side of the sub-basin, with grabens and half grabens being developed as a consequence of this faulting (Plate 20). 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.

Since the Neocomian breakup unconformity is generally at a depth of one second TWT or less, recognition and definition of the major faults is relatively easy. However, the orientation of the seismic grids and the lack of seismic data on the western side of the sub-basin have meant that the overall interpretation of the basin-forming processes has been incomplete and somewhat ambiguous. Seismic interpretation has also been hampered by the generally poor quality of the data. This is largely due to the widespread occurrence of surface limestones that cause ringing and diffraction, which prevent resolution of the seismic signal at depth. The restriction of seismic acquisition to the "bad weather" winter months of the year, as a result of crayfishing activities, has also affected seismic quality to some extent. 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 relatively minor structuring, mainly reactivation of faults, exists. However, the interpretation of the deeper horizons has been difficult as a result of severe disruption by faulting, folding and erosion.

Structural elements, such as the Rottnest Trough, Roe High, Bathurst Syncline, Peel Arch and Koombana Arch, have been delineated by seismic methods (Plate 20). The Rottnest Trough-Roe High region has been investigated in some detail (e.g. Birch, 1984), with more than half the wells being concentrated in this part of the sub-basin. The Rottnest Trough previously has been variably interpreted, both in the literature and in company reports, as (i) part of an aborted rift system; (ii) a consequence of extension and subsidence; and (iii) a collapsed arch (e.g. Birch, 1984). On its eastern side, the Rottnest Trough is bounded by the Badaminna Fault Zone, which in this region has been portrayed as up to three major faults that are downthrown to the west (Plate 20). The western side of the trough is bounded by an easterly dipping fault, which marks the edge of the Roe High (Plate 20). South of the Rottnest Trough lies the Peel Arch, a feature similar to the Rottnest Trough in some respects, but somewhat more complicated in its structure. It too is bounded to the east by the Badaminna Fault Zone and to the west by an easterly dipping fault (Plate 20). West of the Rottnest Trough and Peel Arch lies the broad downwarp of the Bathurst Syncline, which is illustrated as being bounded on its western margin by a zig zag series of faults in Plate 20. South of the Bathurst Syncline, between Parmelia 1 and Sugarloaf 1, the tectonic elements have been displayed as a series of east and west dipping faults.

Previous interpretations show a marked change in structure at about 33°S (Plate 20). The Badaminna Fault Zone appears to die out at around this latitude, as do many other faults to the west. South of 33°S, the fault zone is replaced by the Koombana Arch (Plate 20), and faults to the west of the arch show a marked change in orientation from the previously predominant N-S trend to a NW-SE trend. Onshore, to the south of the Vlaming Sub-basin, the Bunbury Trough forms a deep, but relatively narrow graben (Fig. 2 of Iasky and others, 1991), bounded by the Darling Fault to the east and the Busselton Fault to the west. Immediately to the west of the Bunbury Trough, the Vasse Shelf forms another fault bounded block between the Busselton and Dunsborough Faults. The latter fault separates the Permo-Triassic sequence of the Vasse Shelf from the Precambrian Leeuwin Block. Offshore, aeromagnetic data indicate that the Dunsborough Fault changes direction from its previous N-S orientation onshore (Fig. 2 of Iasky and others, 1991) to a NW-SE orientation. From seismic lines offshore, the Busselton Fault appears to follow this trend as well (Plate 20).

The overall impression of the previous structural interpretation and mapping, as illustrated in Plate 20, is the disjointed nature of the major faults throughout the Vlaming Sub-basin. The branching and bending of faults is indicative of three trends: a major N-S trend that parallels the Darling Fault, and which is best illustrated by the overall Badaminna trend; an intermediate NW-SE trend, as shown by the offshore trace of the Dunsborough and Busselton Faults, plus some segments of other faults further to the north and along the western margin; and a relatively minor NE-SW trend, as shown by some fault segments. This haphazard arrangement is seen as a result of not taking into account large horizontal offsets between faults.

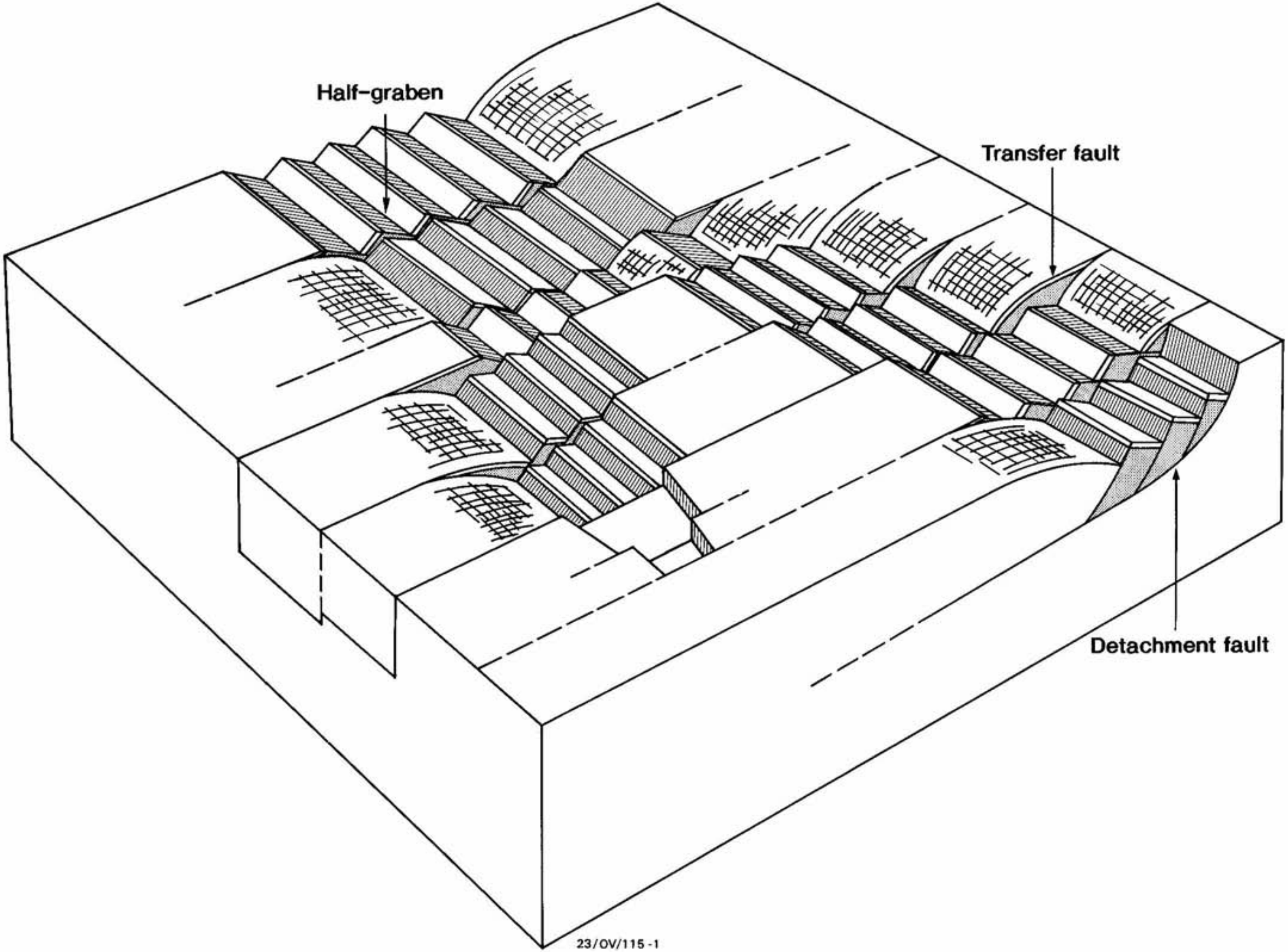
The following interpretation is based on the premise that the faults within the sub-basin form a linked system (Gibbs, 1984, 1990; Etheridge and others, 1987, 1988), commonly with large horizontal offsets between corresponding fault traces. These offsets are, in general, related to pre-existing structures, most of which are transfer faults.

INTERPRETATION AND MAPPING

Re-interpretation of industry data and the interpretation of the AGSO seismic reflection data was undertaken in order to better define the structural style and the occurrence of key seismic horizons. The seismic interpretation was based on a grid of open file company seismic reflection data, which was shot in the early eighties, and the regional lines recorded on the 1988 AGSO surveys. The major horizons that were interpreted and mapped include, in ascending order: Otorowiri Member, base ?Carnac Member, the Neocomian unconformity, top Gage Sandstone Member, top South Perth Shale, and top Leederville Formation. The base ?Carnac Member horizon is a relatively prominent reflection in the Bathurst Syncline, which occurs at the base of a series of closely spaced high amplitude reflections that usually occur in the upper part of the sequence below the Neocomian unconformity. This group of high amplitude reflections is considered to be part of the Carnac Member, and correlation with wells indicates this to be true. What is apparent, however, is that the lowest of these reflections does not necessarily correspond to the actual base of the Carnac Member in every situation, nor could this horizon be mapped with any certainty throughout the basin. However, in the northern part of the Vlaming Sub-basin, where the structure is relatively uncomplicated, it could be mapped with reasonable confidence, and so mapping of this horizon is confined to this part of the basin.

REVISED STRUCTURAL ELEMENTS OF THE VLAMING SUB-BASIN

As stated above, the premise in this interpretation is that the Vlaming Sub-basin forms a series of extensional compartments that are bounded by transfer faults to form a system of linked faults similar to systems described previously by Gibbs (1984, 1990) and Etheridge and others (1987). The basic elements of a linked fault system consist of some form of extensional fault that is bounded laterally by a transfer fault which translates any differential displacement to the adjacent extensional compartment. Extensional compartments with similar or opposite structural polarities, such as shown in Figure 3, are linked by transfer faults. Essentially, "transfer faults are accommodation structures which allow along-strike variations in the position, spacing and/or dip of the normal and detachment faults" (Etheridge and others, 1988). Where the transfer fault is parallel to the extensional direction, no vertical throw is apparent (Gibbs, 1984) and stratigraphic boundaries will show little or no strike change across the transfer fault, whereas if the transfer fault is oblique to the transport direction some displacement will occur (Gibbs, 1990).



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During the seismic interpretation phase, the major faults on individual lines were delineated and mapped. Basically, these faults fall into three categories: extensional faults showing dip displacement with either a westerly or easterly dipping fault plane-the former have been designated red or R faults, whereas the latter have been labelled as blue or B faults (Fig. 4); what are interpreted as possible or probable transfer faults form the third category. While transfer faults are difficult to define from a seismic section, particularly if the transfer orientation is at an oblique angle to the seismic grid, it was considered advantageous to mark the positions of suspected transfer faults to see if some sort of consistent pattern emerged. While this hit or miss approach has obvious limitations, it was felt that the major transfer faults could be mapped with some confidence if certain criteria were followed.

These criteria are essentially the same as those outlined by Etheridge and others (1987) in the Gippsland and Bass Basins, but with some necessary modifications. Because the Vlaming Sub-basin is essentially an intracratonic basin, it is possible to map the bounding faults on both sides of the basin. While the dimensions of the seismic grid are variable throughout the basin, in places it is possible, particularly on the eastern margin, to map the same fault across three or more adjacent dip lines. This relatively straight line trace of the fault is periodically offset, often as little as 1 to 2 km, but up to as much as 25 km. These abrupt offsets are interpreted as displacement of the fault along a transfer fault. By mapping these offsets on both sides of the basin, it is possible to define the more significant transfer faults. Within the basin it is possible to define what appear to be relatively major changes in dip direction and orientation of both beds and faults whose geometries are difficult to interpret unless it is considered that the seismic section has crossed from one extensional compartment to another, via a transfer fault (see Figure 7 of Etheridge and others, 1988). Using these two main criteria, the position and orientation of significant transfer faults were delineated. Although the transfer faults have, in plan, been illustrated as through-going structures, this, in fact, may not be the situation. As mapped, the position of each transfer fault was inferred from the alignment of several intersections at the level of the Neocomian unconformity (the highest level of the transfer faults), and the fault is depicted as a continuous feature. It should be pointed out here, although it will be discussed in more detail later, that the transfer fault traces mapped from the seismic sections are the imprint, within the Late Jurassic sequence, of an earlier tectonic regime that were reactivated at the time of breakup. Therefore, it does not necessarily imply that the reactivated transfer pattern conforms to the original. As illustrated, we believe that the depiction of the transfer faults conforms more to its original pattern rather than as it exists at the level of the Neocomian breakup unconformity.

Transfer Faults

The linked fault system structural elements map (Plate 22) shows, in two dimensions, a series of faults and arches orientated in a general N-S direction that are linked by a series of NW-SE trending transfer faults. What is obvious from this map is that the basin has been compartmentalised by the transfer faults, with some compartments undergoing different amounts of extension from their neighbours. Comparison with the older generation structural elements map (Plate 20) shows that the inconsistencies in fault length and orientation can be explained by the new map. For instance, the sudden termination of the Badaminna Fault Zone at 33°S can be explained by a 25 km offset of the fault zone by a major transfer fault (Plate 22). This particular transfer fault is significant because it appears to form an extension of the onshore Harvey Ridge: the boundary between the Southern Dandaragan Trough and the Bunbury Trough. Similarly, the predominance of NW-SE faults south of 33°S on the old map coincides with large displacements along transfer faults as shown in Plate 22. Even the Busselton Fault is offset by transfer faults to some extent, although the long, linear segment of that fault in the southwest corner probably indicates that it has been reactivated as a strike-slip fault that has probably offset the transfer faults. Another major transfer fault occurs to the south of Rottnest Island. Here, as well as a fairly significant offset of 10 km on the Badaminna Fault Zone, there is a marked change in the orientation of the normal faults from a NNE direction south of the transfer fault to a more northerly trend north of Rottnest Island.

Overall, the transfer faults are depicted as parallel, northwesterly-trending lineaments whose azimuth is approximately 310°. This is the same azimuth as the oceanic fracture zones within the Perth Abyssal Plain and the Wallaby Fracture Zone (Markl, 1974a; Veevers and others, 1985). This coincidence of transfer and transform faults has been remarked on previously (e.g. Etheridge and others, 1989). However, at this stage there is insufficient data to extend the transfer faults beneath the continental slope. Towards the coast, the transfer faults do appear to extend beyond the Badaminna Fault Zone, into the Southern Dandaragan Trough and the Bunbury Trough, but there is no evidence to suggest that they extend onshore. However, regional airborne magnetic data over the Yilgarn Block depict lineaments that are parallel to the transfer faults within the basin, and the major bounding fault of the intracratonic Collie Basin has a similar trend. On Landsat imagery to the east of Perth, a similar trend can also be observed in the alignment of valleys, immediately to the east of the Darling Fault. Gravity anomaly trends depicted by Willcox (1990) from the southern margin of Australia, which he considers to be major transfer faults, have the same orientation as those in the South Perth Basin, and he even depicts an anomaly trend extending from the western transfer fault of the Bremer Basin through the Yilgarn Block and into the Perth Basin. The implication here is that the transfer faults are essentially pre-existing structures whose origin is related to tectonic events that could even predate basin initiation, but which have influenced the structural geometry of the region up to, and including, the generation of new oceanic crust as the Australian continent moved away from the spreading ridge. Conversely, it can be pointed out that while there are significant offsets of the Badaminna Fault Zone, there does not appear to be any significant offset of the Darling Fault. While this could imply that the transfer faults are decoupled at the Darling Fault and that they are not through-going structures (which would contradict the magnetic, gravity and Landsat data), it can be implied from the above-mentioned lack of offset of the trace of the Busselton Fault offshore by successive transfer faults (Plate 22), that the Darling Fault may also have been reactivated as a strike-slip fault relatively late in the basin's development. There are indications that the Darling Fault has had a large strike-slip component throughout most of its history (Iasky and others, 1991).

While the transfer faults have been depicted mainly as parallel traces, there is one area on the western side of the sub-basin where there appears to be some type of switching mechanism of the faults. This area has a relatively good seismic coverage, with about a 3 km line spacing. Plotting of possible transfer faults on this closely spaced grid shows a divergence from the general NW-SE trend immediately to the north of the westernmost trace of the Busselton Fault (Plate 22). What appears to happen is that the transfer fault switches across to its neighbour. There is also a change in the polarity of "normal" fault plane dips in this region (Plate 22); one of the few places where this occurs in the Vlaming Sub-basin. This switching from one transfer fault to the other is somewhat analogous to "transfer zones" as defined by Morley and others (1990). These transfer zones are "a coordinated system of deformational features (i.e. faults) conserving regional extensional strain", and which commonly allow abrupt changes in fault plane orientation such as seen in this part of the sub-basin. A major difference here is that the transfer zone is providing accommodation between two transfer faults rather than extensional faults. The implication here is that the transfer faults are older structures that were reactivated during the Neocomian, and that the reactivated transfer faults could not be accommodated completely within this highly oblique regime. One wonders if the change in polarity of the fault planes is a cause or a consequence of these transfer zones. The transfer zones occur at and on either side of the western boundary of the Vlaming Sub-basin. It is conceivable that the different fault polarity at this basin margin already existed, and that this had to be accommodated during the drift-onset phase in the Neocomian.

STRUCTURE OF INDIVIDUAL BASIN SEGMENTS

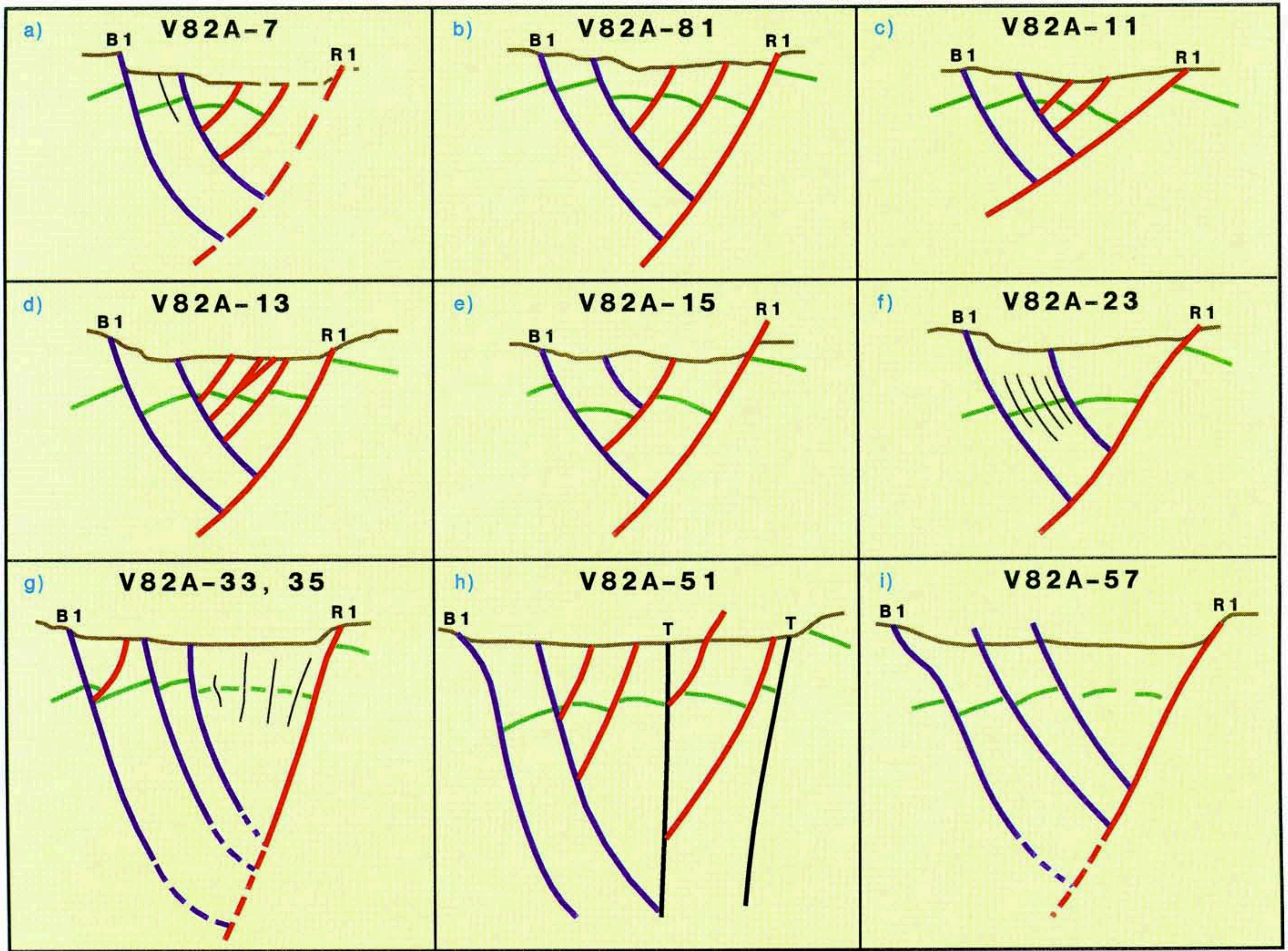
A consequence of mapping the structural elements of the Vlaming Sub-basin was that it became apparent that a unifying structural concept could not be applied to the basin as a whole. The structural elements within one part of the basin often cannot be related to another part. This is highlighted to a large extent by an analysis of the true dip of the faulted sediment packages at the level of the Carnac to Otorowiri reflectors (Plate 23). This was carried out by establishing the vector of maximum dip at the intersection of seismic lines. In most regions, the true dip of the faulted sediments is at 10-45° to the gross trend of the overall structures. The dip direction of the sediments is assumed to reflect the local tectonic transport direction, and to have resulted from rotation on curved faults. Where the fault is pure dip-slip, the hanging wall sediments dip in precisely the opposite direction to the dip of the fault. However, where the net slip vector on the fault is oblique, the dip direction of the hanging wall sediments will be at an angle of between 90° and 180° (or oblique to) the dip direction of the fault. These relations mean that dip analysis of fault-rotated sediment packages provides a relatively reliable indicator of the local tectonic transport direction. What the dip analysis (Plate 23) shows is that, apart from the tendency towards oblique transport directions, there are significant discrepancies in the tectonic transport direction of one part of the basin compared to another. This seeming lack of continuity can be ascribed to varying amounts of dip-slip versus strike-slip. It is considered that the only way to overcome this complexity is to deal with, and structurally analyse, discrete segments of the basin individually, in order to produce a succinct structural overview. This section, therefore, examines the structure of those parts of the basin that have been addressed previously, such as the Rottnest Trough, Bathurst Syncline, Peel Arch etc., and attempts to relate their structure to the previously outlined system of linked faults and the predominant basin-forming processes.

Rottnest Trough

The Rottnest Trough is situated on the eastern side of the Vlaming Sub-basin, extending north from about Rottnest Island to about 31° 20', where it seemingly crosses the coast. To the south, the Rottnest Trough does not appear to extend beyond the major transfer fault south of Rottnest Island. In section, the trough appears as a collapsed arch between two mutually facing faults, designated here as R_1 to the east and B_1 to the west (Plate 24). On both faults the throw on the Otorowiri Member marker horizon is of the order of 0.9-1.8 secs (TWT). However, in some sections the throw on B_1 is negligible; on line V82A-81 in Plate 24, most of the throw is taken up by the fault immediately east of B_1. Throughout all sections, R_1 appears as the major controlling fault and B_1 is antithetic to it (Fig. 4). Within the arch there appears to be a fairly complex pattern of faults, and the structure varies from line to line (Fig. 4). In the northern part of the trough there is usually an easterly dipping fault to the east of and parallel to B_1 with two other faults antithetic to it (Fig. 4a-c). However, to the south (Fig. 4d-i), the fault pattern is less consistent. Attempts at mapping the Otorowiri marker horizon within the trough (Plate 29) are almost impossible because of the complexity of the fault pattern and the inability to carry the contours from line to line. Further complications arise where a particular section crosses a transfer fault, with part of the section either being repeated or omitted (e.g. Fig. 4h). It is also apparent from Figure 4 that the R_1 fault plane varies in dip to form a curvilinear surface. The fault plane varies between shallow (Fig. 4c) and steep (Fig. 4g), whereas by comparison, B_1 does not unduly change its dip; its trace merely shortens or lengthens, depending on the dip of R_1.

Contrary to previous interpretations of the origin of the Rottnest Trough, we believe that the structure is the manifestation of wrenching during the deformational phase at the beginning of the Cretaceous. However, the type of wrench structure departs somewhat from the "classical" type of wrench fault, such as depicted by Harding and others (1985; Figs 20, 21) in that the controlling fault (i.e. R_1) is relatively low angle. A similar situation exists in the Abrolhos Sub-basin to the north, where nearly identical structures exist (Marshall and others, 1989a, b). In the latter case, however, it can be seen that the structures have been produced by reactivation of an earlier (Permian) set of listric faults, and the through-going or major fault still assumes the angle of the original rotational fault. The implication here is that R_1 is the reactivated trace of an earlier rotational? fault, but that movement was predominantly strike-slip during the reactivation phase. The series of mutually antithetic faults, including B_1, was produced as a result of this wrenching, forming a flower structure similar to the reactivated faults in the Abrolhos Sub-basin. The flower structure is dominated by normal dip-slip faults (i.e. negative), which indicates that the Rottnest Trough is a divergent wrench fault (Harding and others, 1985), produced by oblique extension in this part of the basin during the Neocomian.

A feature of this extension within the Rottnest Trough is that it was not uniform. The width of the Rottnest Trough north of 31° 45'S is considerably less than south of this latitude (Plate 22). The amount of extension or divergence appears to be controlled by the transfer faults, each compartment behaving somewhat differently than its neighbour, but almost doubling the amount of extension at 31° 45'S.


a) V82A-7
B1
R1
b) V82A-81
B1
R1
c) V82A-11
B1
R1
d) V82A-13
B1
R1
e) V82A-15
B1
R1
f) V82A-23
B1
R1
g) V82A-33, 35
B1
R1
h) V82A-51
B1
T
T
i) V82A-57
B1
R1

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To the east of the Rottnest Trough is a series of tilted fault blocks, that are dominated by two major faults (designated R_2 and R_3), which, together with R_1, make up the Badaminna Fault Zone (Plate 25a). Between R_1 and R_3, the Otorowiri horizon becomes progressively deeper across each tilt block, with often little throw on the faults (Plate 25a). Beyond R_3 the Otorowiri marker is not apparent, and the beds tend to be horizontal, although they sometimes assume a horizontal aspect beyond R_2. This suggests that R_3 is the reactivated trace of the eastern bounding fault of the Vlaming Sub-basin, and that the beds were tilted during this Early Cretaceous phase of tectonism. However, it appears that during this phase, within some transfer fault-bounded compartments, extension occurred on R_2 and not R_3. This again points out that reactivation did not conform exactly to the tectonic grain of the original basin-forming structures.

Bathurst Syncline

The boundary between the Rottnest Trough and the Bathurst Syncline is commonly referred to as the Roe High, but this feature is not necessarily developed along the entire boundary; strictly speaking, the boundary is the B_1 fault. Where present, the Roe High consists of the eroded edge of a fault block bounded by B_1. Erosional backstepping of the original fault scarp has produced a smoothed topography (Plate 25b). The extent of the high is best illustrated by the Neocomian Unconformity structure contour map (Plate 30).

West of B_1 there is a broad, relatively unstructured tilt block with beds dipping gently to the west (Plate 24). The overall configuration of the Bathurst Syncline is depicted in the Otorowiri horizon structure contour map (Plate 29). This shows the structure to be not so much a syncline, but a relatively elongate downwarp, forming an amphitheatre-like structure. In the north, the structure contours define a fairly uniform southwesterly dip, whereas to the south this rapidly swings around to the west, and ultimately to the northwest.

In the north, this broad downwarp is interrupted by a fault, designated as B_2 (Plate 24), which is downthrown to the east by the order of 0.1-0.4 seconds (TWT). B_2 is shown in section to have been reactivated, commonly showing offset of the unconformity as well as the underlying horizons. Mapping shows B_2 to be a relatively straight fault, with little offset by the transfer faults (Plate 22). This could suggest that this particular fault is a relatively late fault that may have only been generated during the Early Cretaceous structuring phase, compared to the bounding faults that were initially generated during the Permian? phase of basin development. However, while there is little vertical offset, the Otorowiri structure contour map (Plate 29) indicates that there is up to 5 km of horizontal offset on this fault. From the structure contour map it can be seen that the contours on either side of B_2 are more or less perpendicular to the fault trace, suggesting a strong strike-slip component on this fault. This is emphasised by the distinct offset of the isopleths by B_2. Another indication that B_2 may be a late fault is that it does not appear to be present south of about 31°45'S, seemingly being terminated at its intersection with the major transfer fault south of Rottnest Island.

West of B_2, the Otorowiri horizon appears to go into compression, forming a slight arch which is bounded on its western end by another fault, designated B_3 (Plate 24). This fault is slightly curved, with very little indication of reactivation above the Neocomian unconformity. What is noteworthy is that the Otorowiri and ?base Carnac horizons do not appear to extend beyond B_3. While there are indications of reflections to the west of B_3, they tend to be incoherent, and cannot be directly related to the reflection character east of B_3. On this basis, it is considered that B_3 represents the western bounding fault along this segment of the basin[1]. This implies that in the northern part of the basin the distance between R_3 and B_3, the two bounding faults, is only of the order of 45 km, making it a very narrow, but presumably deep basin.

One segment of the western boundary of the Bathurst Syncline shows a complex fault pattern, which we interpret as a wrench structure (Plate 25 c,d). This 12 km wide wrench zone is bounded to the north by the major transfer fault south of Rottnest Island, whereas to the south the boundary is less distinct, but it does appear to be terminated by a transfer fault (Plate 22). The wrench zone is a fairly complex one, showing elements of both positive and negative flower structures. The actual nature of the flower structure varies from line to line. At depth there does appear to be a vertical to near vertical fault, which typically diverges near the top (Plate 25 c,d). Other faults, with both east- and west-dipping fault planes, diverge from this main fault. It is apparent in some sections that the Otorowiri Member marker horizon does not extend beyond the vertical fault.

Between B_1 and B_3 the part of the section between the ?base Carnac and Otorowiri horizons thickens progressively to the west. In places the thickness more than doubles. Initially, this was thought to be growth faulting across B_2, but on further inspection it

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[1] Examination of more recent seismic data acquired by Ampol Exploration in 1991 reveals that the Otorowiri horizon does extend beyond B_3 to another fault, which in fact is the bounding fault.

can be seen that this increase in thickness is related to a general depositional trend of increasing thickness of Late Jurassic sediments into the Bathurst Syncline. This is shown on the lower Parmelia Formation isopach map (Plate 33) for the northern part of the Vlaming Sub-basin, which shows a uniform east to west thickening of the section between the ?base Carnac and Otorowiri horizons. It is also apparent in some sections that a similar thickening occurs within the Yarragadee Formation.

Peel Arch

This 15 km wide structure is located along the eastern boundary of the Vlaming Sub-basin, south of Rottnest Island. To the north, it appears to be bounded by the major transfer fault south of Rottnest Island, whereas to the south its boundary is less well defined, but, again, it does appear to be a transfer fault; the one which cuts R_1 at about 23°30'S (Plate 22). Within this complex basin where most structures are poorly defined or understood, the Peel Arch is probably the least understood. While its name implies some sort of compressional structure, we find little evidence for this, and, indeed, we interpret the structure as extensional (Plate 26).

Across this feature, at depth and on either side, there is a consistent westerly dip of the pre-breakup section (Plate 26). This in itself is somewhat of an enigma, because rotation on the eastern bounding faults would conventionally produce easterly dipping beds (as on the eastern side of the Rottnest Trough). At this stage we have no explanation for this apparent conflict. Within the so called arch itself, there are both easterly and westerly dipping fault planes in the shallow pre-breakup section (Plate 26), much the same as in the Rottnest Trough, and the beds do tend to produce a central rollover or arch. What have been referred to as R_1 and B_1 previously, can be interpreted here as a continuous single fault that forms a detachment, often with a saddle in the middle, from the underlying strata (Plate 26).

While this feature has the appearance of a detachment fault, there are several problems with this interpretation. Strike lines along the arch show the presumed detachment fault shallowing to the north, but being abruptly terminated, both north and south, by transfer faults. If the headwall of the fault lies to the north, as indicated by this shallowing of the fault plane, then extension would have to have occurred from north to south. However, geometrical and space considerations do not allow this. Basically, extension cannot be accommodated in a north-south direction because of the bounding transfer faults, beyond which the supposed detachment no longer exists.

At this stage, our preferred interpretation is that the Peel Arch is an extensional or divergent wrench zone. This would imply that individual sections define a negative flower structure that is shallowly divergent. Within the structure, it can be seen that beds, such as the Otorowiri marker horizon, are successively downfaulted on either side, and eventually form a compressional or arch-like feature in the centre (Plate 26). A possible objection to this interpretation is the lack of a major perpendicular fault at depth; however, given the complexity of the structure, this may be difficult to image on the seismic sections.

Koombana Arch

The previous structural elements map (Plate 20) shows the Koombana Arch to be a poorly defined feature, whereas the linked fault elements map (Plate 22) shows that the arch has been offset along transfer faults by up to 10 kilometres. In section, the arch can be seen as a compressional feature, bounded to the east by a major fault (R_1). Within, and to the west of the arch, there is a series of antithetic faults, which have been instrumental in forming the compressional feature (Plate 27).

To the north, the Koombana Arch is bounded by the major transfer fault that forms an extension of the Harvey Ridge (Plate 22), whereas to the south it appears to cross the coast and possibly link up to the Darradup Fault.

The structural configuration of the Koombana Arch suggests that it was formed by wrenching. However, this part of the Vlaming Sub-basin underwent compression rather than extension to form a positive flower structure (Plate 27). This compressional phase was probably related to reactivation of a previous basin-bounding fault during the Early Cretaceous, and that the wrench structure was produced as a result of this reactivation.

Vasse Shelf

Onshore, the Vasse Shelf has been defined as the narrow zone of Permo-Triassic sediments between the Dunsborough and Busselton Faults (Iasky and others, 1991). According to Iasky and others, the thickness of the Vasse Shelf sequence ranges from 0.5 to 3.0 km, and that it thickens rapidly offshore. As shown in Plate 20, the Dunsborough Fault, soon after it crosses the coast, swings to the northwest. To date, this trend in the Dunsborough Fault has only been interpreted from aeromagnetic data, but it does suggest that there could be a large offset of the fault. A similar offset of the Busselton fault has been suggested from mapping the structures in the southern part of the Vlaming Sub-basin (Plate 22). Both the linked fault structural elements map

(Plate 22) and the previous structural interpretation (Plate 20) agree that there is a prominent NW-SE tectonic grain in the south. We have interpreted this orientation as reflecting transfer faults (Plate 22). It is significant that this interpretation implies a substantial offset of the Busselton Fault by transfer faults after it crosses the coastline; an offset of some 30 km is indicated just south of 33°S (Plate 22). Similarly, the northwesterly swing of the Dunsborough Fault reflects a substantial offset by a transfer fault.

A feature of the offshore Busselton Fault is its linear trace for something of the order of 50 km between 32°40' and 33°05'S along the western margin of the Vlaming Sub-basin. The fault could be delineated on at least six dip lines and four strike lines (Plate 28a), and plotting these intersections on the map (Plate 22) showed a very linear fault trace. On line W82-3 (Plate 28a), the fault plane trace appears to be relatively low angle, which would tend to contradict the assumption of Iasky and others (1991) that onshore the fault is steeply dipping. However, this particular line is fairly oblique to the fault plane, so the true dip may not be apparent; there is some suggestion in this seismic section of a steeper fault trace than the one projected. Iasky and others (1991) imply that the Busselton Fault, onshore, is predominantly strike-slip. This is supported by the offshore trace of the fault, which, while being offset substantially by transfer faults, is a linear feature. It would appear that the fault was active during the Early Cretaceous phase of structuring, since it does appear to have offset transfer faults in places.

East of the implied offshore trace of the Busselton Fault is another fault system that is believed to form the western boundary of the Vlaming Sub-basin in this region (Plate 22). This fault has also been significantly offset by transfer faults, to the extent that the width of the sub-basin increases from something of the order of 15 km in the south to about 70 km around 33°S. In this area the Vlaming Sub-basin is highly compartmentalised, each compartment undergoing increasing amounts of extension to the north. This western bounding fault of the sub-basin appears to be rotational, in that it is a relatively low angle fault. There is a marked low in the Neocomian unconformity along this bounding fault between 32°30' and 33°00'S (Line W82-16 in Plate 28; Plate 30) that is indicative of a fair amount of rotation on it.

Between the western bounding fault of the Vlaming Sub-basin and the Busselton Fault is a relatively narrow zone that is believed to be an extension of the Bunbury Trough to the south. In general, seismic sections in this region show well bedded sediments (e.g. western part of W82-12A in Plate 28). Part of this sequence shows a reversal in fault dip from the Vlaming Sub-basin. This switch is believed to have been accommodated by transfer zones such as the one shown in Plate 28.

AN OBLIQUE-SLIP INTERPRETATION FOR THE VLAMING SUB-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 is, however, evidence in the structural configuration of the Vlaming Sub-basin that clearly indicates that there is a substantial strike-slip component to the basin-bounding faults and to faults within the sub-basin. On this basis, the Vlaming Sub-basin can be interpreted as an oblique-slip basin, whereby extension resulted from a combination of dip-slip and, more predominantly, strike-slip movement. Perhaps the major uncertainty with this interpretation is whether or not this style of extension is a relatively late event, occurring only at the time of breakup, or if it was an ongoing event throughout the history of the basin. Because the original basin-forming structures cannot be imaged, it can be argued that any evidence for oblique-slip basin formation is circumstantial. However, there is sufficient indirect evidence to support an oblique-slip interpretation.

As with most sub-basins of the Perth Basin, the Vlaming Sub-basin is a narrow elongate depocentre, with an anomalously thick basin fill. Elsewhere within the Perth Basin, we know that initial rifting occurred sometime during the Permian; possibly as early as the Early Permian, but most certainly by the Late Permian. Initial rifting was presumably a result of crustal thinning beneath what was to become the Westralian Superbasin of Yeates and others (1987). In the region of the Perth Basin, crustal thinning appears to have been greatest both adjacent to the Darling Fault and along the centre of the proto-rift (which was presumably in the vicinity of the present Houtman and Vlaming Sub-basins). The sub-basins of the offshore North Perth Basin, where the original basin-forming structures are visible, are considered to be transtensional (Marshall and others, 1989a, b). In these sub-basins, the degree of dip-slip extension is minimal and, similar to the Vlaming Sub-basin, they have a thick sedimentary fill. In the Bunbury Trough, Iasky and others (1991) have identified three periods of predominantly strike-slip movement: (a) right-lateral motion along the Darling Fault in the Late Permian-Early Triassic; (b) left-lateral motion along the Dunsborough Fault in the Jurassic; (c) oblique-transcurrent faulting at the time of breakup in the Early Cretaceous.

These results from elsewhere in the Perth Basin indicate that highly oblique extension probably occurred early in the sub-basin's history. This would have resulted from the interaction between the Darling Fault system and a NW-SE tectonic transport direction.

Reactivation of these structures in the Early Cretaceous would have resulted in the interaction between the NW-SE transfer faults and N-S oblique normal faults in the Vlaming Sub-basin to produce an overall transtensional result. This is most apparent from the true dip map of the basin (Plate 23). While the structural style in the Early Cretaceous in the Vlaming Sub-basin is both extensional and strike-slip, the amount of extension normal to the generally north-south strike of the faults is relatively small (<20%), and the principal fault displacement was strike-slip: up to 5 km of horizontal displacement has been measured in the Bathurst Syncline. The strongest indication of 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. The Rottnest Trough, Peel Arch and Koombana Arch are all considered to be the product of wrench faulting.

POST-EARLY CRETACEOUS STRUCTURING

Some faulting extends into the shallow section above the Neocomian unconformity. However, most of these faults tend to have relatively minor offsets, and so many of them have not been displayed on the structure contour map (Plate 30). In contrast, faulting at the top Otorowiri Member level (Plate 29) is so intense and disjointed, particularly within the Rottnest Trough and Peel Arch, that it is impossible to accurately represent the structure at this level on the time structure contour map.

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 (Plate 30). 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 locations of the depocentres.

The Perth Canyon has long been an enigma in the structural analysis of the Vlaming Sub-basin. However structural analysis of the AGSO 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 (Plate 2) there is an offset in the sub-basin boundary, possibly produced by a transfer fault. 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. However, there remains a major structural and stratigraphic discordance along the NNE-trending arm of the canyon. This is best illustrated by the Neocomian unconformity structure contour map (Plate 30) which shows a marked miss-match of the contours along this arm of the canyon. On the northwestern side of the canyon the unconformity is relatively shallow, and it actually crops out on the wall of the canyon, whereas on the southeastern side the unconformity is so deep, it could not be imaged on the watergun data. This has been verified from dredging both walls of this particular arm of the canyon. On the northwestern wall, it was possible to recover Early Cretaceous rocks, whereas on the southeastern wall, only Tertiary limestones were recovered (Marshall and others, 1989c). On the seismic sections, because of the large topographic variation, it is difficult to delineate any fault beneath the canyon. However, if a fault existed it would have to have a throw of the order of up to 1 second (TWT) to be able to explain the discrepancies between the contours in Plate 30. Both the magnitude of the throw of this supposed fault and its NNE strike is at odds with the overall structural analysis of the basin. However, at this stage we have no explanation for this phenomenon.

STRUCTURE IN RELATION TO HYDROCARBON POTENTIAL

There appear 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 mainly along the eastern part of the sub-basin (Plate 22). These arches are interpreted as flower structures that have been produced by wrenching during the Early Cretaceous phase of structuring of the basin. These structures tend to be large and fairly complex. To date, the only wells that have been drilled on this type of structure are Charlotte 1, Mullaloo 1, Peel 1 and Sugarloaf 1 (Plate 22). 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 within the axis of the arch.

Other potential structural traps are closures associated with the upthrown blocks along faults. A typical example is the Roe High where there is closure against the major western bounding fault of the Rottnest Trough. In some examples, there is rollover on the downthrown block. However, the closure on the Roe High is narrow and elongate, and wells sited on this feature, such as Minder Reef 1, Roe 1, Gage Roads 1 and 2, Tuart 1 and Warnbro 1 were drilled on relatively small closures. Bouvard 1 and Challenger 1 have been drilled on similar structures, although their complexity has been increased to some extent by their proximity to normal fault/transfer fault intersections.

An untested structural play in the Vlaming Sub-basin consists of a series of 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 part of the Bathurst Syncline, between B_2 and B_3, 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.

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 30) shows that the largest depression, and potentially the thickest sequence of the Gage Sandstone Member, occurs along the western boundary of the sub-basin. This depression, or series of depressions, is related to continued offset along the major bounding fault in this region, with draping and thickening of sediments over this feature (W82-16 in Plate 28). While the absence of Gage Sandstone 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. We have identified a possible Gage Sandstone equivalent between Challenger 1 and Sugarloaf 1 (W82-16 in Plate 28), which is much thicker than the Gage Sandstone Member in the Rottnest Trough (Plate 34). 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 oblique-slip extension, mainly from localised compressional events during the latter part of the basin's formation. Many potential structures exist along the untested western margin of the sub-basin. The limited amount of industry and AGSO 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.

DEPOSITIONAL ENVIRONMENTS

Yarragadee Formation

The Yarragadee Formation comprises a major alluvial-fan/fluvial/deltaic system, the total thickness of which is not known in the Vlaming Sub-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 Otorowiri Member of the Parmelia Formation, a sand-rich deltaic sequence is evident.

The sandstones are medium to coarse grained, poorly sorted and kaolinitic, and the sequence exhibits little regional lithologic variation. According to Arditto (1982), the average composition of the sandstones is quartz 60%, feldspar 20%, mica trace, authigenic kaolinite 15%, and carbonate cement 5%. The kaolinite matrix has largely resulted from the chemical breakdown of detrital feldspars. This, plus the subarkosic composition of the sandstones indicate that the source was probably Archaean crystalline basement, and the relative abundance of unstable minerals and authigenic kaolinite is consistent with an alluvial depositional environment. 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, that 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, is 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 Quinn's Rock 1, but, in general, the member comprises lacustrine micaceous siltstone, shale and claystone, known to be up to 99 m thick. A regressive cycle in the upper part of the Otorowiri Member is reflected by a sandy deltaic sequence, 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.

Seismic evidence in the northern Vlaming Sub-basin indicates thickening of the Parmelia Formation into the Bathurst Syncline (Plate 24). As was the situation during the deposition of the Yarragadee Formation, the Bathurst Syncline was the major depocentre within this part of the sub-basin towards the end of the Jurassic. This thickening of the sequence into the syncline is evident from the isopach map of the sandstone unit between the Otorowiri Member horizon and the ?base Carnac Member horizon (Plate 33). The isopach map typically shows an increase in thickness of this unit to the west.

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 13). In areas where delta-front and delta-plain sediments did not extend, such as Minder Reef 1 (Plate 16) and Roe 1 (Plate 6), 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.

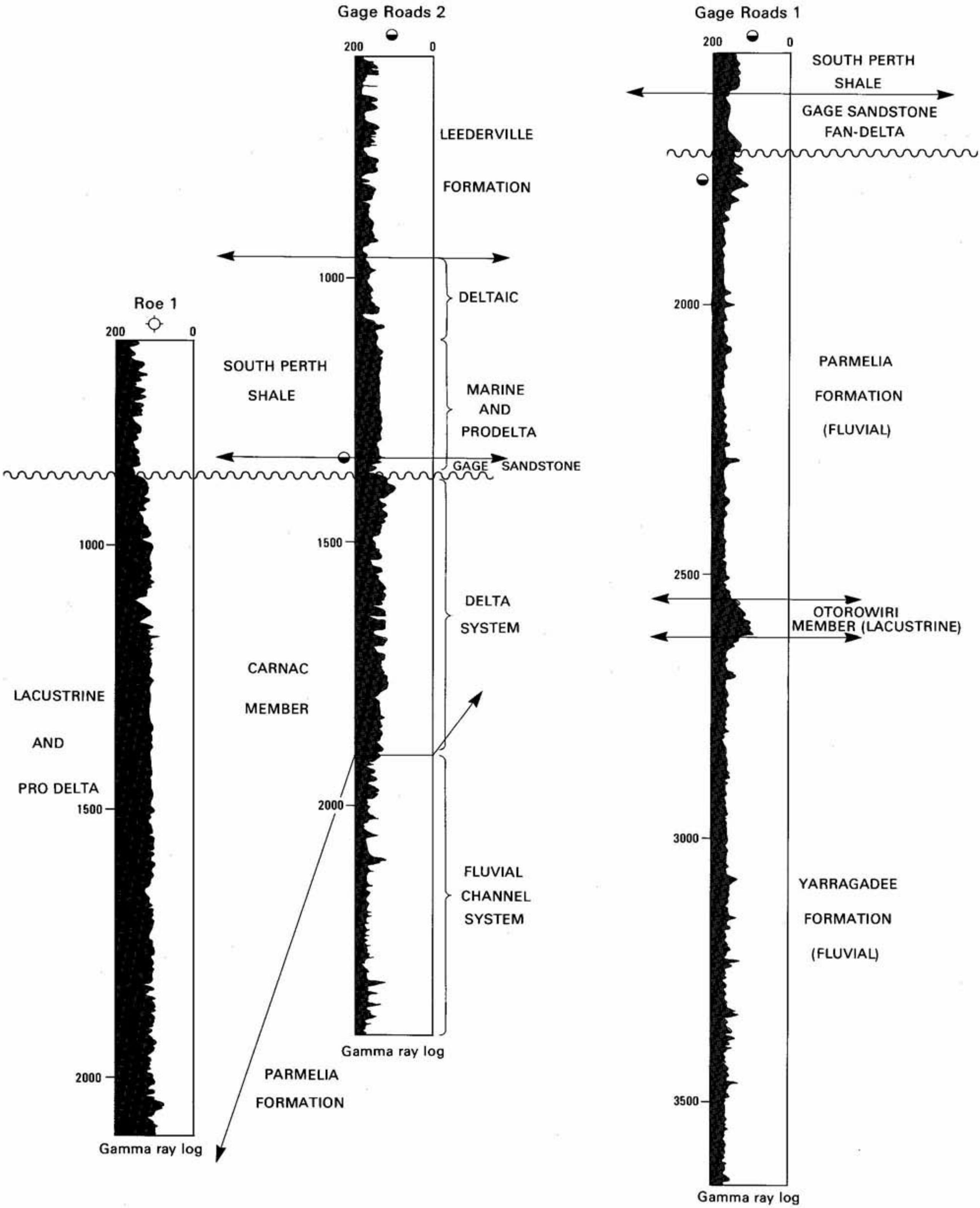

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Figure 5. Log characteristics and environmental interpretation of units intersected in wells from the north Vlaming Sub-basin.

Gage Sandstone Member

The Gage Sandstone Member is an alluvial-fan to fan-delta sequence which, previously, was considered to be mainly restricted to the flanks and axis of the Rottnest Trough. Seismic data from the Rottnest Trough show the top Gage Sandstone horizon onlapping the Neocomian unconformity, usually on both sides of the trough (Plate 24). In general, the Gage Sandstone Member in the north is restricted to the trough, but not exclusively. In places, the Gage Sandstone Member is present in depressions within the unconformity, which don't always conform to the underlying structural 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 the Parmelia Formation. Between 65 and 100 percent of the sequence comprises channel sandstone units from 5 to 30 m 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. 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 7) as comprising turbidite beds in cycles 2 m thick. He considers that the entire Gage Sandstone Member in the offshore Perth Basin was deposited in marine or restricted marine waters. In contrast, he suggests that the Gage Sandstone Member in the onshore southern Dandaragan Trough is fluviatile. In view of the above interpretation, the possible 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.

It is apparent from wells such as Sugarloaf 1 (Plate 10) and Parmelia 1 (Plate 14) that age equivalent sandstones to the Gage Sandstone Member exist outside the Rottnest Trough. In seismic sections in the south of the sub-basin, we have tentatively identified a sequence directly above the Neocomian unconformity that we relate to a Gage Sandstone Member equivalent (e.g. lines W82-12A & 16 in Plate 28). Internal reflections within this sequence show downlap/onlap with the unconformity, as well as low-angle foresets in places, that are distinctly different from the more aggradational reflections directly beneath the top South Perth Shale horizon.

The Gage Sandstone isopach map (Plate 34) shows that in the north the sandstone is restricted to the Rottnest Trough, whereas south of Warnbro 1 there appear to be two major depocentres for the Gage Sandstone Member or its equivalent. East of Bouvard 1 there is an elongate depocentre (Plate 34) that conforms to a pronounced low in the Neocomian unconformity (Plate 30). Alluvial-fans and fan-deltas could have supplied material to this depocentre from the fault-bounded scarp to the east and, to a lesser extent, from the high around Bouvard 1 (Plate 30). The Gage Sandstone Member thins over this high around Bouvard 1, but then increases in thickness once more to the south of Challenger 1 (Plate 34). This western depocentre overlies the significant depression in the unconformity surface (Plate 30), which appears to have been controlled by the western bounding fault of the Vlaming Sub-basin in this area (line W82-16 in Plate 28).

<u>South Perth Shale</u>

This unit attains a maximum thickness of 570 m in wells in the Vlaming Sub-basin. In the south, the thickness of the South Perth Shale is variable, ranging from 60 m in Parmelia 1 (Plate 14) to 560 m in Challenger 1 (Plate 12). Its maximum thickness appears to be in the Rottnest Trough where in Charlotte 1 it is 570 m, but indications from seismic reflection profiles are that, in places, it is probably of the order of 700 m thick. On the flanks of the trough, the South Perth Shale thins (Plate 24), and in crestal areas such as the Roe High it is either thin or absent. In general, it has a fairly wide distribution within the basin (Plate 31), although its extent south of Sugarloaf 1 is not certain.

The sequence tends to be shale-dominated in the north, whereas south of the Rottnest Trough it becomes slightly coarser. 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. 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 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 Quinn's Rock 1. Although largely marine, shale-rich sequences towards the top of the South Perth Shale are considered to reflect pro-delta conditions.

In the northern part of the Vlaming Sub-basin the South Perth Shale is restricted to the Rottnest Trough or downlaps the unconformity immediately beyond the trough, whereas further south it extends beyond the trough on both sides (Plate 31). This restriction of the South Perth Shale in the north is probably related to the configuration of the unconformity, particularly on the western margin of the trough. In the north, the unconformity shows much more relief, and this relief becomes more subdued on the western side of the trough further south. On the eastern side of the trough the South Perth Shale thins dramatically, as the unconformity rises beyond R_1. It also thins and onlaps the unconformity along the Roe High (Plate 24). In places, outliers of South Perth Shale extend beyond the Roe High.

Seismic reflections within the South Perth Shale in the Rottnest Trough show channelling, downlap and mounding. However, most significant is the development of foreset bedding, building out along the axis of the trough. Mounding occurs towards the base, with downlap onto either the top Gage Sandstone horizon or the unconformity. Onlap onto the unconformity occasionally occurs on the western side of the trough. Channelling is more evident at the northern end of the trough, particularly along its western margin. The foresets are gentle and, in general, prograde to the south or southwest. In some seismic sections there appear to be at least three outbuilding phases within the South Perth Shale. This is evident in Esso line V82A-11 (Plate 35), a dip line, which shows three progradational units in the east and a more condensed, and somewhat mounded, distal facies in the west. However, most dip lines show internal reflections which are mounded or aggradational which is more consistent with axial deposition and very little outbuilding in an E-W direction. Conversely, strike lines, particularly those within the Rottnest Trough, show large-scale, low-angle foresets that downlap onto the top Gage Sandstone horizon (Plate 35). Topsets tend to be compressed and at slightly different levels at or directly below the top South Perth Shale horizon.

There was a marked change in sedimentation style in the Rottnest Trough at the end of the deposition of the Gage Sandstone Member, related to a relative rise in sea level. This is reflected in the change in depositional environment from alluvial-fan/fan-delta to shallow marine. According to Birch (1984), discrete pulses of sedimentation led to the building out of large lobes of fine-grained terrigenous sediment down the axis of the trough, the direction of outbuilding being generally in a southerly direction. This outbuilding sequence consists of horizontal topsets that are either parallel to or concordant with the top South Perth Shale horizon. In most examples, the topsets form a condensed sequence at or immediately below the top South Perth Shale horizon. There does not appear to be any erosion of the topsets, nor does the top South Perth

Shale horizon appear to be an erosional unconformity, at least in this part of the sub-basin. The top South Perth Shale horizon is parallel to the predominantly aggradational reflections of the Leederville Formation. Reflections within the thicker foreset interval are relatively low angle, although they do tend to steepen as they build out. In sections such as V82A-38 (Plate 35), initially the foresets tend to be concave upwards, but change to higher angle, convex upwards foresets as the section presumably crosses from one lobe to another. Bottomsets initially downlap onto the Gage Sandstone Member, but they eventually rise in the sequence and form a dominantly aggradational unit between the top Gage Sandstone horizon and the foresets.

Our interpretation of this prograding sequence is that it represents a subaqueous delta, with hypopycnal flow of suspended sediment discharging from the channel mouths and eventually settling on the fore-delta slope. Several factors point to it being a low energy delta, such as the fine grainsize and the low angle and often concave foresets. It is envisaged that the morphology of the Rottnest Trough at that time afforded protection from reworking by waves and currents. With time, the position of the distributary channel changed its position, on at least three occasions, with individual lobes coalescing to form a large deltaic complex. At times, deltaic deposition took place to the west of the Roe High, if and where the unconformity was low enough. In the latter situation the foresets downlapped onto the unconformity rather than the Gage Sandstone Member. Eventually, as the delta built up, it overtopped the original depression formed by the unconformity and spread out as a much thinner deposit, onlapping the unconformity.

Leederville Formation

This sequence is dominated by 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). The structure contour map (Plate 32) shows that the Leederville Formation has a fairly wide distribution within the basin. The map also indicates that possibly some form of ancestral Perth Canyon existed as early as this time; the embayment of the contours west of Rottnest Island in Plate 32 conforms to the present position of the upper part of the Perth Canyon.

HYDROCARBON POTENTIAL

RESERVOIR POTENTIAL

From an analysis of their porosity and permeability, potentially the best reservoirs are, in order: the Gage Sandstone Member, the un-named sandstone units immediately above and below the Carnac Member, and the sandstone units within the upper part of the Yarragadee Formation.

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 ranging from about 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 sequence. Core data show that porosity of the sandstone units of the Yarragadee Formation decreases from 25-30 percent at depths of approximately 1700 m, to 10-15 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 md below 2000 m. Authigenic kaolinite, formed from breakdown of feldspar, has significantly reduced much of the intergranular pore space (Arditto, 1982). Although the clay matrix has considerable microporosity, its presence increases the irreducible water saturation of the 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 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 Member, 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. Analysis of core samples from the lower sandstone unit, at depths of 2000 to 3000 m, shows that porosities of 16-28 percent and permeabilities of 100-2000 millidarcies are present in the fluvial channel units. In fluvial sandstone units of the formation elsewhere, porosity readings range from 23-28 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 types are 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 23-30 percent are evident from core samples of the sequence, while permeability ranges from 200-1800 millidarcies. The sequence has been intersected at depths of between 1400 and 2000 m sub-sea, 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 (average of 20%) and its relatively fine grainsize are a major constraint with respect to its potential as a reservoir. Where present, the sandstone units tend to be thin and have a high matrix content. However, a relatively coarser, but still silty, equivalent of the South Perth Shale was encountered in Bouvard 1, so there might be some textural variation in the southern part of the Vlaming Sub-basin (however, other wells in the south do tend to be shale-dominated). The South Perth Shale is more likely to be a seal to the Gage Sandstone Member or other underlying units of the Parmelia Formation.

Leederville Formation

This sequence has been intersected by petroleum exploration wells at depths between 350 and 500 m sub-sea 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.

SOURCE POTENTIAL AND SEALS

Yarragadee Formation

Potential source rocks in the Yarragadee Formation consist of thin shaly sequences, inter-bedded between the major channel sandstone units. Geochemical analysis (Appendix 2) indicates that the shaly units commonly contain in excess of 1.5 percent total organic carbon (TOC) and, in some wells, such as Warnbro 1 and Sugarloaf 1, TOC values in excess of 2.5 percent are not uncommon (Appendix 2; Plates 7, 10). 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 by the overlying Otorowiri Member of the Parmelia Formation.

Parmelia Formation

Geochemical results from the Parmelia Formation (Appendix 2) show that, overall, the fluvial sandstones contain less organic source material than the deltaic and lacustrine shale units. The TOC content ranges from less than 1 percent in the fluvial sandstones to over 3 percent in shale-rich parts of the sequence. Pyrolysis data (Appendix 2) suggest that there is potential for mixed oil and gas source material in the formation. The greater thickness of fine-grained sediments in the Parmelia Formation, compared to the underlying Yarragadee Formation, makes the former 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 and Carnac Members are both excellent seals. This sealing capability is demonstrated by the Otorowiri Member where a reduction in water salinity, from 38,000 ppm above it to 14,000 ppm below, occurs in Gage Roads 1 and 2. The fine grainsize and thickness of the Carnac Member make it a potentially good seal for the lower sandstone unit, particularly along the western margin of the Rottnest Trough. Seismic profiles in this region indicate that the base? Carnac horizon subcrops the Neocomian unconformity in the northern part of the trough, but in the vicinity of the Roe High it abuts the western bounding fault (B_1) of the trough and is downthrown some 0.5 seconds (TWT) into the trough. This would tend to seal the lower sandstone unit at the high part of the tilt block formed at B_1.

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 2). Although this may be adequate, the 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

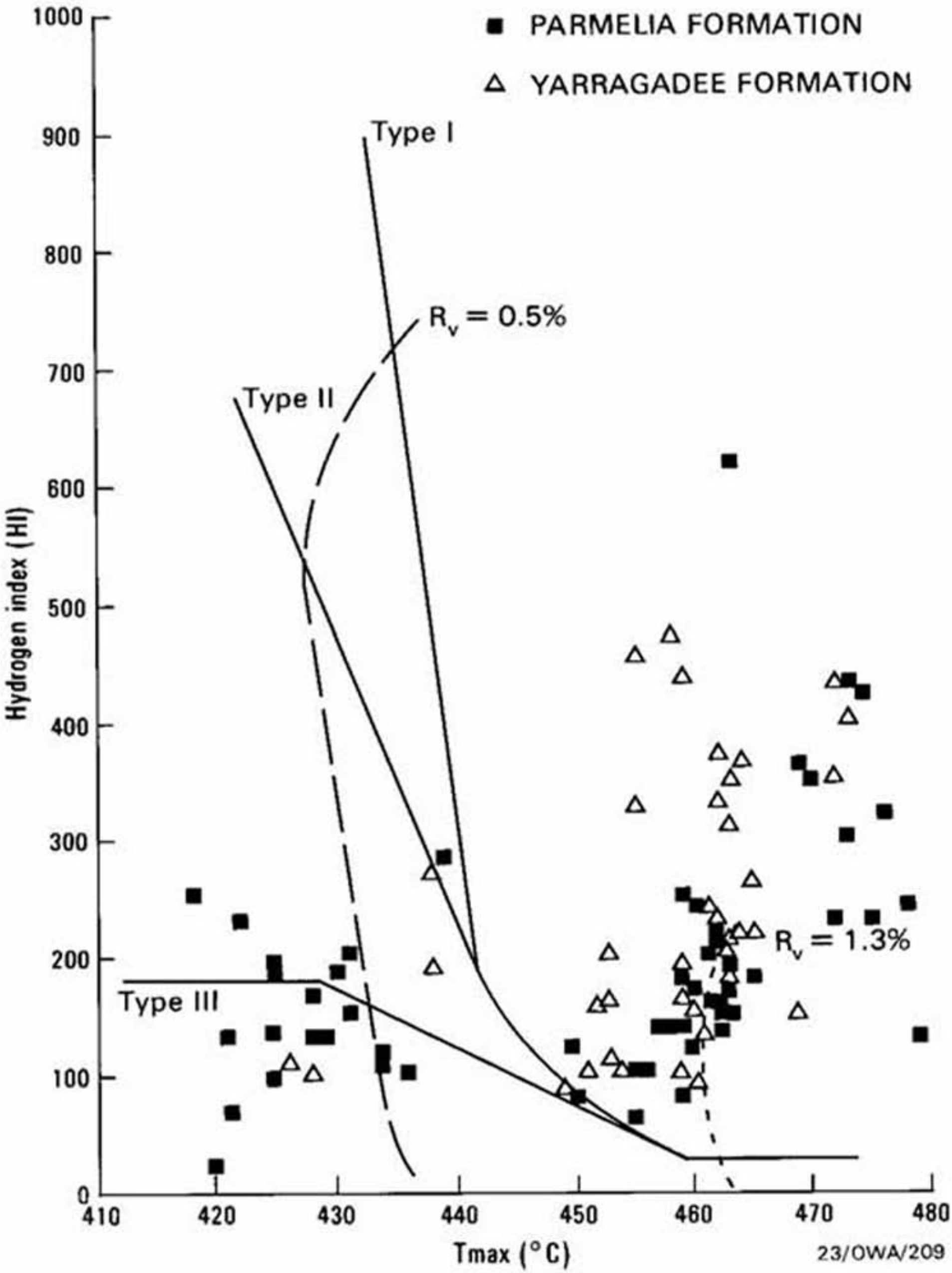
TOC values in the South Perth Shale commonly range from 1 to 3 percent, with one value as high as 70 percent (Appendix 2). At best, a mixed oil and gas product is expected from this sequence if it is oil mature. Its major attribute is its potential to form a regional seal for most of the prospective parts of the sub-basin.

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 2). It is likely to be a reservoir with some potential for internal seal rather than a major source sequence.

MATURATION TRENDS

The amount of vitrinite reflectance data for the South Perth Basin is fairly 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.



PARMELIA FORMATION
YARRAGADEE FORMATION
Type I
Type II
Type III
$R_v = 0.5\%$
$R_v = 1.3\%$
Hydrogen index (HI)
Tmax (°C)
1000
900
800
700
600
500
400
300
200
100
0
410
420
430
440
450
460
470
480
23/OWA/209

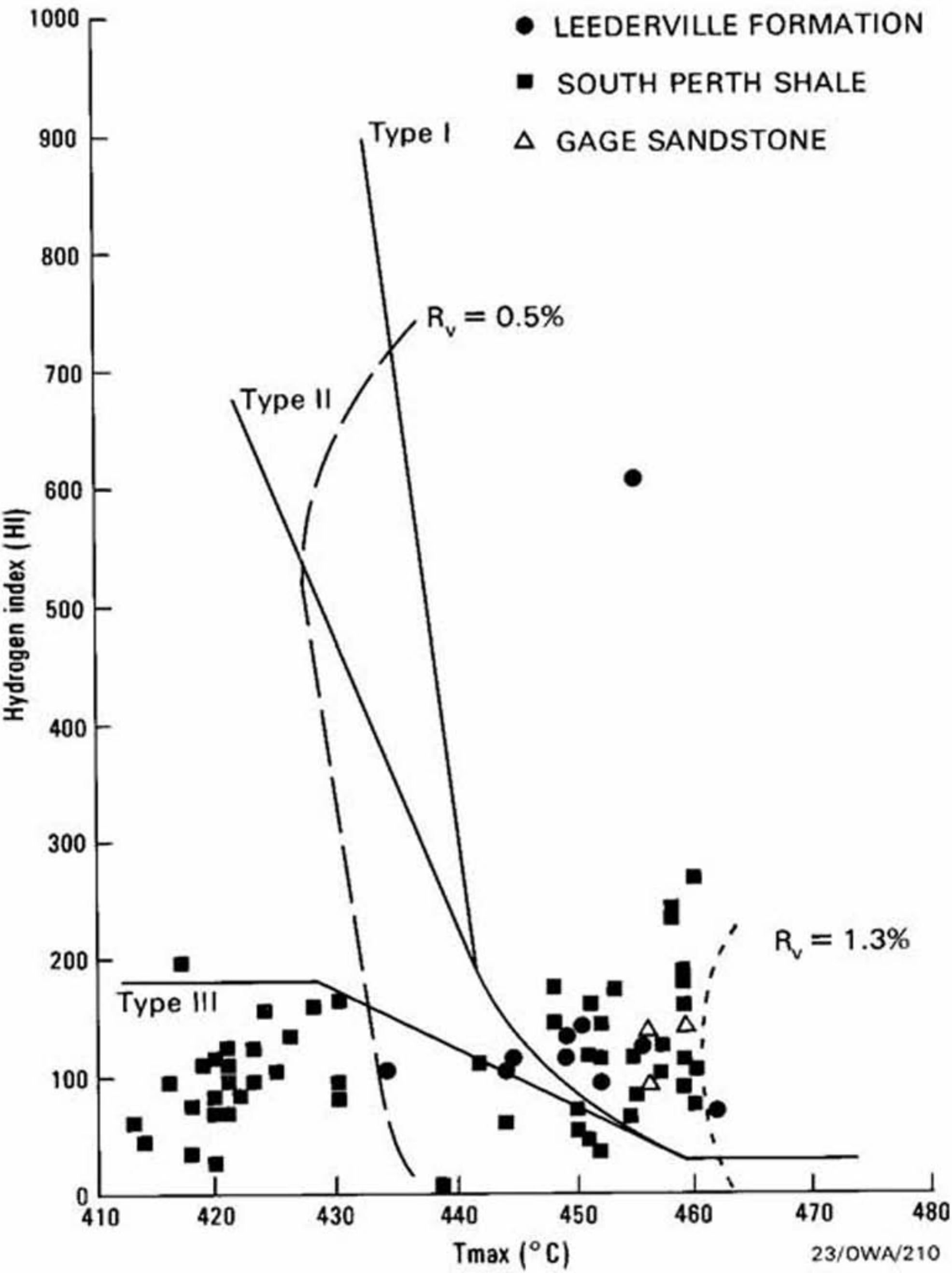
Indications from petroleum exploration wells, such as Sugarloaf 1, Warnbro 1 and Gage Roads 1, show that the onset of early oil generation is likely to be at depths from 1500 m (Sugarloaf 1; Fig. 8) to 3000 m (Gage Roads 1; Fig. 8). Reflectance values for samples in the Yarragadee Formation are depressed by the 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^{-1}. Few of their well plots show evidence of a change of reflectance gradient with depth; Gage Roads 1 is one exception. Their overall assessment was that the Vlaming Sub-basin showed low rank gradients in the Cretaceous section (0.11% R_o km^{-1}) and higher rank gradients (up to 0.34% R_o km^{-1}) 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 2). Other samples from the same sequences contain mature organic matter likely to generate both oil and gaseous hydrocarbons (Fig. 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. Kantsler and Cook (1979) consider that the rank gradients of 0.20 percent to 0.34 percent R_o km^{-1} 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/or 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.

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; i.e. Bathurst Syncline (Hall, 1989; p.445). The Gage Sandstone Member and South Perth Shale are likely to be immature throughout most of the basin because of the relatively shallow depth of burial. Rock Eval results compiled by Surdan


LEEDERVILLE FORMATION
SOUTH PERTH SHALE
GAGE SANDSTONE
Type I
Type II
Type III
$R_v = 0.5\%$
$R_v = 1.3\%$
Hydrogen index (HI)
1000
900
800
700
600
500
400
300
200
100
0
410
420
430
440
450
460
470
480
Tmax (°C)
23/OWA/210

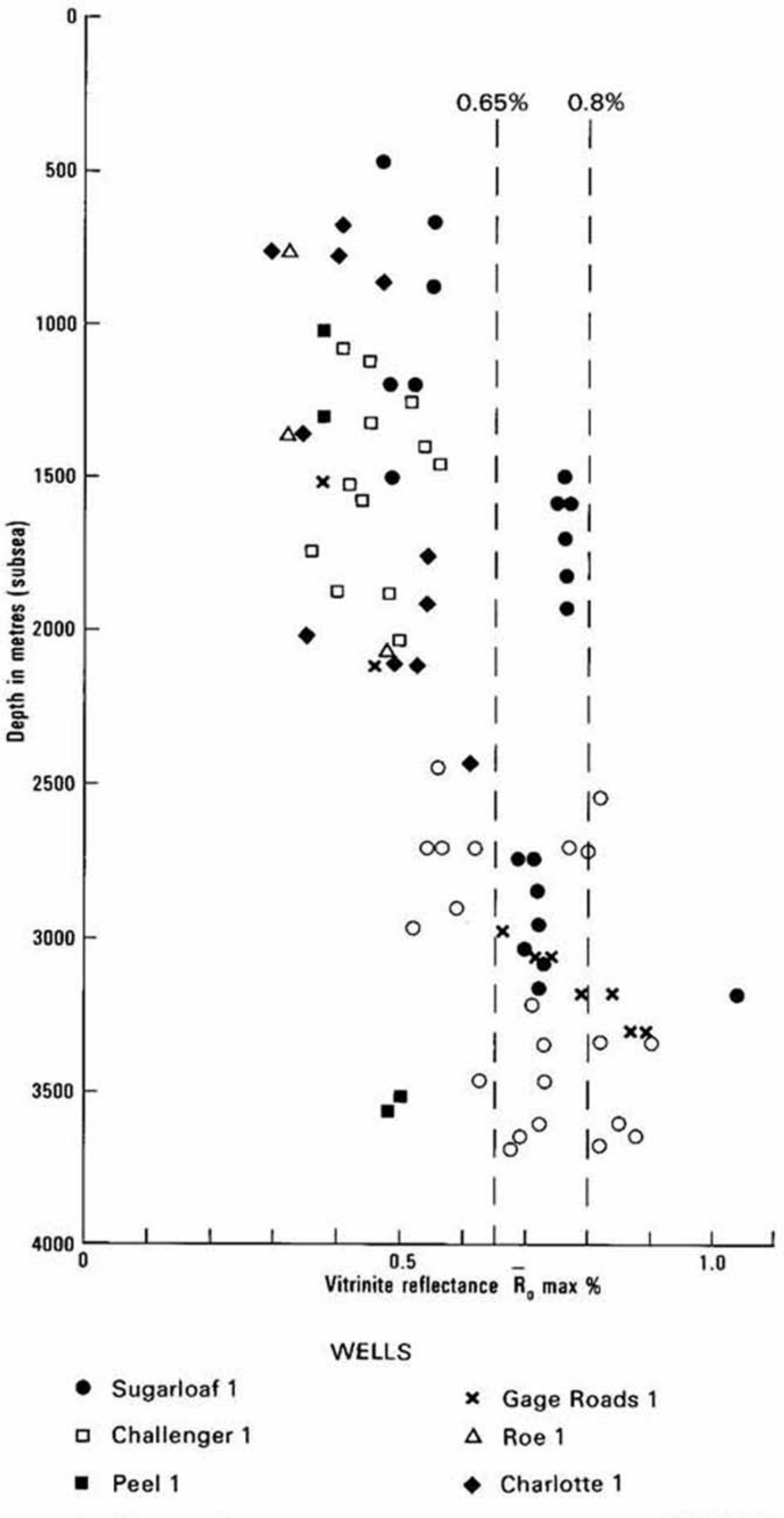
(1982) suggest that parts of the Warnbro Group contain organic matter which appears to be immature, gas-prone source material (Appendix 2).

Dredge samples from the flanks of the Perth Canyon have been analysed by Rock Eval pyrolysis and GC-MS (Marshall and others, 1989c). The rocks, which are dark grey to black mudstones, range in age from Late Permian to Early Cretaceous. Total organic carbon contents are within the range 1.1 to 3.5 percent. The youngest sample, from the late Early Cretaceous Osborne Formation, is reasonably high in TOC content, but the Rock Eval data show that this sample is extremely immature. Rock Eval data for those samples from the Early Cretaceous Carnac Member indicate that they range from immature to overmature. However, the biomarker analyses suggest 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. The HI values are all less than 70, indicating that they have poor source characteristics. The data suggest 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, possibly from an equivalent of the Vasse Shelf to the south, 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 from these 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. However, the high odd-to-even predominance is at variance with the high T_{max} values in some samples, which suggests that the Carnac Member samples, presumably because of their exposure on the canyon walls, have undergone relatively more weathering/biodegradation than the Late Permian samples.

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 are only minor components in these sediments.


0.65%
0.8%
Depth in metres (subsea)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.5
1.0
Vitrinite reflectance $\bar{R}_o$ max %
WELLS
Sugarloaf 1
Challenger 1
Peel 1
Warnbro 1
Gage Roads 1
Roe 1
Charlotte 1

23/OWA/211

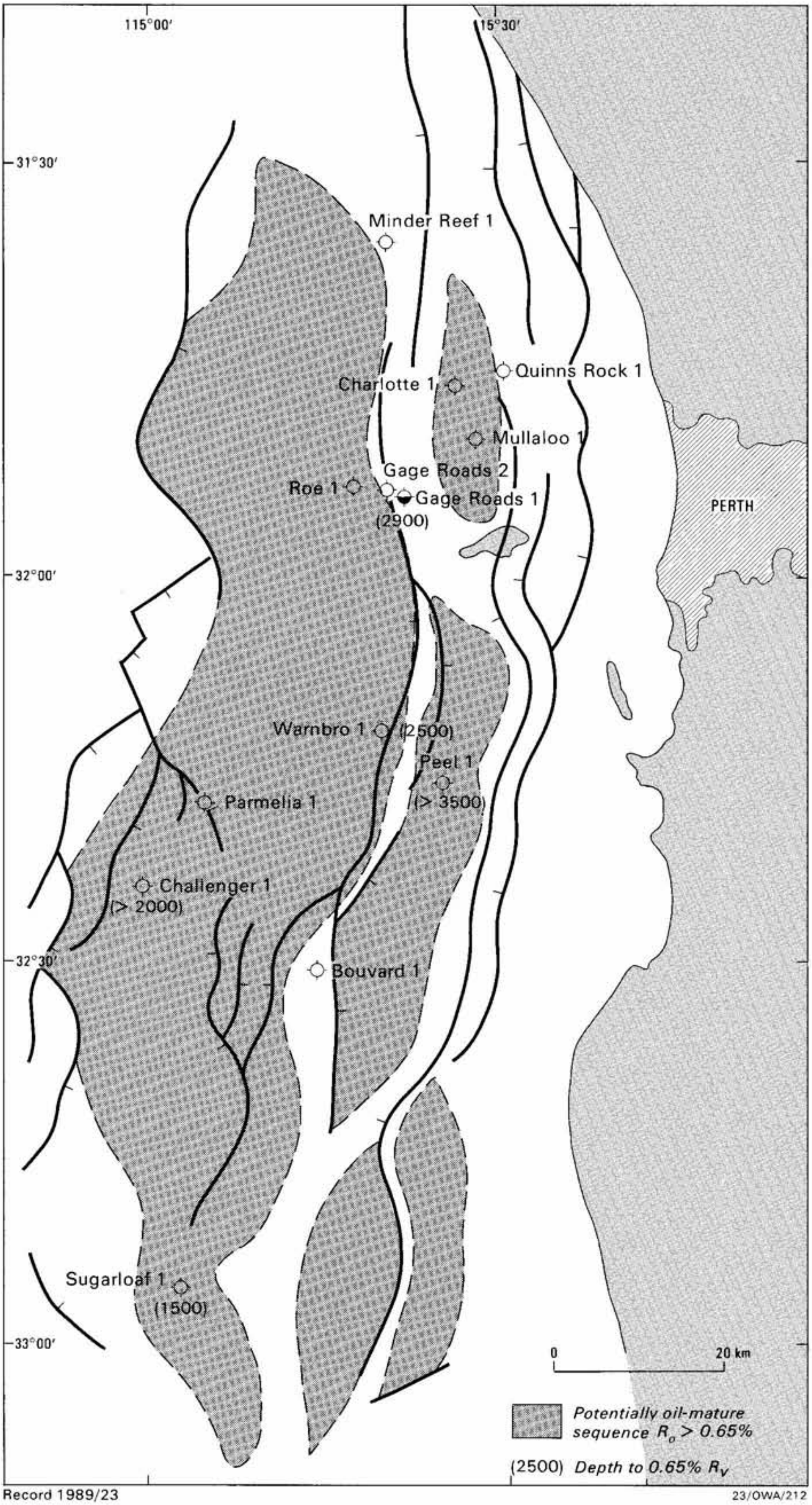


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Figure 9. Distribution of potentially oil-mature sequences in the Vlaming Sub-basin.

In contrast to the Rock Eval analyses, the 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. However, because the Carnac Member samples appear to have undergone weathering/ biodegradation because of exposure on the canyon walls, it is possible that this and underlying units such as the Otorowiri Member are mature along this western margin.

GEOHISTORY ANALYSIS

Geohistory analyses (Plates 36-48) for all the offshore oil exploration wells in the South Perth Basin, with the exception of Tuart 1, 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 are largely derived from well completion reports. In the South Perth Basin the thirteen wells that have been analysed, 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 estimates for these parameters. As thermal conductivity is a major parameter, the model results can only be loosely interpreted. However, the results do have some implications for the oil prospectivity of the region and provide a good basis for an analysis of 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. However, it does indicate that heat flow increases towards the Bathurst Syncline, the main region for potential and significant hydrocarbon generation. Variation is notable in some wells, such as Bouvard 1, which has a lower heat flow of 46 mW m^{-2} than indicated by the regional trend, 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 in 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 distinct 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 both a thermal and subsidence model for small pull-apart basins that could be applicable to our model of the Vlaming Sub-basin. 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 have been 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 palaeoheat flow modelled in this manner is generally higher than that calculated by Falvey and Deighton (1982). Heat flow levels have been relatively constant since the Early Cretaceous to the present day. This 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.

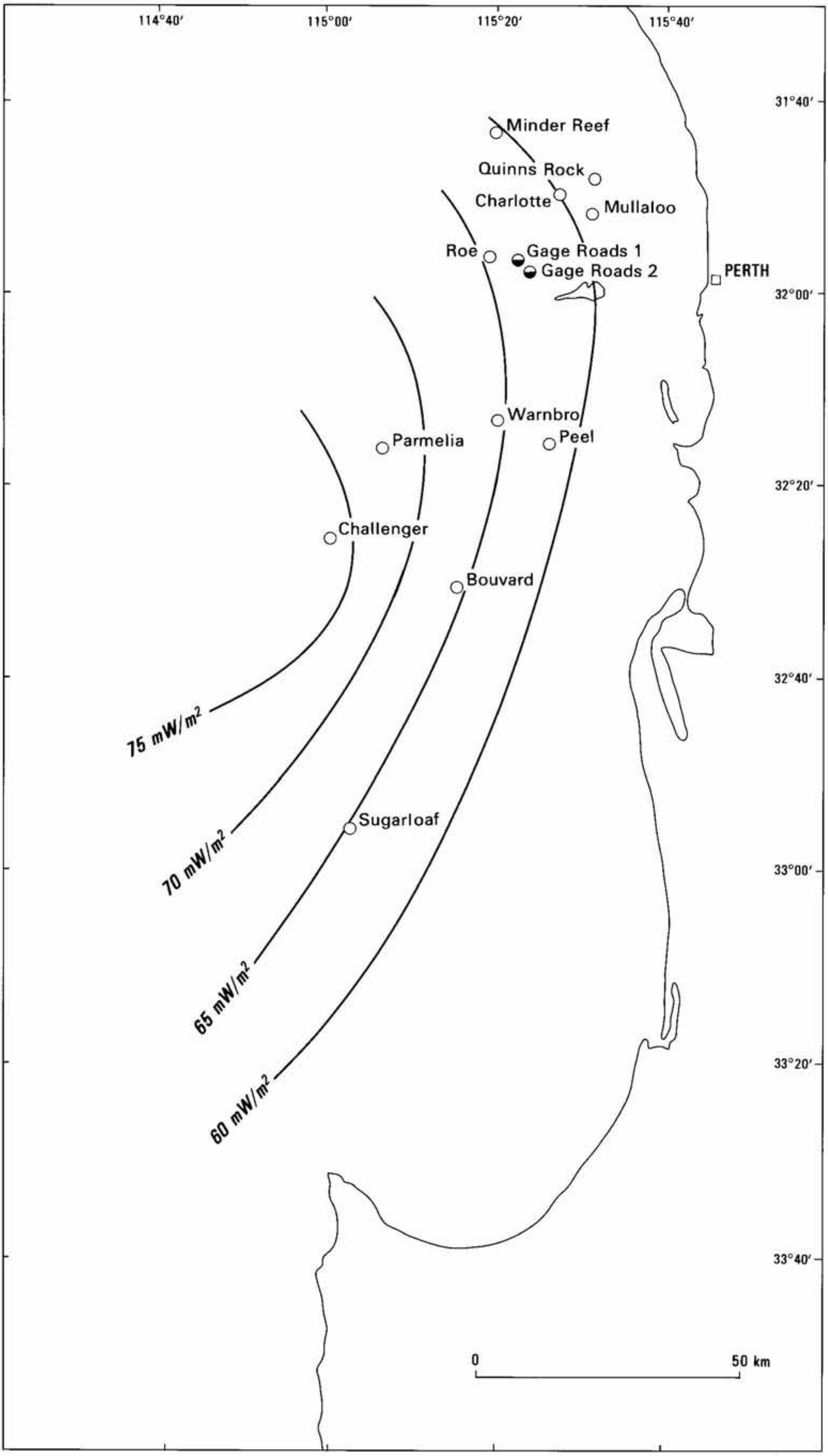

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Figure 10. Heat flow map of the offshore South Perth Basin.

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, palaeoheat flow and, therefore, maturation levels. The lack of deep crustal seismic data in the South Perth Basin means that the depth to basement for the offshore region, and any lateral variation in basement depth, is difficult to quantify. In the south, the AGSO lines show what is possibly shallow basement on the western margin 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 similar to 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 aspect of the tectonic subsidence curves is the sharp and relatively short lived tectonic anomalies contained within them. 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 tectonic 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 reasonably simple to make basin-wide extrapolations. A brief description of the salient points of the geohistory diagrams shown in Plates 36-48 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 total depth (T.D.) 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 palaeoheat flow 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 palaeoheatf low and subsidence plot. One curve plots the stripped basement depth (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 to 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 palaeoheat flow 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 palaeoheat flow curve constitutes the primary thermal signature from which the palaeotemperatures 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 a particular iso-vitrinite zone.

The tectonic subsidence plot for the wells describes a rather smooth deepening of the basement through time. In the Early Cretaceous, however, there is a large tectonic subsidence anomaly. It can be seen from the plots of the wells that this time marks a period of rapid subsidence for the whole sub-basin. The Peel 1 well tectonic subsidence plot (Plate 43) 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. In general, this period of subsidence represents a major phase in the basin's development. 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 rifting phase. The levelling 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.

Gage Roads 1 and 2 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 38, 39). One feature that begins to emerge from both these wells 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.

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 most wells means that it is not possible to corroborate the calculated vitrinite reflectance values. However, in general, measured vitrinite reflectance does support the calculated results.

PETROLEUM PLAYS

Most of the wells that have been drilled to date in the Vlaming Sub-basin, particularly the earlier wells, can be shown to have either been drilled off structure or drilled in positions where there is no valid seal to the structure. Of the older wells (pre-1980) only two, Gage Roads 1 and 2, tested valid traps, and both wells encountered significant oil shows. Each of the major sedimentary units from the Yarragadee Formation up to, and including, the South Perth Shale has, to varying degrees, the major elements required for the generation, migration, entrapment and preservation of petroleum. Previous drilling shows that much of the Late Jurassic and Early Cretaceous sequence is mature or marginally mature for petroleum generation, and in the case of the Gage Roads 2 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.

In Gage Roads 1 the sandstones directly beneath the Otorowiri Member gave strong fluorescence with cut and large high homologue gas readings (Seggie, 1990). The wireline logs indicate a gross hydrocarbon column of 35 metres with high porosity and permeability and low water saturation, but core recovered from this interval revealed low porosity and permeability and no test was performed. According to Seggie (1990), the core analysis was misleading, in that the SP and Induction responses were excellent, and he suggests that a significant oil and gas pool remained untested. He also suggests (Seggie, op. cit..) that the reservoir quality of the sandstone improves substantially below the hydrocarbon/water contact, and this could lead to a play up-dip from Gage Roads 1.

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 overlying 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 Roads 1 flowed oil at a projected rate of 350 barrels per day from a sandstone reservoir directly beneath the base of the Carnac Member. The gross oil column is interpreted to be 50 metres thick on the basis of electric logs and gas readings (Seggie, 1990). Gage Roads 2 showed fluorescence and cut, but no log anomaly directly beneath the Carnac Member, indicating a low hydrocarbon saturation.

Gage Sandstone Member

The recovery of hydrocarbons from this unit in the Gage Roads 2 well is a major feature of the petroleum prospectivity of the Vlaming Sub-basin. In this well there was a strong log anomaly over the interval 1350-1375 m, within the Gage Sandstone Member. This zone also showed good fluorescence and cut, while the FITs recovered oil and indicated excellent permeability (Seggie, 1990). In most plays involving the Gage Sandstone Member it can be assumed that it would have good reservoir potential and be sealed by the relatively arealy more extensive South Perth Shale sequence. The Gage Sandstone Member has the potential to be a significant stratigraphic play where it pinches out along the flanks of the Rottnest Trough.

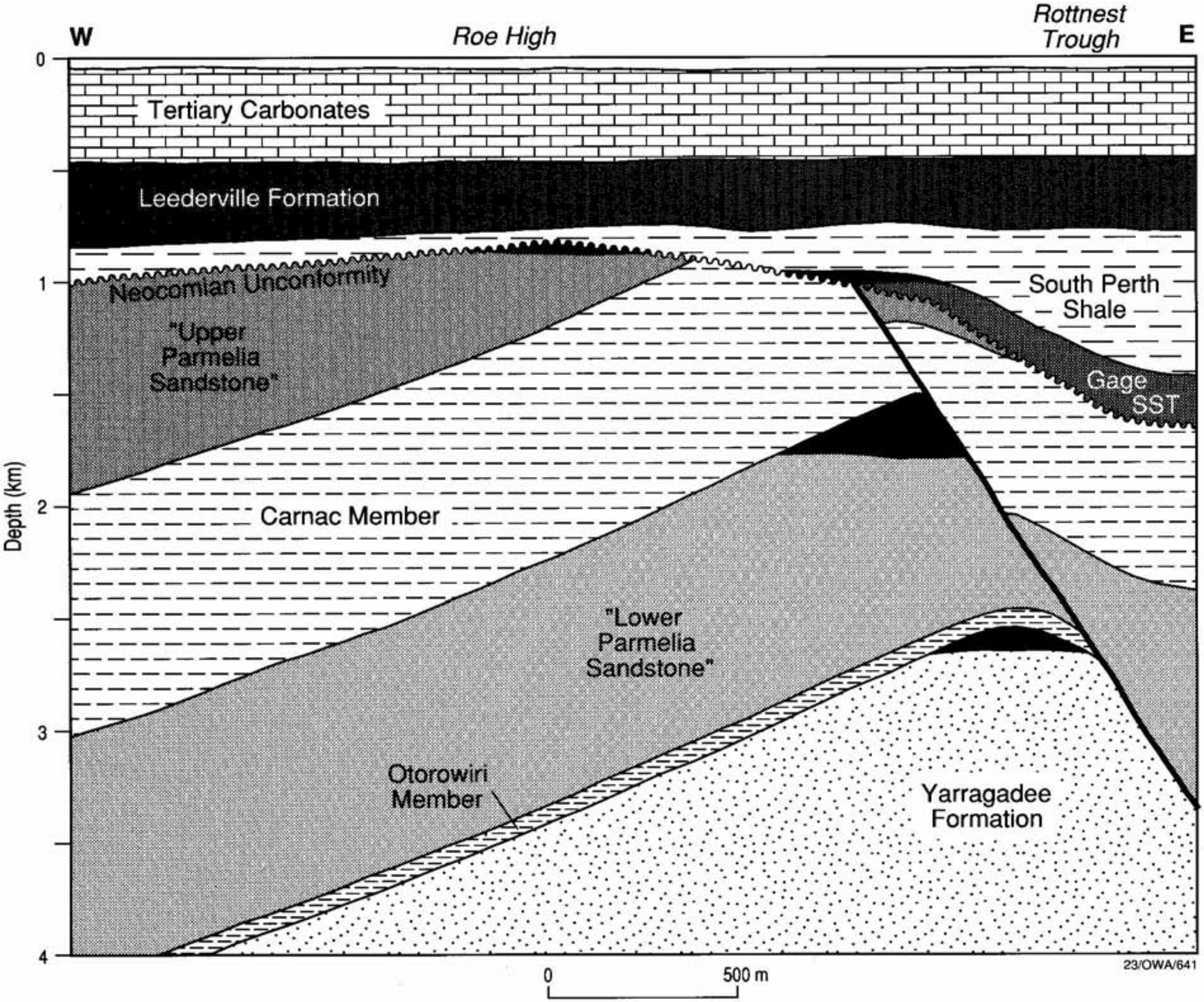
South Perth Shale

As a seal this sequence is of critical importance to the 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.

DISCUSSION

Although there have been fourteen wells drilled in the Vlaming Sub-basin and some 6000 km of post-1980 company seismic coverage, it definitely remains an immature basin from an exploration point of view. This can be further subdivided, in that eight of the fourteen wells are in the Rottnest Trough or on its flanks, while five of the remaining six wells are between Garden Island and Mandurah (Plate 1). South of Mandurah the Vlaming Sub-basin can be considered to be relatively unexplored. One other area of the sub-basin that also is under explored is its western margin.

Because of the concentration of wells and seismic data in the Rottnest Trough and environs, most play types have evolved from this part of the sub-basin. The play types illustrated in Figure 11 are typical of scenarios for the western flank of the Rottnest Trough and the Roe High. These include the base Carnac play and the Gage Sandstone stratigraphic play (Fig. 11). Other possibilities include the top Yarragadee play, if there is sufficient rollover of the Otorowiri Member or possible lateral seal by the Carnac Member on the downthrown side of the fault (not illustrated in Figure 11), and the upper Parmelia sandstone (Charlotte Sandstone Member) play, where there is sufficiently good seal by the South Perth Shale. With respect to the first two play types, Seggie (1990) has indicated potential reserves of 250 and 16 million barrels of oil respectively in the Gage Roads prospect, while he tentatively assigns some 250 million barrels for the top Yarragadee play. These play types, either individually or collectively, exist elsewhere in the Rottnest Trough.


W
Roe High
Rottnest Trough
E
0
1
2
3
4
Depth (km)
Tertiary Carbonates
Leederville Formation
Neocomian Unconformity
"Upper Parmelia Sandstone"
South Perth Shale
Gage SST
Carnac Member
"Lower Parmelia Sandstone"
Otorowiri Member
Yarragadee Formation
0
500 m
23/OWA/641

South of Rottnest Island, however, these tectonic elements are largely absent, and, as a consequence, play types are more variable and less well understood than to the north. This variety can be illustrated by the structures that have already been drilled. For example, Peel 1 was drilled on an extremely complicated structure, which has been interpreted here as a wrench structure. Another example is Bouvard 1, whose structure is interpreted as a horst block related to a reversal in the dip direction of faults on either side, which, in turn, has been brought about by variations in extension on either side of a transfer fault. Other structures such as those at Warnbro 1 and Challenger 1 are related to tilted fault blocks that developed during the Valanginian phase of structuring within the basin. All of the holes drilled previously on these structures have been shown not to have been valid tests, so that the potential of this part of the sub-basin has not as yet been realised.

From a maturation viewpoint, the most attractive source area is the Bathurst Syncline where the fine-grained, relatively organic-rich sediments of the Yarragadee and Parmelia Formations are mature. While it is questionable whether or not the entire Carnac Member has reached generative depths in the Bathurst Syncline, it is encouraging to note that pyrolysis data for this sequence in Roe 1 (Appendix 2) does indicate that it is oil mature. This is crucial from the point that its thickness makes the Carnac Member the most likely sequence to generate sufficient hydrocarbons to fully charge the updip reservoirs. The amphitheatre-like structure of the Bathurst Syncline (Plate 29) indicates that migration pathways would be to the north, east and south. The least interrupted pathway is to the east or northeast up onto the Roe High where the structure in between is relatively simple. To the south and southeast, the basin structure becomes more complex and highly faulted, and migration pathways are much more difficult to predict. The northern pathway is reasonably direct, but it tends to be orthogonal to the transfer fault direction; this is also the case with the eastern pathway to some extent. However, the effect, if any, of the transfer faults on migration is unpredictable. While they are older structures that have been reactivated after the basin was filled, they commonly divide blocks where the sediments dip at significantly different angles and in different directions, even though there is often little or no throw on these faults. The major problem to the north seems to be the absence of suitable traps, other than possibly some wrench-related structures along the western margin. However, this area remains under explored, particularly because of the lack of wells in this part of the Vlaming Sub-basin.

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

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
Tuart 1	Ampolex	Aug. 1991	86	1600

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

* Commercial surveys subsequent to the 1988 BMR survey have been conducted for Ampolex, Shell/Petrofina and Woodside.

Appendix 2: Geochemical data from wells in the Vlaming Sub-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

Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Sugarloaf 1							
640	59.83	5.60	363.0	455	0.02	607	368.0
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	204.0
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	0.07	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. South Perth Shale

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	0.0	460	0.08	75	0.8
1189	0.37	0.10	0.0	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

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	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
1600	1.57	0.09	2.47	424	-	157	0.42

3. Gage Sandstone Member

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

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

Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Roe 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

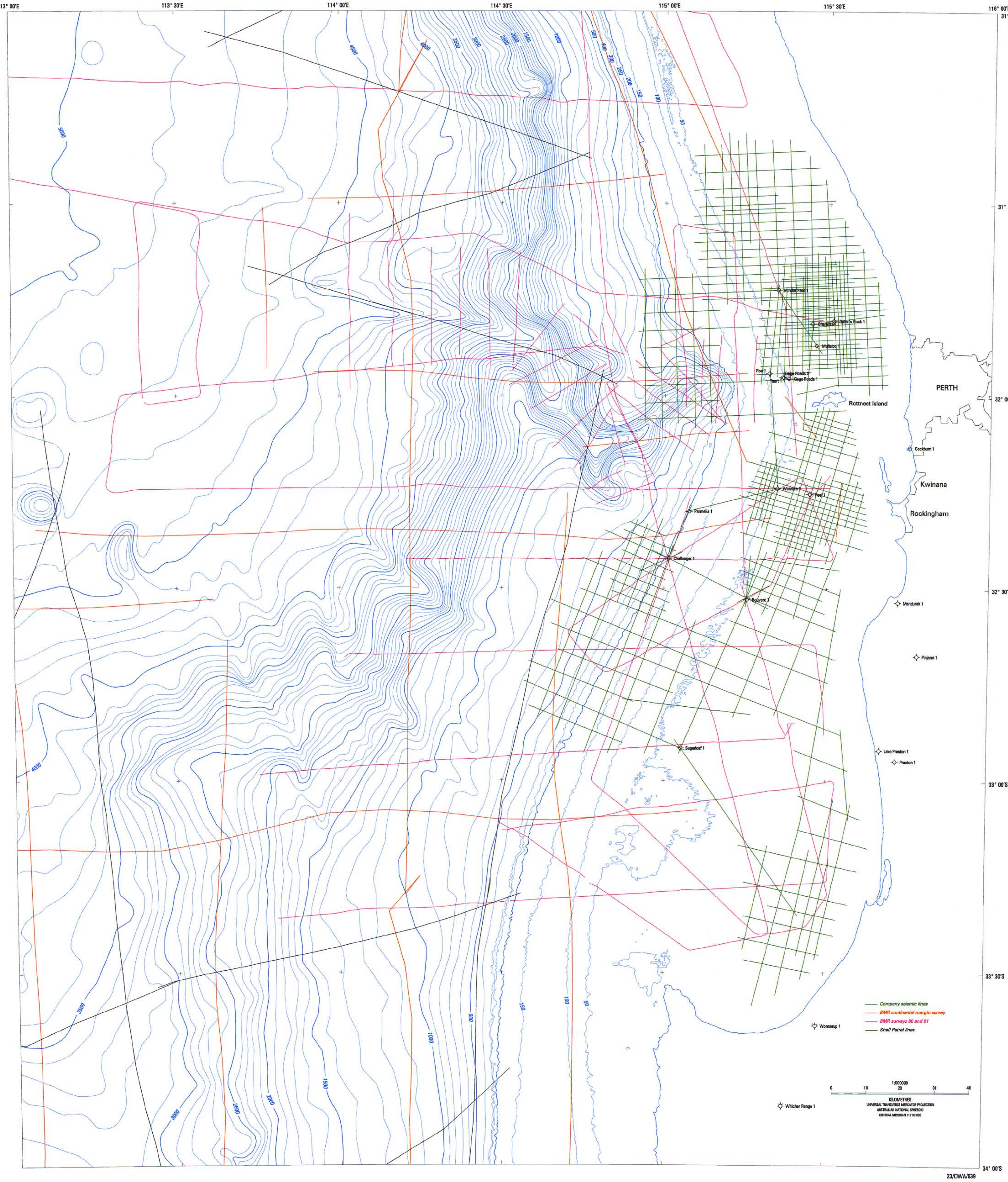
Challenger 1							
1865	2.09	0.10	2.7	460	0.04	127	2.8
Gage Roads 1							
2555	2.72	0.24	3.9	458	0.06	142	4.1
2593	1.83	0.11	2.86	433	-	156	0.55
2615	1.71	0.11	2.50	433	-	146	0.45
2621	1.51	0.12	2.43	430	-	160	0.50
2626	0.60	0.15	1.1	473	0.13	183	1. 3
Quinn's Rock 1							
1606	1.14	0.44	2.66	422	-	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

Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
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

Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
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	451	0.05	106	3.7
2434	1.15	0.08	1.6	461	0.05	135	1.6
Sugarloaf 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
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

Depth(m)	TOC%	S1	S2	TMAX	PI	HI	GP
Bouvard 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	7.0
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



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CONTINENTAL MARGINS PROGRAM
VLAMING SUB-BASIN
Offshore South Perth Basin

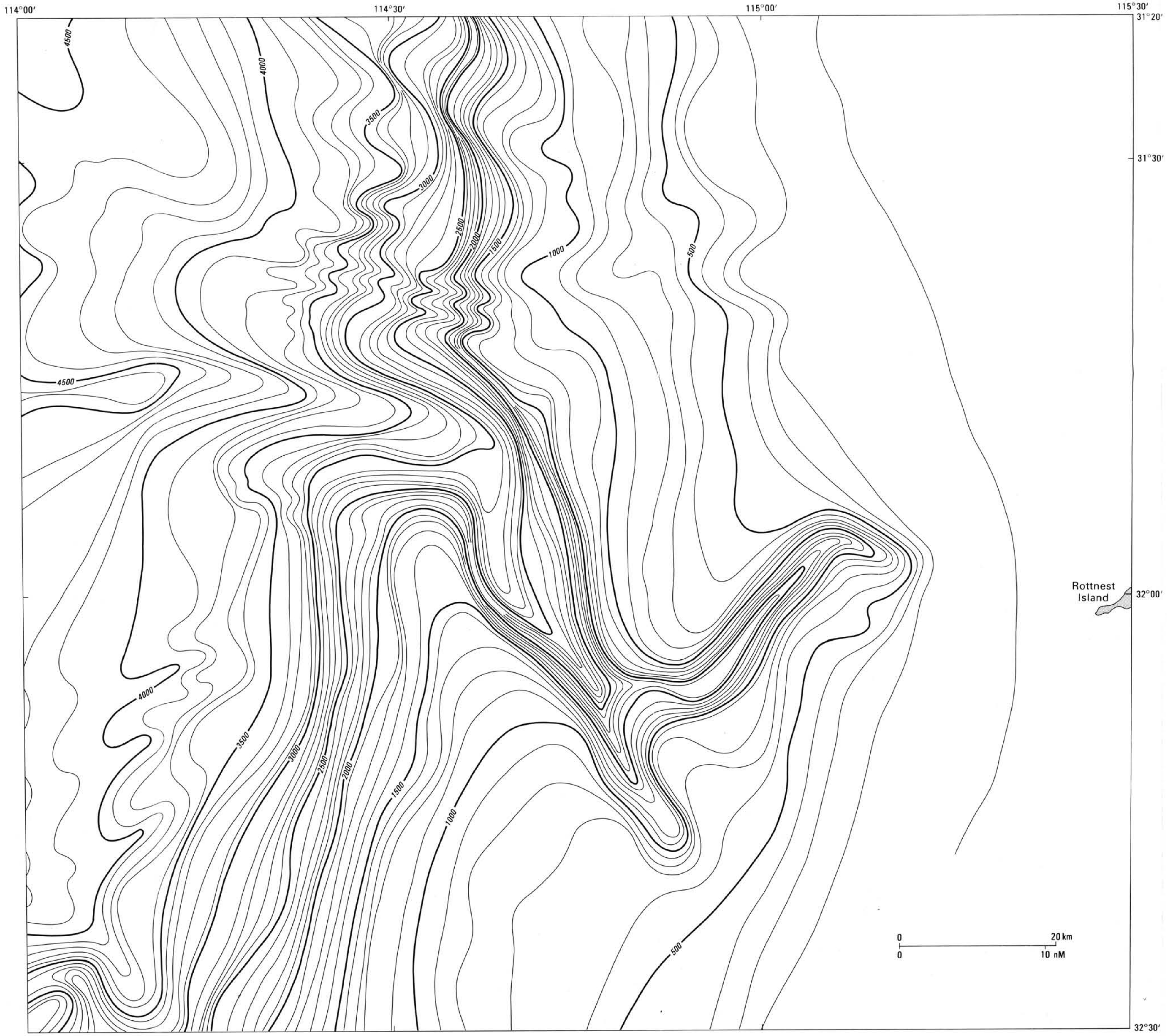
Marine
Geoscience &
Petroleum
Geology

Bathymetry of the offshore South Perth Basin, showing the position of wells and seismic lines

Folio 7
August 1993

Plate 1

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation



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Offshore South Perth Basin

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Geology

Bathymetry of the Perth Canyon

Folio 7
August 1993

Plate 2

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

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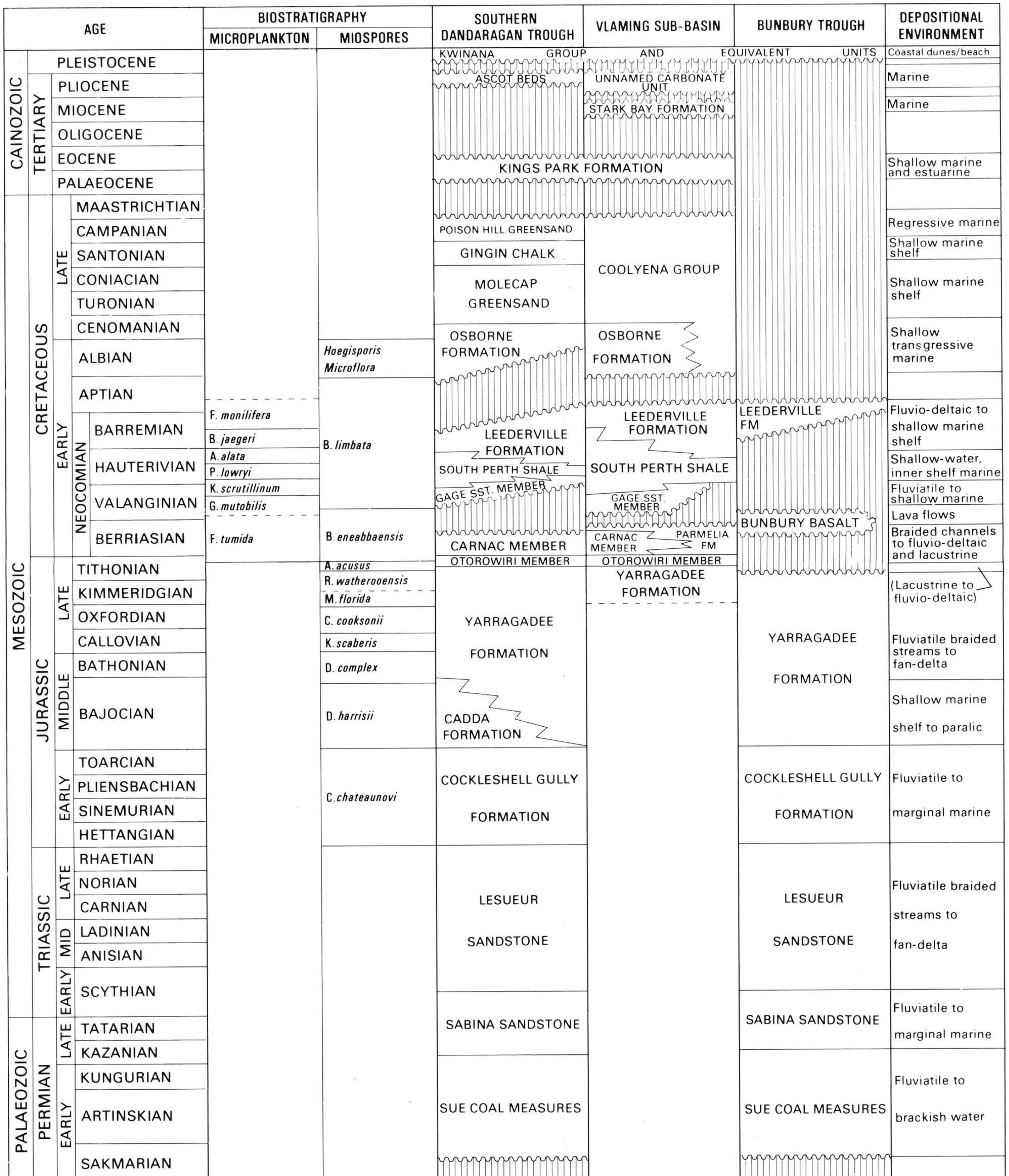

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VLAMING SUB-BASIN
Offshore South Perth Basin

Marine Geoscience & Petroleum Geology

Stratigraphy of the South Perth Basin

Folio 7
August 1993

Plate 3

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

WELL: QUINNS ROCK 1

District: VLAMING SUB-BASIN

Latitude: 31° 48'09"S
Longitude: 115° 30'50"E

Operator: WAPET
Status: PLUGGED AND ABANDONED
Spud date: 10.10.1968
Completion date: 21.11.1968 (rig release)

Total depth: 2209m

PLATE 4

ELEVATIONS Water depth: 40.5m
R.T. to sealevel: 24.1m

1 Berggren & others, (1985a, b), Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)

TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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VLAMING SUB-BASIN
Offshore South Perth Basin

Marine Geoscience & Petroleum Geology

Well analysis diagram
Quinn's Rock 1

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Plate 4

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

WELL: GAGE ROADS 1

District: VLAMING SUB-BASIN

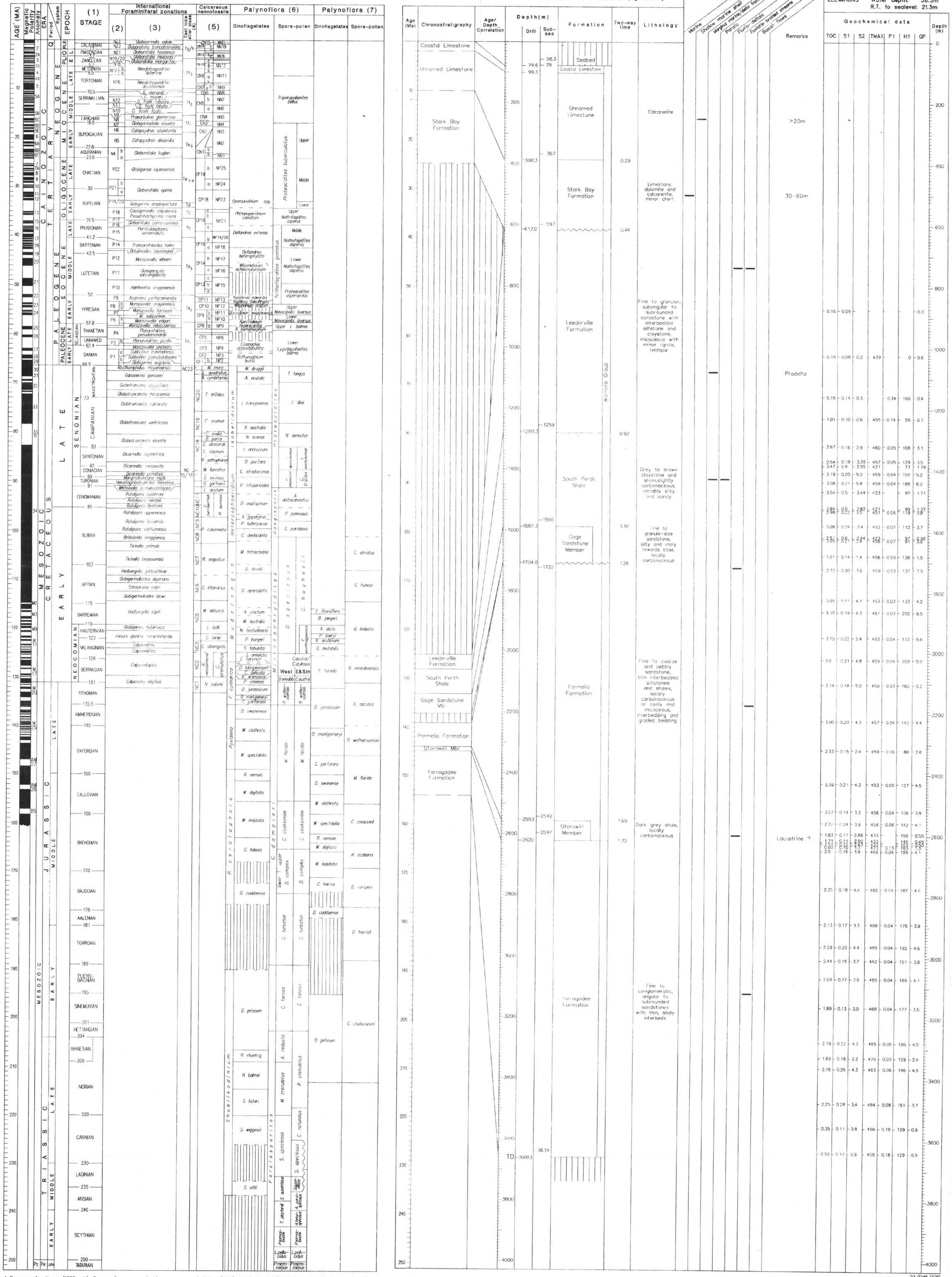
Latitude: 31°57'12"S
Longitude: 115°22'38"E

Operator: WAPET
Status: PLUGGED AND ABANDONED
Spud date: 27.11.1968
Completion date: 21.03.1969 (rig release)

Total depth: 3660.3m

PLATE 5

ELEVATIONS Water depth: 58.3m
R.T. to sealevel: 21.3m



1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)

TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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VLAMING SUB-BASIN
Offshore South Perth Basin

Marine Geoscience & Petroleum Geology

Well analysis diagram
Gage Roads 1

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Plate 5

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

WELL: ROE 1

District: VLAMING SUB-BASIN

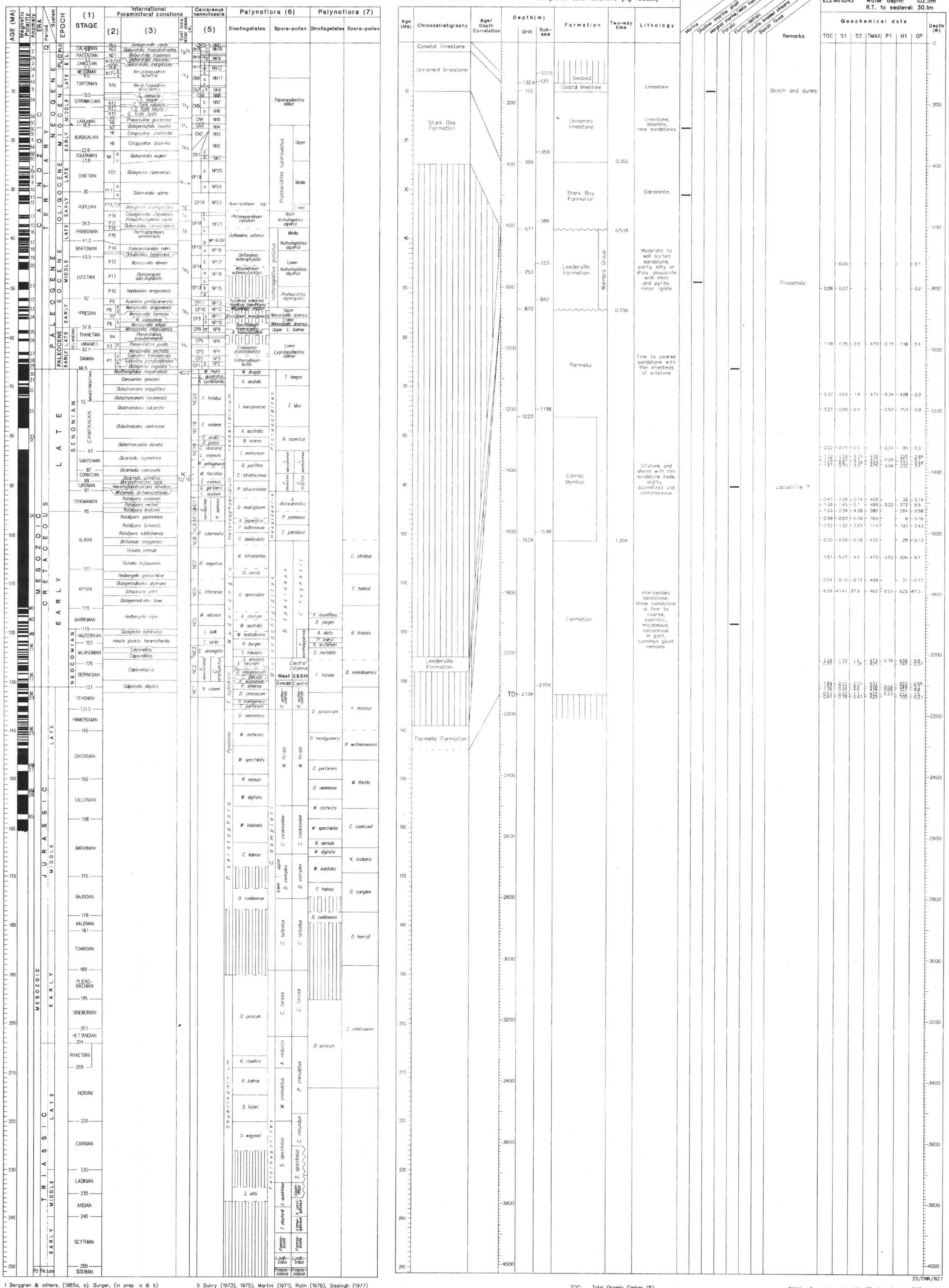
Latitude: 31°56'26"S
Longitude: 115°19'07"E

Operator: WAPET
Status: PLUGGED AND ABANDONED
Spud date: 23.10.1970
Completion date: 18.12.1970 (rig release)

Total depth: 2134m

PLATE 6

ELEVATIONS Water depth: 102.5m
R.T. to sealevel: 30.1m



1 Berggren & others, (1985a, b), Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)

TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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Well analysis diagram
Roe 1

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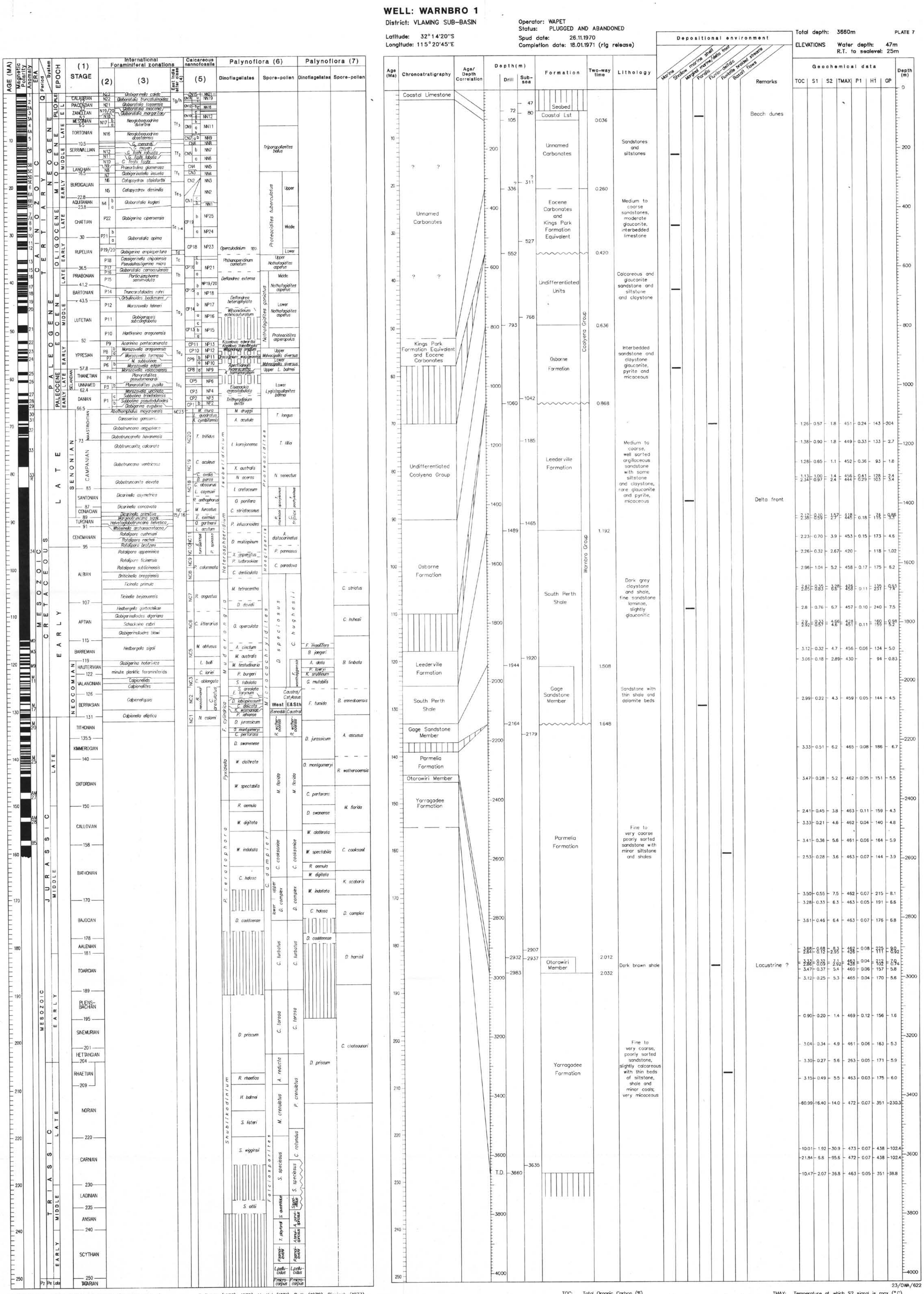
Plate 6

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation



1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)
TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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Well analysis diagram Warnbro 1

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Plate 7

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

WELL: CHARLOTTE 1

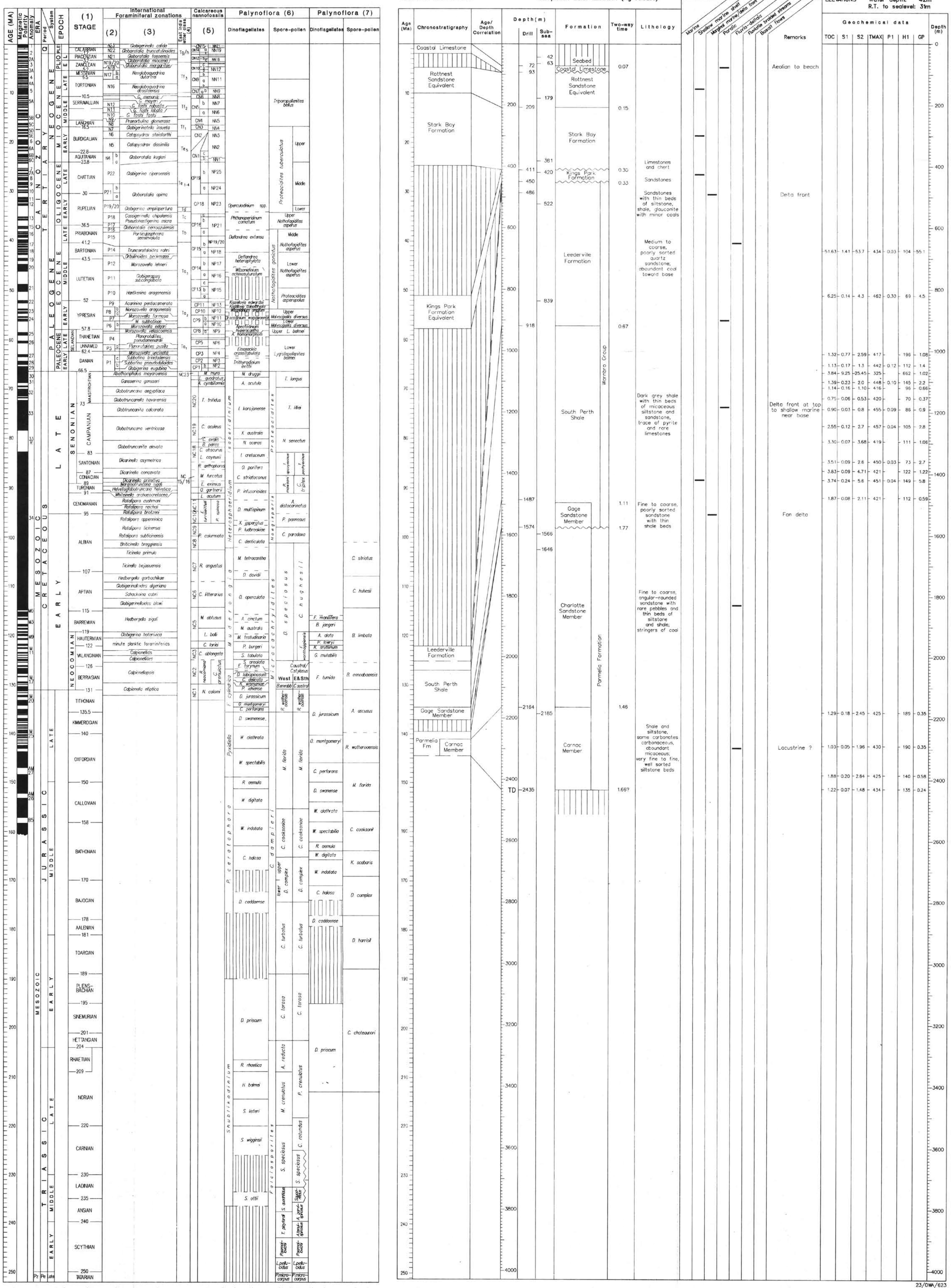
District: VLAMING SUB-BASIN

Latitude: 31° 48'36"S
Longitude: 115°26'56"E

Operator: WAPET
Status: PLUGGED AND ABANDONED
Spud date: 19.12.1970
Completion date: 12.01.1971 (rig release)

Total depth: 2435m
ELEVATIONS Water depth: 42m
R.T. to sealevel: 31m

PLATE 8



1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973, 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)
TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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VLAMING SUB-BASIN
Offshore South Perth Basin

Marine Geoscience & Petroleum Geology

Well analysis diagram Charlotte 1

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Plate 8

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

WELL: GAGE ROADS 2

District: VLAMING SUB-BASIN

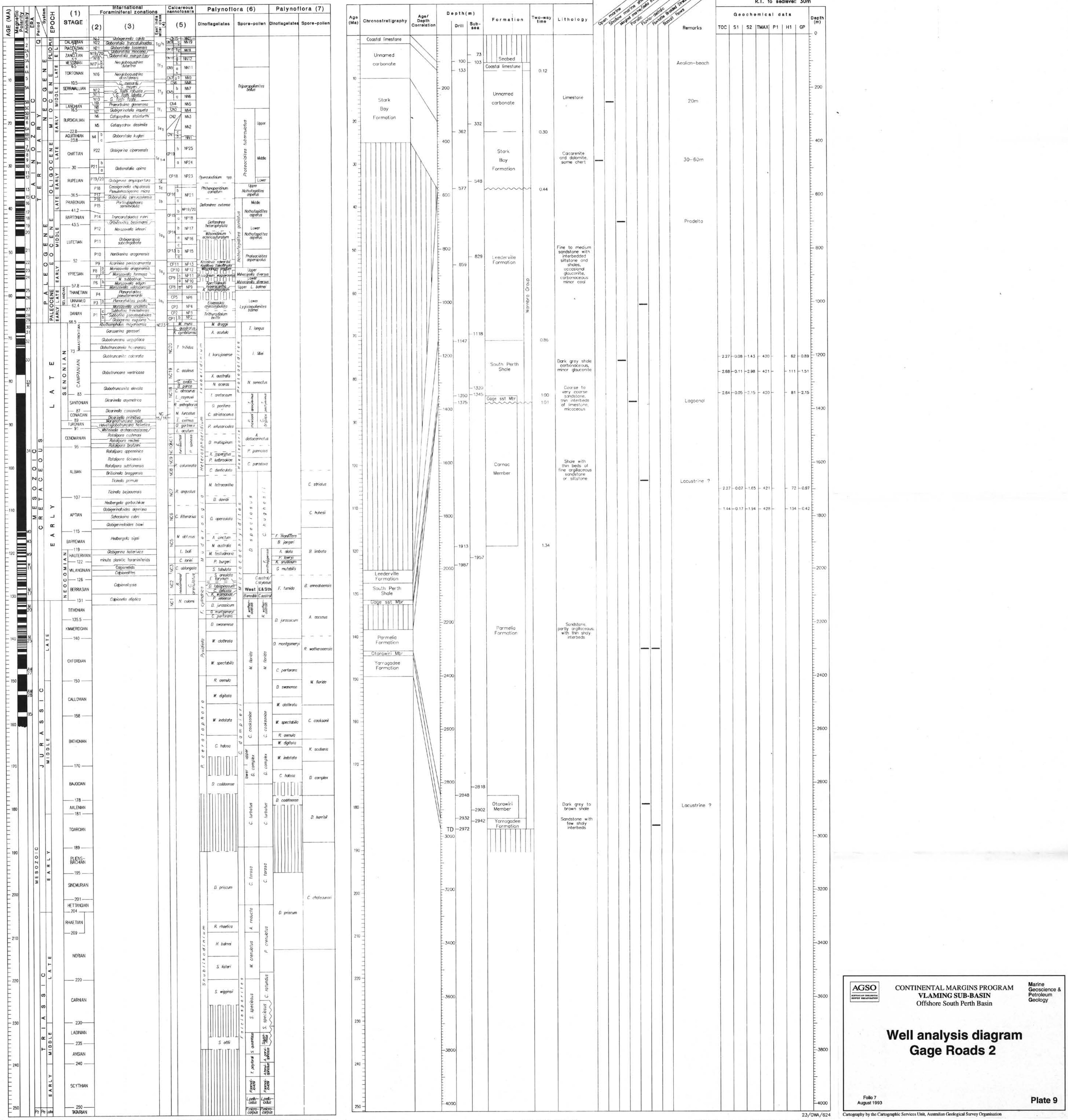
Latitude: 31°57'05"S
Longitude: 115°21'45"E

Operator: WAPET
Status: PLUGGED AND ABANDONED
Spud date: 14.01.1971
Completion date: 12.02.1971 (rig release)

Total depth: 2972m

PLATE 9

ELEVATIONS
Water depth: 73m
R.T. to sealevel: 30m



1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)
TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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Well analysis diagram
Gage Roads 2

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Plate 9

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

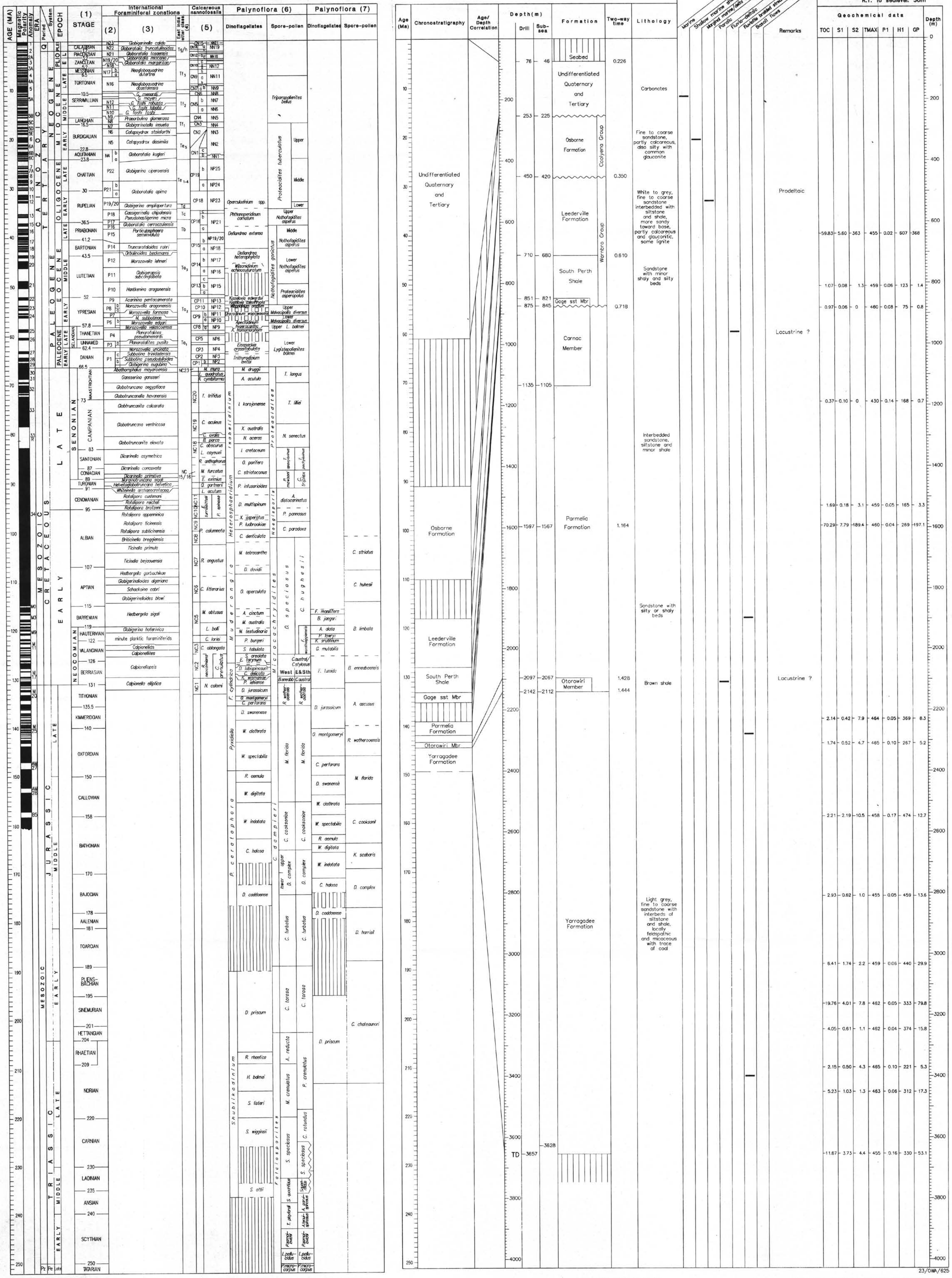
WELL: SUGARLOAF 1

District: VLAMING SUB-BASIN
Latitude: 32°54.92'S
Longitude: 115°03.15'E

Operator: WAPET
Status: PLUGGED AND ABANDONED
Spud date: 14.02.1971
Completion date: 12.04.1971 (rig release)

Total depth: 3658m
ELEVATIONS Water depth: 46m
R.T. to sealevel: 30m

PLATE 10



1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)

TMAX: Temperature at which S2 signal is max (°C)
PI: Production index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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Well analysis diagram Sugarloaf 1

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Plate 10

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

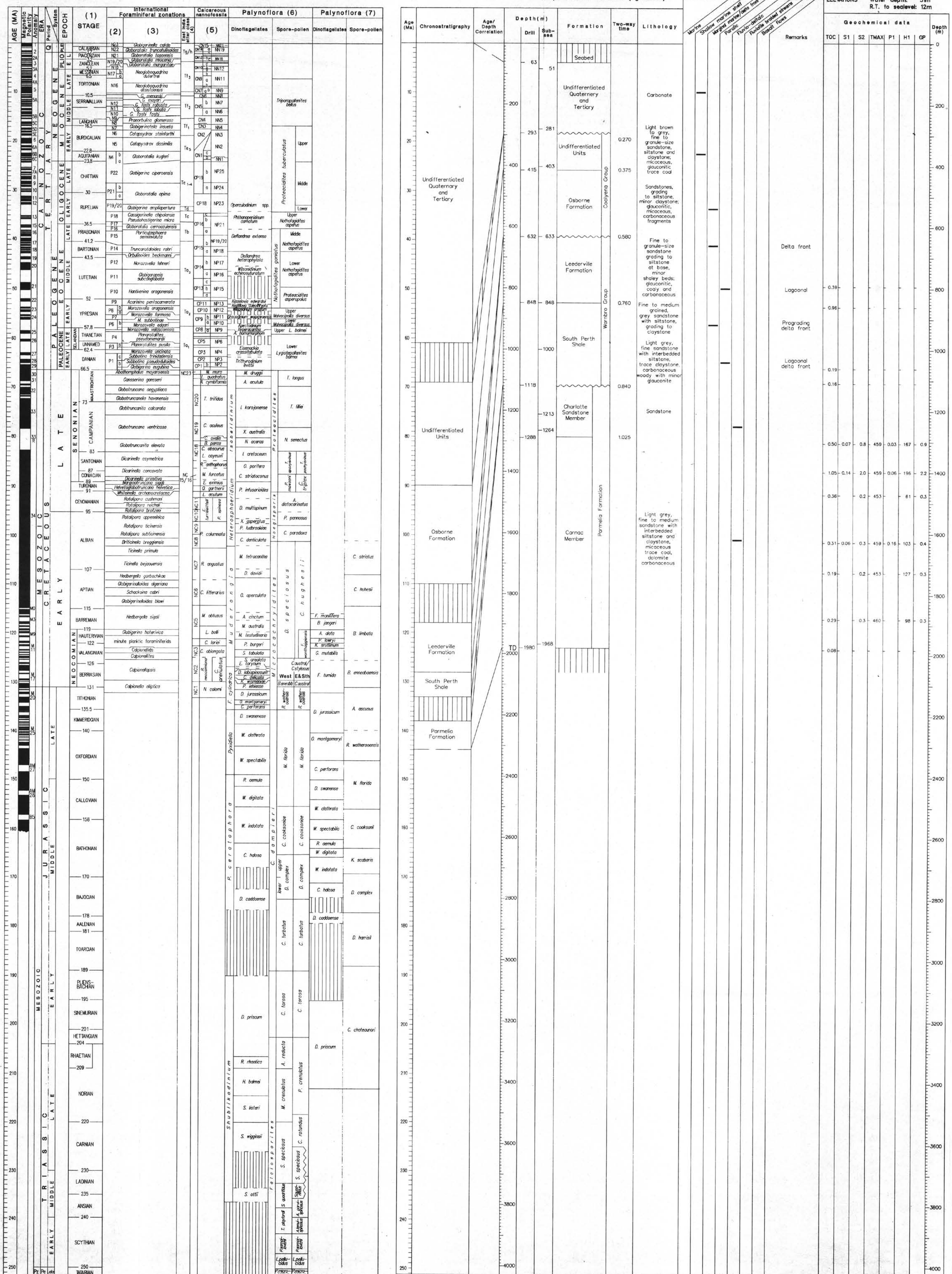
WELL: BOUVARD 1

District: VLAMING SUB-BASIN
Latitude: 32° 31'43"S
Longitude: 115°15'18"E

Operator: WAPET
Status: PLUGGED AND ABANDONED
Spud date: 3.01.1975
Completion date: 3.02.1975 (rig release)

Total depth: 1980m
ELEVATIONS Water depth: 51m
R.T. to sealevel: 12m

PLATE 11



1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979). Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)
TMAX: Temperature at which S2 signal is max (°C)
P1: Production Index (S1-S2)
H1: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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Well analysis diagram Bouvard 1

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Plate 11

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

WELL: CHALLENGER 1

District: VLAMING SUB-BASIN

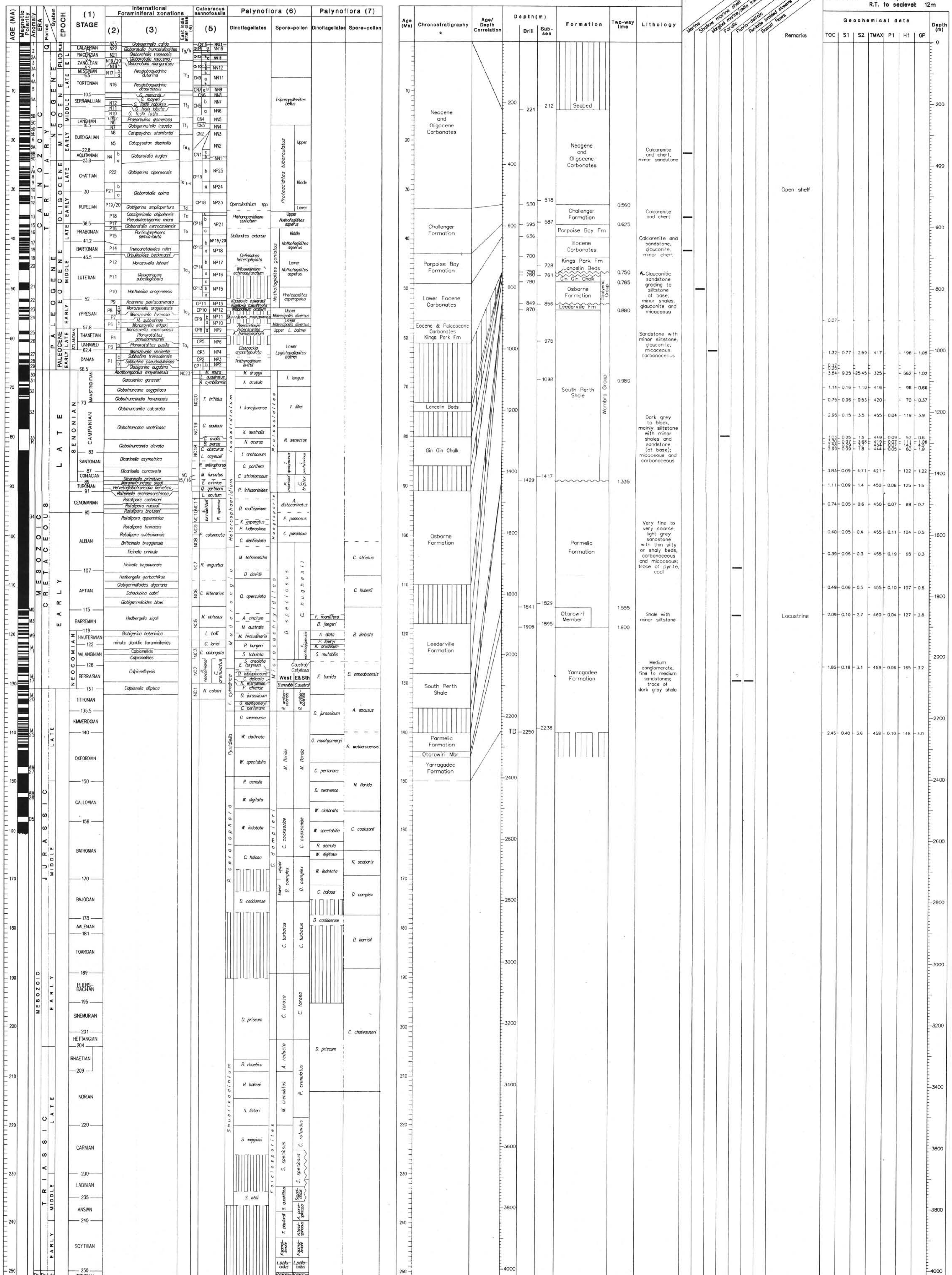
Latitude: 32° 25'20.784"S
Longitude: 115°00'46.288"E

Operator: WAPET
Status: PLUGGED AND ABANDONED
Spud date: 19.03.1975
Completion date: 3.04.1975 (rig release)

Total depth: 2250m

PLATE 12

ELEVATIONS Water depth: 212m
R.T. to sealevel: 12m



1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

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TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)
* Tertiary chronostratigraphy after Shafik (1992)

TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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Well analysis diagram Challenger 1

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Plate 12

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

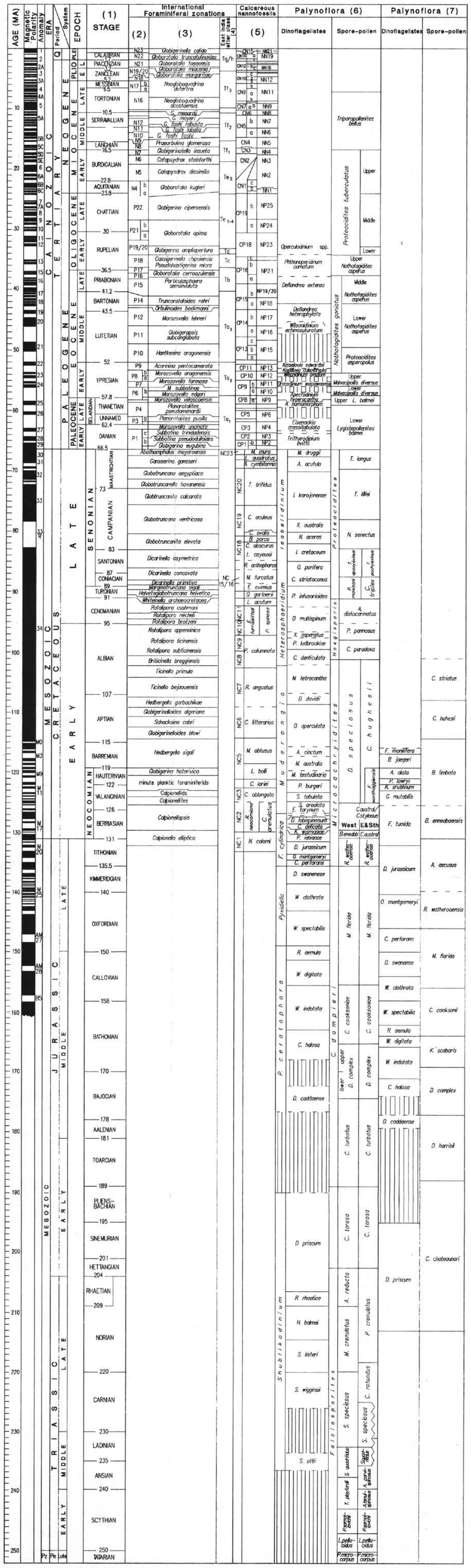
WELL: PEEL 1

District: VLAMING SUB-BASIN
Latitude: 32°15'15"S
Longitude: 115°26'43"E

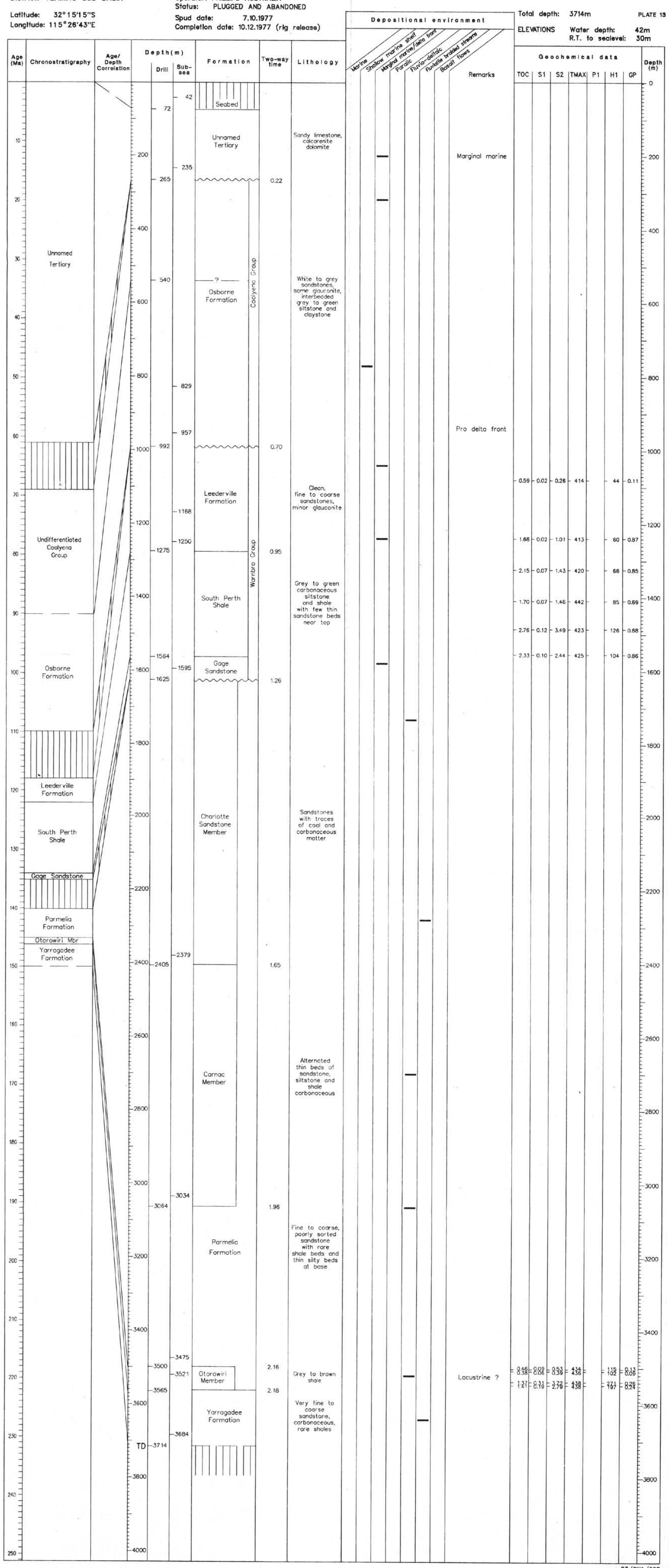
Operator: PHILLIPS AUSTRALIA
Status: PLUGGED AND ABANDONED
Spud date: 7.10.1977
Completion date: 10.12.1977 (rig release)

Total depth: 3714m
PLATE 13

ELEVATIONS Water depth: 42m
R.T. to sealevel: 30m



1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)



23/OWA/628

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)

TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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Offshore South Perth Basin

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Well analysis diagram
Peel 1

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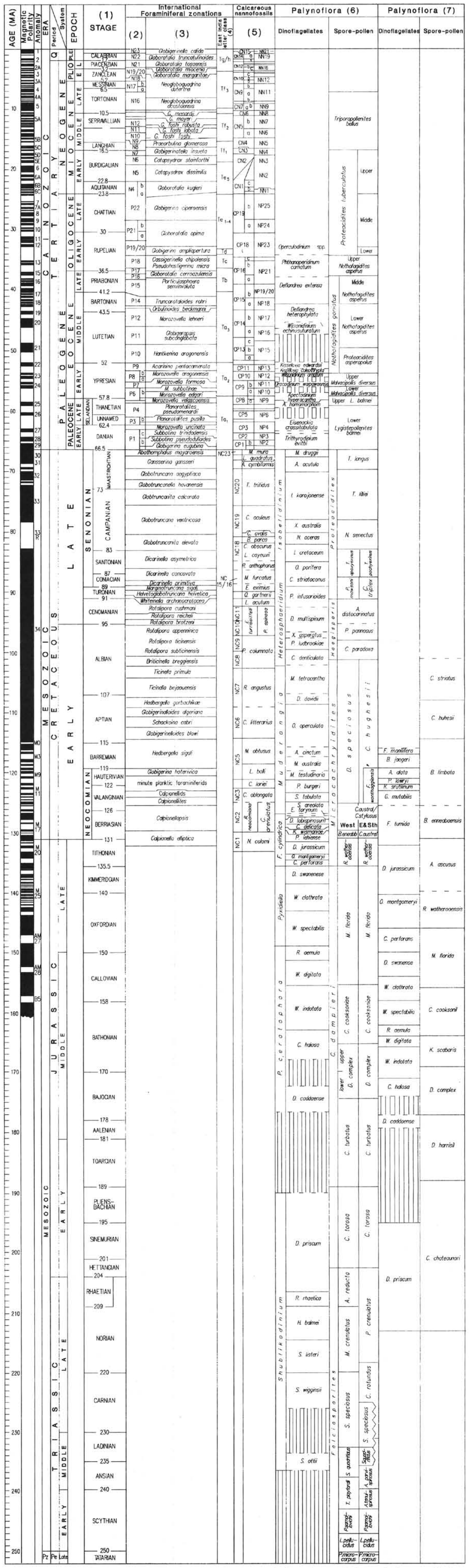
Plate 13

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation



WELL: PARMELIA 1

District: VLAMING SUB-BASIN

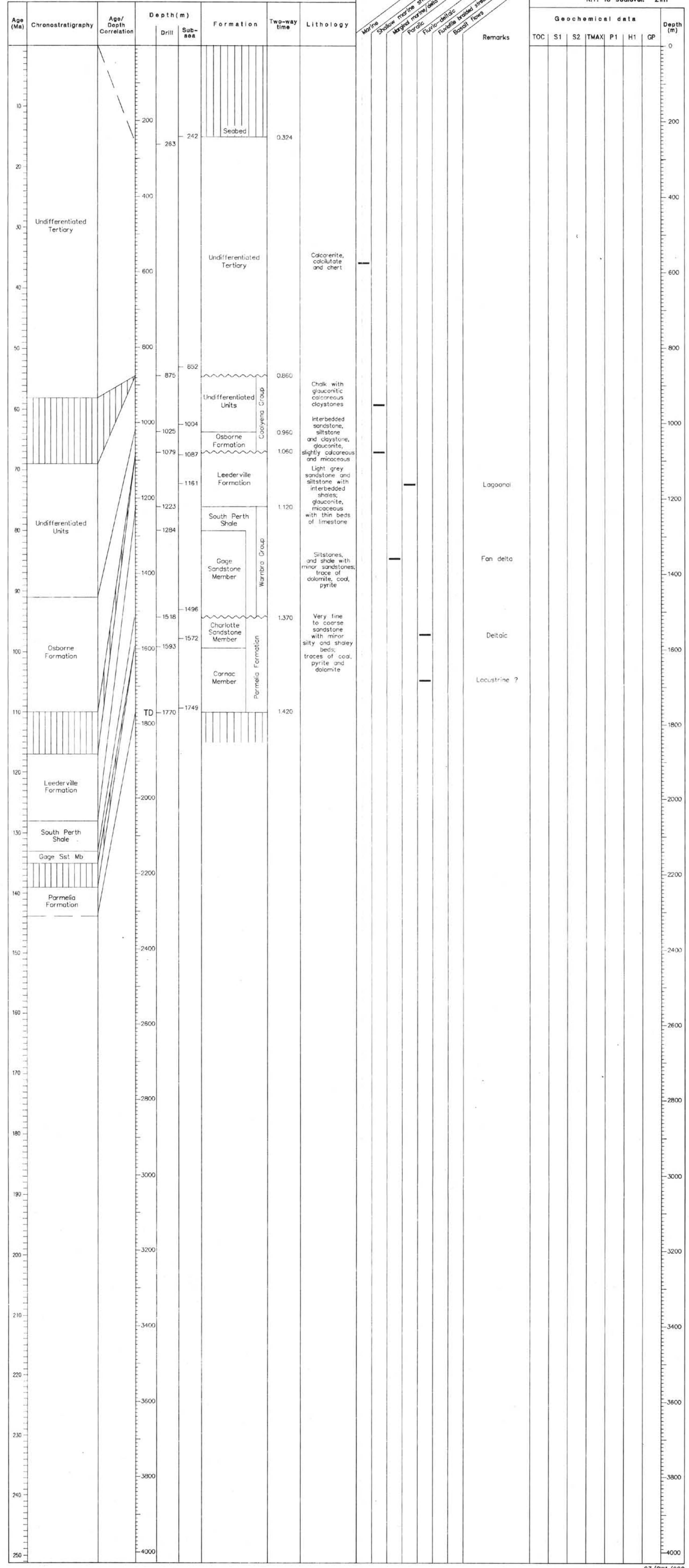
Latitude: 32°17'57"S
Longitude: 115°04'32"E

Operator: WAPET
Status: PLUGGED AND ABANDONED
Spud date: 29.04.1981
Completion date: 10.06.1981 (rig release)

Total depth: 1770m

PLATE 14

ELEVATIONS Water depth: 242m
R.T. to sealevel: 21m



23/OWA/629

1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)

TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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Well analysis diagram Parmelia 1

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Plate 14

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

WELL: MULLALOO 1

District: VLAMING SUB-BASIN
Latitude: 32°52'03"S
Longitude: 115°27'42"E

Operator: WAPET
Status: PLUGGED AND ABANDONED
Spud date: 15.04.1984
Completion date: 20.05.1984 (rig release)

Total depth: 2030m
PLATE 15
ELEVATIONS Water depth: 43.5m
R.T. to sealevel: 30.0m

1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)

TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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Well analysis diagram
Mullaloo 1

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Plate 15

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

WELL: MINDER REEF 1

District: VLAMING SUB–BASIN

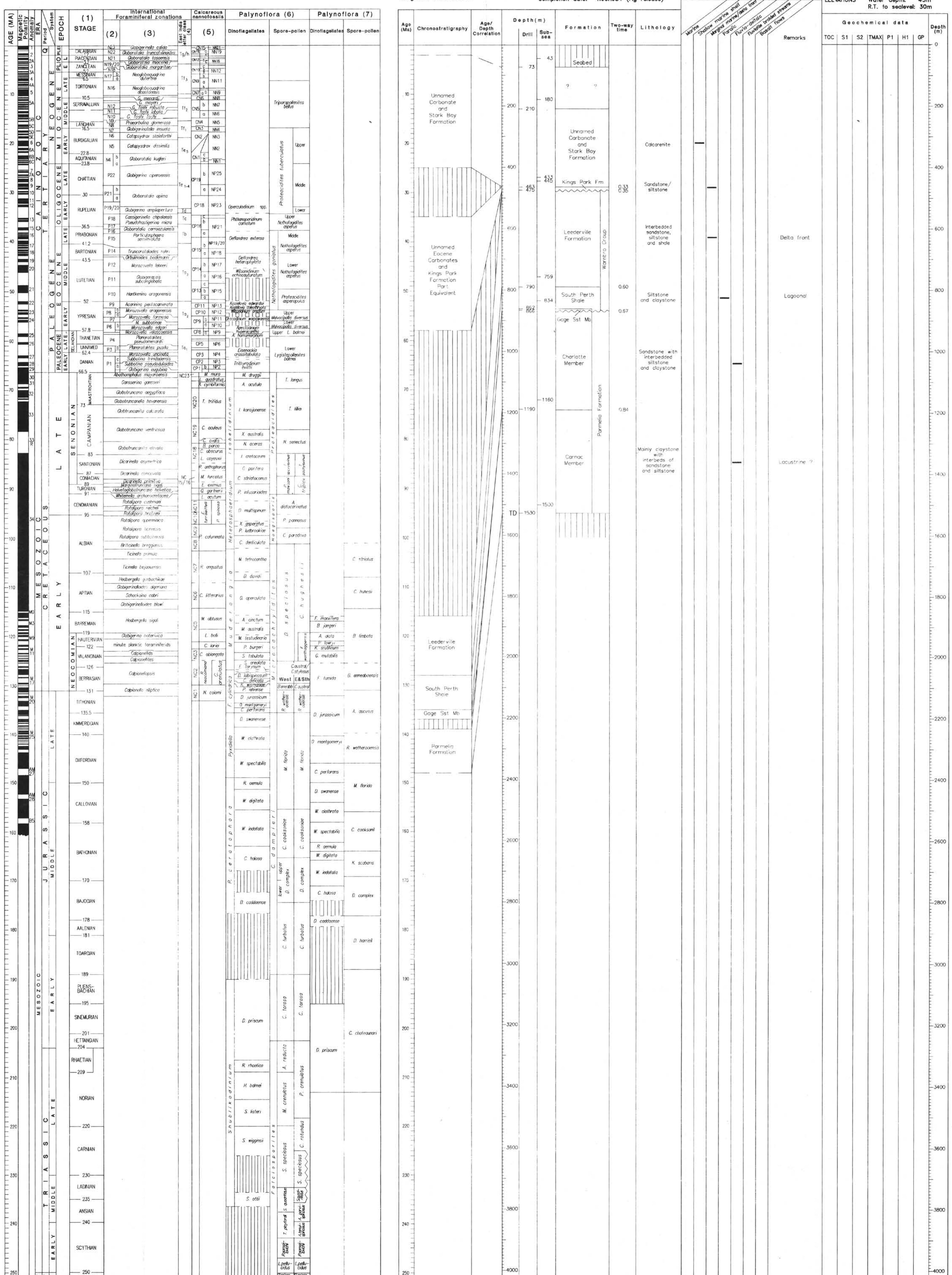
Latitude: 31°43'21"S
Longitude: 115°20'37"E

Operator: ESSO
Status: PLUGGED AND ABANDONED
Spud date: 23.05.1984
Completion date: 4.06.1984 (rig release)

Total depth: 1530m

PLATE 16

ELEVATIONS Water depth: 43m
R.T. to sealevel: 30m



1 Berggren & others, (1985a, b). Burger, (in prep. a & b)
2 Blow (1969, 1979), Berggren (1969)
3 Bolli (1957, 1966), Stainforth & others, (1975), Bolli & Premoli-Silva (1973), Caron (1985)
4 Adams (1984), Adams & others, (1986), Chaproniere (1981), (1983), Jenkins & others, (1985)
5 Bukry (1973), 1975), Martini (1971), Roth (1978), Sissingh (1977)
6 Burger (1973), 1988, in prep. a), Dettmann (1986), Dettmann & Playford (1969), Helby & Morgan (1987), Helby & others, (1987), Ingram & Morgan (1988), Partridge (1976), Stover & Evans (1973), Stover & Partridge (1973)
7 Backhouse (1988)

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TOC: Total Organic Carbon (%)
S1: Pyrolysis free – hydrocarbon signal (mg S2 hydrocarbons/g rock)
S2: Pyrolisis kerogen signal (mg S2 hydrocarbons/g rock)

TMAX: Temperature at which S2 signal is max (°C)
PI: Production Index (S1–S2)
HI: Hydrogen Index (mg hydrocarbons/g organic carbon)
GP: Genetic Potential (Kg hydrocarbons/ton rock) (S1+S2)
VR: Vitrinite Reflectance

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Offshore South Perth Basin
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Well analysis diagram Minder Reef 1

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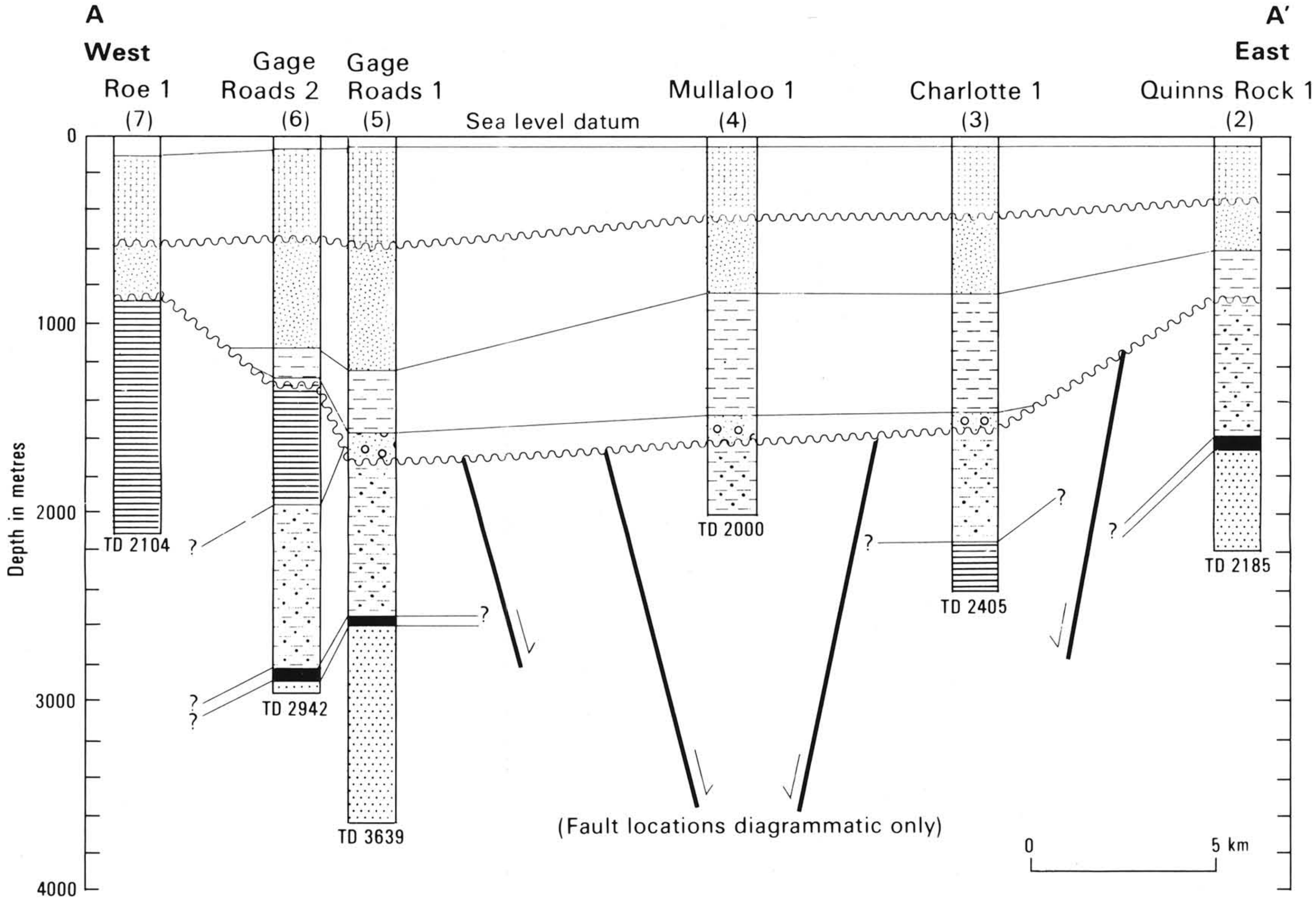
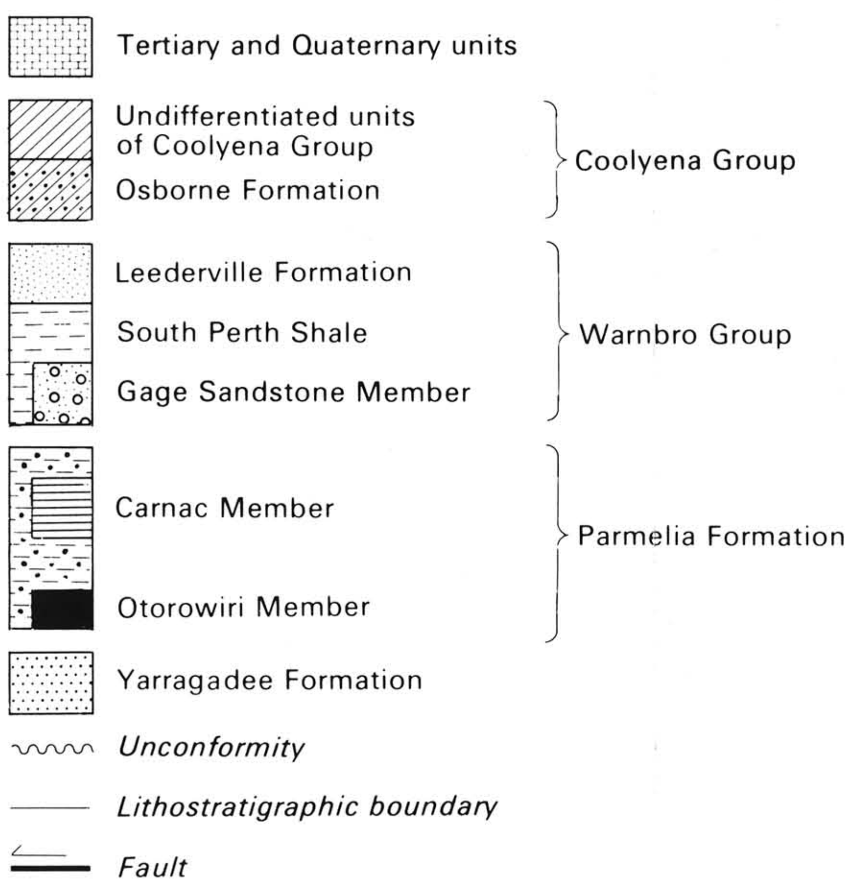
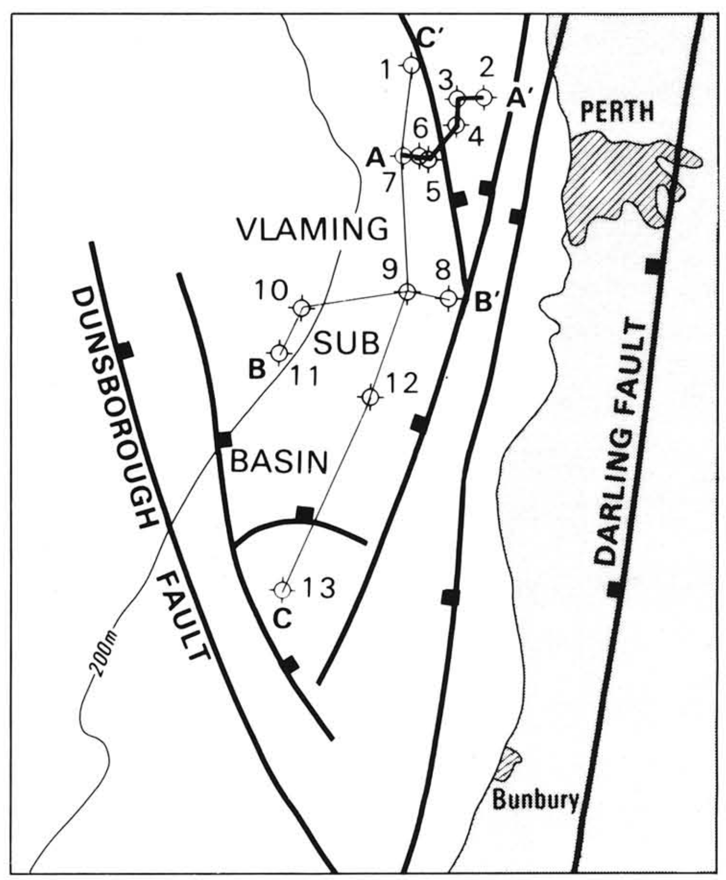
Plate 16

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation







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Well correlations northern Vlaming Sub-basin

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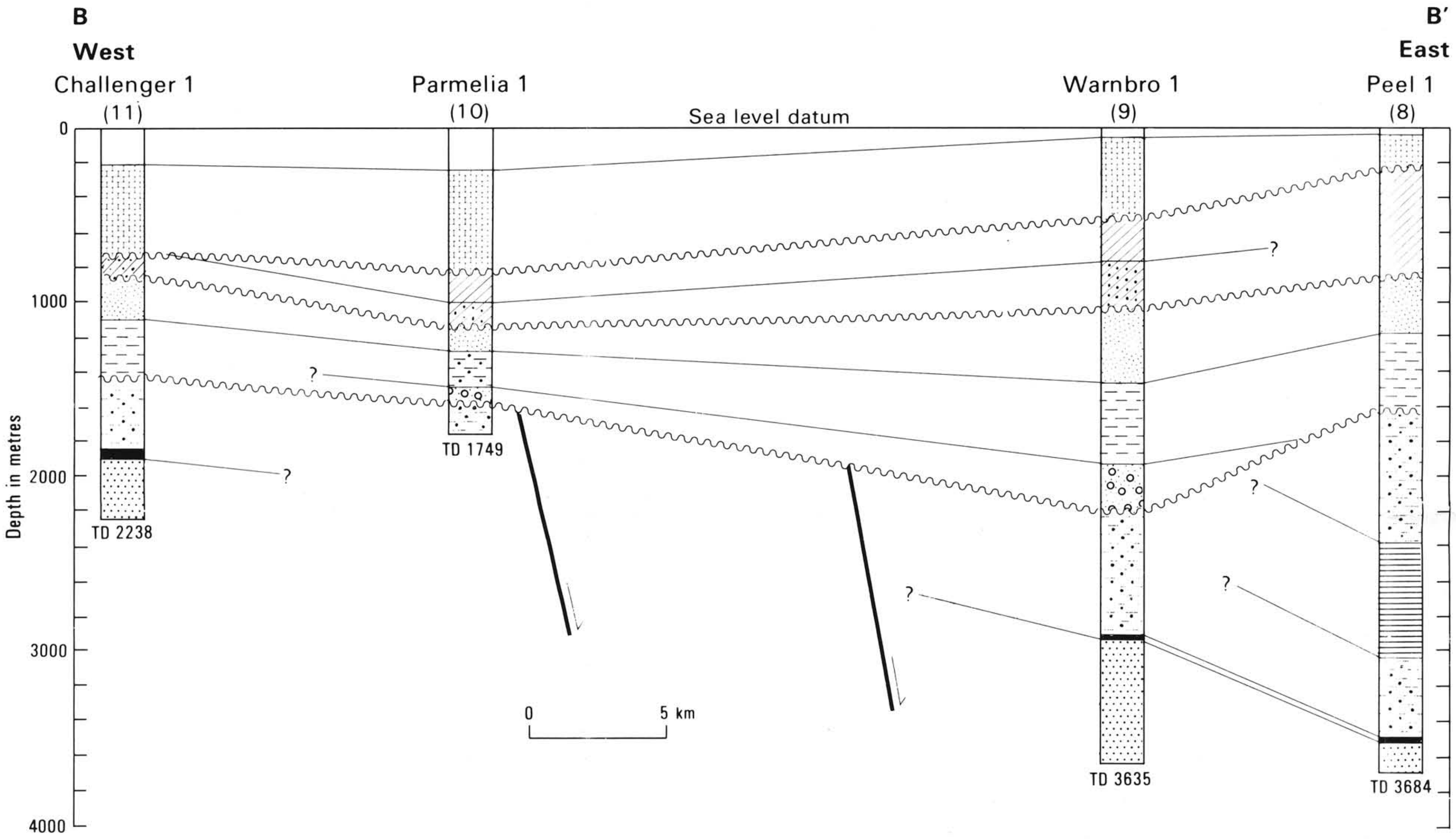
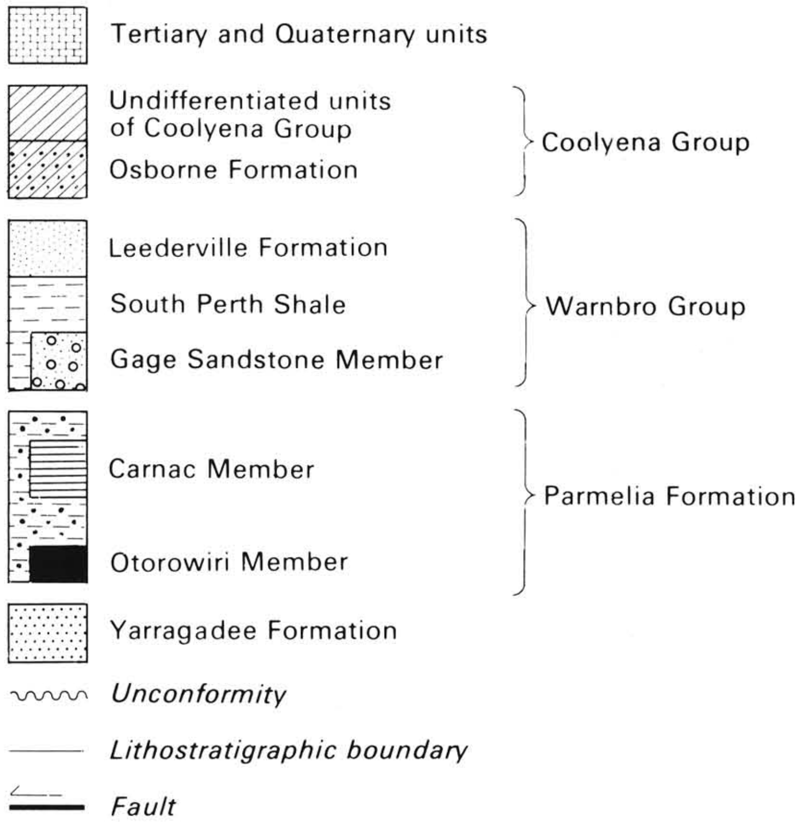
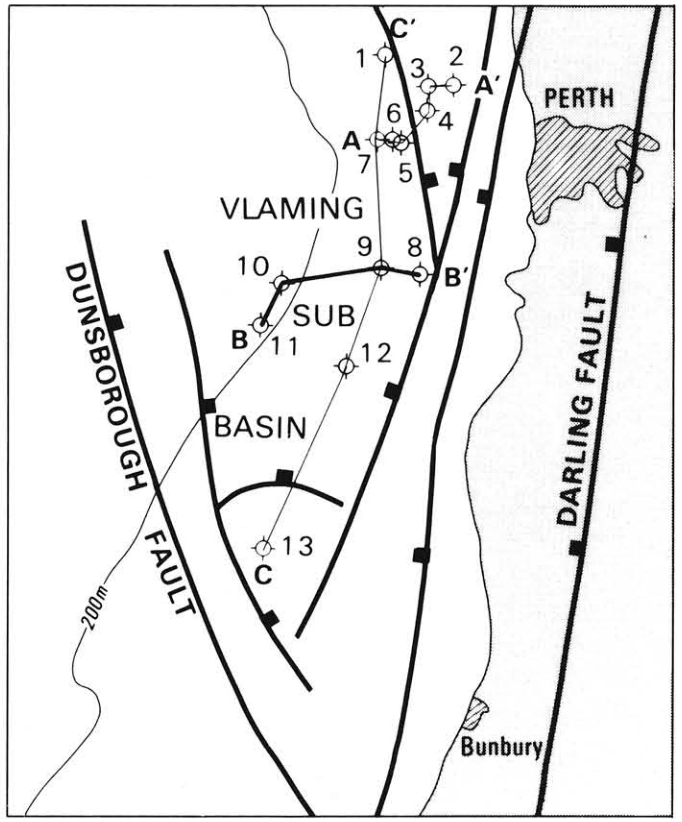
Plate 17

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation







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VLAMING SUB-BASIN
Offshore South Perth Basin

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Well correlations in the central Vlaming Sub-basin

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Plate 18

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

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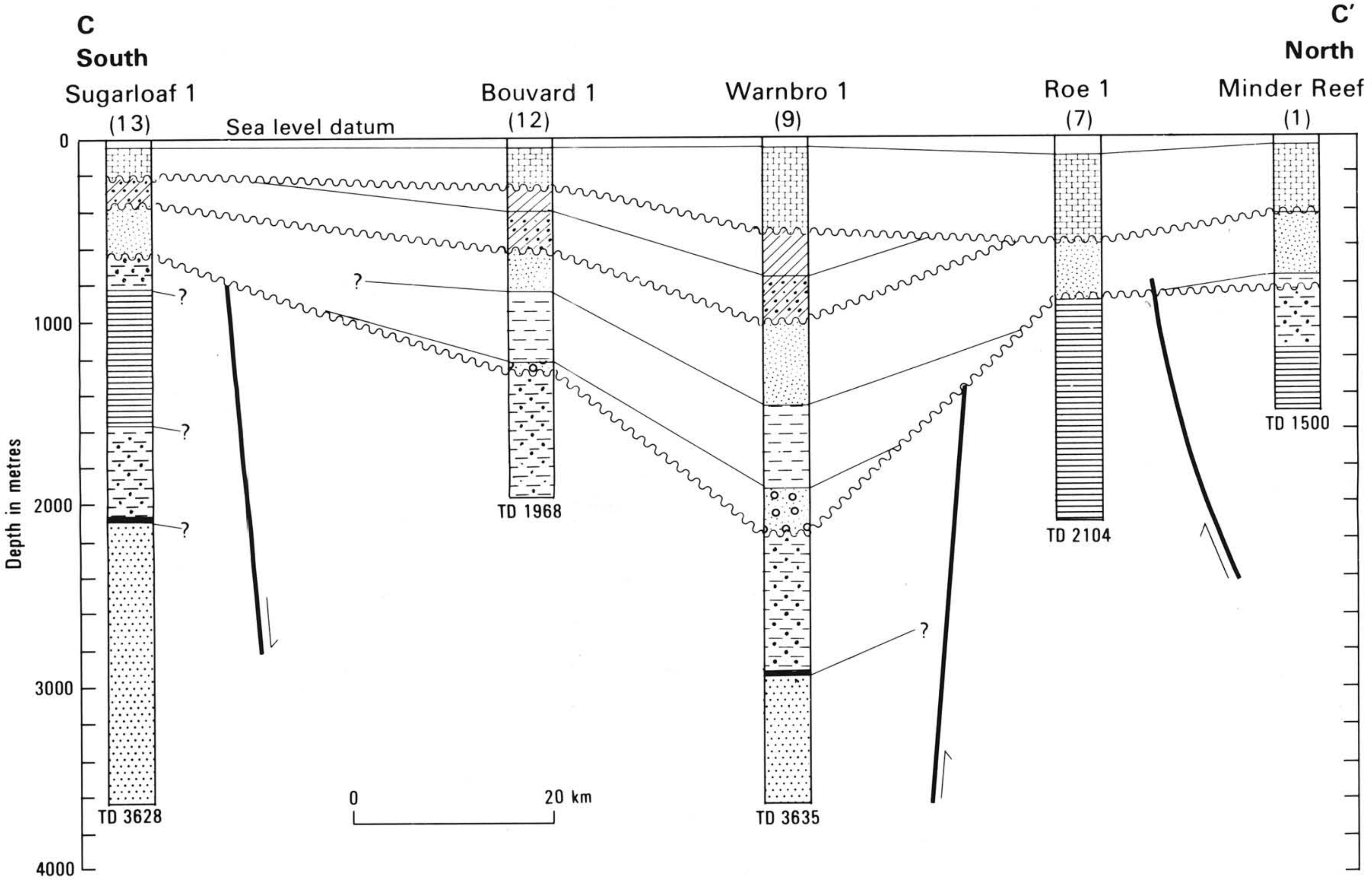

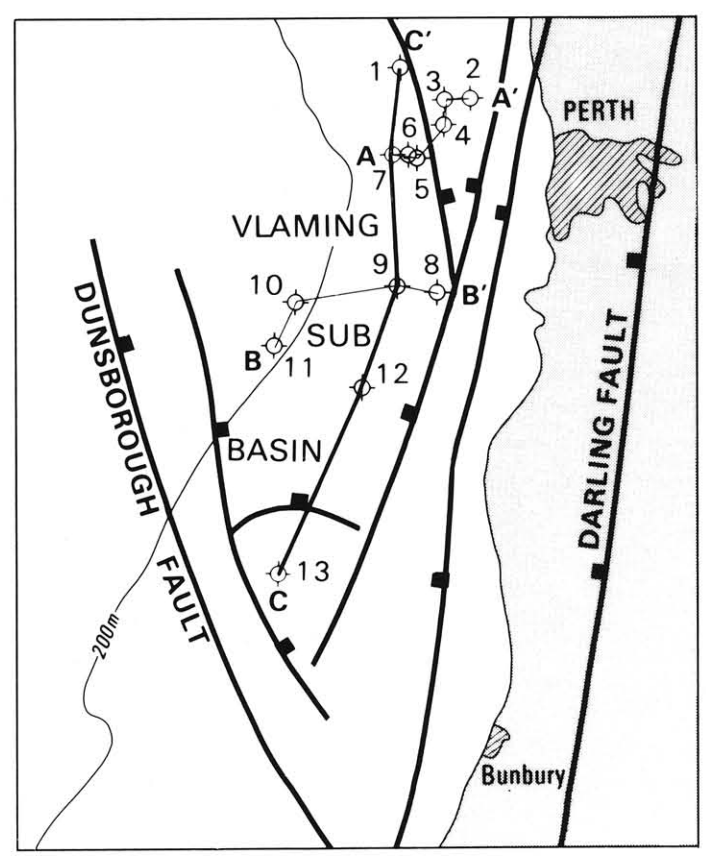

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North-south section showing well correlations in the Vlaming Sub-basin

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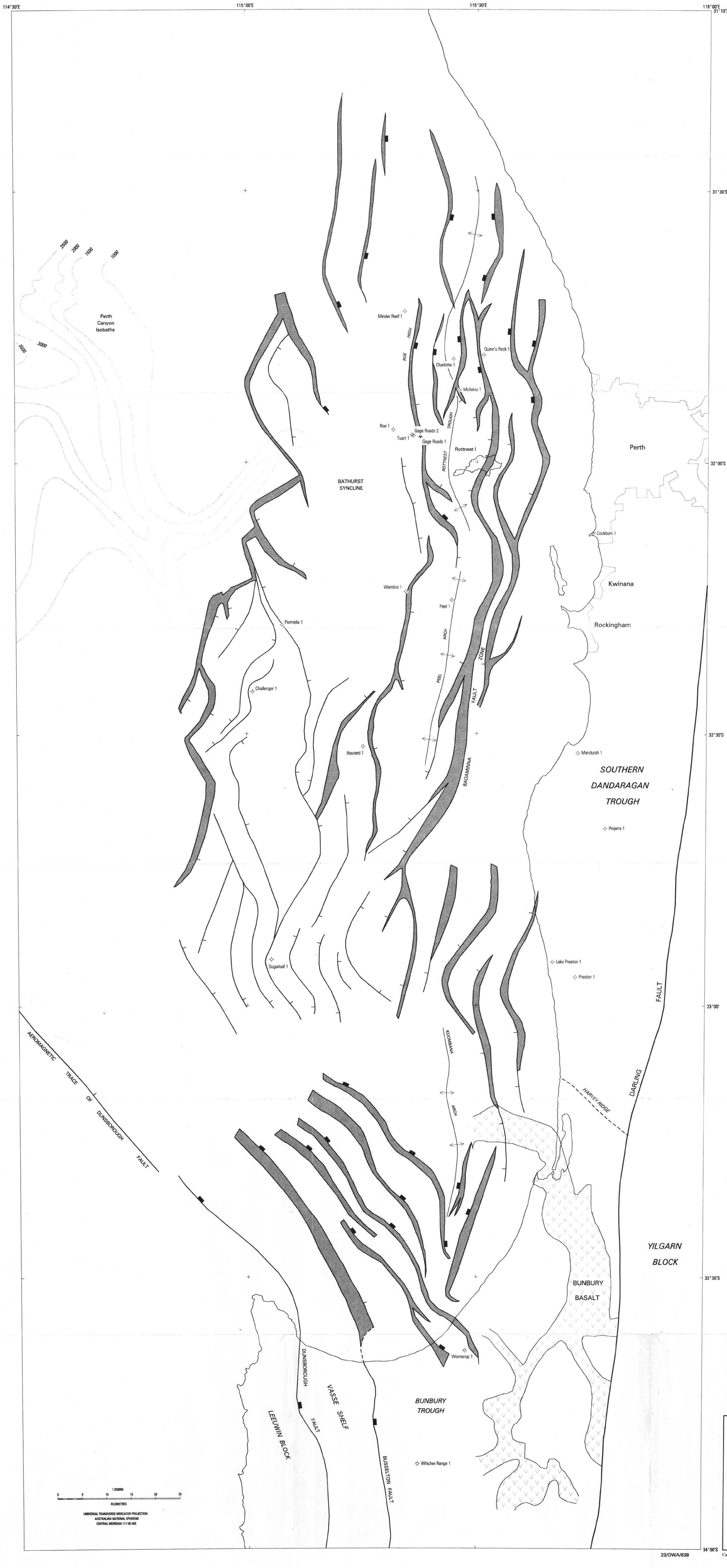
Plate 19

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation



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Previous structural interpretation of the Vlaming Sub-basin

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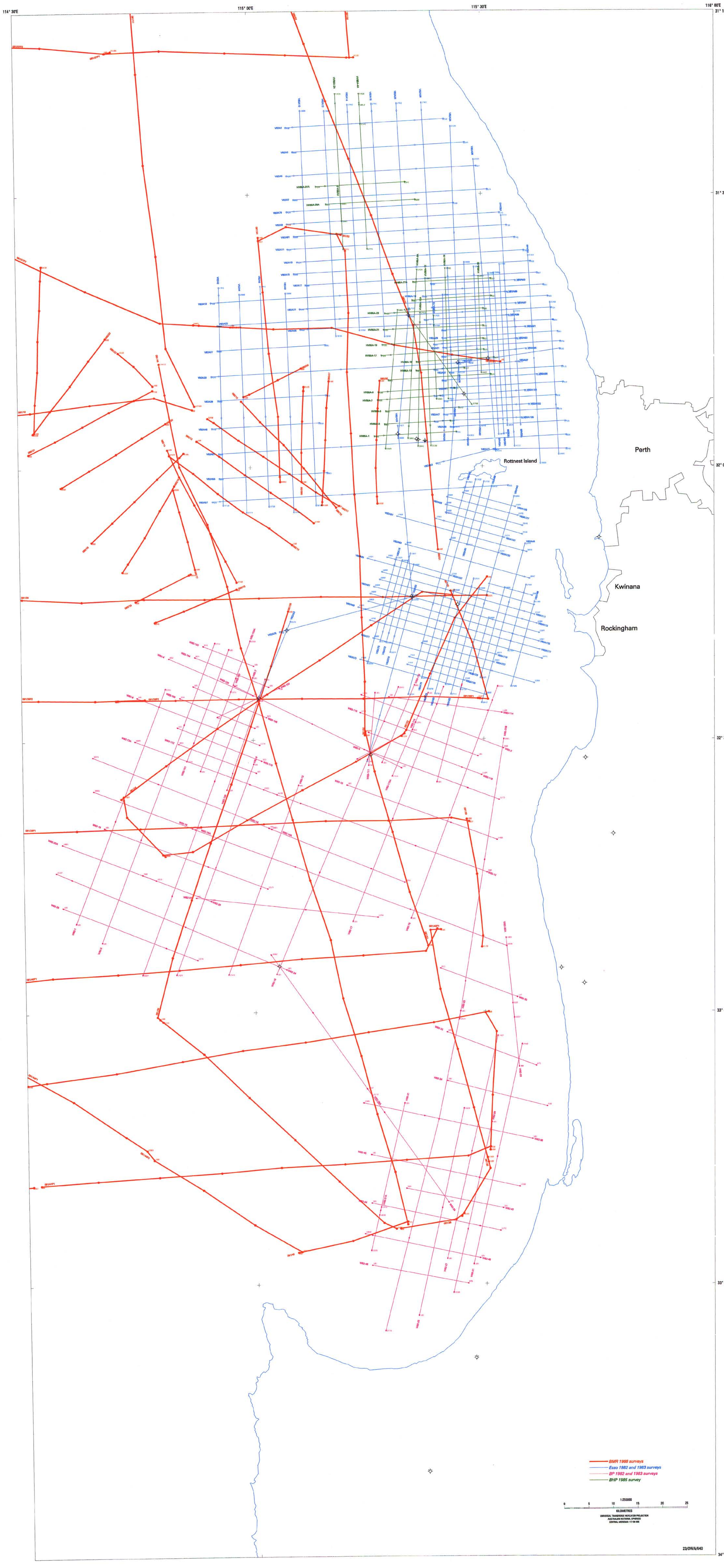
Plate 20

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation



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Line and shot point location map for the Vlaming Sub-basin

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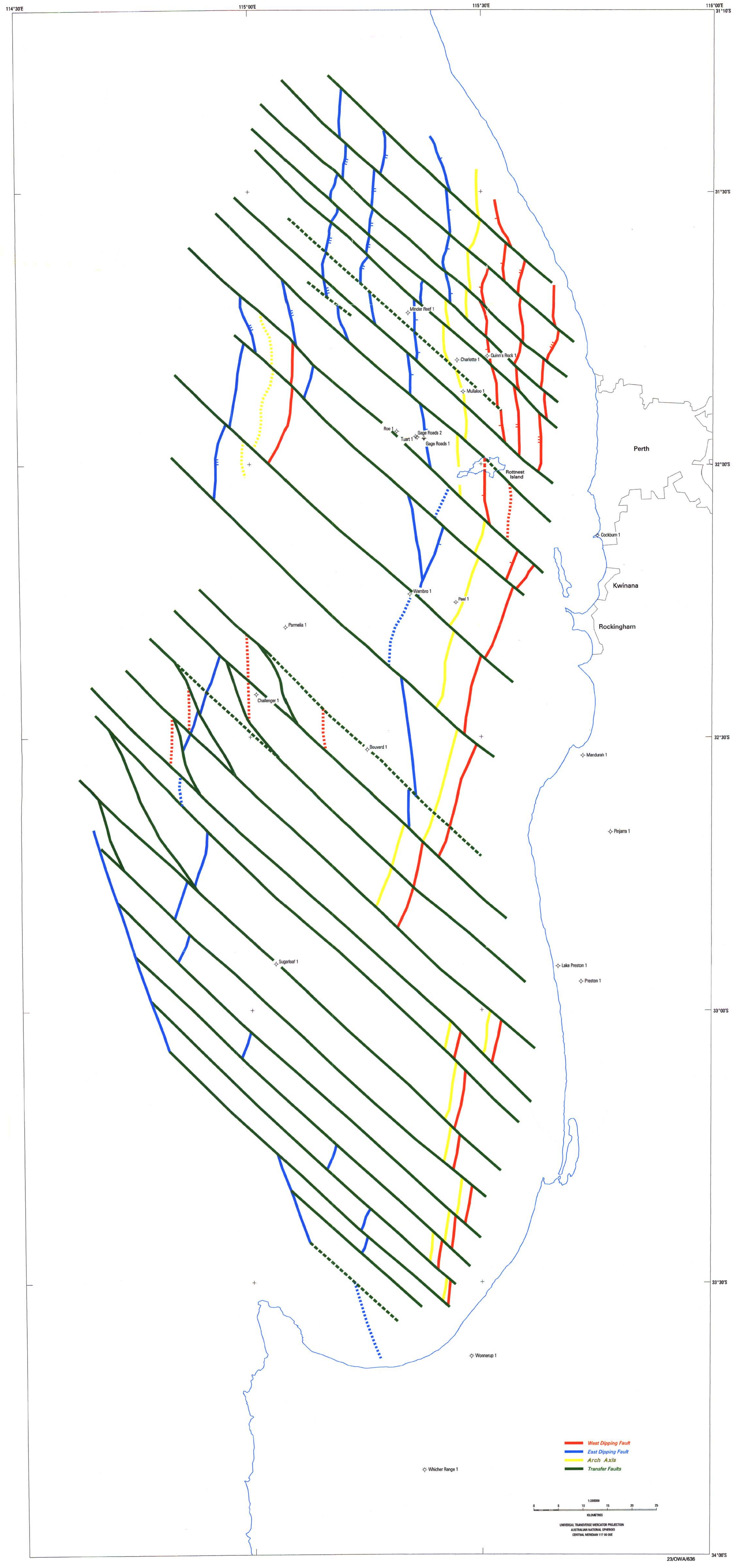
Plate 21

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation



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Linked fault structural interpretation of the Vlaming Sub-basin

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Plate 22

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

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True dip analysis map of the Vlaming Sub-basin

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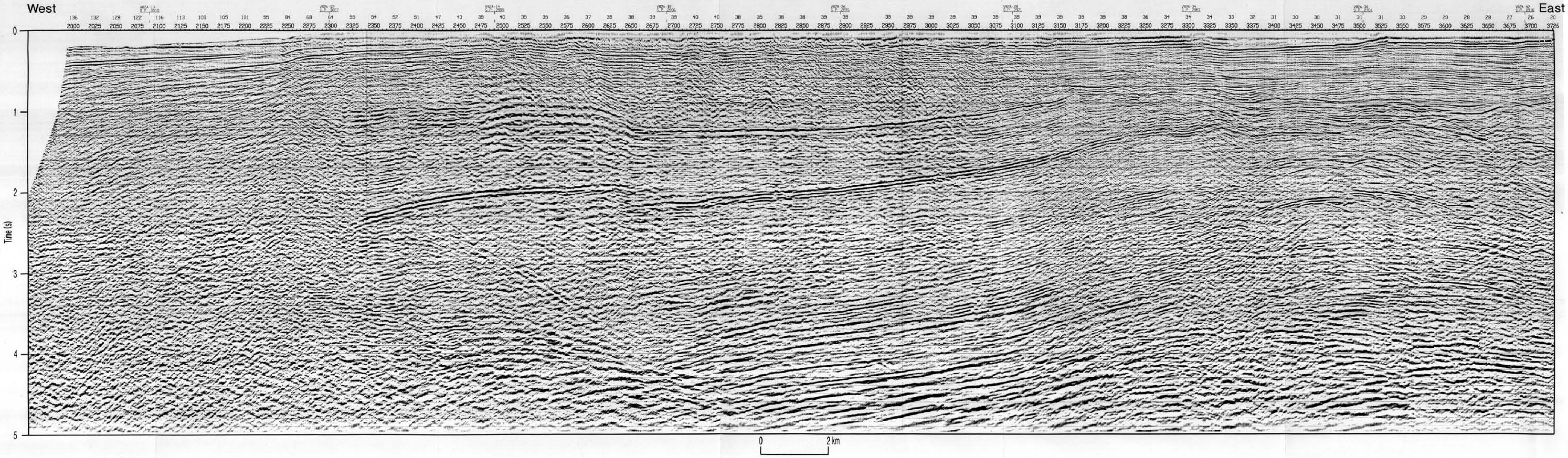
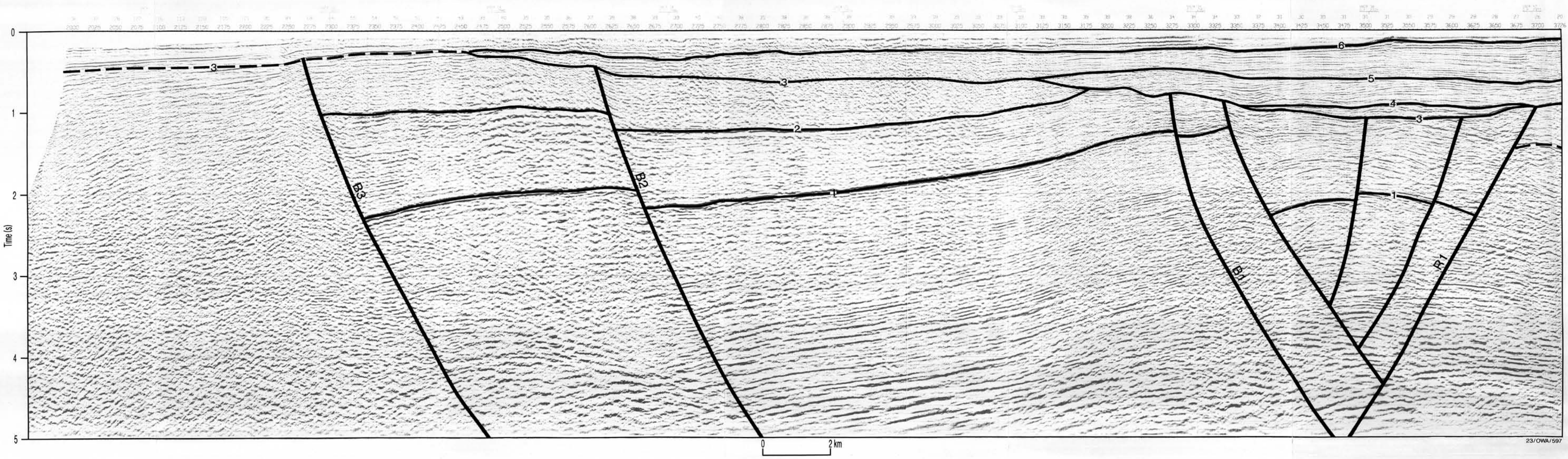
Plate 23

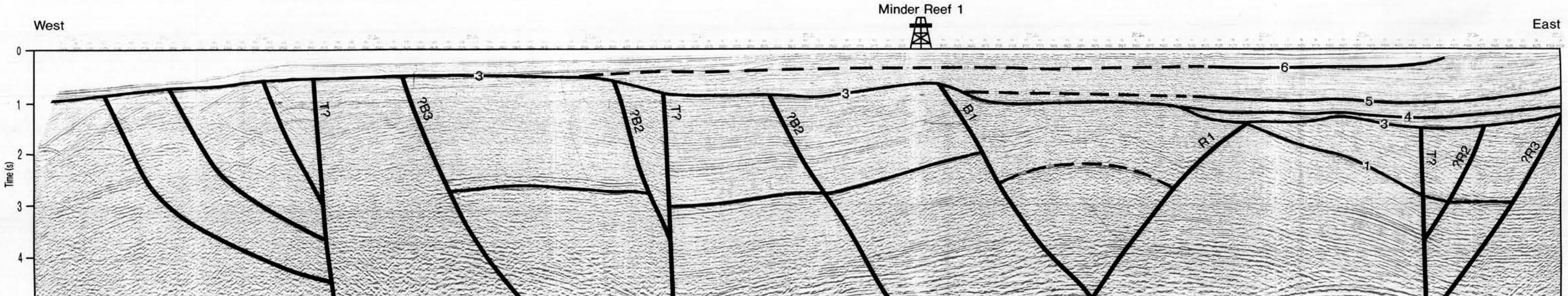
Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

Line V82A-81





Line V82A-23



1 Otorowiri Member marker horizon
2 ?Base Carnac Member
3 Neocomian Unconformity
4 Top Gage Sandstone Member
5 Top South Perth Shale
6 Top Leederville Formation

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Seismic sections northern Vlaming Sub-basin

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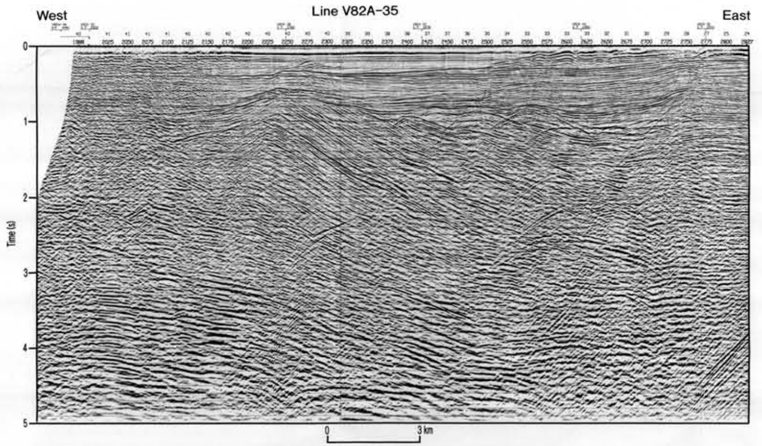
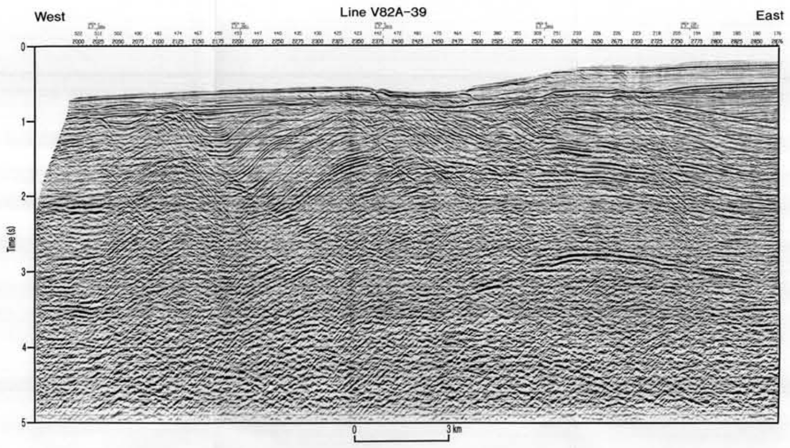
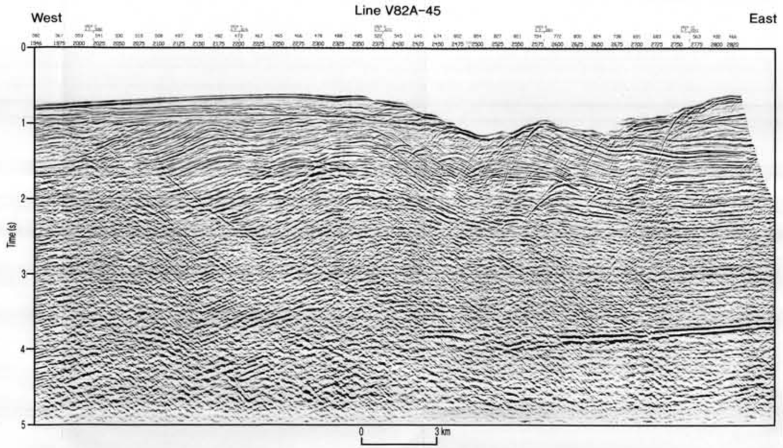
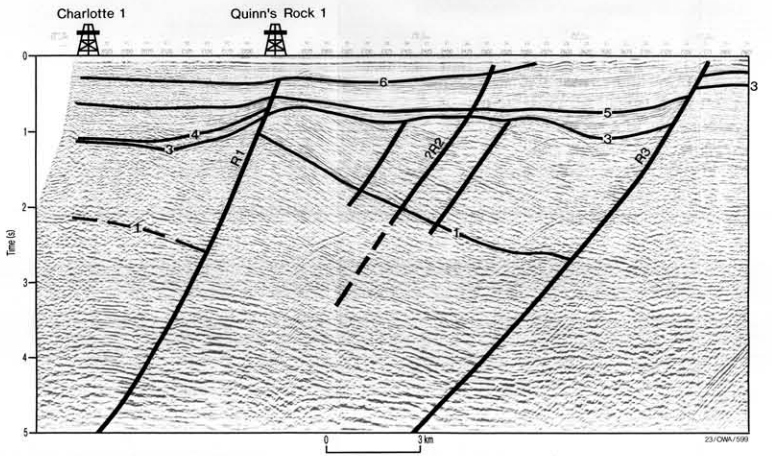
Plate 24

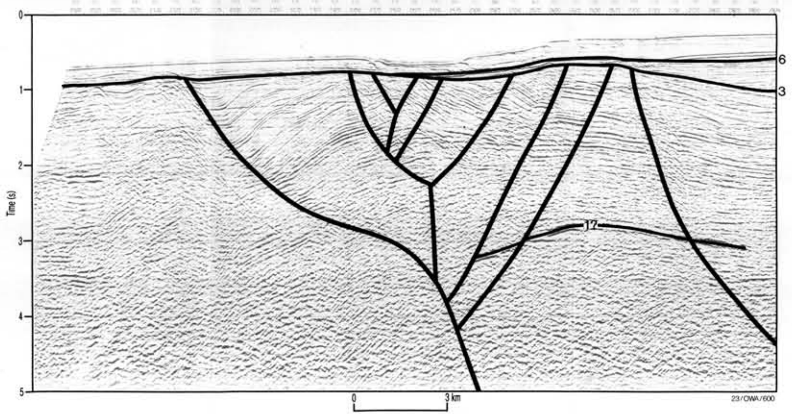
Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

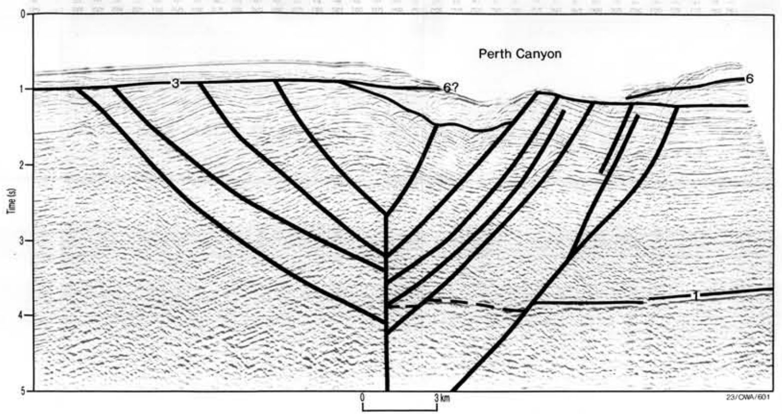












1 Otorowiri Member marker horizon
3 Neocomian Unconformity
4 Top Gage Sandstone Member
5 Top South Perth Shale
6 Top Leederville Formation

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Seismic sections northern Vlaming Sub-basin

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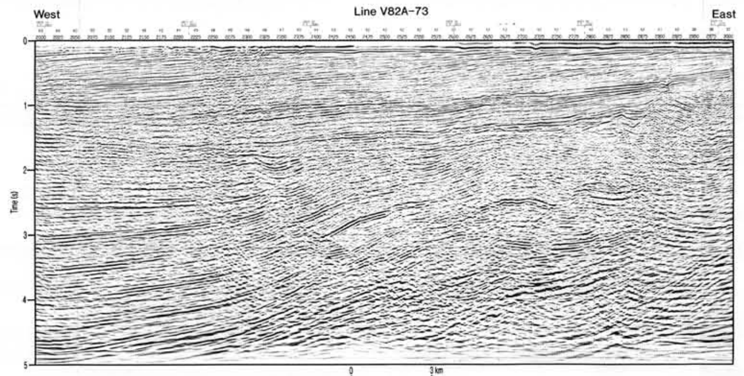
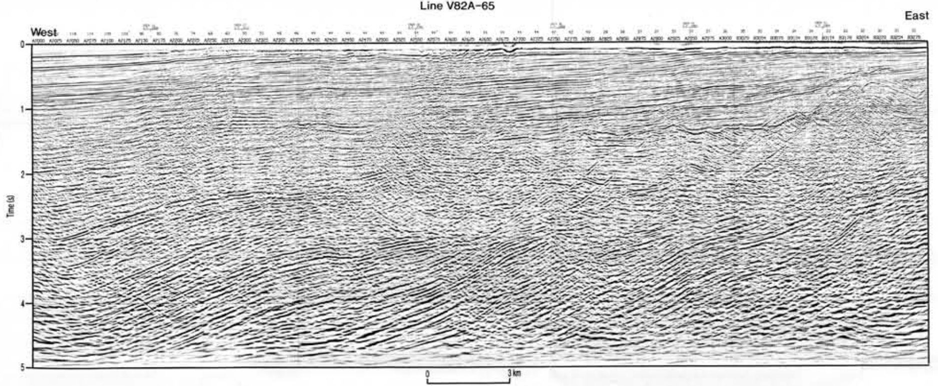
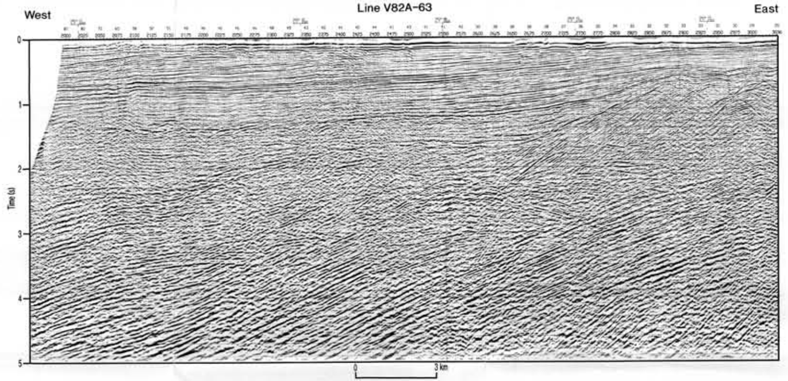
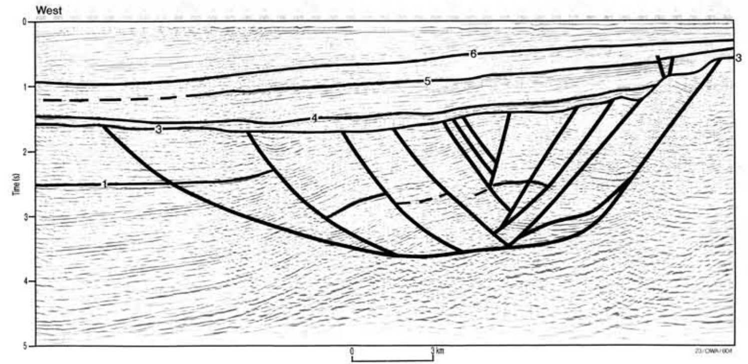
Plate 25

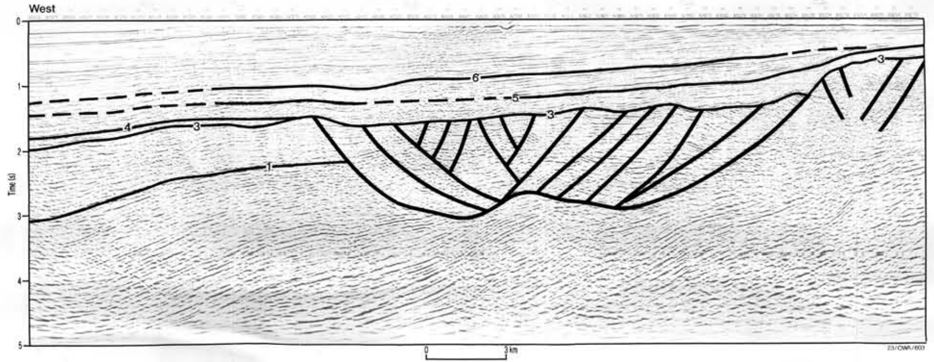
Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

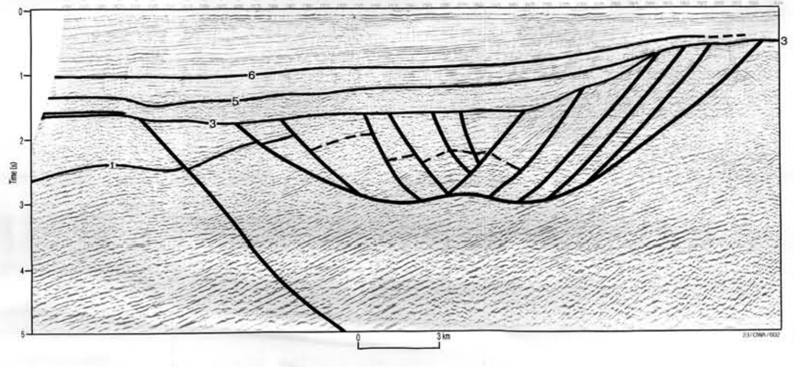












1 Otorowiri Member marker horizon
3 Neocomian Unconformity
4 Top Gage Sandstone Member
5 Top South Perth Shale
6 Top Leederville Formation

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Seismic sections Peel Arch

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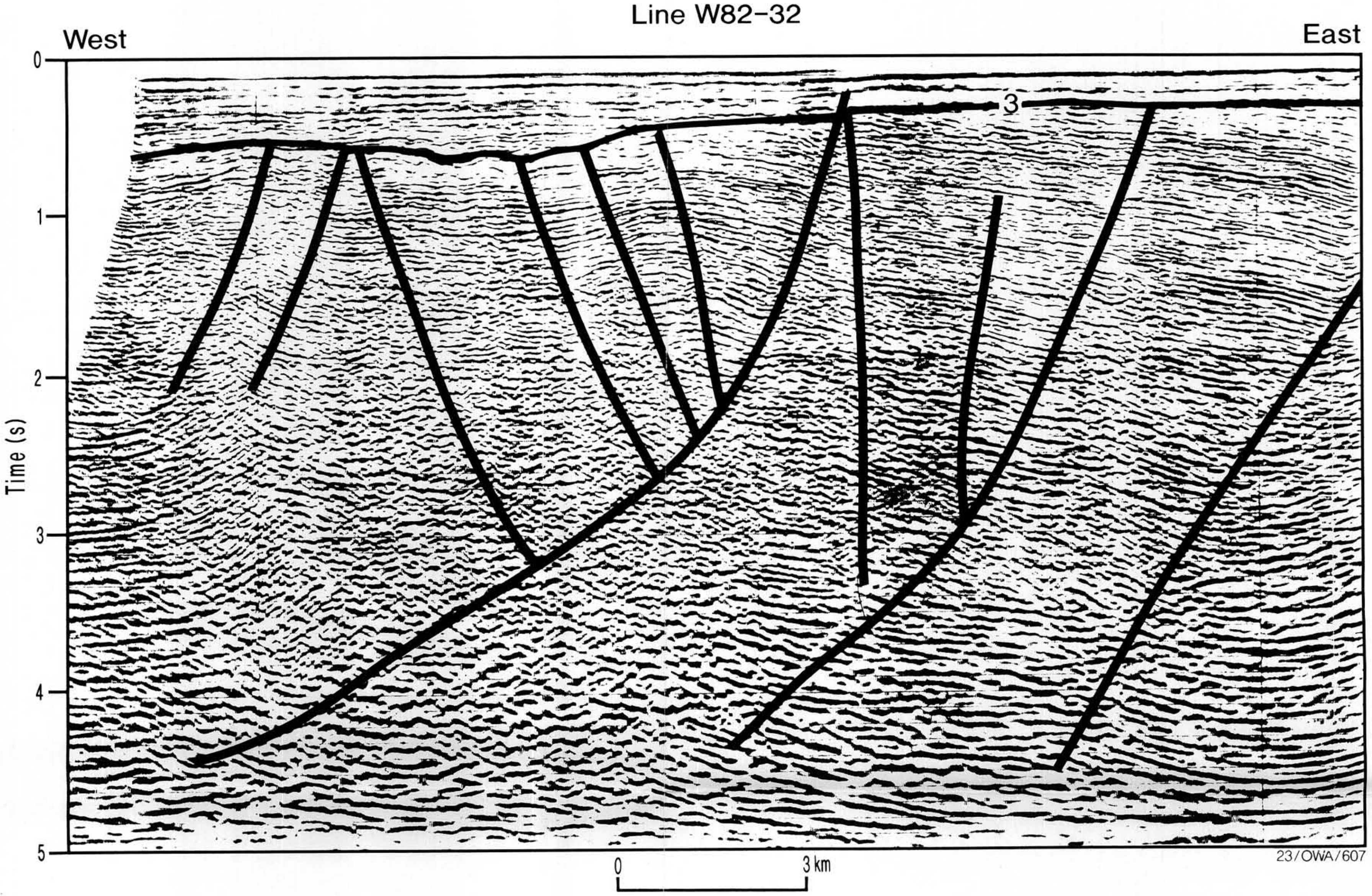
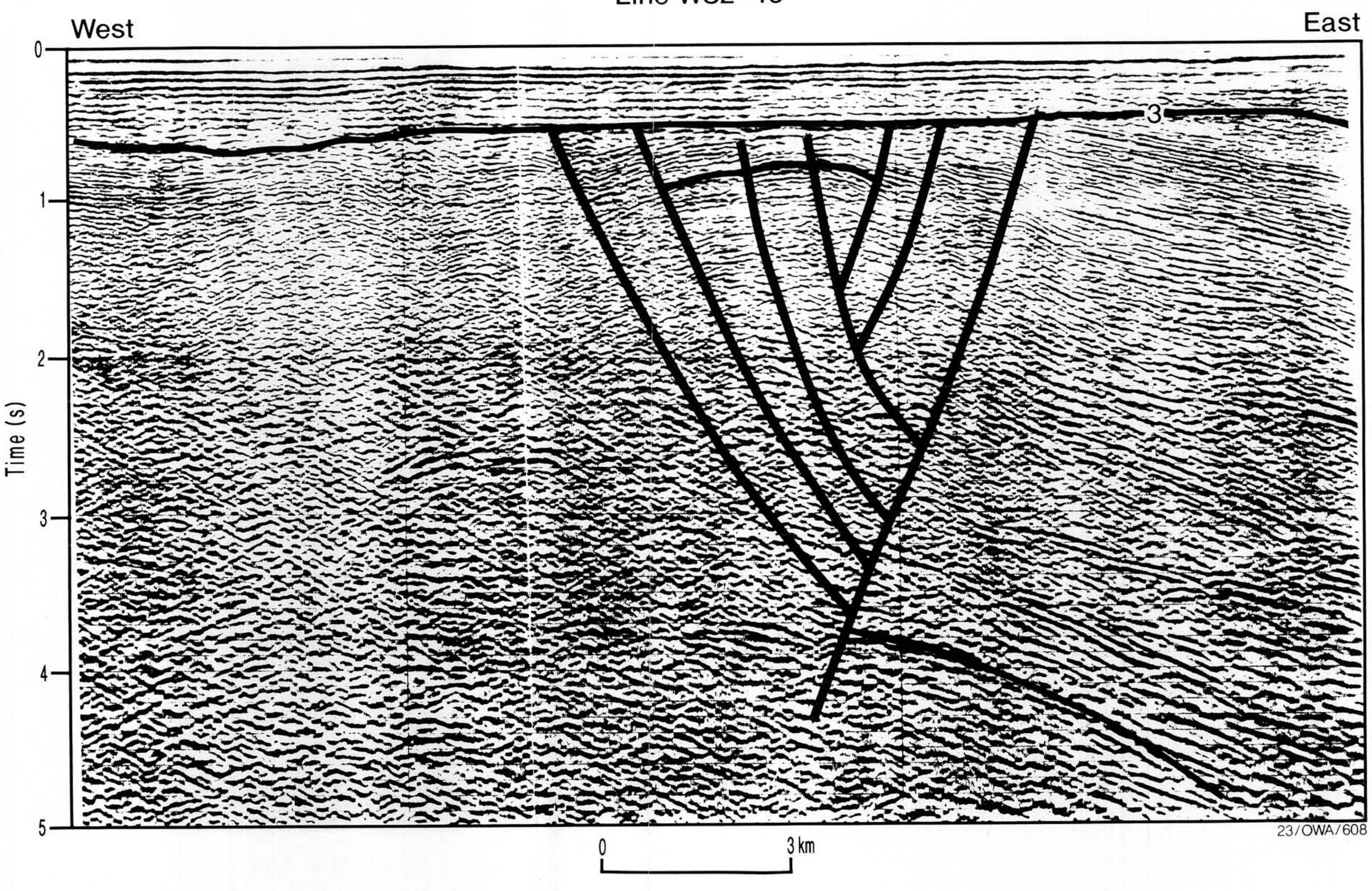
Plate 26

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

Line W82-32



Line W82-40



3 Neocomian Unconformity

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Offshore South Perth Basin

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Seismic sections
Koombana Arch

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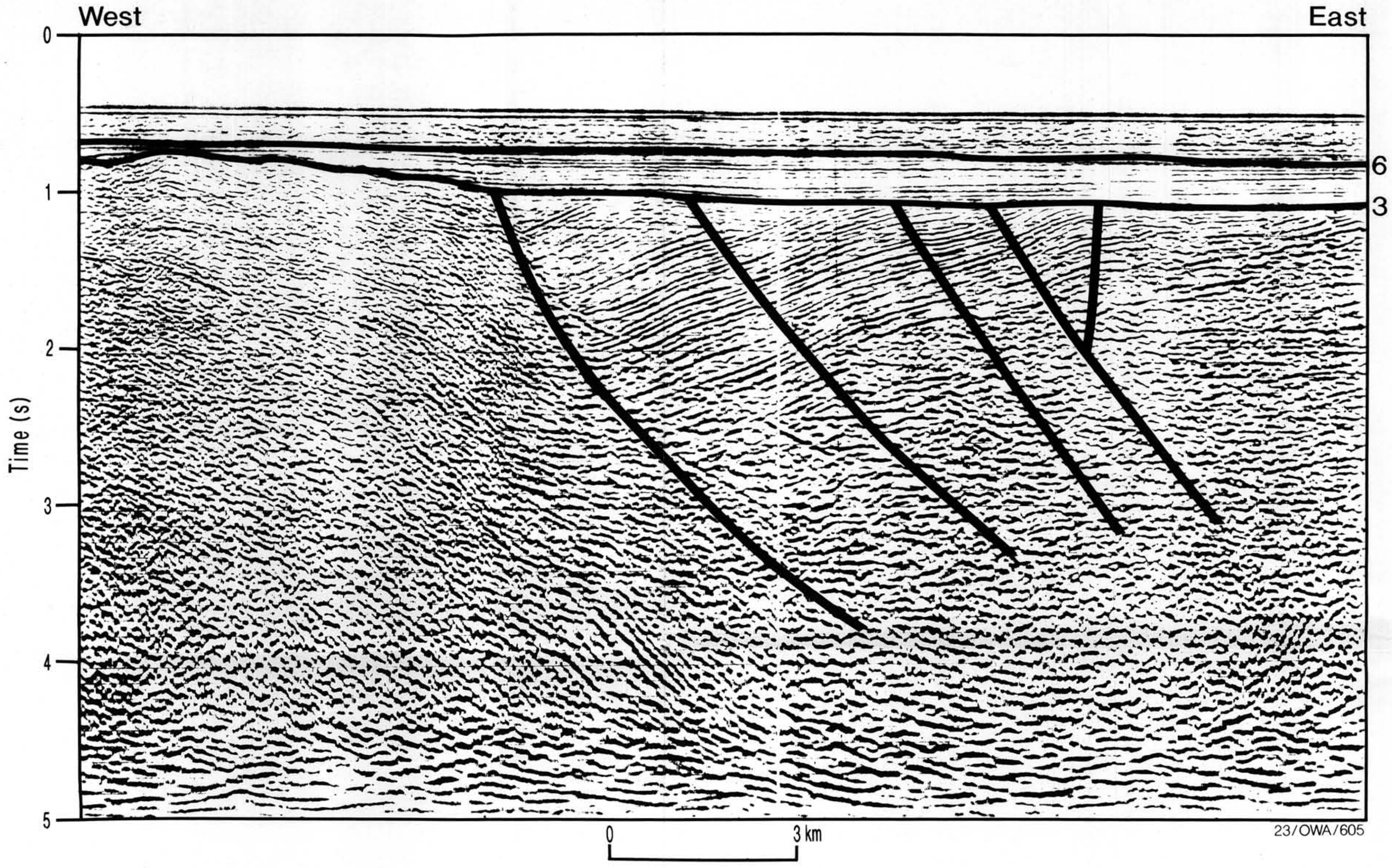
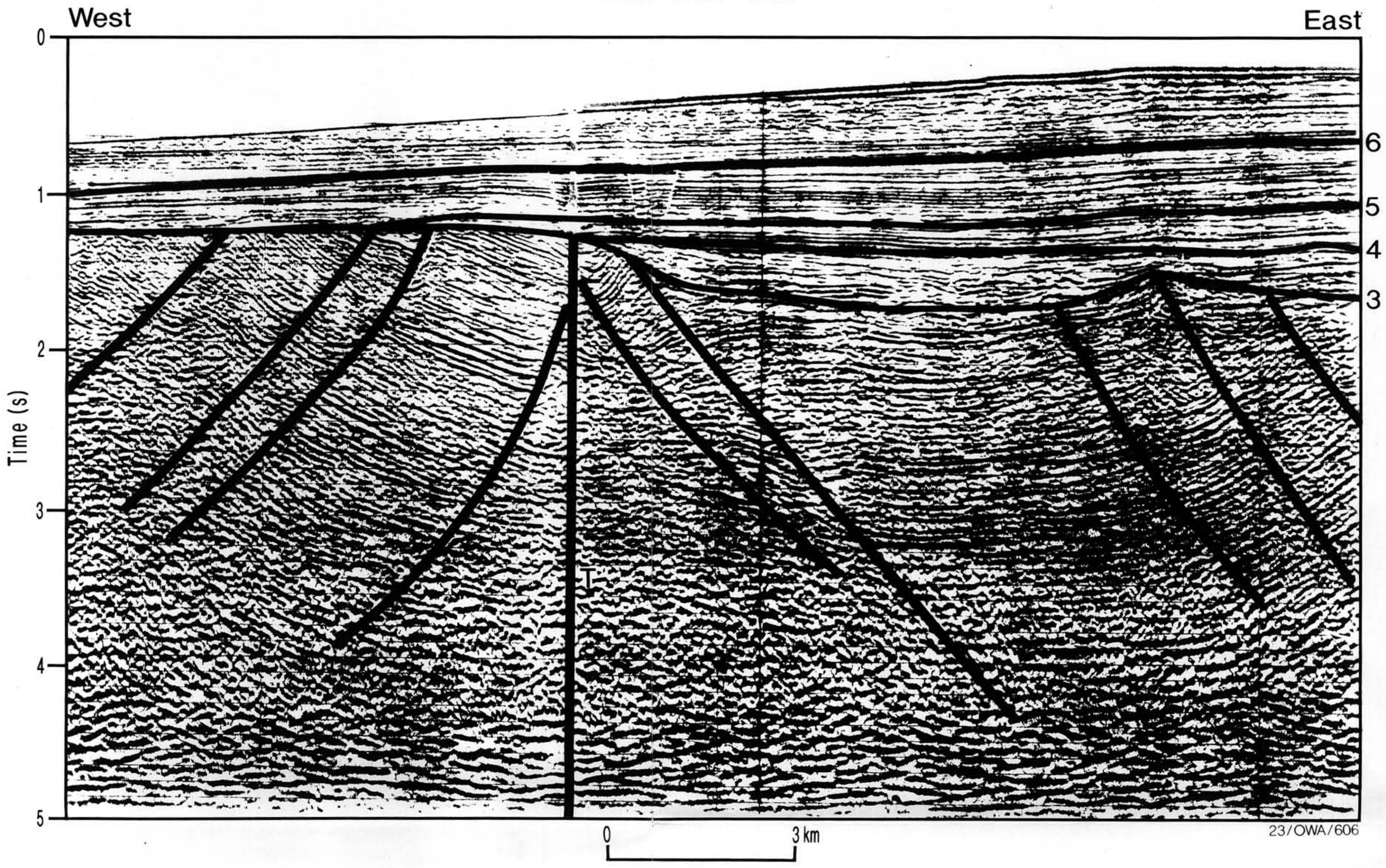
Plate 27

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

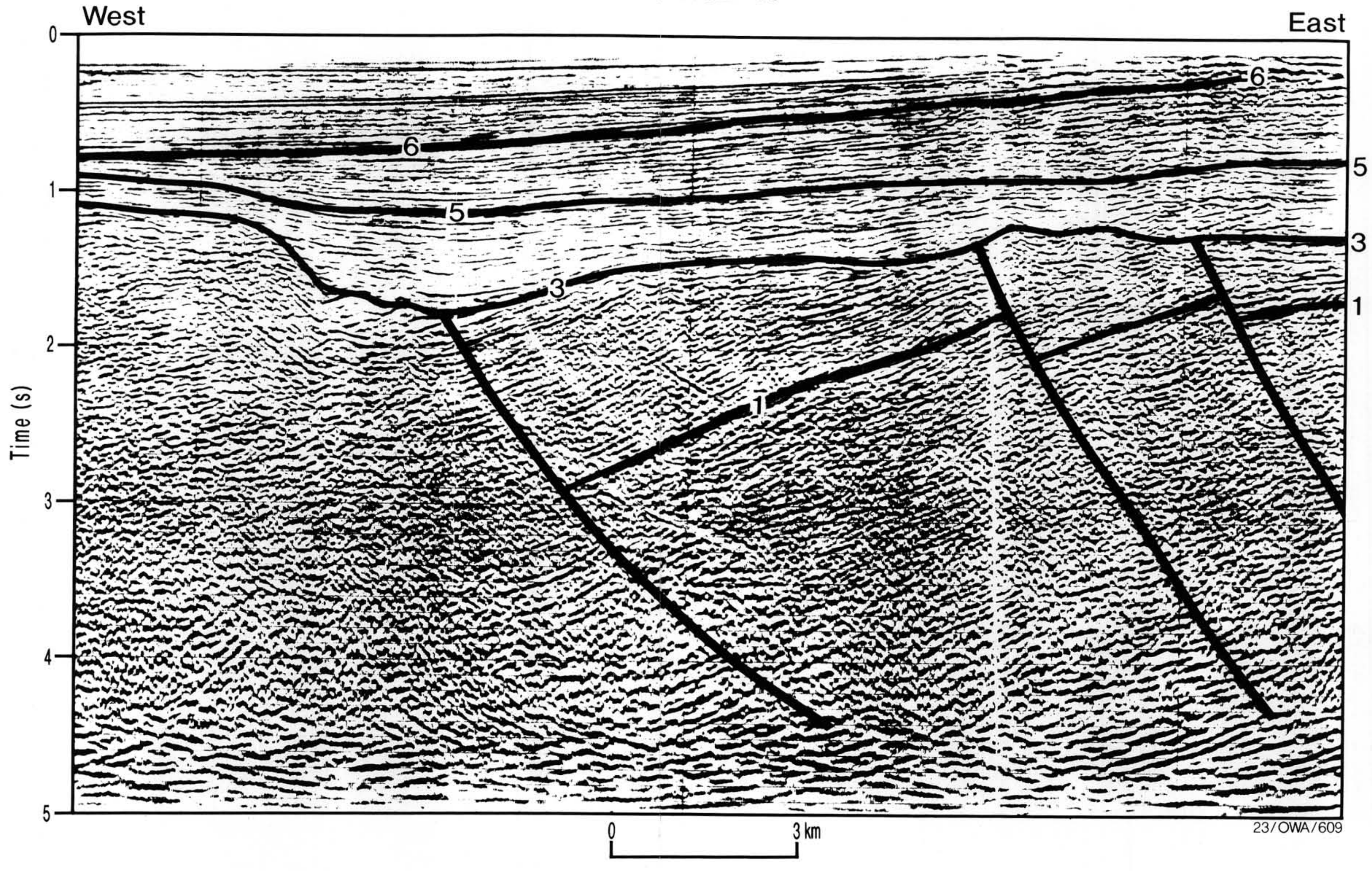
Line W82-3



Line W82-12A



Line W82-16



1 Otorowiri Member marker horizon
3 Neocomian Unconformity
4 Top Gage Sandstone Member
5 Top South Perth Shale
6 Top Leederville Formation

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Seismic sections southwestern Vlaming Sub-basin

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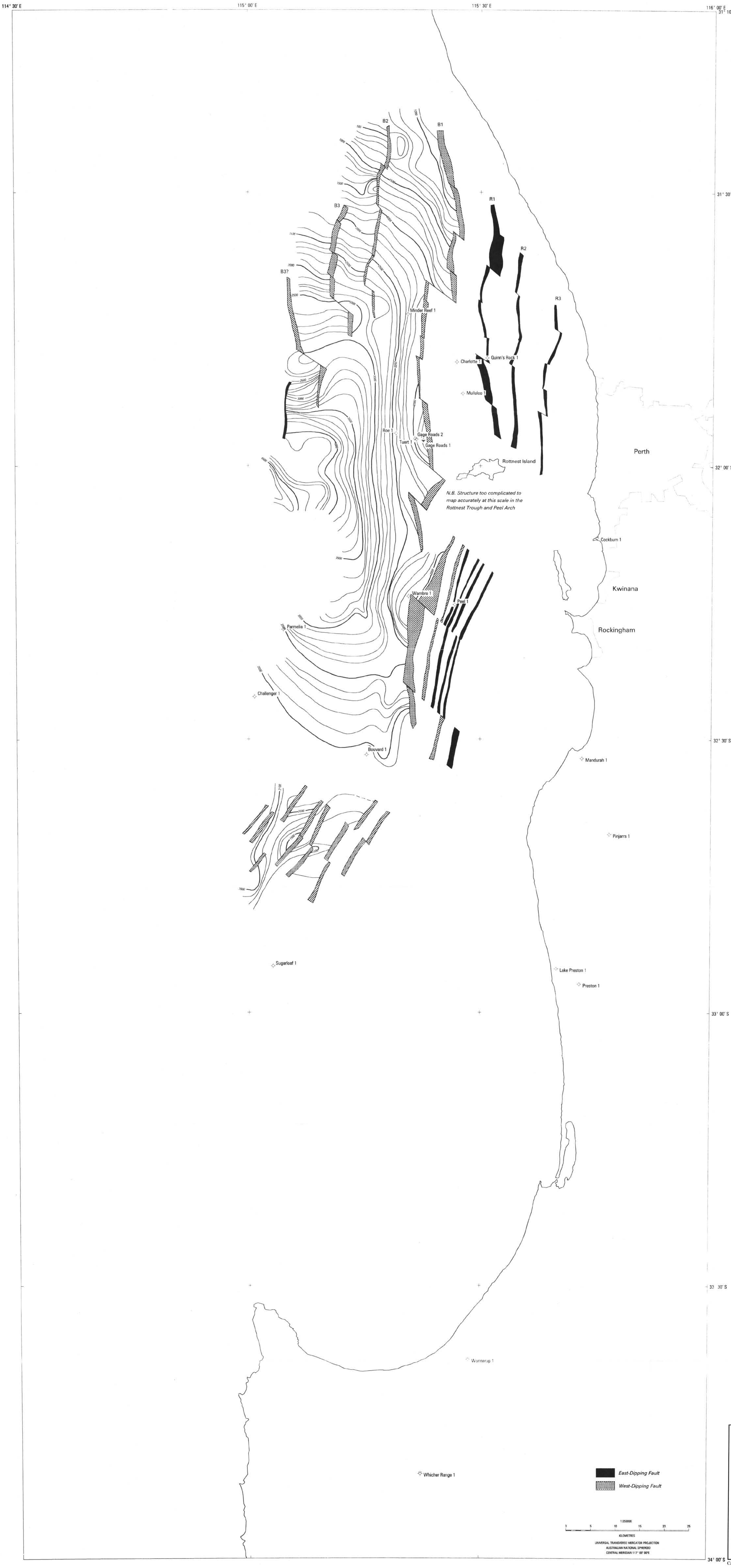
Plate 28

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation



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Time structure contour map of the Otorowiri Member

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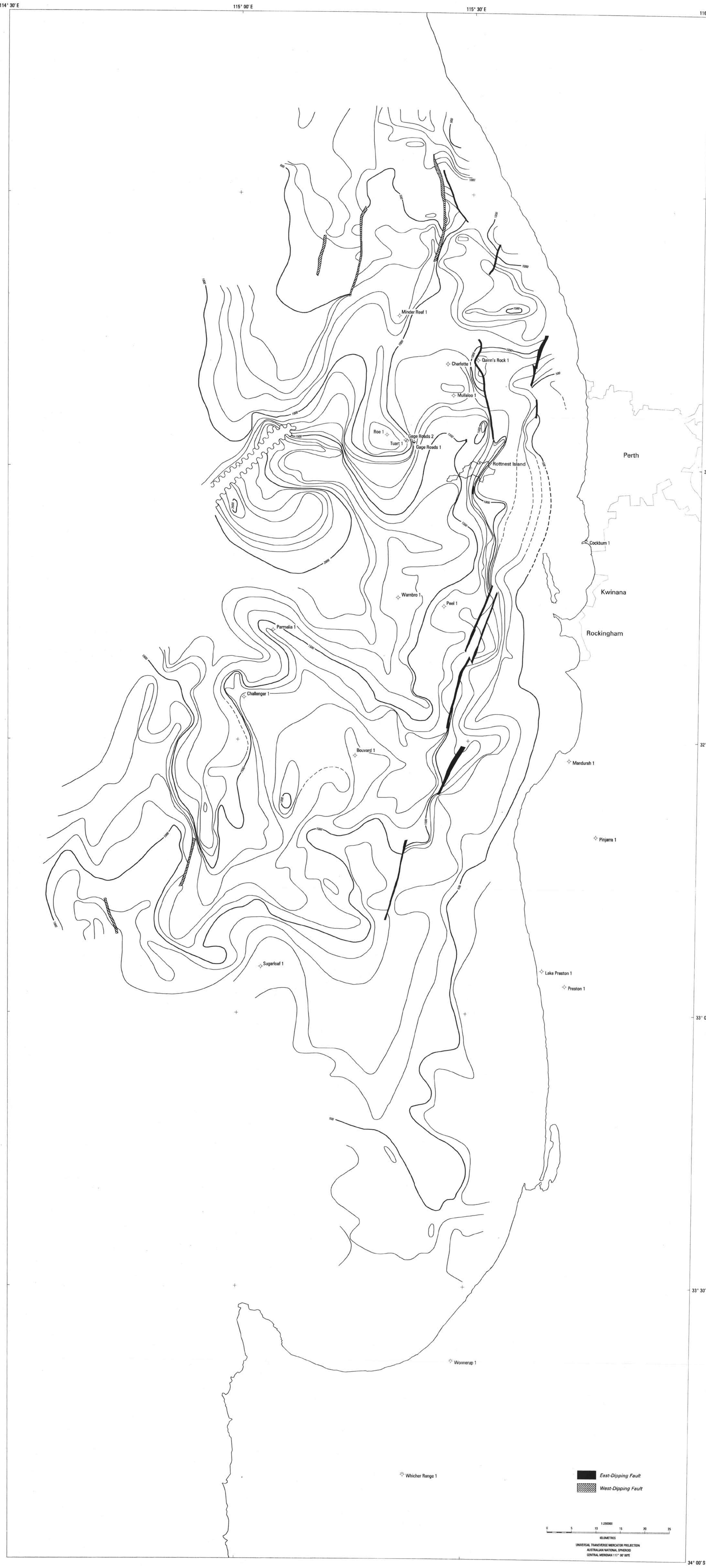
Plate 29

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

23/OWA/612



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Time structure contour map of the Neocomian unconformity

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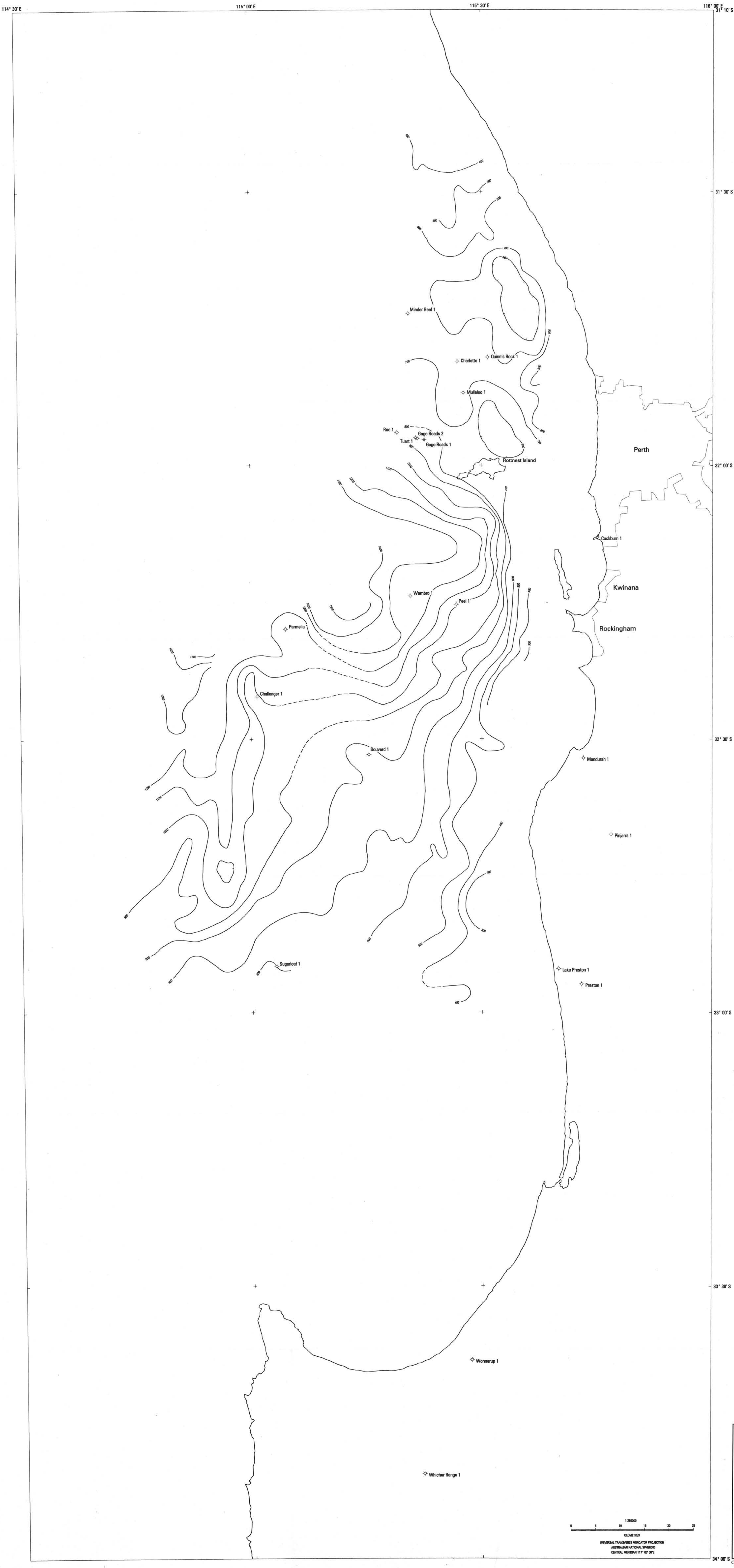
Plate 30

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

23/AWO/613



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Time structure contour map of the top South Perth Shale horizon

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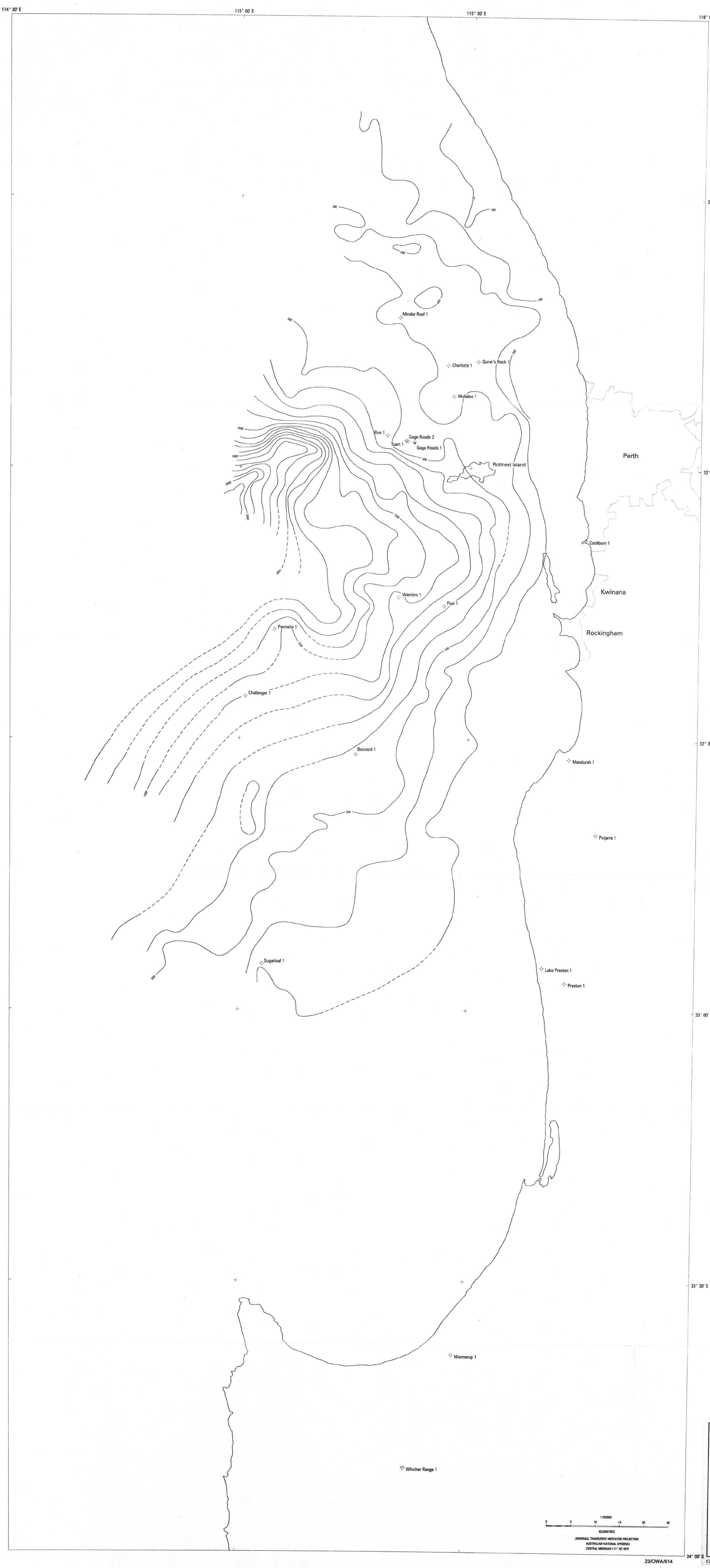
Plate 31

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

23/OWA/616



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Time structure contour map of the top Leederville Formation horizon

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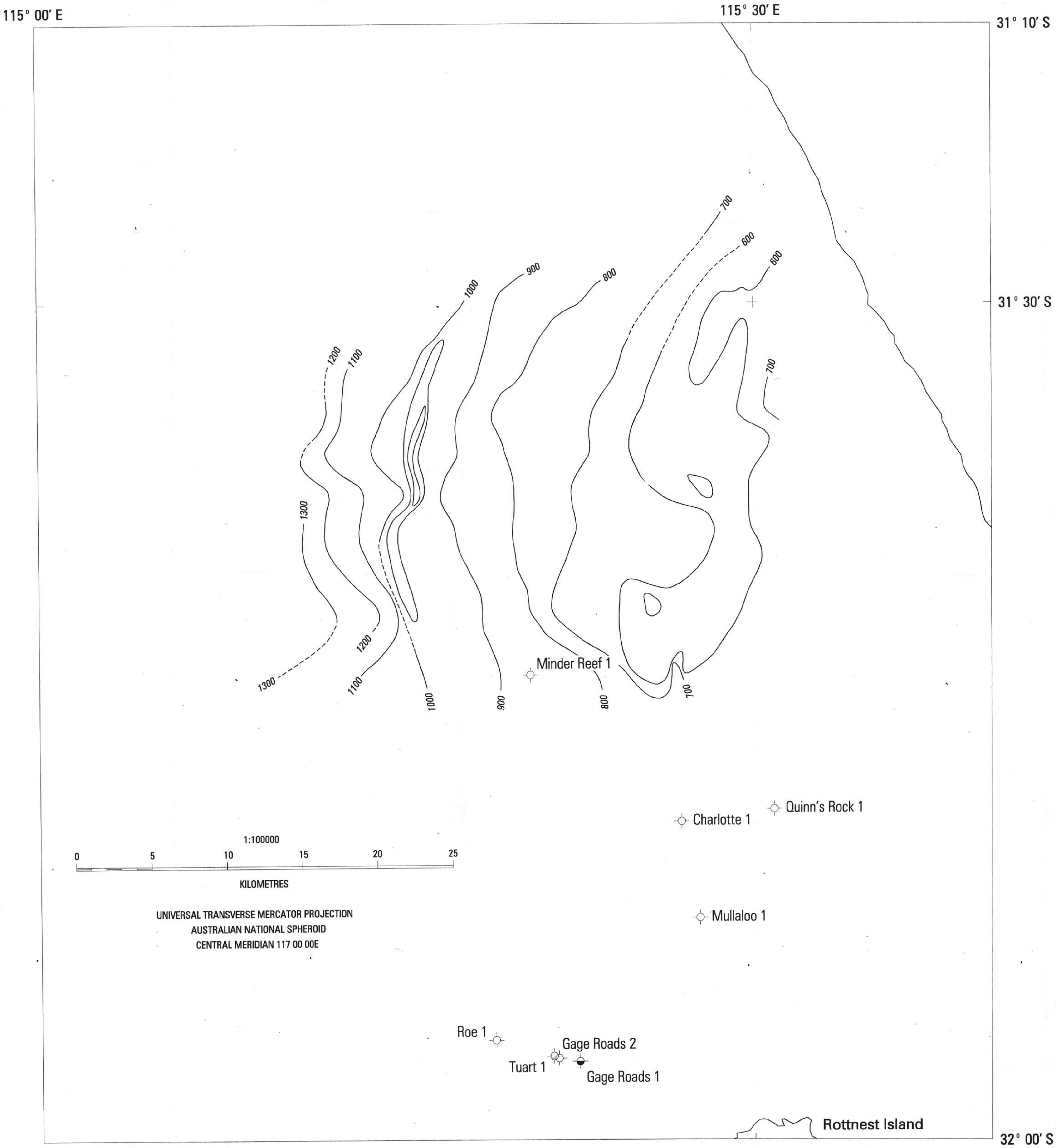
Plate 32

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation



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Isopach map of the lower Parmelia Formation

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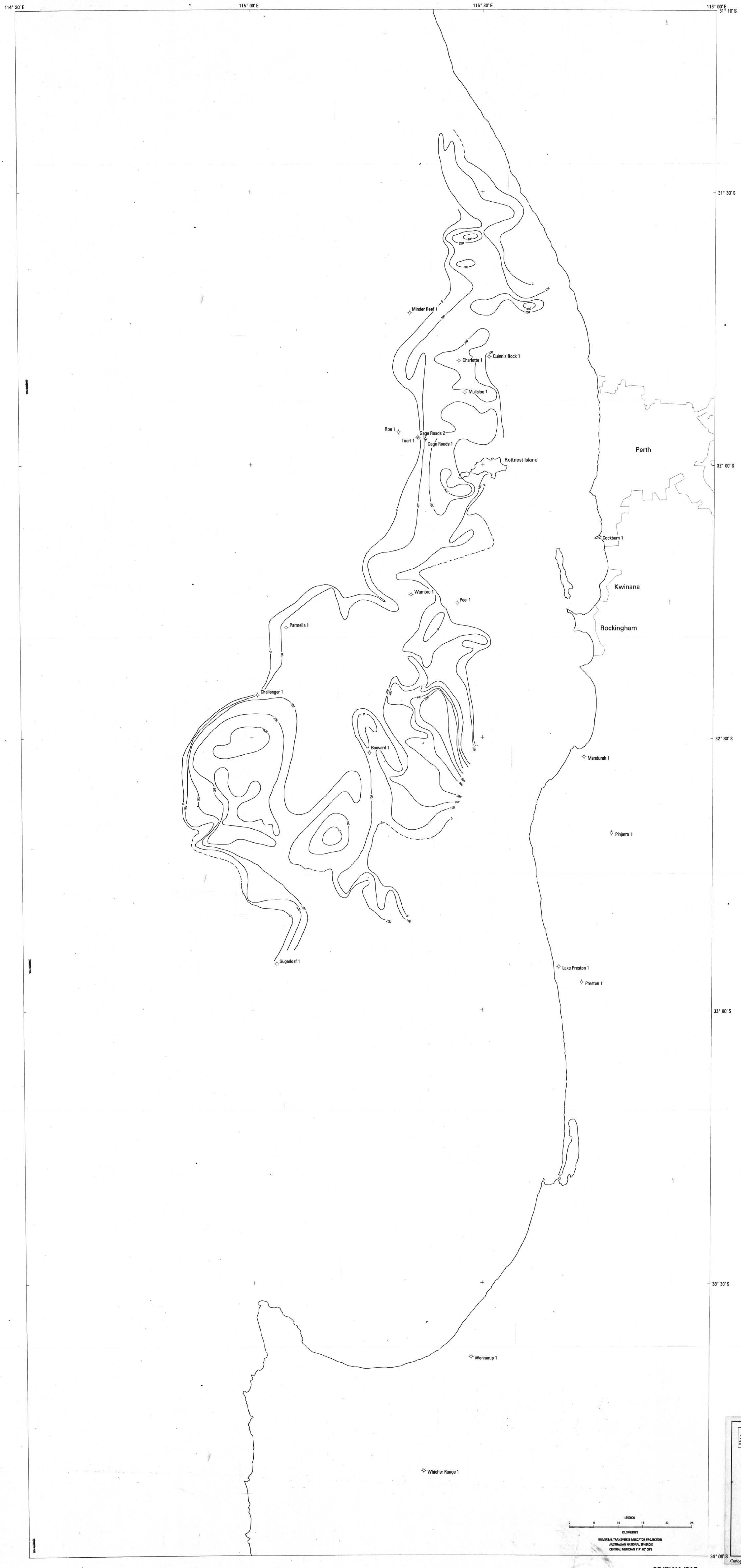
Plate 33

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

23/OWA/617



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Isopach map of the Gage Sandstone Member and equivalents

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Plate 34

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation

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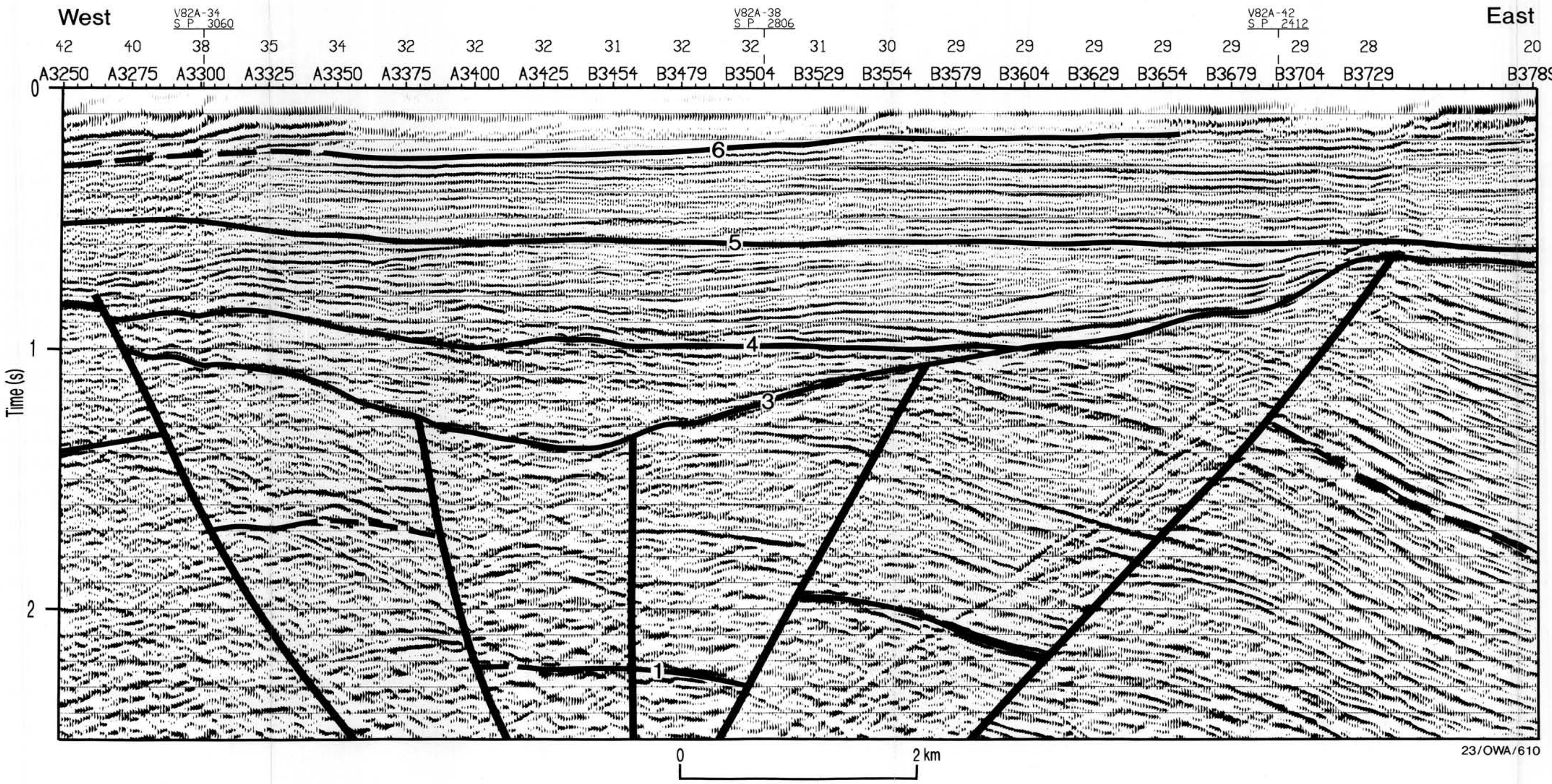
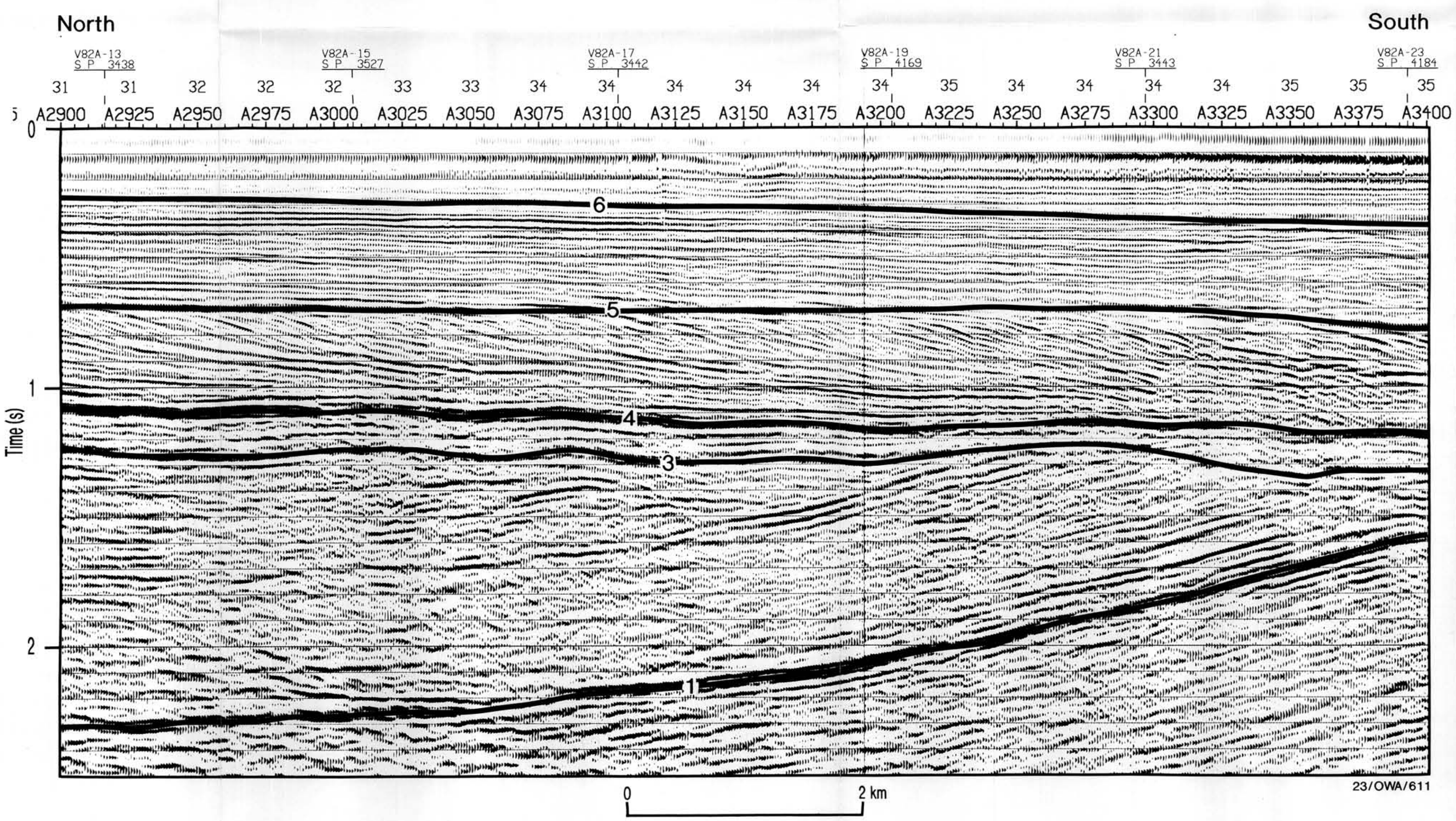
Line V82A-11



Line V82A-38



1 Otorowiri Member marker horizon
3 Neocomian Unconformity
4 Top Gage Sandstone Member
5 Top South Perth Shale
6 Top Leederville Formation

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Seismic sections South Perth Shale progradation

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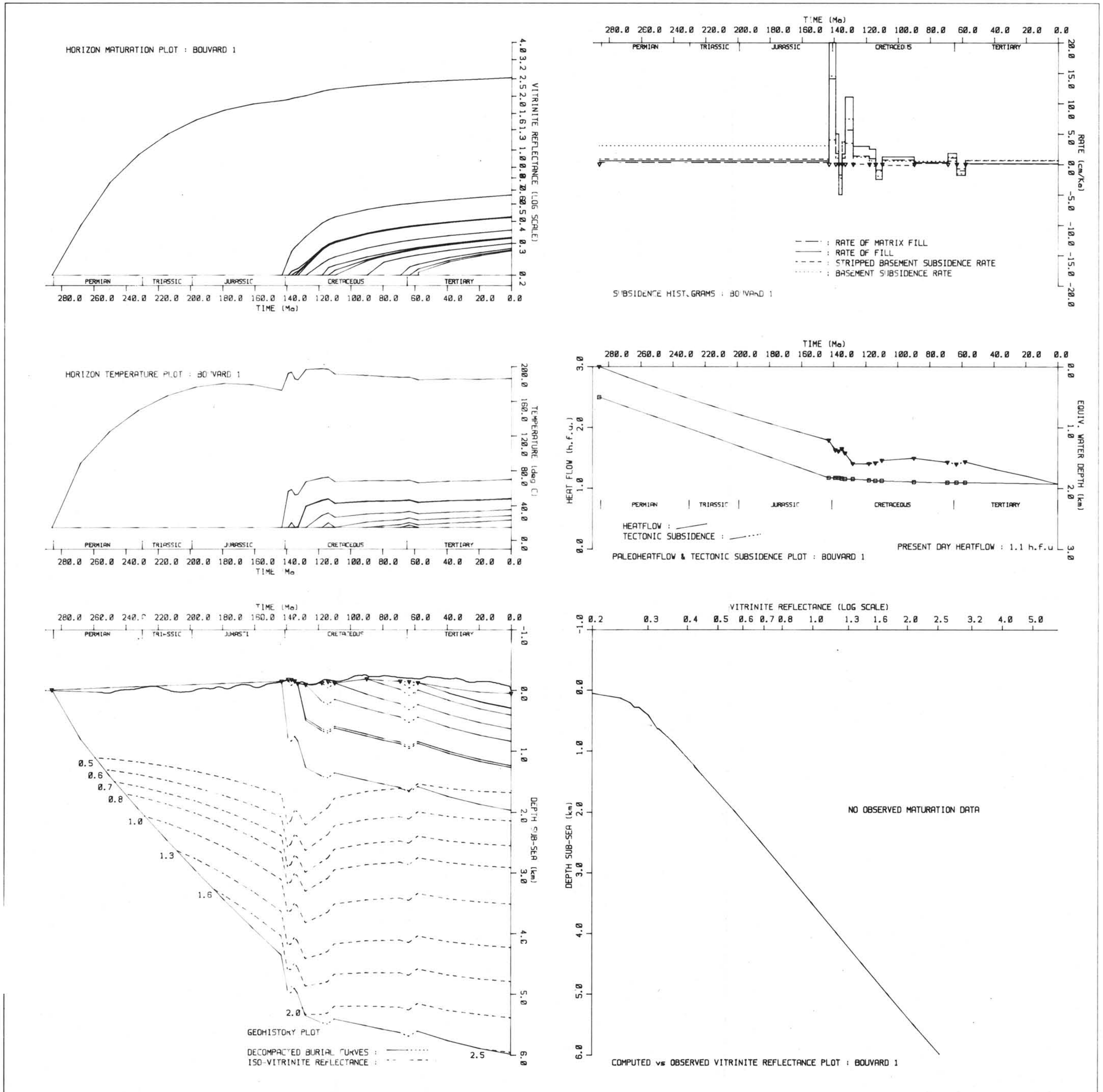
Plate 35

Cartography by the Cartographic Services Unit, Australian Geological Survey Organisation



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Geohistory analysis Bouvard 1

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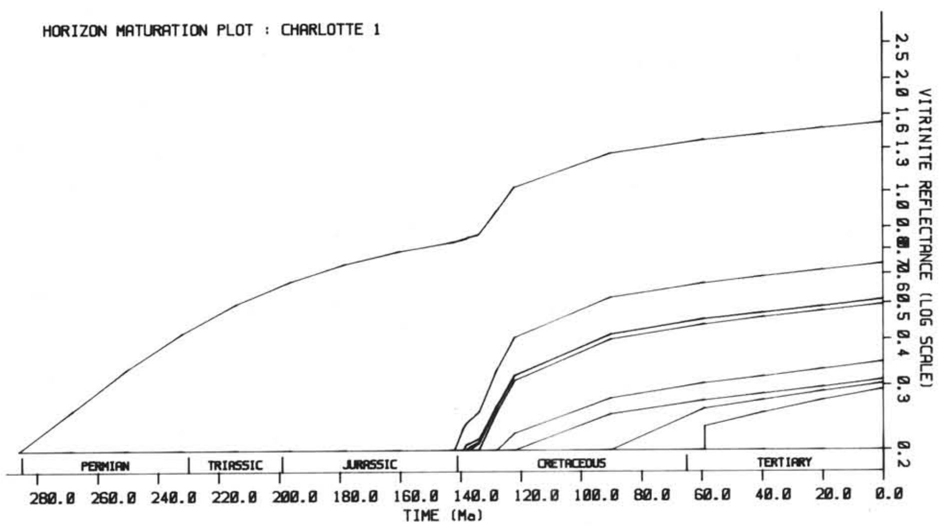
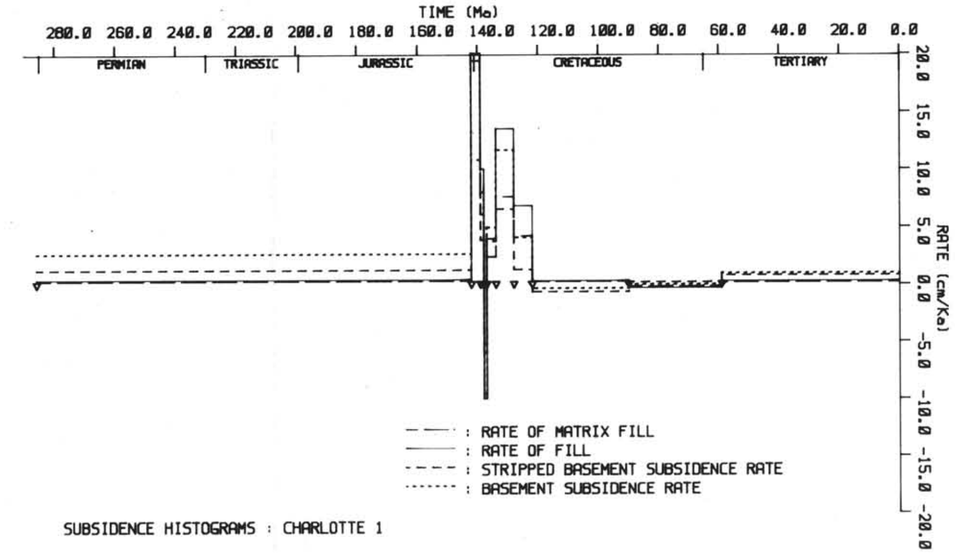
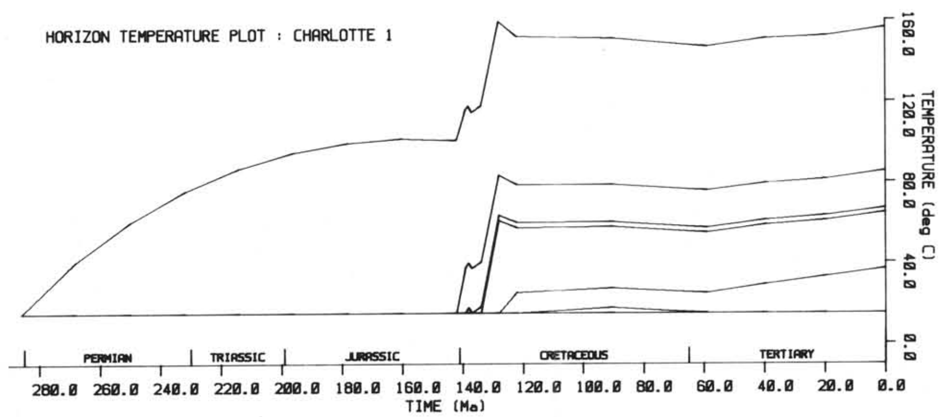
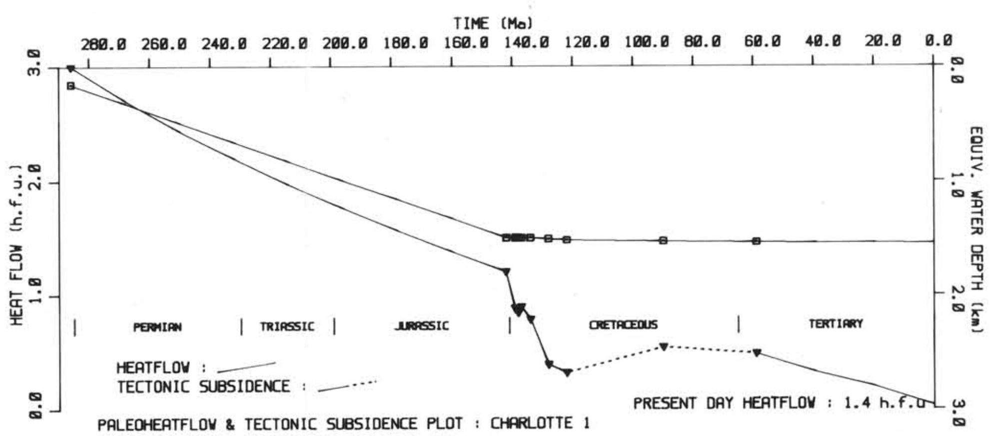
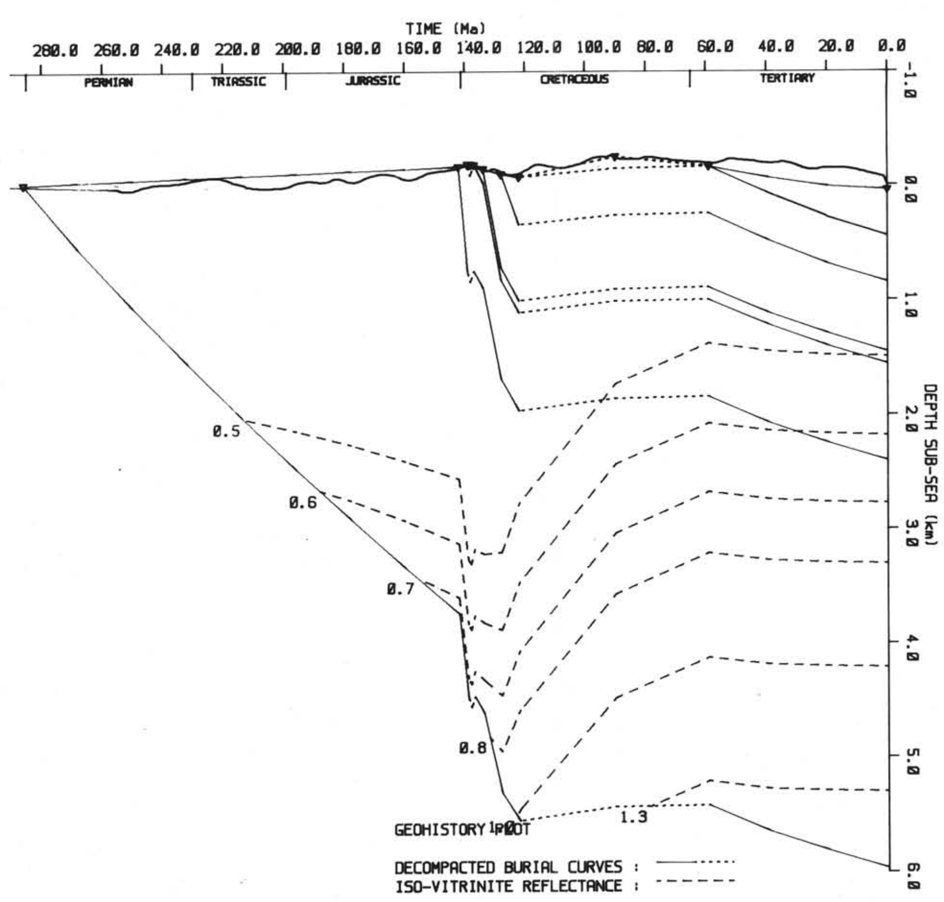
Plate 36

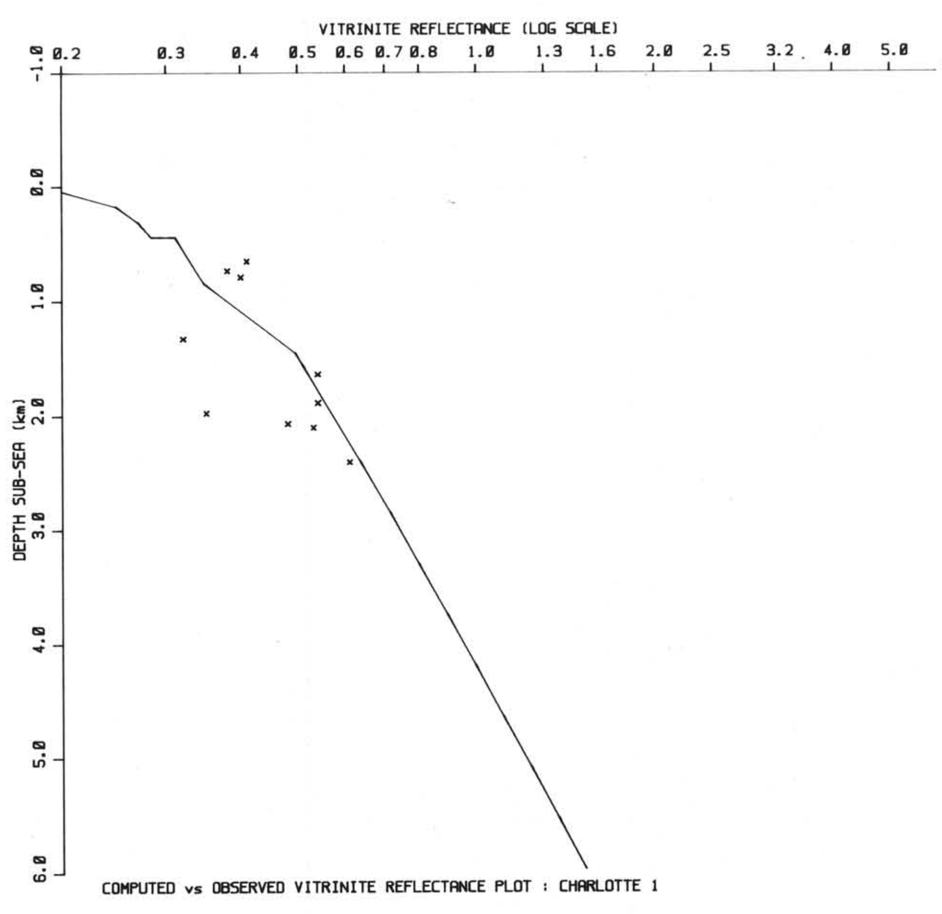












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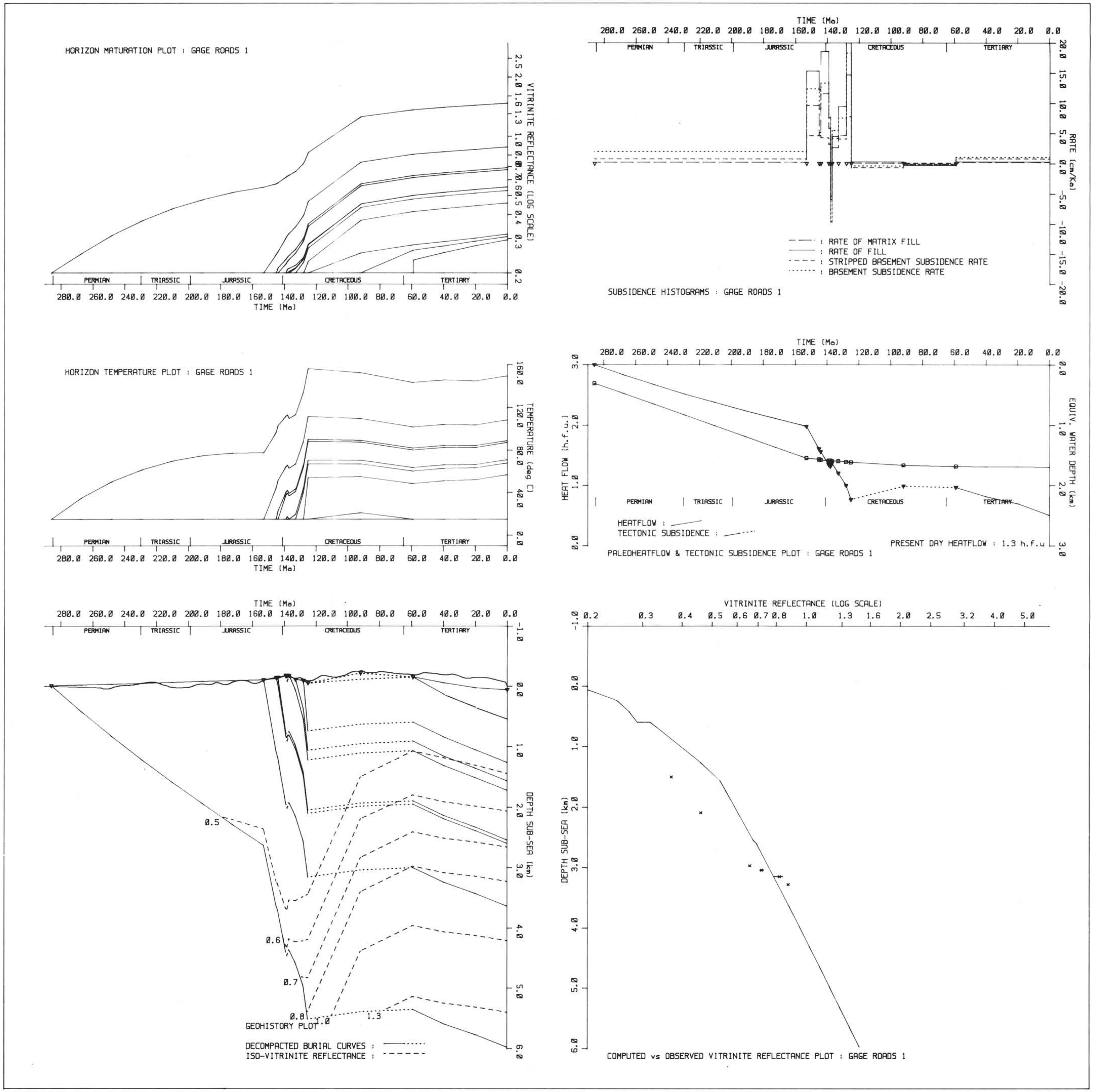

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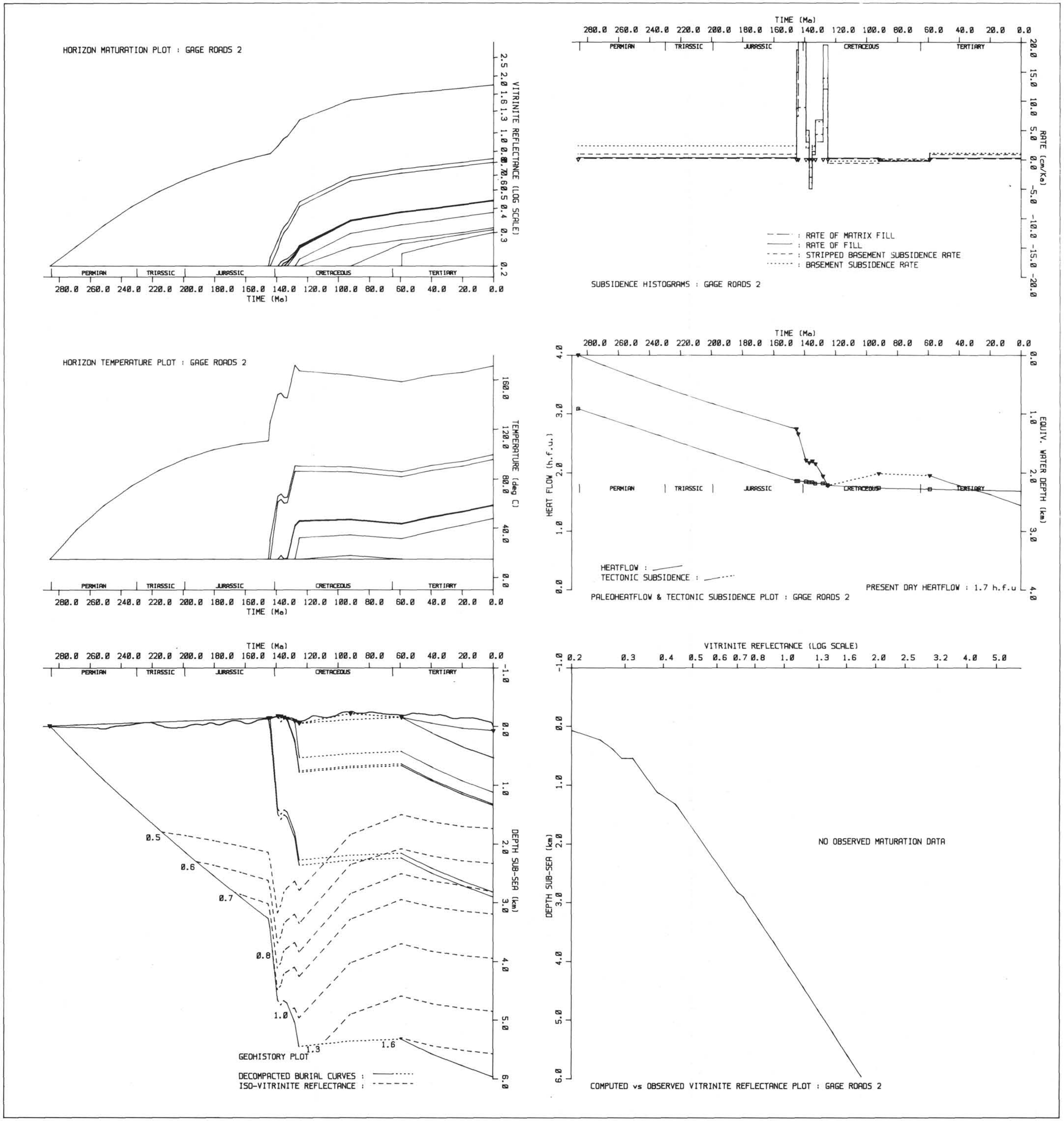

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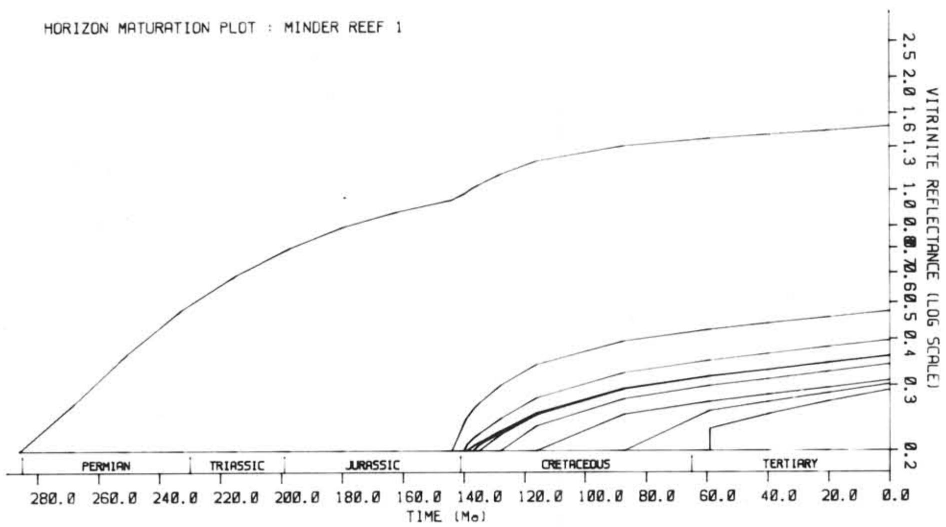

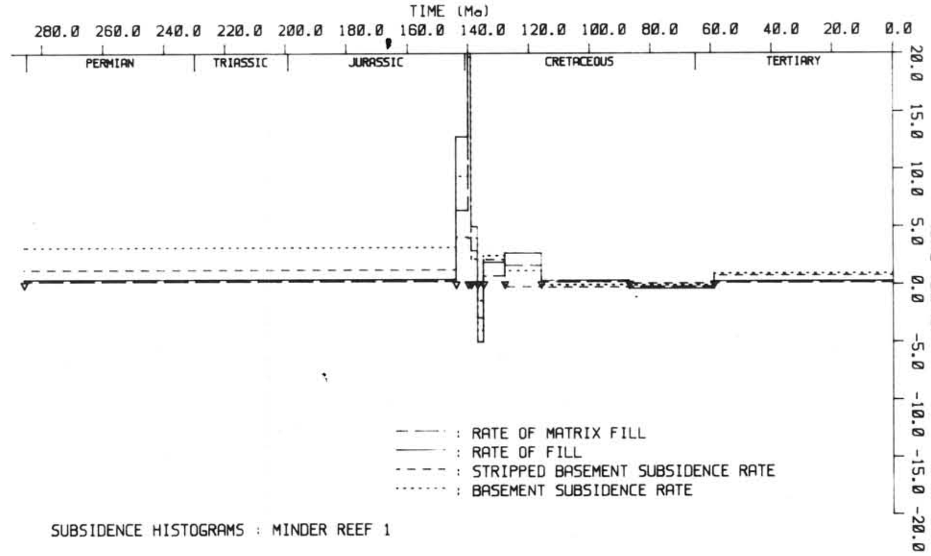

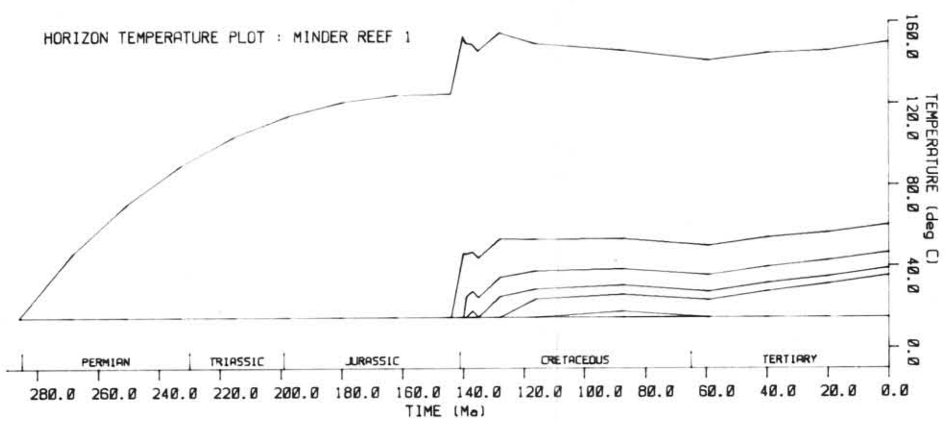

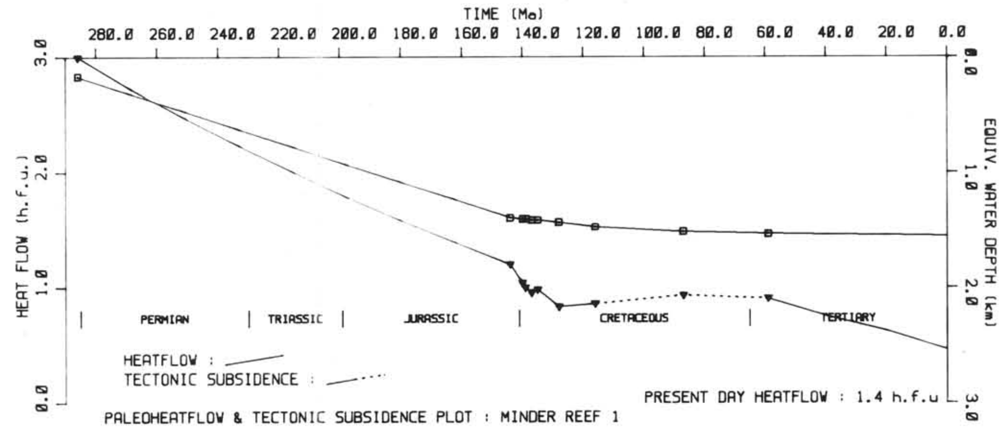

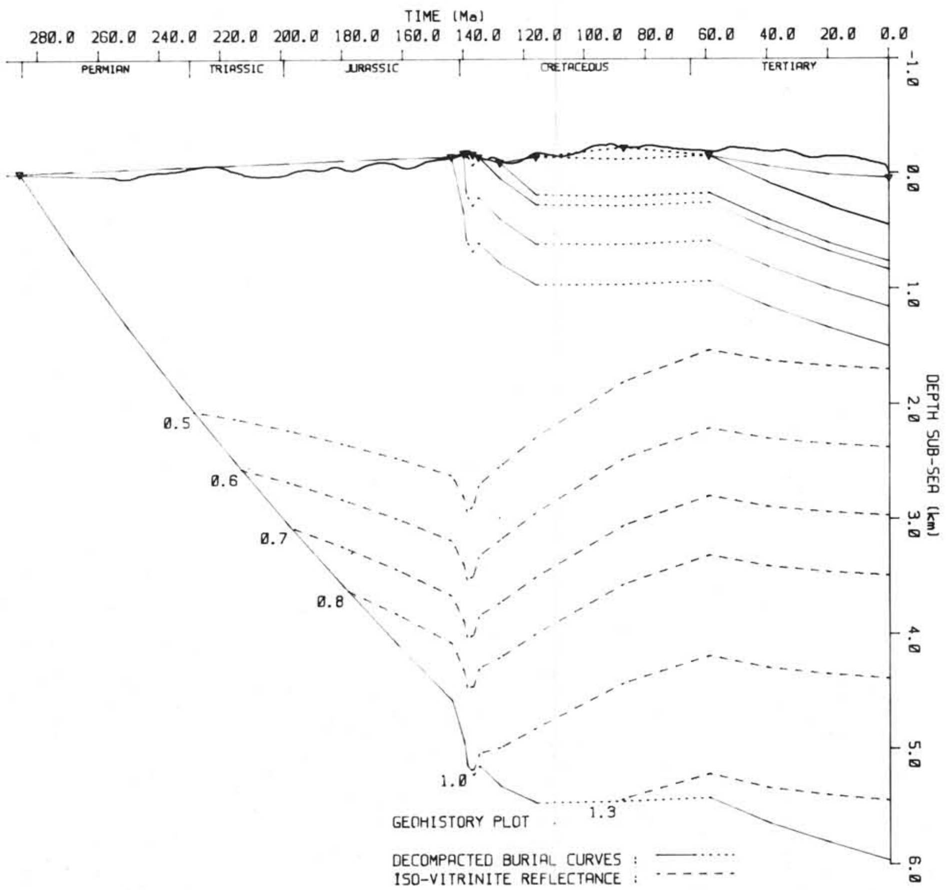

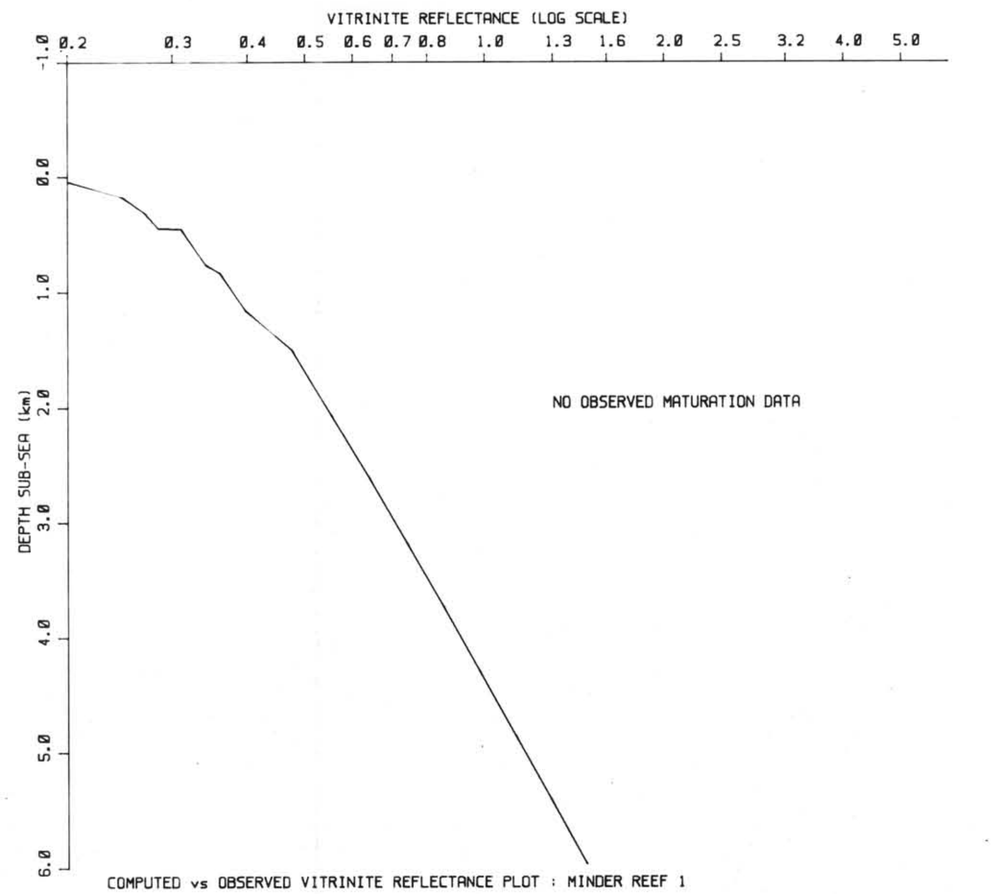

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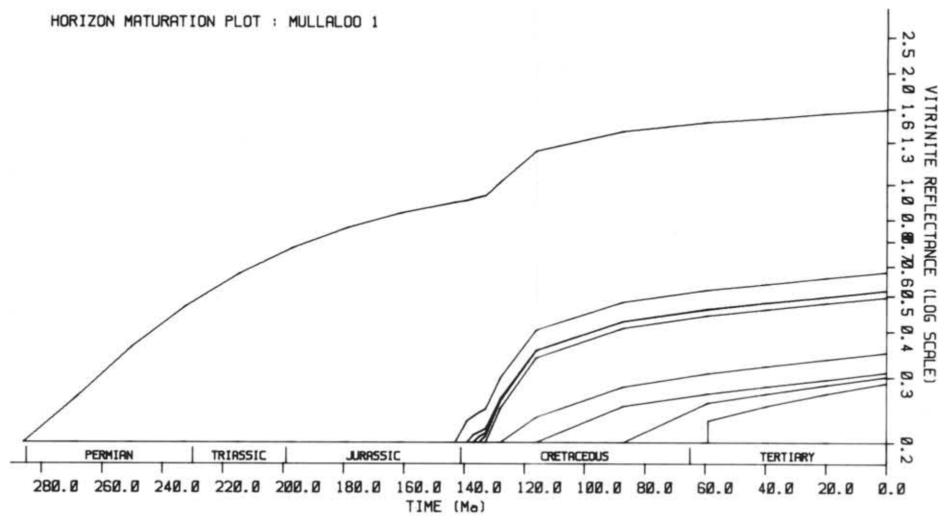

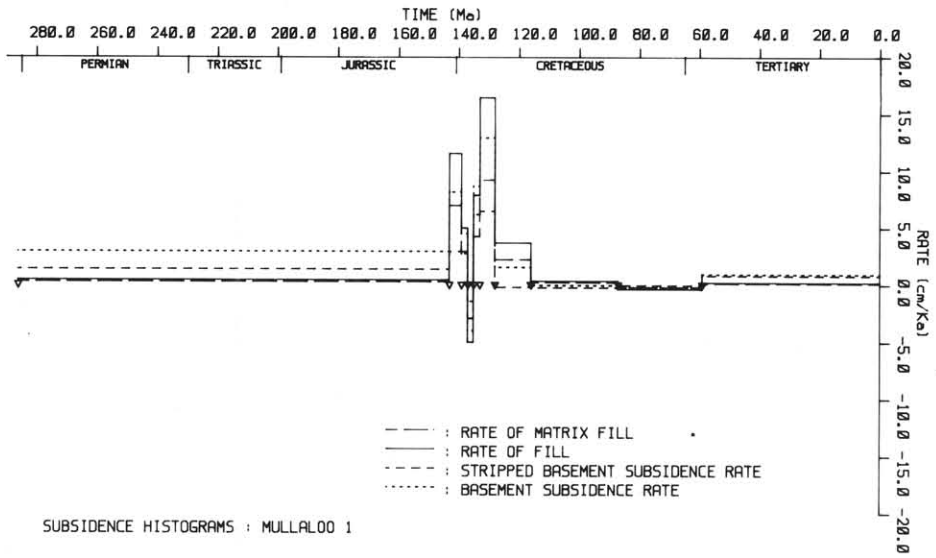

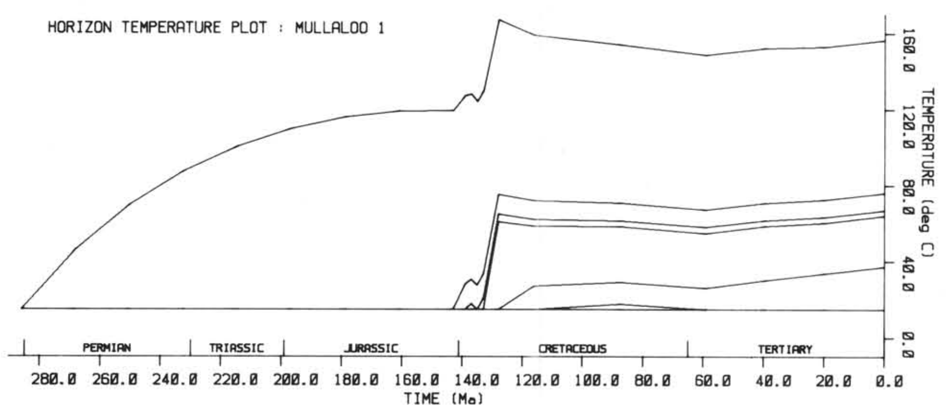

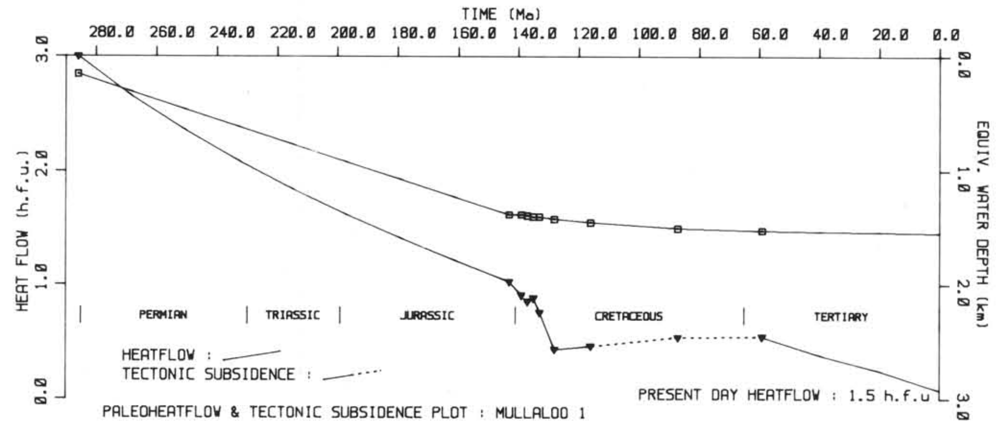

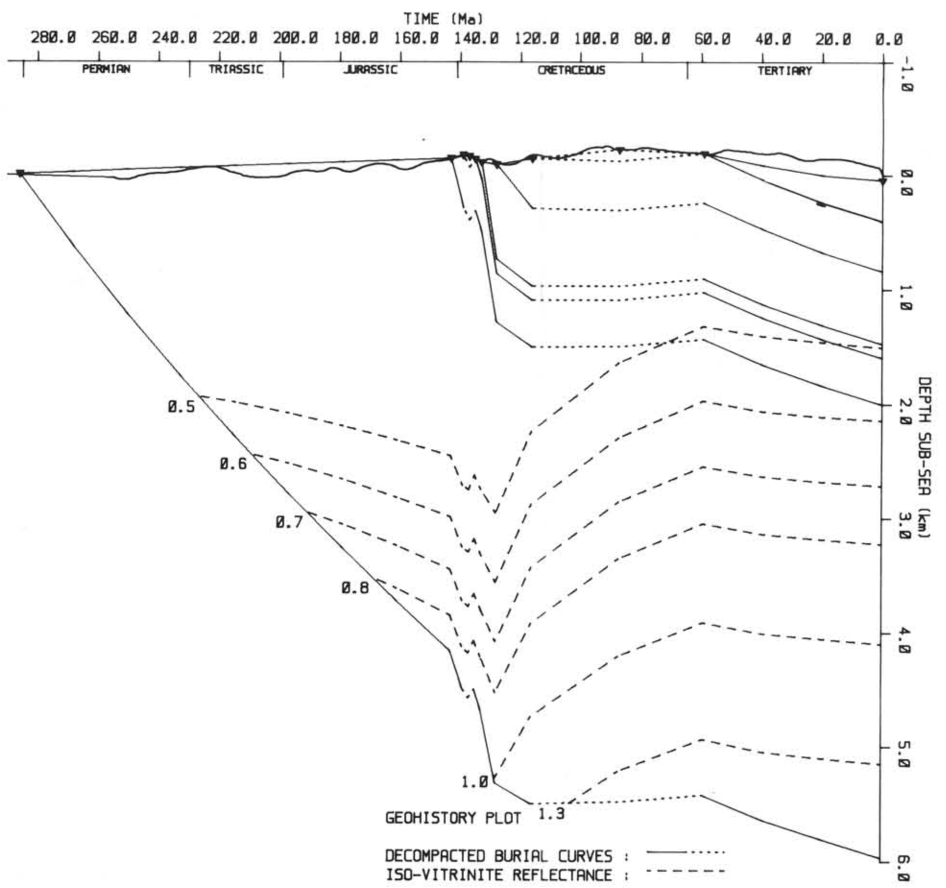

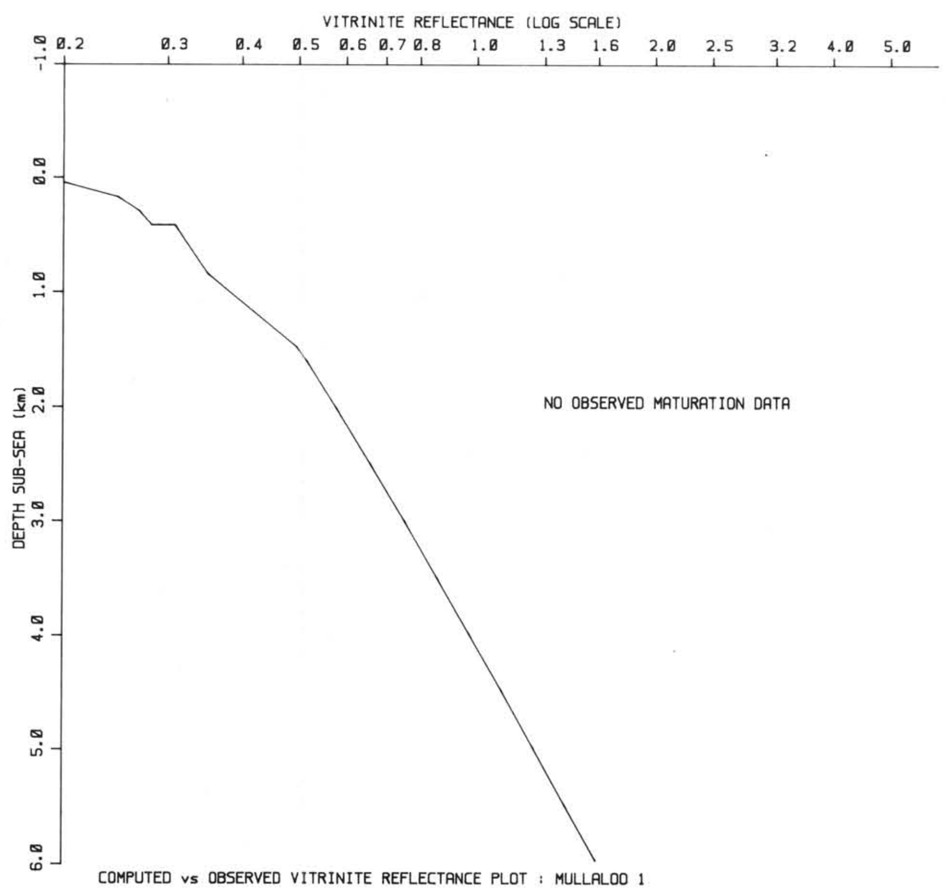

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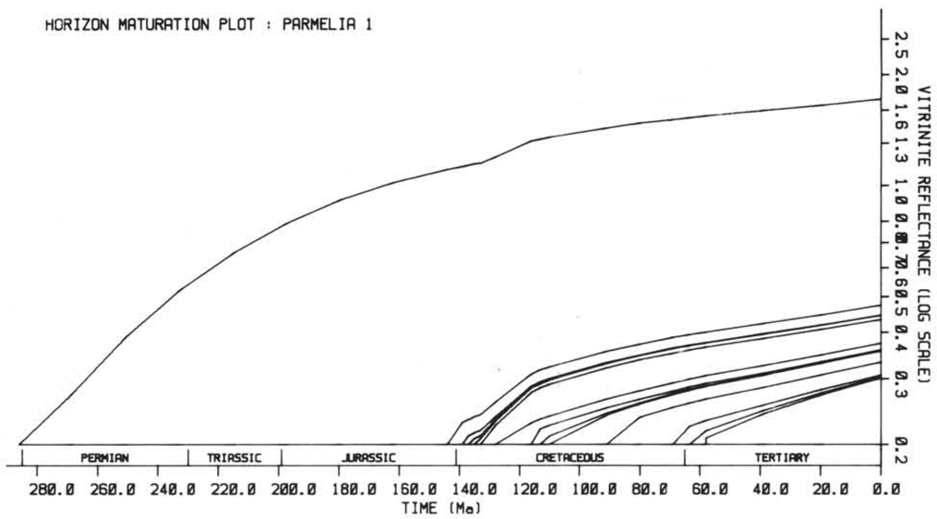

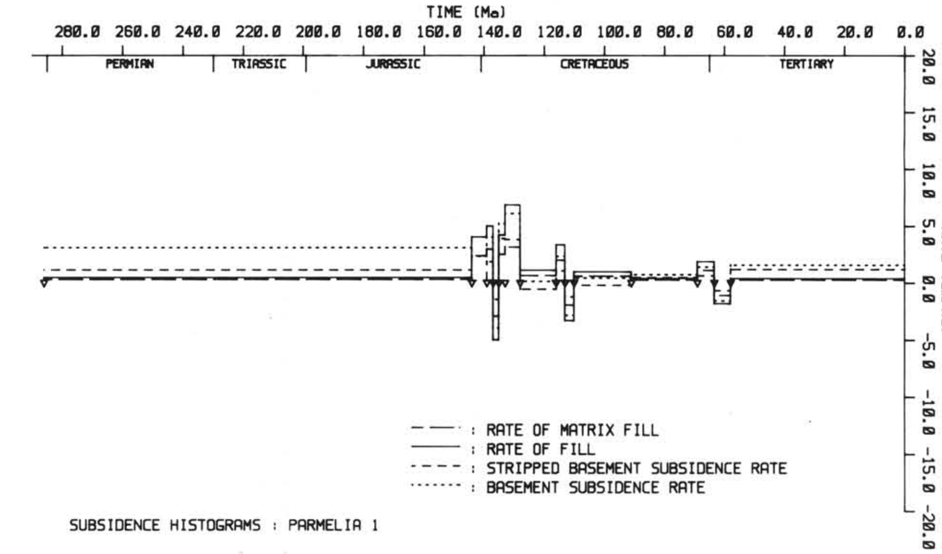

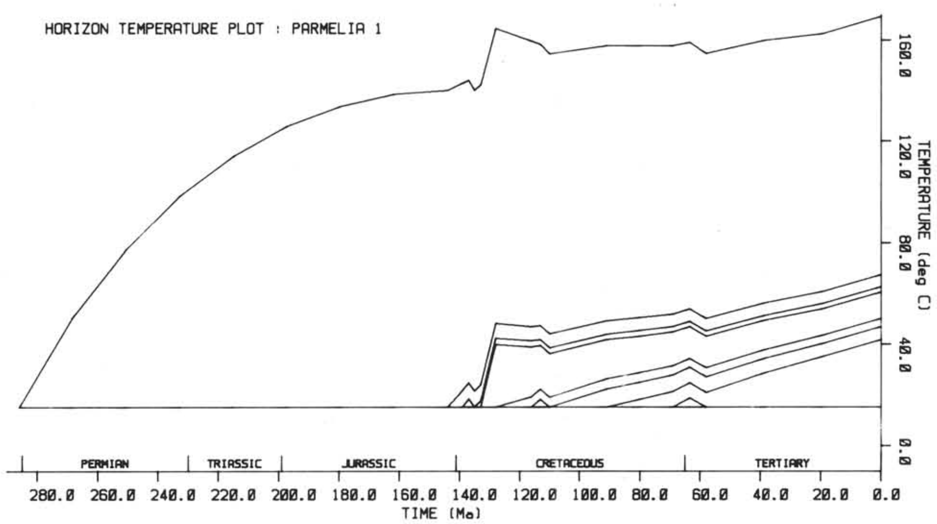

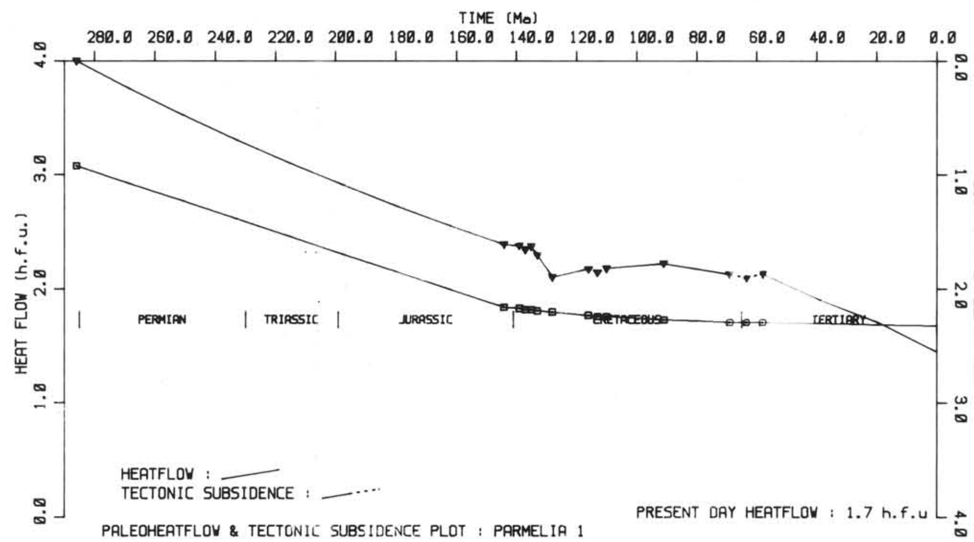

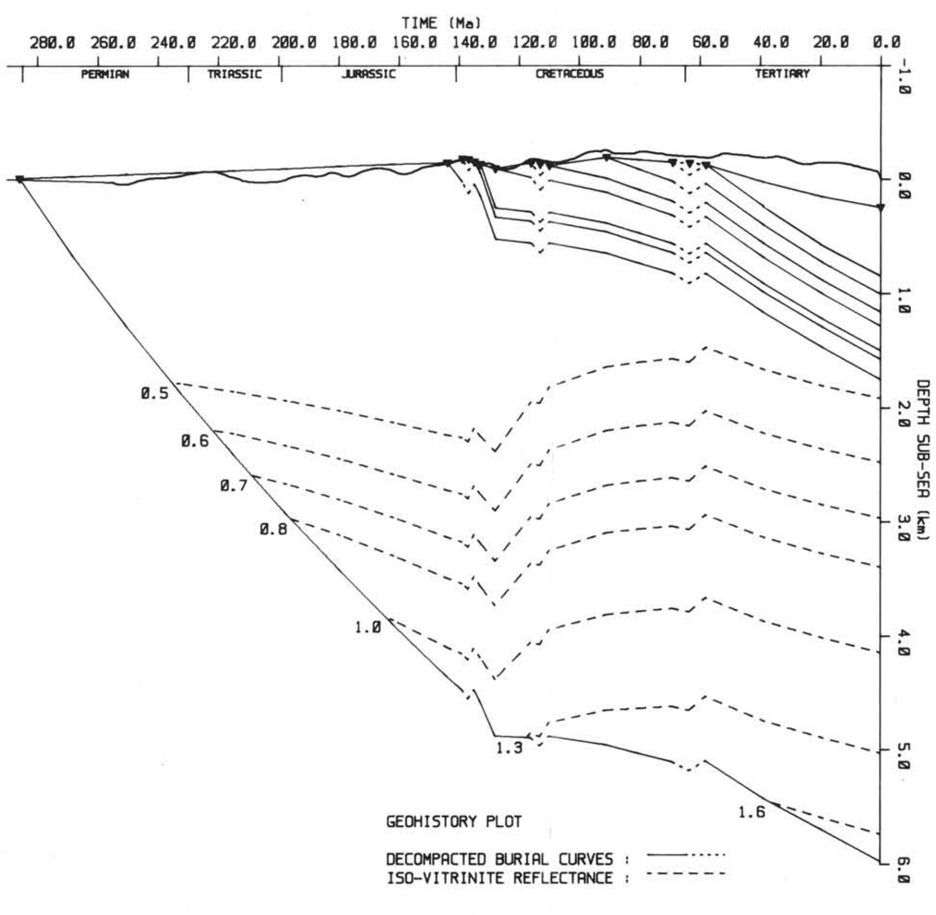

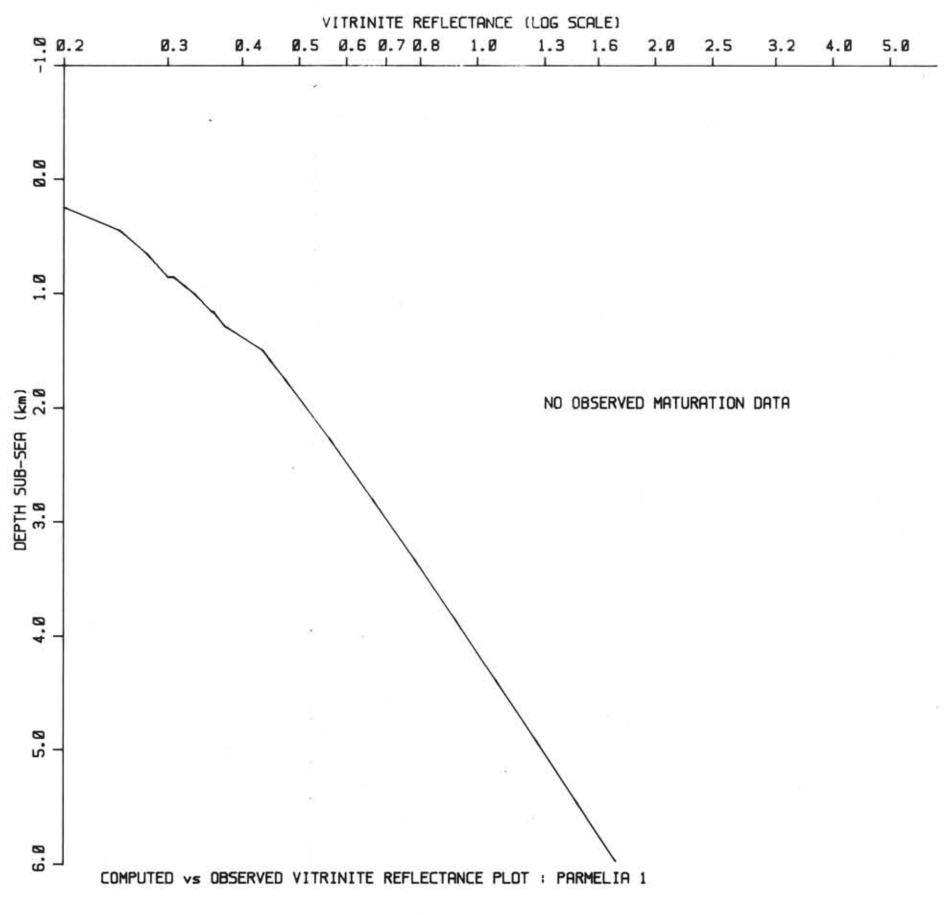

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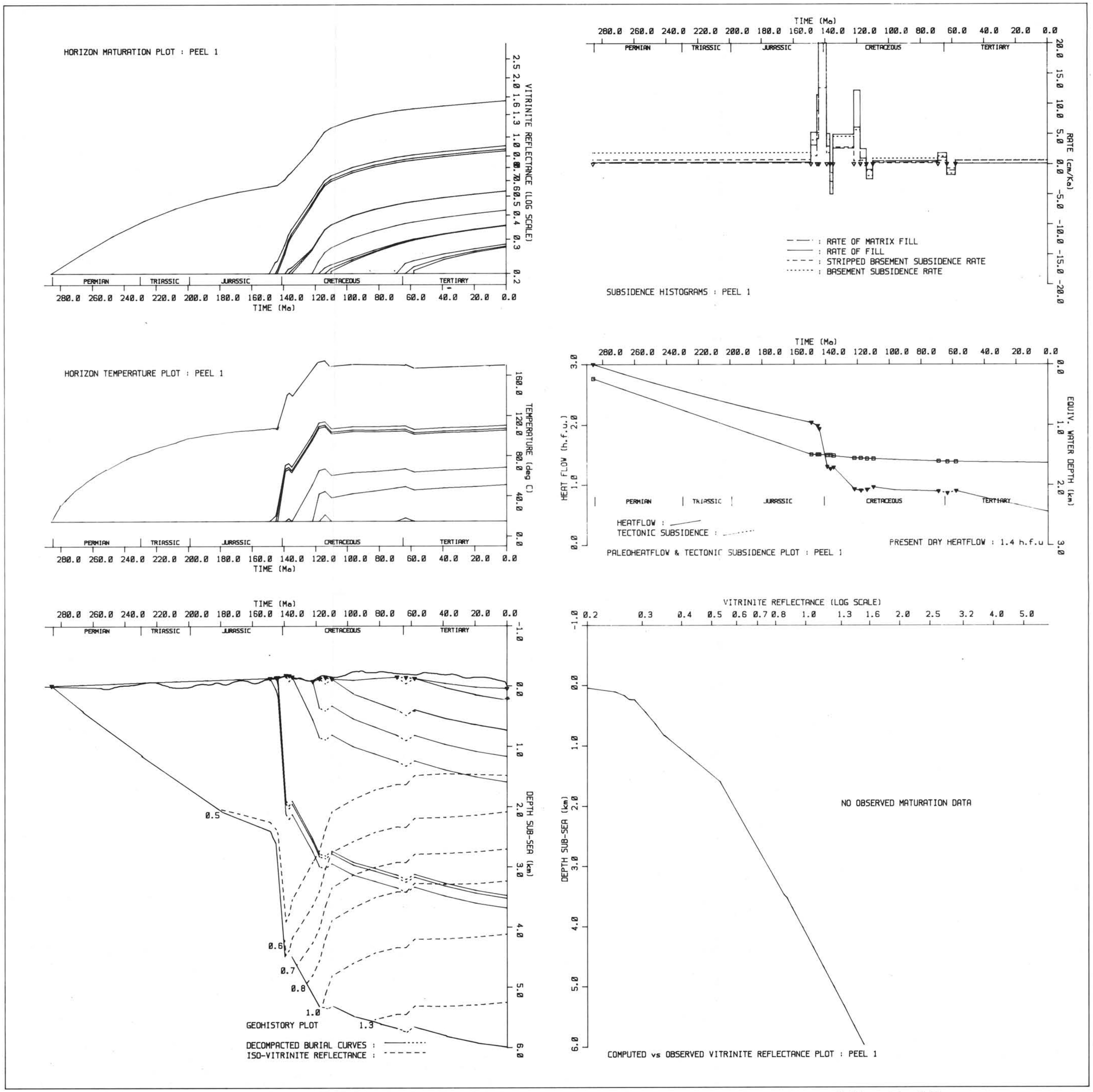

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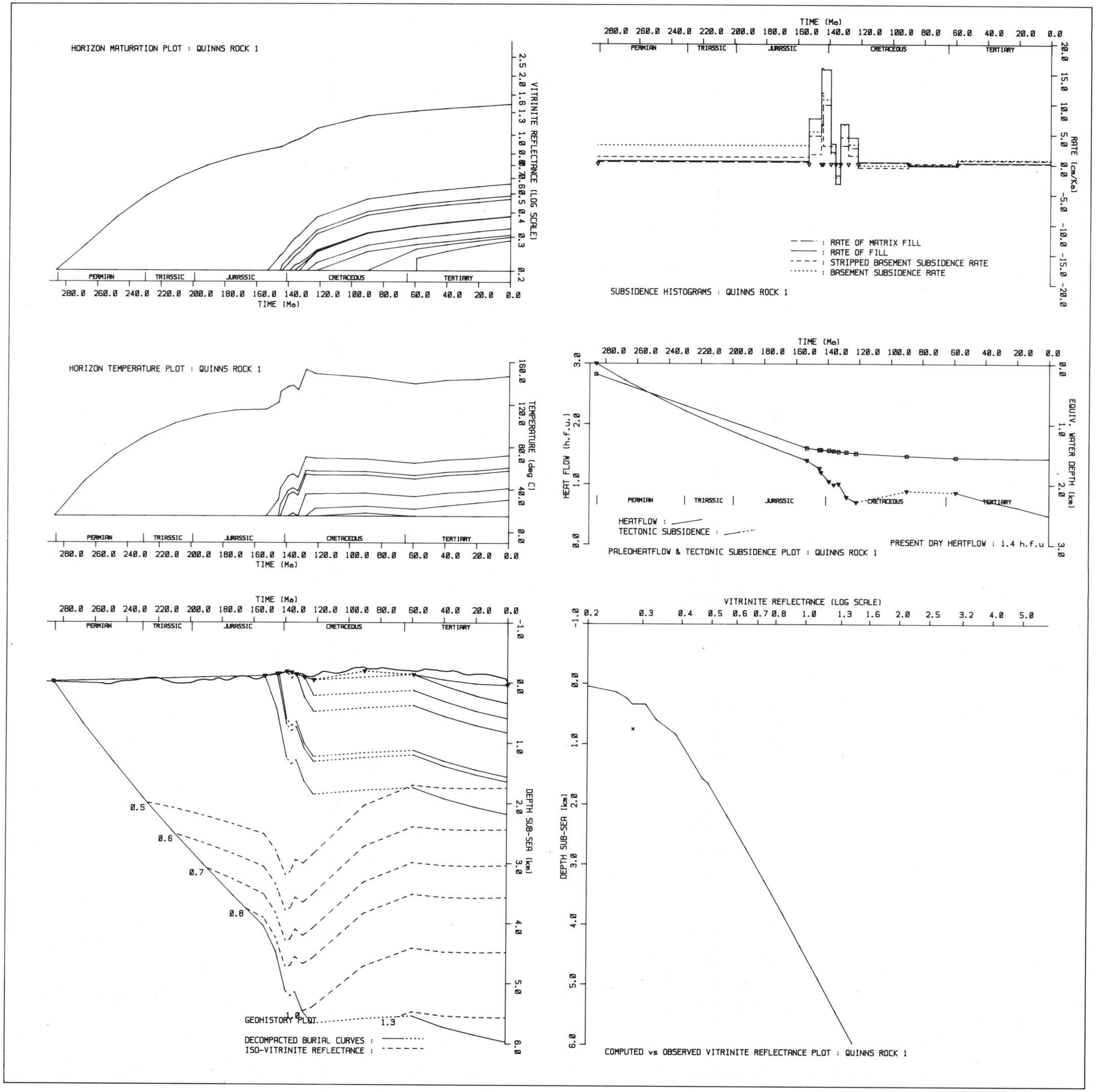

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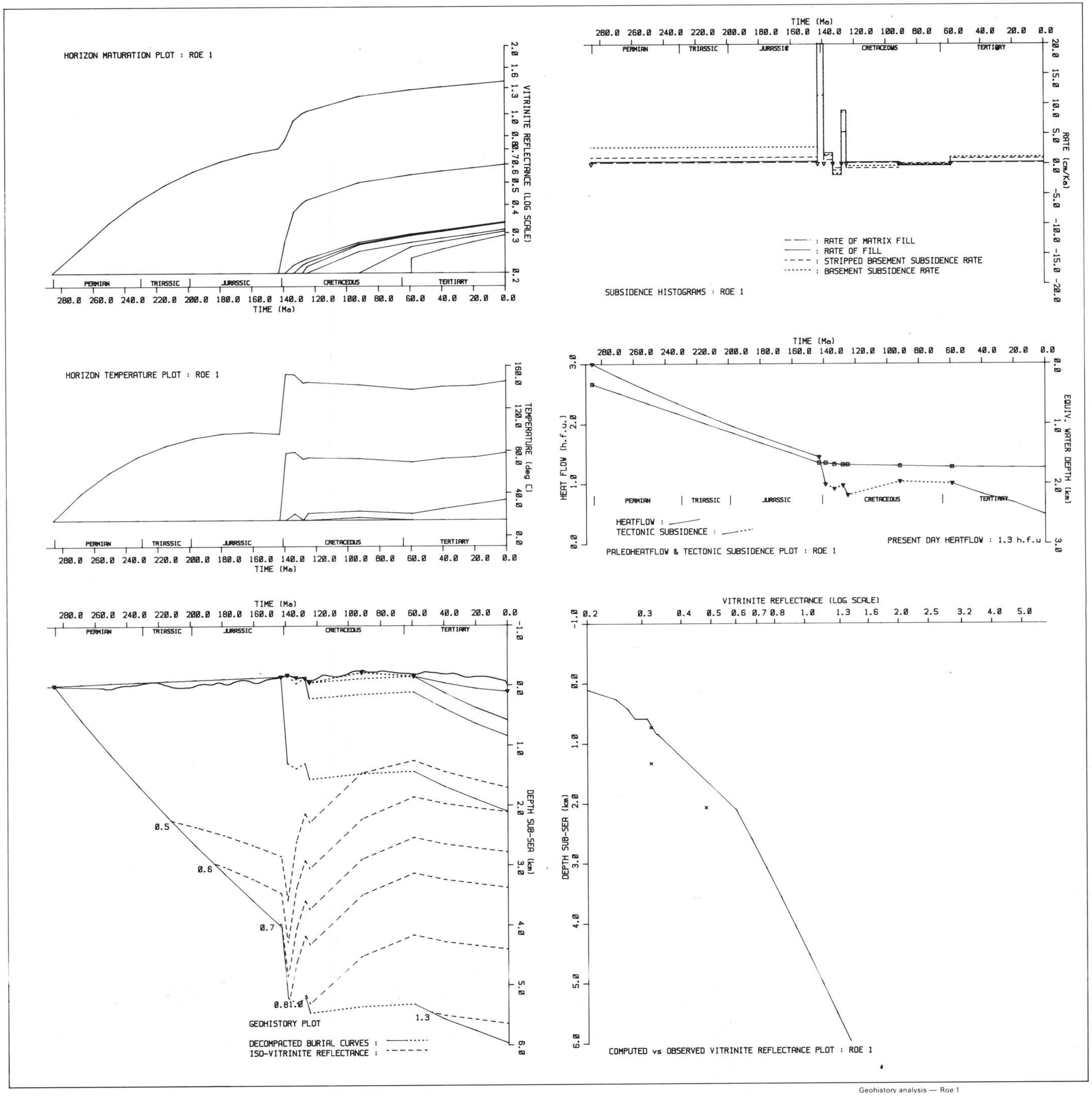

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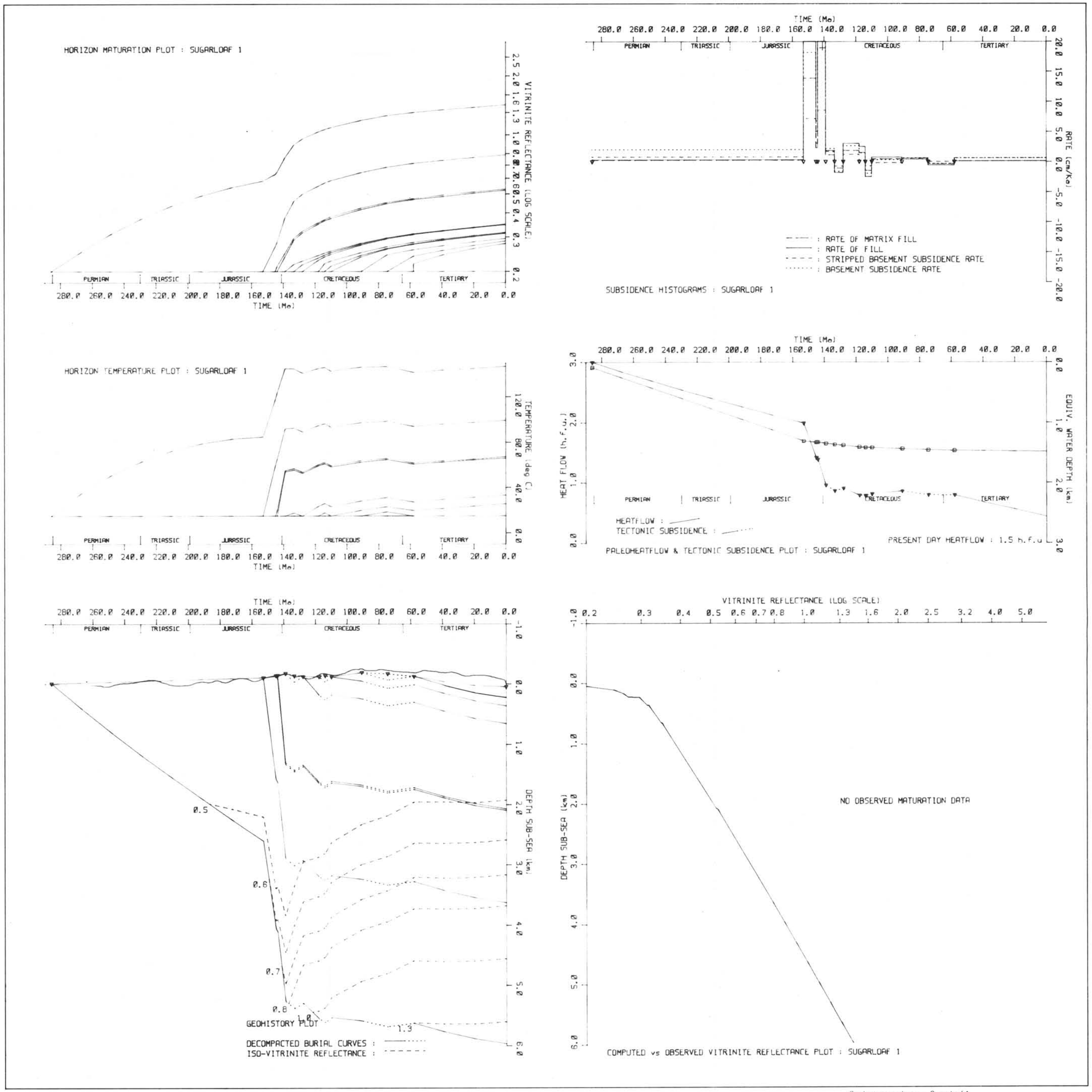

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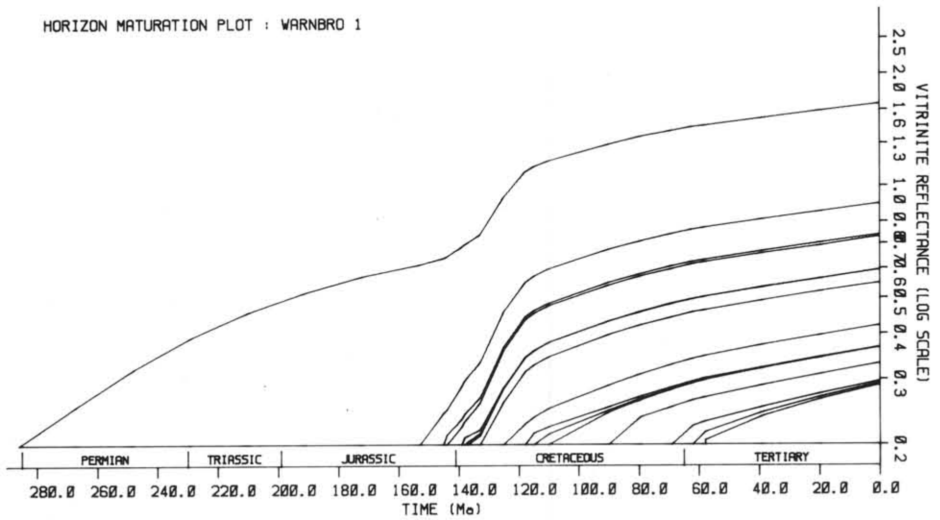

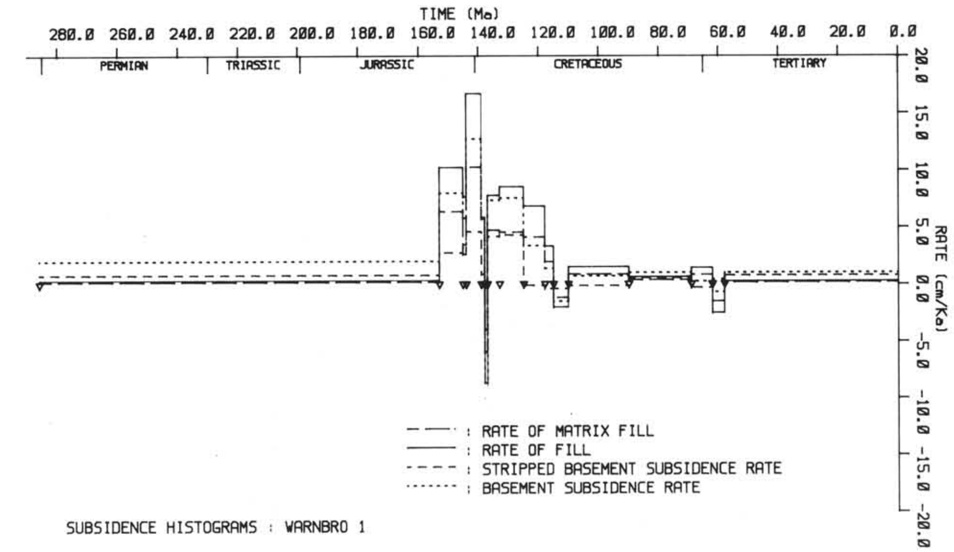

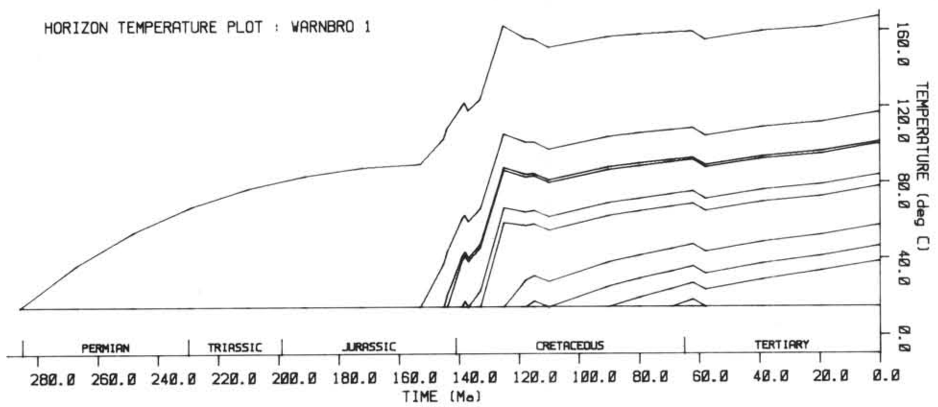

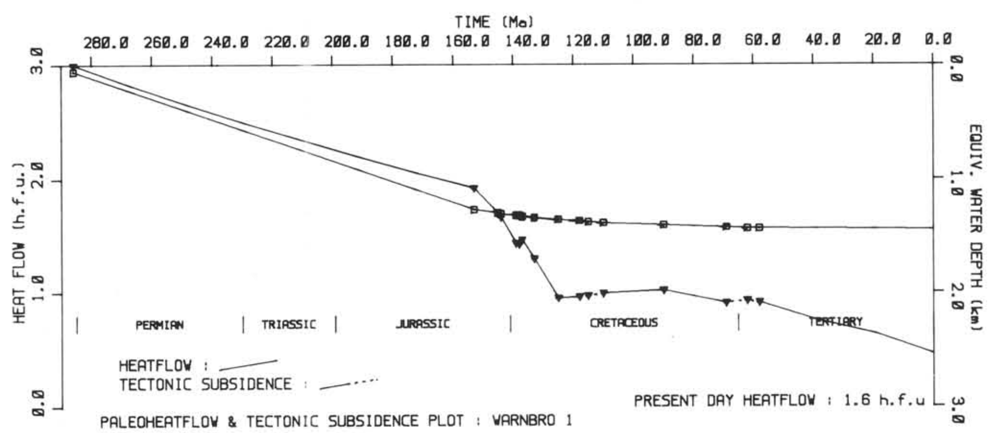

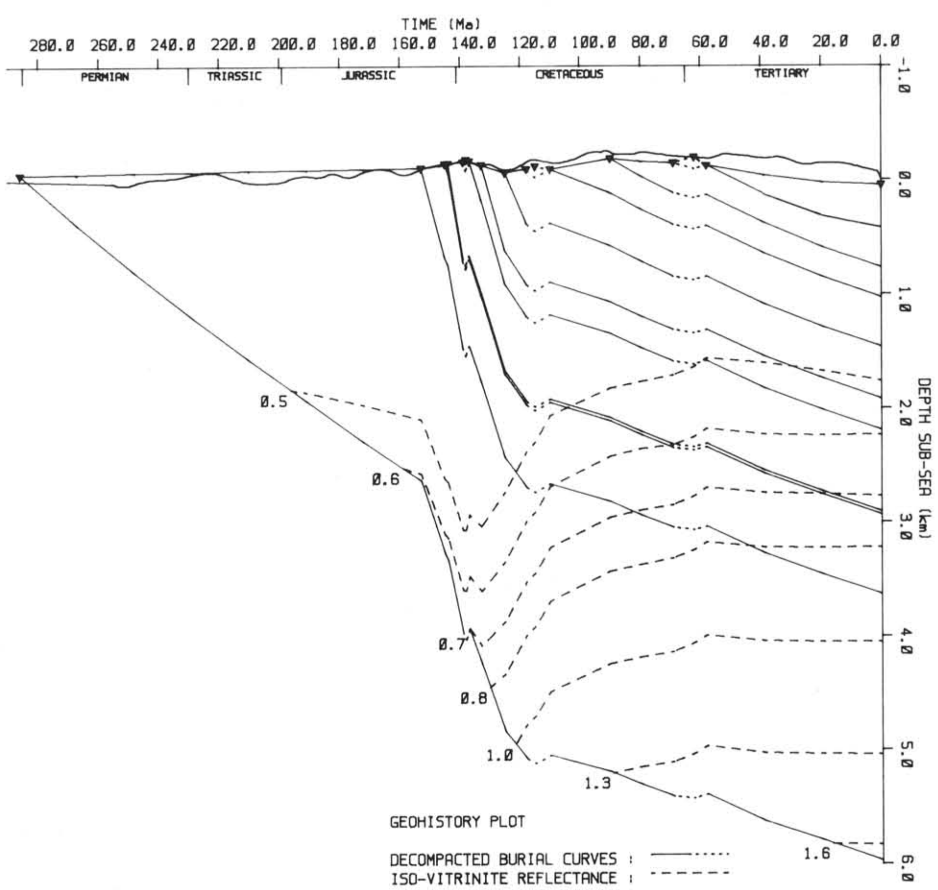

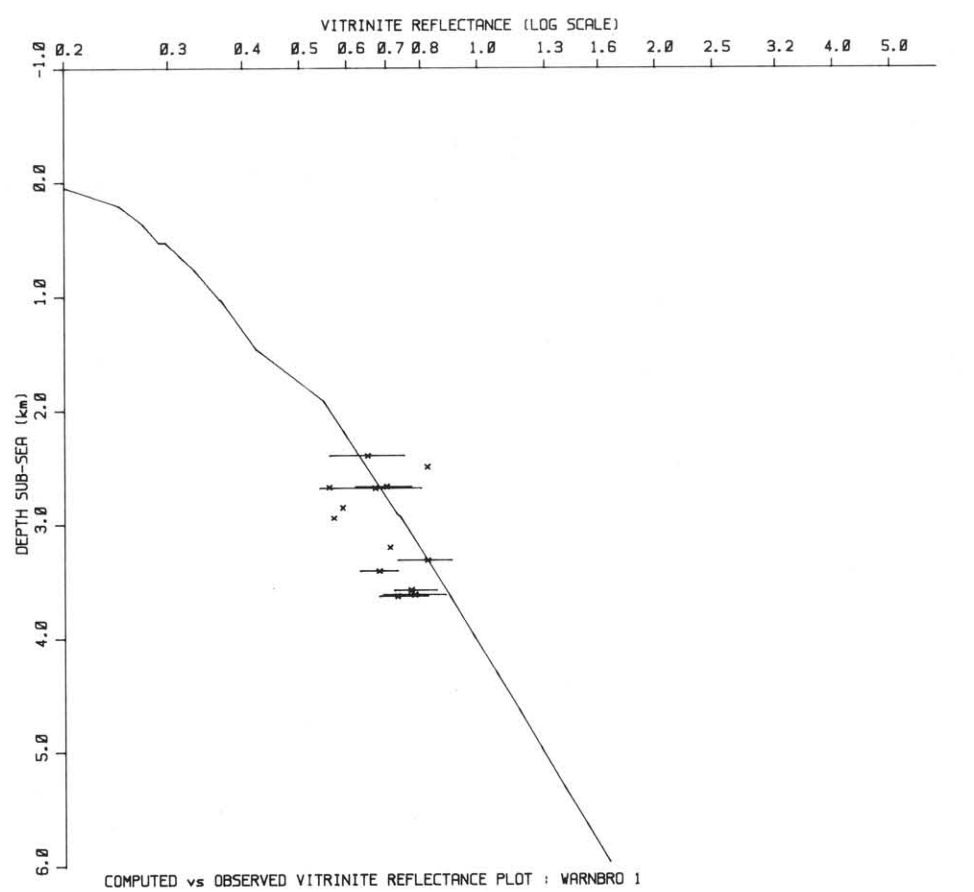

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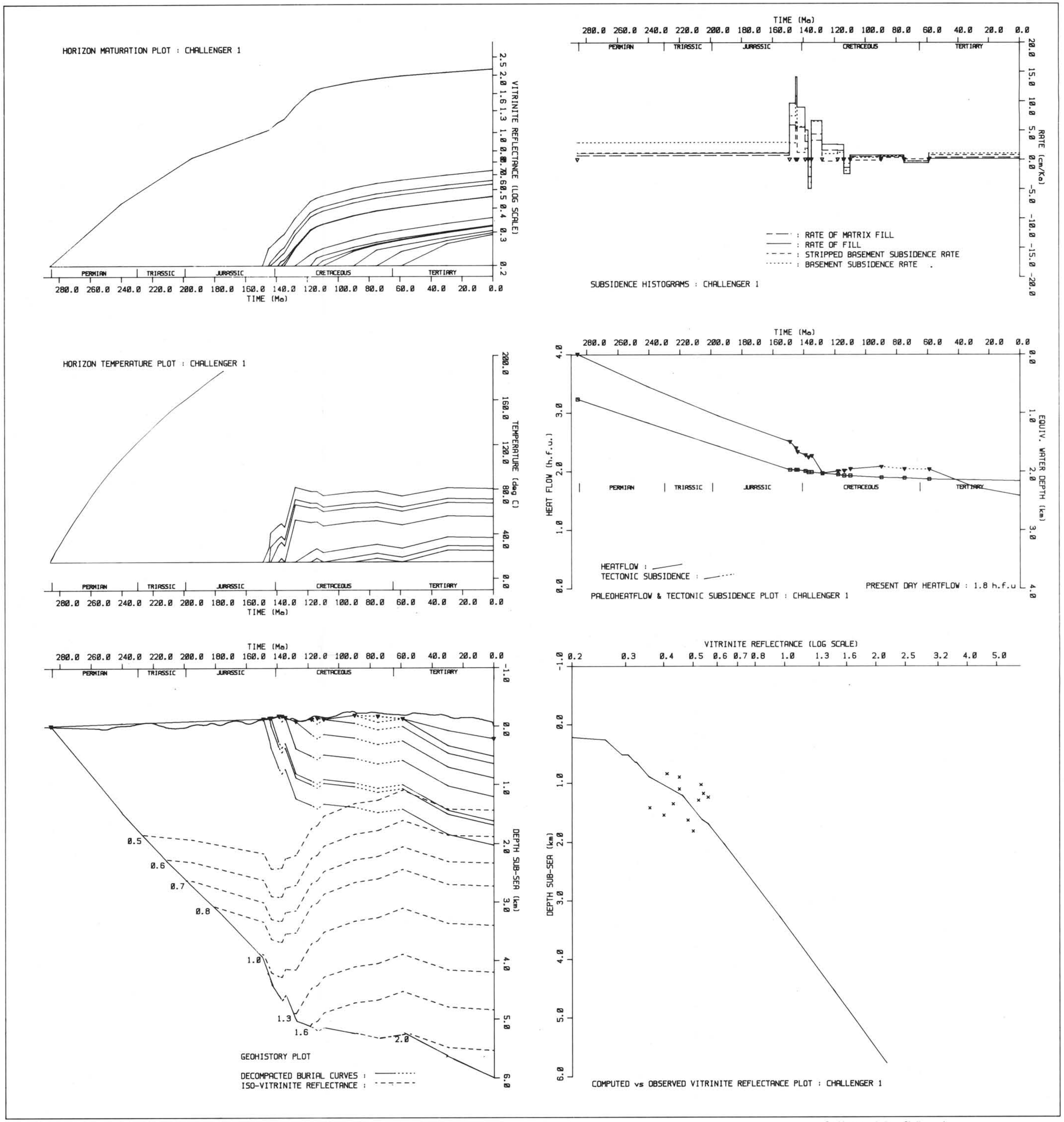

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