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GEOLOGICAL CROSS-SECTIONS OF THE EYRE, DENMAN AND CEDUNA BASINS

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SUMMARY

The Southern Margin region of Australia is a divergent, passive continental margin characterised by a series of offshore Mesozoic extensional basins. A total of nine wells have been drilled in five of the Southern Margin basins, with each well dry and abandoned. Petroleum exploration has been virtually dormant since 1986, with the area remaining underexplored.

The Eyre Sub-basin contains up to 6000 m of ?Jurassic to Cainozoic sediment. Basin development is strongest in the west, where rotated basement blocks form two ENE trending half-grabens. Basement faulting is interpreted to have commenced by the Middle to Late Jurassic. Possible petroleum source rocks are seismically inferred as ?Jurassic syn-rift sediments which lie in the deeper half-grabens. A fluvio-lacustrine depositional environment is proposed for these sediments. Jerboa-1 was drilled by Esso Australia Limited as a compaction drape over a faulted basement block, and identified two moderate to good quality sandstone reservoirs within a Lower Neocomian sequence. A zone of initial maturation was intersected near the base of the well. The age of basal sediments at Jerboa-1 have been reinterpreted here as Lower Neocomian (TS K1) (Morgan, 1990), rather than Middle to Late Jurassic (Huebner, 1980). Deposition during the Cretaceous consisted of two phases, with an intervening period of erosion and non-deposition which lasted approximately 15 Ma: a) an Early Cretaceous (TS K3-K1) non-marine sequence; and, b) an Early to Late Cretaceous (TS K8-K7) marine sequence. After an extended period of erosion and non-deposition in the Late Cretaceous (TS K11-K9), open marine sedimentation commenced in the northern region of the basin during the Paleocene (TS Cz1).

The Ceduna Sub-basin is the largest sub-basin of the Great Australian Bight Basin, and contains in excess of 10 km of Cretaceous (?Late Jurassic) to Tertiary sediment in the central basinal area. Seismic data in the area are of a moderate to good quality, although clear definition of basement features is limited the northern basin margin. Extensional faulting is interpreted to have commenced in the Middle to Late Jurassic. From magnetic and gravity data, three structural elements of the Ceduna Sub-basin are recognised (Stagg & others, 1990): the Northeast Ceduna Monocline, Central Ceduna Depositional Axis and the Outer Margin High. Potoroo-1 was drilled by Shell Development (Australia) Pty. Ltd. as a dip closure against a basement controlled fault and recorded no shows of hydrocarbons. Cretaceous sands at Potoroo-1 had moderate to good porosity and a moderate source capacity, although the entire sequence was thermally immature.

The Cretaceous was a period of high sediment influx in the subsiding Ceduna Sub-basin, and deposition proceeded in three phases: a) an Early Cretaceous (TS K3/K2) non-marine sequence; b) an Early to Late Cretaceous (TS K6/K7) marine sequence; and, c) an Late Cretaceous (TS K11-K8) paralic to non-marine sequence. Each phase of sedimentation is bounded by an unconformity of varying duration. Late Cretaceous (TS K11-K8) sedimentation was probably marine in the deeper central basin areas, particularly after the mid-

Valanginian breakup along the southern margin of Western Australia (Markl, 1974, 1978). Tertiary open marine sedimentation commenced in the Paleocene (TS Cz1). Faulting in the basin is largely synsedimentary, affecting the Early and Late Cretaceous sequences. Willcox & Stagg (1990) have interpreted "flower" structures along the southwest Outer Margin High which they attributed to wrenching and post-breakup subsidence. Although water depths in the Ceduna Sub-basin are economically restrictive in terms of exploration (200-2500 m), the possibilities of increased maturity and marine sediments in the central basin warrants further consideration of the area for hydrocarbon prospectivity.

The Palaeozoic Denman Basin forms a shallow depression within the larger Eucla Basin, and may be structurally related to other Permian intracratonic basins in the area (Arckaringa, Pedirka, Cooper and Renmark Basins). Structurally inherent basement topography was subsequently modified by Permian glacial erosion. The basin appears to be have been unaffected by the extensional processes which formed the larger Great Australian Bight basins to the south. Sedimentary sequences of Permian (glacial), Cretaceous (non-marine to marine) and Tertiary (open marine) sediments rarely exceed 1000 m in thickness. Apollo-1 intersected porous and permeable sandstone intervals of Permian and Lower Cretaceous age, although no shows of hydrocarbons were recorded. A thin sedimentary sequence in combination with a probable history of low heat flow does not offer encouraging prospects for hydrocarbon generation in the Denman Basin, however, the possible migration of hydrocarbons from outside the basin into subtle stratigraphic traps cannot be dismissed.

INTRODUCTION

REGIONAL SETTING

Progressive rifting between Australia and Antarctica began in the Jurassic and culminated in the Cenomanian with breakup of the continents and the onset of seafloor spreading (Veevers, 1986). This period of extension resulted in the formation of a series of basins along the southern Australian continental margin. Three basins have been selected to highlight the structure, stratigraphy and hydrocarbon prospectivity of the area. The Eyre and Ceduna, both sub-basins within the Great Australian Bight Basin, were formed by Mesozoic rifting and hence have similar structural and depositional histories. The Denman Basin is a Palaeozoic pre-rift basin, and although older than the Eyre and Ceduna Sub-basins, it is included in this report because of its geographic proximity and post-Jurassic basin fill history. Results of the study are discussed in the order of presentation on the Southern Margin Basins Cross-Section (Plate 1), the Eyre Sub-basin, Denman Basin and Ceduna Sub-basin. Results of Time Slice stratigraphic correlations emphasise the regional aspects of basin formation.

DATABASE

Seismic

Basin/Sub-basin	*Marine Seismic Survey*	*Operator/Year*
Eyre	E79A Marine Seismic Survey	Esso, 1979
Denman	Denman Basin Survey	Outback Oil, 1972
Ceduna	R4 South Australian Shelf	Shell Dev, 1969 (1975)
Ceduna	1970 S. Australian Offshore	Shell Dev, 1970
Ceduna	1970 S. Australian Deepwater	Shell Dev, 1970
Great Australian Bight	Rig Seismic Survey 65	BMR, 1986

Wells

Basin/Sub-basin	*Well Name*	*Operator/Year*
Eyre	Jerboa-1	Esso, 1980
Denman	Apollo-1	Outback Oil, 1975
Denman (Eucla)	Mallabie-1	Outback Oil, 1969
Ceduna	Potoroo-1	Shell, 1975

Biostratigraphy

Jerboa-1	Morgan, 1990; pers comm, Nov 1990
Apollo-1 and Potoroo-1	Morgan, 1990
Mallabie-1	Scott and Speer, 1969

SCALE

Cross-sections of the Eyre Sub-basin and Denman Basin were constructed at a 1:50,000 scale. The Ceduna Sub-basin cross-section was constructed at a 1:100,000 scale. Each cross-section has a 1:1 vertical to horizontal exaggeration. Line lengths of the cross-sections are: Eyre-53 km; Ceduna-222 km; and Denman-85 km. There are no direct seismic ties between basins. Interpreted and uninterpreted seismic sections are supplied for the Eyre Sub-basin and the Denman Basin in their entirety. Only portions of the Ceduna Sub-basin seismic sections are supplied, with the appropriate shot point locations noted on the constructed cross-section.

HORIZONS DRAWN

A total of 23 seismic horizons were identified in the Eyre and Ceduna Sub-basins and the Denman Basin. Utilising the time slice (TS) approach, horizon ages were determined from Time/Depth Plots of the Jerboa-1 (Eyre), Potoroo-1 (Ceduna) and Apollo-1 (Denman) wells, and by stratigraphic correlation with dated horizons.

Eyre Sub-basin

A total of six horizons were identified at Jerboa-1 and carried along the cross-section.

Time Slice	*Age*
Base Cainozoic	Cainozoic/Base Tertiary
Intra-K8	Cretaceous/Approximate mid-Cenomanian
Top K7	Cretaceous/Upper Albian
Top K3/K2	Cretaceous/Top Barremian
Top K1	Cretaceous/Approximate Top Berriasian
Basement	Precambrian/Top Basement

Two additional horizons not present at Jerboa-1 were correlated across the cross-section: (1) Top TS Cz1, Cainozoic/Paleocene to Lower Eocene, a prograding unit present only in the northern Eyre Sub-basin; and, (2) Top Pre-TS K1, Pre-Cretaceous (?Jurassic).

Denman Basin

Four seismic horizons were identified at Apollo-1 and drawn across the cross-section. Note that due to seismic processing, the exact position of seabed does not appear on seismic lines (Plates 5 & 6).

Time Slice	*Age*
Base Cz2	Cainozoic/Base Middle Eocene
Top K3-K1	Cretaceous/Top Barremian
Top P3/P2	Permian/Lower Artinskian
Basement	Precambrian/Top Basement

Ceduna Sub-basin

Of the eight horizons identified at Potoroo-1, only two reliably coincide with time slice boundaries (excluding basement). The remaining five horizons are picked as marker beds, and either approximate time slice boundaries or fall within previously defined time slice intervals.

Time Slice	*Age*
Approx Top of Cz2	Cainozoic/Top Eocene
Base of Cz1	Cainozoic/Base Tertiary
Approx Top of K9	Cretaceous/Approximate Top Santonian
Approx Base of K9	Cretaceous/Base Turonian
Intra K8B	Cretaceous/Cenomanian
Intra K8A	Cretaceous/Cenomanian
Top K7	Cretaceous/Upper Albian
Basement	Precambrian/Top Basement

Three additional horizons not present at Potoroo-1 were correlated across the cross-section: (1) Approximate Top TS K10, Cretaceous/Maastrichtian; (2) Intra-TS K8, Cretaceous/Lower Cenomanian; and, (3) Approximate Top TS K1, Cretaceous/Lower Valanginian.

RESULTS

EYRE SUB-BASIN

BASINAL STRUCTURE

The Eyre Sub-basin has been described as a "perched" extensional basin (Stagg & others, 1990), in that it lies beneath the upper continental slope. Underlying the bathymetric Eyre Terrace between water depths of 200-1200 m, the Eyre Sub-basin is approximately 8000 km^2 in area. A single exploration well, Jerboa-1, was drilled and abandoned (dry) in 1980 by Esso Australia Limited. The largest basinal area occurs in the west, where rotated basement fault blocks form two major, ENE trending half-grabens. Each rotated block is bounded by steep, southerly dipping normal faults with throws in excess of 1500 metres. The smaller, northern half-graben contains approximately 3000m of sediments, while the larger, southern half-graben contains up to 6000 m of sediment. The two half-grabens are separated by a large, rotated basement block designated the "Wombat feature" by Bein and Taylor (1981).

Basin forming basement faults trend predominantly ENE in the western part of the basin. The faulted blocks are in turn abruptly offset along SE trending transfer faults (Stagg & others, 1990). The northern margin of the basin is defined by a major crustal detachment fault (Etheridge & others, 1989), while the southern boundary is formed by a massive ENE trending basement high. The eastern boundary of the basin is ambiguous as it appears to be contiguous with the Recherche and Ceduna Sub-basins (Stagg & others, 1990). The western termination of the basin is postulated by Stagg & others (1990) to be a series of NW-SE orientated transfer faults. A major fault scarp is located oceanward of the southern bounding basement block which separates the Eyre and Recherche Sub-basins. This escarpment has been interpreted by Etheridge & others (1989) to be a major sub-branch of the main detachment fault and the demarcation between moderately extended lower crust of the Eyre Sub-basin (20%) and highly extended lower crust of the Recherche Sub-basin (200%).

DATING OF HORIZONS

Proterozoic

Jerboa-1 penetrated 28.5 m of Precambrian granitic basement rock and metasediments (Bein and Taylor, 1981), which yielded fission track dates of 793±35 to 864±37 Ma yr from zircon and sphene, respectively (Huebner, 1980). In addition, BMR Survey 66 (Dredge DR02) recovered granodiorite of presumed Precambrian age from a lower basement scarp south of the Eyre Terrace (Davies, & others, 1989). Similar rocks are excepted to underlie the Eyre Sub-basin. On seismic data, basement forms a prominent reflector which can be traced with confidence throughout the basin (Plates 3 & 4).

Pre-Cretaceous (Top Pre-TS K1)

A wedge of syn-rift and early post-rift sediment fills the half-grabens north of Jerboa-1. A prominent reflector near the top of this sequence appears to onlap the basement block north of the Jerboa-1 well site (Plate 4). The oldest rocks overlying basement at Jerboa-1 are redated here as Lower Neocomian (TS K1) age (see Top TS K1). Accordingly, the onlapping wedge of syn-rift sediments are interpreted as earliest Lower Neocomian (TS K1) to Late Jurassic in age. This sequence is restricted to the deeper areas within the half-grabens and is thickest in the central western part of the basin. To the east and west, the Pre-TS K1 sequence thins slightly and becomes more spatially restricted where the basin is narrow.

Cretaceous (Top TS K1)

Basal sediments at Jerboa-1 are Berriasian to Lowest Valanginian (TS K1) in age. The original Callovian-Kimmeridgian age assigned by Powis and Partridge (1980) was modified by Morgan (1990; pers. comm. Nov, 1990) to emphasise the distribution of *C. stylosus* and *D. specious*, both Early Cretaceous spore-pollen zonations, which overlap the original Jurassic *M. florida* zonation at Jerboa-1. This interpretation is supported by the poor preservation state of the Jurassic spore and pollen recovered from sidewall cores (Huebner, 1980), which suggests the older assemblage may be incorporated as reworked components. The Callovian-Kimmeridgian age may more accurately reflect the age of the underlying syn-rift sequence. Further work on the Jerboa-1 sequence by Wagstaff (in prep) may possibly clarify the age relationship of the basal sediments, although conclusions of this work are presently held confidential (Wagstaff, Univ. Melb., pers. comm. Nov, 1990). The basal sediments are sandstones with interbedded siltstones and shales deposited in fluvial and lacustrine environments. Progradational sequences in the upper part of this interval suggest outbuilding into a deep lacustrine environment (Bein & Taylor, 1981). Regionally, the sequence forms a blanket which thickens moderately in the grabens and thins and/or onlaps faulted basement blocks.

Cretaceous (Top TS K3/K2)

Conformably overlying the basal sandstone sequence is a thick, homogeneous section of Lower Valanginian to Barremian dark shale. The absence of marine indicators suggests this sequence was deposited in a lacustrine, fresh to brackish environment. The original Aptian *C. hughesi* zonation assigned by Powis and Partridge (1980) has been revised by Morgan (1990) to the Neocomian to Barremian zonation of *F. wonthaggiensis*. This sequence forms a thick wedge over the deeper basinal areas, and thins or is absent over intra-basin highs (ie, "Wombat feature", Plate 1).

Cretaceous (Top TS K7)

The onset of marine sedimentation occurs in the middle Albian with the deposition of a thin (35m) prograding sequence of dark shales. This sequence is bounded above and below by unconformities lasting approximately 15 Ma and 3 Ma, respectively.

Base Cainozoic (Cretaceous/Top TS K8)

Marine sedimentation recommenced in the Cenomanian with the deposition of dark shales and claystones with basal sands. Thickness of the sequence varies widely, generally thickening to the south and east. At the extreme eastern end of the basin, erosion in the Eocene cut deep channels into the upper Cenomanian sequence. Faulting of the sedimentary sequence (?Jurassic to Cenomanian) usually occurs over and adjacent to raised basement blocks as a result of differential compaction or subsidence. This horizon marks a basinwide unconformity of varying duration (~25 Ma in the north to ~40 Ma in the south parts of the sub-basin), and is also evident in the Denman Basin. On seismic data, the horizon truncates the underlying Cenomanian sequence and dips gently to the south. A strong reflector (Intra-TS K8) occurring within the interval Top TS K7 to Base Cainozoic can be correlated across the central western basin and tied to a lithologic change at Jerboa-1. This interval was the informal unit JA of Bein & Taylor (1981), and contained numerous coarsening upward sandstone and siltstone sequences. The interpreted age of this horizon closely corresponds to the estimated time of breakup of the southern margin (95 Ma ± 5 Ma, Veevers, 1986).

Cainozoic (Top TS Cz1)

This sequence is a thin prograding marine unit which downlaps onto the Late Cretaceous to early Cainozoic unconformity (Base Cainozoic) in the northern Eyre Sub-basin (Plate 1). This sequence is inferred to be Paleocene to Early Eocene in age, but is absent at Jerboa-1. Cainozoic sedimentation commenced at Jerboa-1 with the deposition of a thin, regional sequence of Middle Eocene sandstones (TS Cz2). Conformably overlying the sandstone is a thick section of open marine carbonates (calcilutites and marls), with the abrupt lithologic change unmarked by an apparent palaeontological break (Bein & Taylor, 1981). The remaining section between the top of the sample interval and seafloor is interpreted to be marine carbonates, with several prograding sequences within this interval apparent from seismic data.

STRUCTURAL AND DEPOSITIONAL HISTORY

The quality of seismic data and the relatively small size of the basin allows the confident definition of basin margins, structural trends and basin infill history. The interpretation of basement structure in the Eyre and Recherche Sub-basins forms the basis of recent models on the extension and breakup of Australia and Antarctica (Etheridge & others, 1988; Etheridge & others, 1989; Willcox and Stagg, 1990).

Palaeozoic

Palaeozoic rocks are absent at Jerboa-1, but are interpreted from seismic data in the western end of the sub-basin by Bein and Taylor (1981), who interpreted parallel reflectors, conformable with the basement surface and cut by basement faults, to be remnants of a Palaeozoic basin infill sequence (line E79A-3; not included). The sedimentary sequence is proposed as Permian in age, and is probably related to Permian diamictites which are recorded in the onshore Eucla Basin (Harris and Ludbrook, 1966), the Polda Trough (McClure, 1982a, 1982b) and the Denman Basin (Carter and Scott, 1976). The structural origin of the Palaeozoic basin is unclear.

Jurassic

The age of syn-rift sediments in the grabens flanking Jerboa-1 is inferred to be pre-Cretaceous. Thus, extension in the Eyre Sub-basin probably began in the Jurassic, conceivably by Callovian or earlier, and continued to the Late Jurassic. Based on balanced sections, Etheridge & others (1989) estimate the Eyre Sub-basin has undergone 20% extension. There is no clear evidence for wrenching within the Eyre Sub-Basin. Maximum displacement occurred along faults at the northern basin boundary (detachment fault of Etheridge & others, 1989), the southern boundary of the Wombat structure and south of the southern basin basement high that separates the Eyre and Recherche Sub-basins. The faulted basement blocks show increased rotation to the south, and have a highly fractured appearance on the seismic data. Bein and Taylor (1981) suggested the early syn-rift sediments were poorly sorted weathering products and debris locally derived from the adjacent faulted blocks. It is interpreted that, as extension progressed, deposition commenced in spatially restricted lacustrine environments, which were locally influenced by fluvial and paludal environments. Stagg & others (1990) envisaged two large intermontane lakes which were isolated within the half-graben structures. This scenario would be favourable for the deposition of Jurassic age source rock.

Cretaceous/Non-Marine

Early Cretaceous rift-fill sediments comprised sandstones with interbedded shales, deposited in fluvial to lacustrine environments. Post-rift subsidence led to the deposition of a thick sequence of monotonous lacustrine shales. The lacustrine environment became increasingly less restricted as the sediments coalesced around and over the intervening basement highs. Lacustrine conditions probably prevailed until the end of the Barremian, when a period of non-deposition and erosion commenced and continued until the Middle Albian. Although variable in duration, this regional unconformity is also present at Potoroo-1 (Ceduna sub-basin) and Apollo-1 (Denman Basin) and is represented by a non-marine shale and coal sequence in the Duntroon and Otway Basins, indicating the event was widespread along the continental margin.

Cretaceous/Marine

Marine sedimentation which commenced in the Middle Albian was interrupted by a ?hiatus in the Late Albian to early Cenomanian. Stagg & others (1990) relate this break in sedimentation to the breakup of the Southern Ocean, which Veevers (1986) interpreted to have occurred at around 95 $\pm$ 5 Ma yrs. However, this sedimentation break predates breakup by several million years (approximately 3-9 Ma yrs), and hence a direct coincidence with breakup remains unclear. Transgressive Cenomanian marine claystones unconformably overlie the Albian sequence, and grade up to sandy siltstones and shales. A strong basin-wide reflector occurs within the Cenomanian sequence which can be related to a lithologic change at Jerboa-1. Although not a "breakup unconformity", this lithologic change may relate to the breakup of Australia and Antarctica. A Cenomanian to Cainozoic basinwide unconformity spanning 25-40 Ma yrs was originally interpreted as the breakup unconformity by Bein and Taylor (1981). Stagg & others (1990) suggest this unconformity, which is also strongly developed in the outer Ceduna Sub-basin, is related to delayed post-breakup subsidence.

Faulting of the sedimentary sequence is predominantly confined to Lower Valanginian to Upper Cenomanian, and is concentrated over basement highs as at Jerboa-1 and adjacent to major basement faults. Movement on faults is usually minimal (<30m) and probably results from differential compaction and subsidence. Faulting adjacent to basement faults (ie, south of "Wombat feature") is generally late Cenomanian and may be directly related to late post breakup subsidence. Thinning of units over basement highs combined with subsidence related faulting presents some difficulty in tying sequences between the two half-grabens.

Cainozoic

Early Cainozoic sedimentation commenced with a thin, seaward prograding sand of inferred Paleocene age. Bein & Taylor (1981) noted a period of erosion during the Early to earliest Middle Eocene, followed by two phases of deposition. The first phase is a regional sandstone, followed by a second phase of prograding open marine carbonates. This pattern of sedimentation is also evident in the Ceduna sub-basin and Denman Basins.

HYDROCARBON PROSPECTIVITY

Reservoir

Sandstones within the basal Berriasian to Lower Valanginian (TS K1) sequence were identified as potential reservoirs at Jerboa-1. This sequence contained three sandstone intervals which totalled 224m in thickness (informal units JF, JH, JJ of Bein and Taylor, 1981). Porosities ranged from 17 to 20%, although total water saturation was recorded at Jerboa-1. Another potential reservoir exists in a Paleocene prograding sand unit which is present in the northern region of the sub-basin.

Seal

Overlying the basal sandstones is a regional sequence of thick lacustrine shales and claystones (TS K3/K2) providing an excellent seal. This lacustrine sequence also provides a potential source of organic material. Sediments overlying the Paleocene prograding unit are marine sands and limestones (TS Cz3/Cz2) which are probably inadequate seals.

Source and Maturation

Hydrocarbon source rocks may occur within the seismically inferred wedge of Late Jurassic syn-rift sediments which infill the deeper half-grabens. A restricted fluvial to lacustrine environment of deposition is proposed for this sequence. Average total organic carbon (TOC) values for the Lower Neocomian interval at Jerboa-1 ranged from 1.51 to 2.88% (Burns, 1981; Stagg & others, 1990). The entire sequence at Jerboa-1 was evaluated as immature for hydrocarbon generation (Bein and Taylor, 1981), although a zone of initial maturation was identified close to the base of the well. This zone offers an encouraging possibility of increased maturation of Jurassic source rocks in the deeper grabens.

Hydrocarbon Indicators

Jerboa-1 was drilled as a compaction drape over a faulted basement block. No hydrocarbon fluorescence was noted during drilling, although later analysis showed residual oil in pores and traces of light hydrocarbons near the top and base of the Lower Neocomian (TS K1) interval (Bein and Taylor, 1981). A small gas peak was recorded near the base of the well (TS K1), and was assumed to be associated with a thin coal band within the basal sandstone.

The failure of Jerboa-1 to produce hydrocarbons has been attributed in part to the marginal maturity of source rocks, possible inadequate trapping, or, more likely, to poor migration pathways. Jerboa-1 did however, identify moderate to good quality sandstone reservoirs (TS K1), a thick regional seal (TS K3/K2 claystones) and a zone of initial maturation near the base of the well. The possible presence of Jurassic lacustrine source rocks and increased maturity in the deeper grabens, offers support for updip migration into graben bounding structures and localised syntectonic sandstone facies.

DENMAN BASIN

BASINAL STRUCTURE

The Palaeozoic Denman Basin is a N/NW trending elongate depression within the larger Eucla Basin. The Eucla and Denman Basins are located in a region of shallow, gently southward dipping basement, which is overlain by thin deposits of Palaeozoic, Cretaceous and Tertiary sediments. The rifting and separation event which formed the larger Ceduna, Eyre and Recherche Sub-basins to the south appear to have had a negligible effect on the Denman and Eucla Basins.

The geographic boundary of the Denman Basin is defined by the distribution of Permian (TS P3/P2) glacial sediments which overlie and partially infill the basement depression. The eastern, western and southern boundaries are distinct, as Permian sediments clearly onlap the surrounding shallow basement. The less apparent northern boundary extends onshore where Permian sediments of a similar age were recovered in Mallabie-1 (TS P1) and Nullarbor-8 (TS P3/P2). A large, N/NW trending, intra-basin basement high partially divides the Denman Basin into two asymmetric troughs that merge both north and south of the basement high. Basin margins are steep and appear to be unfaulted. Minor basement and post-depositional faulting is confined to the southern basinal region. Apollo-1 was sited south of the Denman intra-basin high (initially interpreted as a Mesozoic feature) in an area of an anomalous thickening which was thought to be a bioherm or sand build-up (Carter and Scott, 1976).

DATING OF HORIZONS

Basement

Basement rocks at Apollo-1 are granite or granitic gneiss which were interpreted as Archaean or Lower Proterozoic age, respectively (Carter and Scott, 1976). At Mallabie-1, north of Apollo-1, basement rocks are Archaean granitic gneiss. A gas kick (methane) recorded during drilling of the basement gneiss at Mallabie-1 was attributed to a fracture filled gas pocket (Scott and Speer, 1969).

Proterozoic/Early Palaeozoic

Sediments of this age are absent at Apollo-1, however the occurrence of a thick section of Upper Proterozoic/early Palaeozoic (?Cambro-Ordovician) volcanics, sandstone, siltstone and rudite were noted onshore at Mallabie-1 (900 m) and Nullarbor No. 8 bore (250 m) (Cockshell, 1990). Poor correlation between magnetic and seismic basement depths in the northern Denman Basin has been attributed to the presence of non-magnetic late Proterozoic/early Palaeozoic sediments, which locally form seismic basement (Stagg & others, 1990). Cambro-Ordovician(?) sediments extend approximately 40 km southward from Mallabie-1 into the offshore Denman Basin. This region is not included on the constructed cross-section (Plate 1) or seismic sections (Plates 5-6) (north of SP 2532).

Permian (Top TS P3/P2)

Lower Permian (TS P3/P2) (Stage 3, Carter and Scott, 1976) unnamed claystones were recovered from Apollo-1. This sequence thickens in the basin troughs and thins and/or onlaps the surrounding shallow basement. The upper surface of TS P3/P2 has been modified by erosion from an Early Cretaceous channel which cuts through the eastern trough of the basin (Stagg & others, 1990). The top of the Permian in the southernmost basement depression is uncertain due to the difference in seismic character between this interval and the sequence which ties to Apollo-1 (SP0372-SP0540). Seismic ties within the area are of marginal to poor quality and do not resolve the discrepancy. In this instance, an additional Cretaceous horizon is added as an alternative interpretation. In the southern area, the Permian sequence is affected by minor faults which appear to extend to basement, indicating the possible reactivation of older fault systems. Permian sequences are noted in Nullarbor No. 8 (claystones) (Harris & Ludbrook, 1966) and at Mallabie-1 (sandstones, siltstones, claystones) (Scott and Speer, 1969).

Cretaceous (Top TS K3-K1)

A sequence of Neocomian to Barremian fluvial sandstones and shales blanket the southern basin, thinning over basement highs and infilling the deeper parts of the basin. A similar sequence of fluvial sandstones, siltstones and conglomerates are recorded to the north at Mallabie-1 (TS K3-K1).

Cainozoic (Base TS Cz2) (Cretaceous/Top TS K8-K5)

This horizon marks the top of a seaward thickening wedge of Aptian to Cenomanian shallow marine sandstones, claystones and shales. Apollo-1 and Duntroon-1 (Duntroon Basin) are the only wells in the Great Australian Bight Basin containing an Aptian sequence. This sequence is time equivalent to the fluvio-lacustrine Lower Eumeralla Formation which are source rocks in the Otway Basin. Aptian sediments (TS K4) occur onshore in Mallabie No. 8 bore as siltstones, sandstone and claystones deposited in a paralic setting. Basal Middle Eocene (TS Cz2) sands unconformably overlie the Cretaceous sequence, and are in turn conformably overlain by a seaward thickening wedge of Late Eocene (TS Cz2) carbonates. Within the interval Top TS K3 to seabed, reflectors are parallel and flat lying, and show only minor localised variations in dip. Erosional truncation of the Cenomanian sequence by the overlying Middle Eocene sequence is virtually absent, however the boundary is well marked by a strong reflector which can be tied to the Apollo-1 well.

STRUCTURAL AND DEPOSITIONAL HISTORY

Palaeozoic

The rugged erosional appearance of the basement horizon hinders any clear definition of basement faults. Thus, it is difficult to establish whether the Denman Basin had a structural origin which was subsequently modified by glacial erosion, or if the basin itself was a product of the erosional event. Wopfner (1980) has suggested that the Denman Basin is structurally related to other northwest trending Permian intracratonic basins in the area (Arckaringa, Pedirka and Cooper and Renmark Basins), and that tectonic forces which formed the basins began before glaciation and continued intermittently during the Permian. However, it is clear from basement topography (steep sided basin margins and deeply eroded basement surface) that structurally derived basin morphology was significantly modified by glaciers which moved W to NW from Antarctica to Australia. Following the Early Permian ice retreat, a period of rapid transgression flooded the Denman Basin, depositing a thick sequence of marine claystones. Stagg & others (1990) have suggested that Permian deposition of the claystones occurred in a lacustrine environment. Wopfner (1980), however, notes the presence of Permian (TS P3/P2) marine sediments north and east of the Denman in the Arckaringa, Troubridge and Renmark Basins, which suggests a linked seaway existed which extended eastward along the present day southern margin (BMR Palaeogeographic Group, 1990).

Cretaceous

The condensed nature of the Cretaceous section (TS K8-K5, TS K3-K1) is apparent from the Time/Depth plot of Apollo-1 (Plate 2). Potoroo-1, south of Apollo-1 on the northern margins of the Ceduna Sub-basin, has a much thicker, although chronostratigraphically similar, sequence to Apollo-1. This suggests a tectonic hinge line is present between the two basins, accounting for the thin deposition of Cretaceous sediments at Apollo-1 in a stable platform setting, while deposition to the south was in a subsiding (rift) basin. In view of the highly condensed nature of the Cretaceous sequence, the absence of a Late Albian unconformity (TS K8/K7) which is evident elsewhere in the Bight Basin (Jerboa-1 and Potoroo-1) may be due to poor palynological control at Apollo-1 (Morgan, 1990). An Early to Late Cretaceous period of basement sag resulted in a moderate east to west tilting of the basin, indicated by a thickening of the Cretaceous sequence to the west (Stagg & others, 1990). Potoroo-1 contains a Late Cretaceous (TS K11-K9/Maastrichtian to Turonian) sequence of fluvial sands and shales which is absent at Apollo-1 by either thinning and erosion, or non-deposition. The Late Cretaceous sequence (TS K11-K9) is likewise absent at Jerboa-1, in the Eyre Sub-basin.

Cainozoic

Following an extended period of erosion and non-deposition, marine sedimentation recommenced in the Middle Eocene with the deposition of a thin blanket of sand and a subsequent period of extended open-marine carbonate deposition.

HYDROCARBON PROSPECTIVITY

There were no velocity or temperature surveys, nor geochemical or formational tests performed at Apollo-1. Estimates of porosity and permeability were determined from electric logs. The sequence recovered at Apollo-1 was much thinner than anticipated from seismic data, due to the misinterpretation of the "basement" as a Mesozoic horizon. "Horizons" at depth (1.0-1.5 s TWT at the Apollo-1 well site) which were previously interpreted as basement were in fact multiples (Carter and Scott, 1976). The "Mesozoic buildup" drilled at Apollo-1 was a Permian claystone sequence whose anomalous geometry was probably due to subsequent erosion by an Early Cretaceous fluvial channel which cut through the area.

Reservoir

Cambro-Ordovician(?) sandstones at Mallabie-1 have low to moderate porosities, which are further reduced by interstitial clays and diagenesis (pressure solution, secondary quartz overgrowths). Apollo-1 intersected Permian and Lower Cretaceous sandstones which showed varying degrees of porosity and permeability. In the lower part of the Permian sequence (TS P3/P2) are three thin sandstone beds which displayed "moderate porosity and permeability" (Carter and Scott, 1976). The Permian (TS P3/P2) and Lower Cretaceous (TS K3-K1) interval between 547-782 m is primarily sandstone with shale interbeds, and also appears to be "porous and permeable" (Carter and Scott, 1976). Permian sandstones at Mallabie-1 (TS P1) are argillaceous, recording a porosity of 18% and permeability of <.10 millidarcy. Basal Cretaceous sandstones at Mallabie-1 (TS K3-K1) are well-sorted, quartzose sands with siltstones and conglomerate that are locally "very porous and permeable" (Scott and Speer, 1969). The Aptian sand sequence at Mallabie-1 is locally argillaceous, with porosities and permeabilities ranging from 35.2 - 39.8 % and 1610 - 3500 millidarcies, respectively (Scott and Speer, 1969). At Apollo-1, a thin basal Cainozoic sandstone (15 m) (TS Cz2) contains porous and permeable intervals, while a similar sequence at Mallabie-1 contains more silt and clay.

Seal

At Apollo-1, the lowermost Permian sands are directly overlain by thick Permian claystones which have good sealing potential. Early to Late Cretaceous (TS K8-K5) shales may provide a seal for the Lower Cretaceous and uppermost Permian sands. These shales, however, are interbedded with sands which may hinder the continuity of a regional seal. The Cainozoic sands (TS Cz2) are overlain by open marine calcarenites which may have "porous and permeable" intervals (Carter and Scott, 1976), thus providing a doubtful seal for the sands.

Source and Maturation

There were no hydrocarbon shows in cuttings from Apollo-1 (Carter and Scott, 1976) or Mallabie-1 (Scott and Speer, 1969). Similarly, there was no visible organic carbon source recorded in the sequence. Permian (TS P3/P2) marine claystones may provide a marginal quality and spatially restricted organic source, although by comparison with the onshore Eucla Basin, this does not seem plausible. The Lower Cretaceous (TS K3-K1) sandstone, siltstone and claystone sequence recovered in Mallabie-1 recorded very low TOC values (0.05%) (Saxby, 1977). A similar result is likely for the Cretaceous sequence in the offshore Denman Basin. The condensed Cretaceous sequence which was deposited in the stable platform setting of the Denman Basin resulted from sediment bypass, and does not appear to be favourable circumstances for the concentration of organic material. Heat flow for hydrocarbon maturation is estimated to be low to moderate (Stagg & others, 1990). The potential of an external source of hydrocarbon, such as the deepwater Ceduna Sub-basin, cannot be dismissed. However, this proposition requires the horizontal migration of hydrocarbons over large distances (minimum of 50-100 km) within a regionally sealed, laterally continuous porous and highly permeable unit. Stagg & others (1990) note that hydrocarbon occurrences of this nature would be subtle structural and stratigraphic traps.

CEDUNA SUB-BASIN

BASINAL STRUCTURE

The Ceduna Sub-basin is the largest sub-basin within the Great Australian Bight Basin. Underlying the bathymetric Ceduna Terrace, the sub-basin covers an area of approximately 90,000 km^2 in water depths of 200-4000 metres. Early Cretaceous to Tertiary sediments reach a maximum thickness of at least 10 km in the central portion of the sub-basin. Potoroo-1 was drilled and abandoned in 1975 by Shell Development (Australia) Pty. Ltd. as a small fault dip closure on the northern margin of the sub-basin.

The arcuate northern margin of the sub-basin trends approximately E/W, and is well defined by a major basement scarp. The eastern and western margins have been interpreted by Stagg & others (1990) as NE trending accommodation zones. Gravity and magnetic data of Fraser and Tilbury (1979) showed the basement surface dips southward from 500 m below seabed on the shelf to around 1000 m near the shelf break. At the shelf break, basement depths increase rapidly to 6 km and reach a maximum depth of approximately 10-12 km in the central part of the terrace (Fraser and Tilbury, 1979). Gravity modelling suggests a gradual southward shallowing of basement from 12 km in the central basin to about 7 km beneath the abyssal rise (Mutter, 1978; Fraser and Tilbury, 1979). Stagg & others (1990) have designated these features as the Northwest Ceduna Monocline, the Central Ceduna Depositional Axis and the Outer Margin High. The approximate geographic boundaries of the monocline and outer margin high are shown on the location map of Plate 1.

Seismic data are generally of good quality, this particularly applies to reprocessed sections (1975) from the Shell Development R4 South Australian Shelf Survey (1969), which served as the primary seismic database for this project. Regional BMR seismic lines shot in the western sub-basin supplemented the dataset. Several seismic horizons identified in the northern Ceduna Sub-basin and tied to Potoroo-1 proved difficult to trace confidently across the sub-basin. This is presumably due to major facies changes within the basin and the massive basinward thickening of the entire sedimentary sequence which reduced seismic quality in the central basin. Horizons which were tentatively correlated are shown as dashed lined on the constructed cross-section and on the interpreted seismic lines (Plates 1 & 7). Seismic results relied primarily on the interpretation of several key horizons which tied to marker beds at Potoroo-1. These horizons were generally of a more regional extent and were often related to shorter term depositional events (ie, coal seams, thin sands or calcareous shale). In addition, as a consequence of almost continuous Early Cretaceous to Tertiary deposition, seismic horizons quite often did not coincide with time slice boundaries, as was the case in the Eyre and Denman Basins. Thus, several horizons are designated as "approximate" time slice boundaries on the cross-section.

DATING OF HORIZONS

Basement

Potoroo-1 penetrated 112 m of basement rock described as "granitic gneiss with affinities to the Lower Proterozoic Clove metamorphics of the Gawler Block" (Fraser and Tilbury, 1979). Definition of basement from seismic data is limited to areas along the northern and northeastern basin margin. A single low angle fault displaces basement up to 6 km and separates a seaward dipping, shallow basement platform to the north from the deep central basin to the south. Data from the *Rig Seismic* Survey 65 has tentatively identified the top of the first rotated basement block south of the basin margin fault (Stagg & others, 1990). A prominent "basement rise" south of Potoroo-1 may also be evidence of a rotated basement block, although the seismic data does not allow clear definition of any bounding faults (Plate 7). Approximately 50 km south of Potoroo-1, the basement horizon falls below seismic definition. Interpretation of basement structures in the central and outer basin relies solely on gravity and magnetic data, although basement geometry is clearly mirrored in the overlying sedimentary sequence which massively thickens in the central basin before thinning and rising towards the outer margin high (Plate 1).

?Cretaceous (Pre TS K1)

South of Potoroo-1, a large basement depression has formed between the northern basin margin and the previously described "basement rise" to the south. Top Pre-TS K1 is the first strong, continuous reflector above basement, and marks the top of a syn-rift to early rift-fill sequence of ?Late Jurassic to Early Cretaceous (Lower Valanginian) age. The reflector clearly thins and onlaps the basement surface south of Potoroo-1, and can be traced with decreasing confidence to the southern edge of the "basement rise", approximately 35 km south of Potoroo-1. This horizon cannot be seismically resolved in the deeper central sub-basin.

Cretaceous (Top TS K7)

This horizon marks the top of a seaward thickening wedge of Valanginian to Albian age sediment. At Potoroo-1, basal sediment are Valanginian to Barremian age fluvial sandstones which grade upwards to sandy siltstones. This sequence is unconformably overlain by a Middle Albian age sequence of marine shales, siltstones and sandstones. The Top TS K7 horizon can be traced approximately 35 km south of Potoroo-1 before becoming faint and discontinuous.

Cretaceous (Intra-TS K8, Intra-TS K8a, Intra-TS K8B and Approximately Base TS K9)

Seismic horizon Approx Base TS K9 is a strong, regional reflector which is particularly well developed in the central sub-basin. This horizon marks the top of a thick sequence of Cenomanian paralic sandstones, siltstones and shales, and the base of a Turonian to Santonian deltaic sandstone. Horizons Intra-TS K8, Intra-TS K8A and Intra-TS K8B relate to coal horizons at Potoroo-1 occurring within the Cenomanian paralic sequence. Horizon Intra-TS K8A is present only in the northern parts of the basin (extending approximately 60 km south of

Potoroo-1), while Intra-TS K8B can be correlated throughout most of the sub-basin, providing the most regionally reliable mid-Cretaceous seismic horizon. The age of horizon Intra-TS K8B is estimated to be between 90-95 Ma, corresponding closely to the proposed time of breakup in the Southern Ocean. Overlying horizon Intra-TS K8B is a distinctive carbonaceous mudstone deposited under paralic to deltaic conditions and interpreted here as late Cenomanian in age. Stagg & others (1990) have designated the mudstone as Turonian, however the interval in question falls within a sampling zone described as containing "very lean samples" (Morgan, 1990). In addition to poor sampling, there is an apparent overlap of palynological zonations further complicating the age interpretation of the mudstone.

Cretaceous (Approximate Top TS K9)

Seismic horizon Top TS K9 is a strong, regionally continuous seismic horizon marking the top of a thick Turonian to Santonian deltaic sequence. The sequence comprises a wedge which thickens seaward from Potoroo-1, grading into distinctive large scale foresets which prograde into the southern and western parts of the basin. At Potoroo-1, conditions were fluvio-deltaic, although several glauconitic intervals are recorded which suggests periodic incursions of paralic to marine conditions from the deeper basin. The prominent progradation and downlapping of reflectors onto horizon Approximate Base TS K9 in the central and southern basin, as well as the large scale of foresets suggests outbuilding from paralic conditions at Potoroo-1 into bathyal environments in the central basin. The upper age limit of the deltaic sequence (Approximate Top TS K9) is inferred from seismic as this position coincides with a sample gap at Potoroo-1 (994-1300 m).

Cainozoic (Base TS Cz1)

The base of the Cainozoic is marked by an erosional surface which is particularly well developed in the outer basin. Underlying this unconformity is a sequence of Campanian to Maastrichtian sandstones and siltstones deposited in fluvial and paralic environments. This sequence extends into the basin as a sheet which thickens only slightly in the deeper central basin. An additional horizon (Approximate Top TS K10?) is evident approximately 20 km south of Potoroo-1 and extends southward across the basin. This sequence was probably deposited under more marine conditions which may have existed basinward of Potoroo-1. The basal Cainozoic horizon also marks the upper extent of faulting of the sedimentary section.

Cainozoic (Top TS Cz2)

Unconformably overlying the Cretaceous sequence at Potoroo-1 is a thin prograding wedge of Palaeocene paralic to shallow marine sandstone. This sequence is conformably overlain by a thick wedge of Middle Eocene to Miocene open marine carbonates. The carbonate sequence extends to just north of the Outer Margin High. There is an unconformity in the Upper Oligocene carbonate sequence.

Previously described sequences overlying basement can be traced shoreward where they thin and overlie shallow basement as a sheet drape.

STRUCTURAL AND DEPOSITIONAL HISTORY

Basement structures originally described by Fraser and Tilbury (1979) and formally named by Stagg & others (1990) cannot be used to suggest original basin forming trends as these structures have been heavily influenced by sediment loading (Stagg & others, 1990). The onset of rifting is interpreted to have commenced in the Jurassic, similar to the Eyre Sub-basin to the west, with the age of syn-rift and early rift-fill sediments inferred from seismic as ?Late Jurassic to early Neocomian. Syn-rift and early rift-fill sediment were probably deposited in continental to fluvial environments. The Cretaceous was a time of extremely high sedimentation rates in the central and outer sub-basin. Following breakup along the southern margin of Western Australian, the continental, paralic and shallow marine conditions which existed at Potoroo-1 were likely to have been almost continually marine in the deeper basin during the middle to Late Cretaceous (Early Albian to Maastrichtian). This scenario is further supported by several Cenomanian coal seams of variable thickness (4-40 m) (ie, Intra-TS K8, Intra-TS K8A) which are well developed at Potoroo-1, but appear to terminate in the sub-basin. The principle source of sediment was probably the Gawler Block to the north, or perhaps related to a major erosional event which affected Central Australia during the Late Cretaceous and early Cainozoic. Cainozoic sedimentation occurs in two phases, similar to the Eyre Sub-basin. A thin prograding siliciclastic sheet is initially deposited, followed by the onset of open marine conditions and the deposition of a thick sequence of carbonates.

Faulting of the sedimentary sequence is usually confined to the Cretaceous interval. Faults are largely synsedimentary and probably result from differential compaction of the thick Cretaceous sequence. Stagg & others (1990) have described the end of the Cretaceous as a time of major tectonic movement in the outer Ceduna Sub-Basin. Structural events included uplift and wrenching of the Outer Margin High, possible overthrusting on the seaward flank of the Outer Margin High and the emplacement of mounded structures along the Base Cainozoic horizon (Stagg & others, 1990). These features are partially the result of an Early Cretaceous phase of NNE directed rifting which overprinted existing features on the Outer Margin High. The uplift which produced substantial erosion of the Ceduna Sub-basin Outer Margin High probably also affected the Eyre Sub-basin where a major erosional event is also recorded in the Late Cretaceous. The Cainozoic/Cretaceous unconformity is only moderately developed at Potoroo-1.

HYDROCARBON PROSPECTIVITY

Reservoir

Mid-Valanginian sandstones at Potoroo-1 (TS K3/K2) have porosities of 9-25%, although reservoir characteristics are highly variable within this sequence. The porosity of Cenomanian paralic sandstones and shales (TS K8) is reduced by the interbedded nature of the sequence. In addition, coally laminae within the sandstones often produced anomalously high log derived porosities (Alexander, 1990). Turonian to Maastrichtian deltaic sandstones (TS K10/K9) are up to 50 m thick and have porosities up to 30%.

Seals

Mid-Valanginian sandstones (TS K3/K2) are overlain by a thin sequence of Albian marine shales and siltstones. Approximately 200 m of late Cenomanian (TS K8) carbonaceous shale overlies the interbedded Cenomanian sandstones and shales (TS K8) providing a good regional seal within the basin. Late Cretaceous deltaic sands (TS K10/K9) are overlain by Cainozoic sands and carbonates which are probably inadequate seals.

Source and Maturation

Five Cretaceous samples analysed for organic carbon (%TOC) yielded the following results: (1) Neocomian shales and siltstone (TS K3/K2) contained an average of 1.25% TOC, while (2) Cenomanian (TS K8) paralic siltstones and sandstones averaged 1.4% TOC (Alexander, 1990). The moderate source capacity indicated by the TOC values is downgraded due to the presence of inertinitic material (Alexander, 1990). The entire Cretaceous sequence at Potoroo-1 was evaluated as thermally immature for hydrocarbon generation.

Hydrocarbon Indicators

Potoroo-1 was drilled as a dip closure against a basement controlled fault. There were no hydrocarbon shows detected during drilling, although numerous gas peaks were recorded which were generally associated with coally intervals. Sporadic gas peaks were also recorded within the Middle Albian (TS K7/K6) restricted marine mudstone sequence (Shell WCR, 1975). There were no formation tests carried out at Potoroo-1. The possibility of marine sediments, as well as the prospects of increased maturation, are likely in the deeper central Ceduna Sub-Basin. Falvey & others (1990) and Stagg & others (1990) outline the following play types recognised for the area: (1) Early to mid-Cretaceous tilted fault blocks in the central Ceduna Sub-basin; and, (2) the juxtaposition of thick Late Cretaceous deltaic deposits above fine grained shallow marine Early Cretaceous sediments (Alexander, 1990).

TIME AND FACIES DIAGRAMS

TIME SPACE

Sediments recovered from Jerboa-1, Potoroo-1 and Apollo-1 range from Permian to Cainozoic in age. No Jurassic sequences were recovered, however their presence is inferred from seismic data in the Eyre and Ceduna Sub-basins. The Time Space diagram highlights the difference in continuity of sedimentation within the areas. At Potoroo-1 (Ceduna Sub-basin), sedimentation has been virtually continuous since basin inception, while Jerboa-1 (Eyre Sub-basin) and Apollo-1 (Denman Basin) have experienced periodic sedimentation during the Early Cretaceous (TS K3-K1), the middle to Late Cretaceous (TS K8-K6) and the middle Tertiary (TS Cz3-Cz2). Each phase of sedimentation is bounded by a regional unconformity clearly evident in the well sequences. These unconformities occur during (1) the Aptian (TS K4); (2) the Late Cretaceous (TS K11-K9); and, (3) the Oligocene (Top TS Cz3). A regional hiatus of relatively short duration (~ 3 Ma) in the Late Albian (between TS K8/K7) is present in Jerboa-1 and Potoroo-1. In Apollo-1, this "unconformity" may in fact be a condensed interval. At Potoroo-1, sedimentation recommences in the Turonian.

TIME SLICE CORRELATION

Basal Permian glacial sediments penetrated in Apollo-1 are indicative of the earlier formation of the Denman Basin relative to the Ceduna and Eyre Sub-basins. However, as noted previously, Permian sediments may also be present in the Eyre Sub-basin. At Jerboa-1 and Potoroo-1, basal sequences are Early Cretaceous (TS K1 and K2/K3 respectively). Late Cretaceous (TS K11-K9) sediments are present only at Potoroo-1, being absent from Jerboa-1 and Apollo-1 either by non-deposition (ie, no fluvial outbuilding as at Potoroo-1) or from uplift and erosion.

TIME SLICE FACIES CORRELATION

In the Ceduna Sub-Basin and the Denman Basin, initial Early Cretaceous (?Late Jurassic) sedimentation was of a fluvial nature. At Jerboa-1, a localised lacustrine and fluvio-lacustrine environment was established in the half-grabens. Following a period of non-deposition and erosion during the Aptian (TS K4), marine sedimentation commenced, first in the late Aptian/early Albian in the Denman Basin (Apollo-1), followed by the Ceduna Sub-basin in the early to middle Albian (TS K6) and finally in the Eyre Sub-basin in the Late Albian. From this pattern of submergence, it would appear the marine waterway encroached from the northeast. However, marine conditions probably prevailed in the deeper Ceduna Sub-Basin from as early as the Neocomian, following breakup along the southern margin of West Australia (Markl, 1974, 1978). Marine sedimentation was interrupted in the Late Albian (TS K7) throughout the region, and later recommenced during the Cenomanian at Jerboa-1 and Apollo-1. Paralic conditions dominated at Potoroo-1 during the Cenomanian, followed by an extended period of fluvial outbuilding during the Late Cretaceous. The onset of Cainozoic sedimentation occurred throughout the basins in two phases: (1) as a basal sandstone in the Eocene (TS Cz2); followed by (2) open marine carbonate sediments in the Late Eocene to Oligocene (TS Cz3-Cz2). An early Paleocene (TS Cz1) prograding sand is present along the northern margins of the Ceduna and Eyre Sub-basins.

GEOLOGIC HISTORY OF THE SOUTHERN MARGIN

STRUCTURAL HISTORY

Rifting along the Australian southern margin probably commenced by Middle to Late Jurassic, and later culminated with breakup and the onset of seafloor spreading by the Late Cretaceous (Veevers, 1986). A broad magnetic quiet zone (MQZ) extends along the entire southern margin from southern Western Australia eastward to at least Kangaroo Island. The northern margin of the MQZ (also referred to as the Magnetic Trough) occurs south of the Eyre Sub-basin in the Recherche Sub-basin, and extends eastward across the Ceduna Sub-basin. The southern boundary of the MQZ is coincident with the oldest identified magnetic anomaly. Traditionally, a MQZ is thought to signify a period of magnetic quiescence or continuity, such as occurred in the mid-Cretaceous. Etheridge & others (1989) suggest that the southern margin MQZ is the signature of highly extended, metamorphosed and underplated continental crust. Anomalies south of the MQZ were originally modelled as 22-19 (Early to Middle Eocene) (Weissel and Hayes, 1972). These were later revised to anomalies 34-20 (Campanian to Middle Eocene) (Cande and Mutter, 1982), with the time of breakup estimated at 95 ± 5 Ma (Veevers, 1986). Patterns of magnetic anomalies along the Southeast Indian Ridge suggest an initial period of slow spreading (anomalies 34-20) (Cande and Mutter, 1982). Normal spreading rates commenced in the Middle Eocene (anomaly 20), coincident with a time of major plate reorganisation.

Recent application of detachment models of margin formation to the Australian southern margin (Etheridge & others, 1988; Etheridge & others, 1989) has attempted to explain tectonic elements, such as the MQZ, and the asymmetry of the opposing Australia and Antarctica passive margins. The detachment model proposes that the lower plate margin (Australia) formed the footwall of a major detachment fault, and was subsequently pulled from beneath of the upper-plate margin (Antarctica) which originated as the hanging wall of the detachment fault (Etheridge & others, 1989). The detachment model has implications for the uplift, subsidence and thermal histories of the southern margin. Areas which have underdone greater extension (Recherche Sub-Basin-200% and outer Ceduna Sub-Basin-undetermined) would consequently experience a unique history of heatflow and subsidence. The Eyre Sub-Basin formed as a result of limited extension (20%) between the head of the detachment and a branch fault (Etheridge & others, 1989), and thus would have a correspondingly different thermal history.

Willcox and Stagg (1990) have used deep seismic, magnetic and gravity data from the southern margin basins to suggest a NW/SE direction of initial extension, rather than the N/S orthogonal direction modelled from magnetic anomalies. A subsequent period of NNE/SSW extension in the Early Cretaceous resulted in the formation of the Otway, Bass and Gippsland basins (Etheridge & others, 1985), and produced a structural overprinting of the Great Australian Bight basins.

Dating of syn-rift sequences is crucial in determining the time of rift onset, which is essential when modelling geohistory plots. Jerboa-1 provides the best opportunity for resolving this issue. The basal, post-rift sequence at Jerboa-1 has been reinterpreted as Berriasian to lowest Valanginian in age, suggesting that extension in this basin was complete by the Early Cretaceous. By comparison, the history of Vlaming Basin of Western Australia is dominated by a major structuring event which culminated in the mid-Valanginian and resulted in substantial uplift and erosion (Seggie, 1990). Extension on the southern margin appears to be a long term, progressive event beginning in the ?Jurassic and concluding prior to or coincident with the western margin breakup. Along the central southern margin, there is an intervening period between rift basin formation (Jurassic to mid-Valanginian) and breakup (mid-Cenomanian), accounting for approximately 40-45 Ma. It is approximately during this time (Early Cretaceous) that a NNE/SSW directed extensional event produced the Otway, Bass and Gippsland Basins to the east (Etheridge & others, 1985). This event may have been triggered by events occurring on the southwest margin of Western Australia, and may have produced an overprinting of previous structures in the southern margin basins. Again, this adds to the already complex thermal, uplift and subsidence histories of the southern margin basins and may have crucial consequences for thermal maturation of hydrocarbons in the region.

DEPOSITIONAL HISTORY

Jerboa-1, Potoroo-1 and Apollo-1 recovered granite or granitic gneiss as basement rock. Fission track dates from Jerboa-1 indicate that basement rocks have not been heated above 200-300°C since the Late Proterozoic. Initial ?Jurassic syn-rift deposits were primarily fluvial sequences, with probable deposition in localised lacustrine environments (Eyre Sub-basin and Duntroon Basin). At the end of the Barremian, a major gap in sedimentation occurred lasting throughout most of the Aptian (TS K4). Elsewhere in Australia, the Aptian is a time of extensive marine flooding of the continent. However, the only evidence of an Aptian (marginal) marine influence along the central southern margin occurs in the Duntroon Basin (TS K4) (fluvial shale and sand, containing evidence of minor marine incursions). Coincidently, portions of the Aptian sequence in the Duntroon Basin contain coally sequences and have been described as possible source rocks. The absence of a clear Aptian marine influence suggests that either, (a) the linked southern margin seaway was incomplete at this time, or, (b) this is a period of "post-rift" uplift related to the thermal history of the area. Confirmation of the presence or absence of an Aptian or younger marine sequence in deeper parts of the Ceduna and Recherche Sub-basins would help to resolve this question.

Marine sedimentation began during the late Aptian (TS K5) in the northeast and proceeded in a southwestly direction in the Albian (TS K7/K6). Veevers and Evans (1975) have suggested this is evidence of marine encroachment from the northeast, possibly via the Eromanga Basin. This breech would link the seaways of the southern margin and inland western Australia with the seaway covering the Eromanga Basin and northern Australia (BMR Palaeogeographic Group, 1990). However, in view that marginal marine conditions existed in the Duntroon Basin during the Aptian, an alternative explanation is that the developing southern seaway was highly influenced by rift related events of uplift. Again, evidence of marine conditions in the deep Ceduna and

Recherche Sub-basins would resolve the issue.

Another regional unconformity of approximately 3 Ma duration occurs in the upper Albian (TS K8/K7). Marine conditions resumed across the region in the early Cenomanian. Stagg & others (1990) have suggested this period approximates the time of breakup. Alternatively, the Intra-TS K8B coal horizon in the Ceduna Sub-basin and the Intra-TS K8 in the Eyre Sub-basin also approximate the time of Mid-Cenomanian breakup. Marine conditions persisted throughout the Cenomanian in the Eyre and Denman Basins, becoming paralic in the Ceduna Sub-basin. Deltaic outbuilding occurred during the Turonian to Maastrichtian in the Ceduna Sub-basin and to a lesser extent in the Duntroon Basin. Source of the sediment is presumed to be an (?uplifted) Gawler Block to the north and east. The deltaic outbuilding did not affect the Eyre Sub-basin, where no Late Cretaceous sediment is recorded. Likewise, the Denman Basin was starved of sediment during this period as sediment bypassed the platform and was deposited in the ?subsiding Ceduna Sub-basin. The massive thickening from the Denman Basin into the Ceduna Sub-basin is further evidence of a tectonic hinge between the two areas. Prograding Cainozoic siliciclastics and carbonates are thin in comparison with the underlying Cretaceous sequences. Open marine carbonate conditions presently exist on the shelf.

IMPLICATIONS FOR HYDROCARBON PROSPECTIVITY

Despite the drilling of nine wells in five basins along the southern margin, the area remains inadequately explored for hydrocarbons. The wells were drilled over a period of 14 years and are distributed as follows: one well each in the Eyre and Ceduna Sub-basins and the Denman Basin; three each in the Polda Trough and Duntroon Basin. In general, the entire Cretaceous sequence along the northern flanks of the Great Australian Bight Basin is viewed as immature for hydrocarbon generation. However, the reinterpretation of age dating at Jerboa-1 has revived the prospect of possible ?Late Jurassic syn-rift sediment in the deeper basin. In addition, the thick sedimentary sequence in the Ceduna Sub-Basin holds the prospect of marine source rocks in the central basin, possibly associated with various fault related traps.

A general review of the hydrocarbon potential of the area is summarised in two recent BMR papers (Symonds and Willcox, 1989; Falvey & others, 1990), and a joint BMR/SADME Folio which covers in detail the structural and depositional history of the southern margin (Stagg & others, 1990). In addition, data collected on the 1986 *Rig Seismic* research cruises 10 and 11 conducted in the central Great Australian Bight are summaried by Willcox and others (1988). Several models pertaining to the development of passive margins are applied to the Australian southern margin region, with direct implications for heatflow and subsidence histories in each basin (Etheridge & others, 1988; Etheridge & others, 1989). In summary, the seismic data provides an adequate working knowledge of the general stratigraphy of each basin, although a thorough understanding of the region is hampered by a dearth of well information. In addition, the southern margin region has undergone a complex history of structural development which is likely to influence hydrocarbon maturation.

ADDENDUM

Previously unavailable results of the palynological reassessment of Jerboa-1 by Wagstaff (in prep; pers. comm, Feb, 1991) offer two alternative interpretations of the well sequence. Firstly, Wagstaff suggests that the basal sequence at Jerboa-1 is indeed Jurassic, thus altering the age of syn-rift sediments from earliest Neocomian-?Late Jurassic to Late-Middle Jurassic. The older age for basal sediments not only alters the timing of basin formation, it downgrades the maturation potential of syn-rift sediments as Late Jurassic source rocks. In view of the absence of Middle Jurassic sediments elsewhere in the Great Australian Bight and Duntroon Basins, the Neocomian interpretation of basal sediment still has merit. Secondly, the spore-pollen zonation of Upper *C. paradoxa* (TS K7) was revised to *P. pannosus* (Wagstaff, pers comm, Feb, 1991), however this does not significantly alter our interpretation of the sequence as TS K7.

REFERENCES

Alexander, E.M. (Complier), 1990, Petroleum exploration and development in South Australia: South Australia Dept Mines & Energy Report Book 90/34.

Bein, J. and Taylor, M.L., 1981, The Eyre Sub-Basin, recent exploration results: APEA Jour., 21, 91-98.

BMR Palaeogeographic Group, 1990, Australia, Evolution of a continent: Bureau of Mineral Resources, Australia, 49-50.

Burns, B.J., 1981, Geochemical report, Jerboa-1 well, Eyre Basin, Western Australia: *in*, P.U. Huebner (Complier), Well Completion Report, Appendix 9, Esso Australia Limited, unpublished report.

Cande, S.C. and Mutter, J.C., 1982, A revised identification of the oldest sea-floor spreading anomalies between Australia and Antarctica: Earth and Planetary Science Letter, 58, 151-160.

Carter, B.R. and Scott, A.F., 1976, Apollo No. 1 well completion report, Outback Oil Company, N.L.: South Australia Dept Mines & Energy Open File Env 2620 , unpublished report.

Cockshell, C.D., 1990, A seismic study of offshore Denman and Eucla Basin, South Australia: South Australia Department of Mines & Energy Report Book 90/29.

Davies, H.L., Clarke, J.D.A., Stagg, H.M.J., McGowran, B., Alley, N.F., and Willcox, J.B., 1989, Dredged rocks and sediment cores from the Great Australian Bight, *Rig Seismic* Cruise 11, 1986: Bureau Mineral Resources Report 288.

Etheridge, M.A., Branson, J.C., and Stuart-Smith, P.G., 1985, Extensional basin-forming structures in Bass Strait and their importance for hydrocarbon exploration: APEA Journal, 25 (1), 34-361.

Etheridge, M.A., Symonds, P.A., and Powell, T.G., 1988, Application of the detachment model for continental extension to hydrocarbon exploration in extensional basins: APEA Journal, 28, 168-187.

Etheridge, M.A., Symonds, P.A., and Lister, G.S., 1989, Application of the detachment model to reconstruction of conjugate passive margins: *in*, Extensional Tectonics and Stratigraphy of the North Atlantic Margins, AAPG Memoir 46, 23-40.

Falvey, D.A., Symonds, P.A., Colwell, J.B., Willcox, J.B., Marshall, J.F., Williamson, P.E., and Stagg, H.M.J., 1990, Australia's deepwater frontier petroleum basins and play types: APEA Jour., 239-262.

Fraser, A.R. and Tilbury, L.A., 1979, Structure and stratigraphy of the Ceduna Terrace region, Great Australian Bight Basin: APEA Journal, 19, 53-65.

Harris, W.K. and Ludbrook, N.H., 1966, Occurrence of Permian sediment in the Eucla Basin, South Australia: Quarterly Geological Notes, Geological Survey South Australia, 17, 11-14.

Huebner, P.U. (Compiler), 1980, Jerboa-1 well completion report: Esso Australia Limited, unpublished report.

Markl, R.G., 1974, Evidence for the breakup of eastern Gondwanaland by the early Cretaceous: Nature, 251, 196-200.

Markl, R.G., 1978, Basement morphology and rift geometry near the former junction of India, Australia and Antarctica: Earth and Planetary Science Letters, 39, 211-225.

McClure, I., 1982a, Mercury #1, offshore Polda Basin, well completion report, Australian Occidental Pty Ltd: South Australia Dept Mines & Energy Open File Env 5161, unpublished report.

McClure, I., 1982b, Columbia #1, well completion report, Australian Occidental Pty Ltd: South Australia Dept Mines & Energy Open File Env 5160, unpublished report.

Morgan, R., 1990, Rapid palynology of four Bight-Duntroon Basin wells, Report for APIRA Project P298 Bight-Duntroon Basins Study: South Australia Dept Mines & Energy Confidential Envelope 6978.

Mutter, J.C., 1978, An analysis of the Mesozoic-early Cenozoic rifting history of Australia and Antarctica, implications for generalised geo-dynamic models of rifting: M.Sc. Thesis, University of Sydney, unpublished.

Powis, G. and Partridge, A.D., 1980, Palynological analysis of Jerboa-1, Eyre Basin, Western Australian: *in*, Huebner, P.U., (Compiler), 1980, Jerboa-1 well completion report, Esso Australia Limited, (unpublished).

Saxby, J.D., 1977, Source rock analysis on samples from thirteen Australian sedimentary basins: South Australia Dept Mines & Energy Open File Env 1172, unpublished report.

Scott, A.F., & Speer, G.W., 1969, Mallabie No. 1 well completion report, Outback Oil Company, N.L.: South Australia Dept Mines & Energy Open File Env 1172, unpublished report.

Seggie, R., 1990, Geological cross-section of the offshore Vlaming Sub-Basin, South Perth Basin: Bureau Mineral Resources Record 1990/64.

Shell Development (Australia) Pty. Ltd., 1975, Potoroo-1 well completion report, Permit SA-5, Great Australian Bight Basin: South Australia Dept Mines & Energy Open File Env 2580, unpublished report.

Stagg, H.M.J., Cockshell, C.D., Willcox, J.B., Hill, A.J., Needham, D.J.L., Thomas, B., O'Brien, G.W. and Hough, L.P., 1990, Basins of the Great Australian Bight region, geology and petroleum potential: Bureau of Mineral Resources, Continental Margins Program Folio 5.

Symonds, P.A. and Willcox, J.B., 1989, Australia's petroleum potential in areas beyond an Exclusive Economic Zone: BMR Jour., 11, 11-36.

Veevers, J.J., 1986, Breakup of Australian and Antarctica estimated as mid-Cretaceous (95 ± 5 Ma) from magnetic and seismic data at the continental margin: Earth and Planetary Science Letters, 77, 91-99.

Veevers, J.J. and Evans, P.R., 1975, Late Palaeozoic and Mesozoic history of Australia: *in*, Campbell, K.S.W., (Ed), *Gondwana Geology*, Australian National University Press, Canberra, 579-607.

Wagstaff, B., in prep, A new palynological zonation and palaeoenvironmental analysis of Jerboa-1, Eyre Sub-Basin, Great Australian Bight Basin.

Weissel, J.K. and Hayes, D.E., 1972, Magnetic anomalies in the southeastern Indian Ocean: *in*, D.E. Hayes (Ed), Antarctic oceanology II; The Australian-New Zealand sector, Antarctica Research Series, 19, 234-249.

Willcox, J.B., Stagg, H.M.J., and Davies, H.L., 1988, *Rig Seismic* research cruises 10 & 11, geology of the central Great Australian Bight region: Bureau of Mineral Resources Report 286.

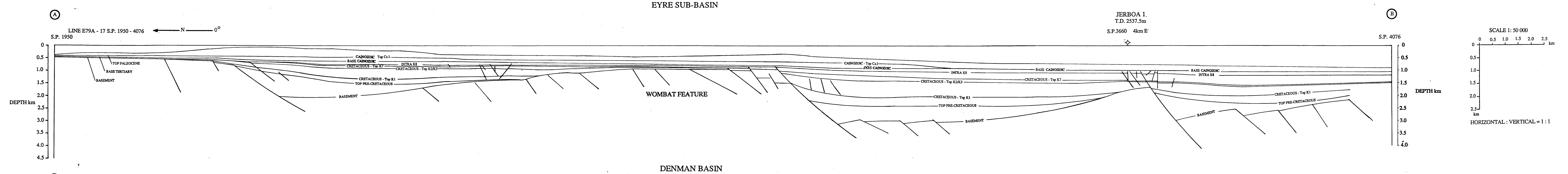
Willcox, J.B. and Stagg, H.M.J., 1990, Australia's southern margin, a product of oblique extension: Tectonophysics, 173, 269-281.

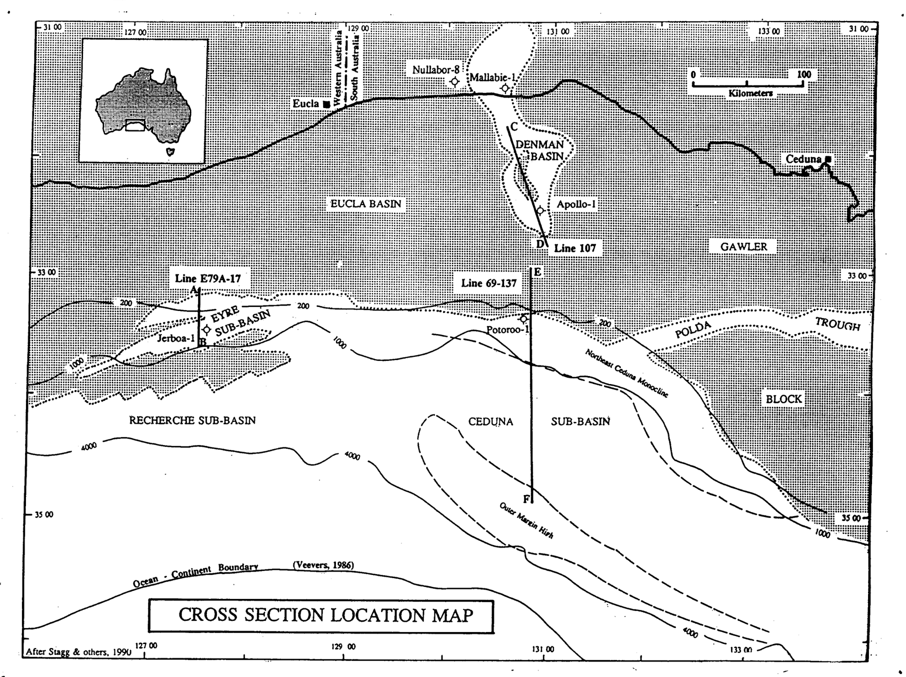
Wopfner, H., 1980, Development of Permian intracratonic basins in Australia: *in*, M.M. Cresswell and P. Vella (Eds), Fifth International Gondwana Symposium, Wellington, New Zealand, 185-190.

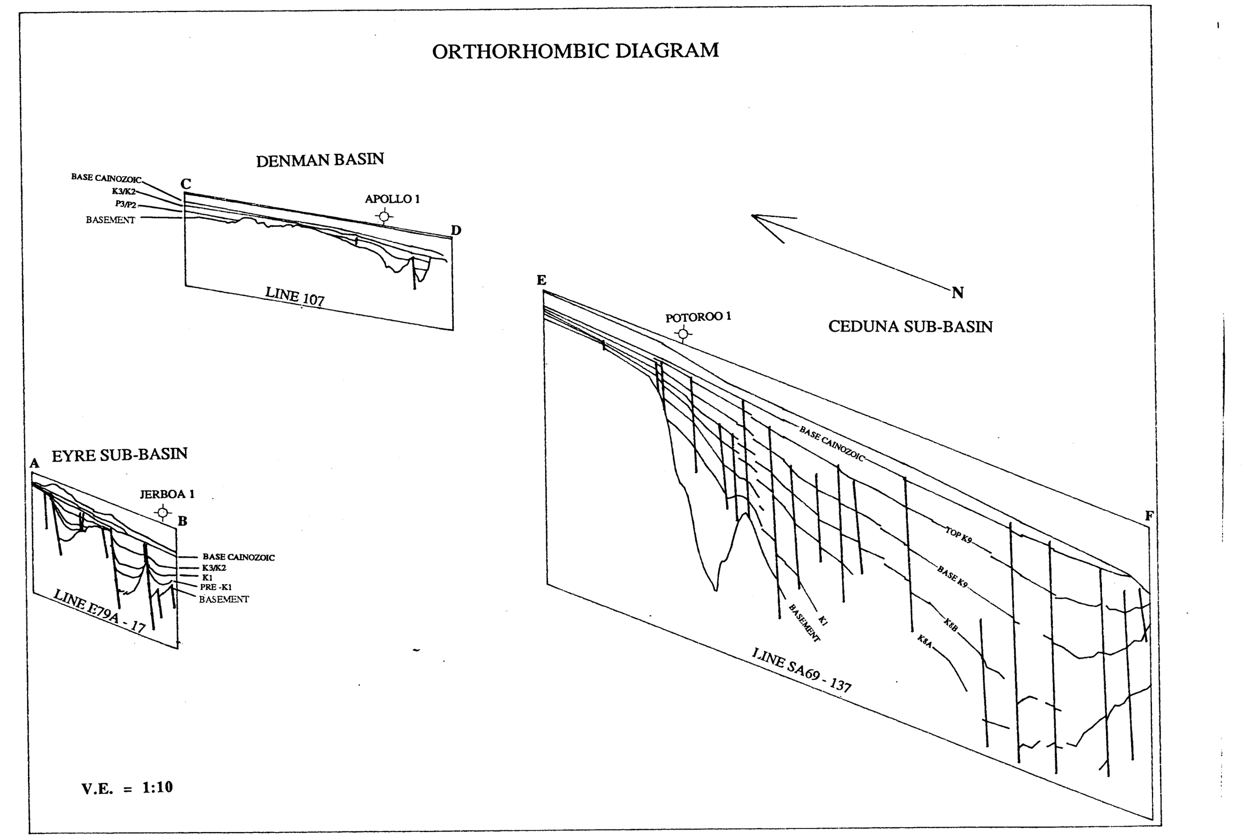
SOUTHERN MARGIN BASINS STRUCTURAL CROSS - SECTIONS

JANE BLEVIN

PLATE 1







NOTE: Scale change from 1:50 000, for the Denman Basin and the Eyre Sub-Basin, to 1:100 000 for the Ceduna Sub-Basin.

Drafted by	Scott Edgecombe
Version 1	November,1990

(Palaeogeographic Maps Project -Phase 2)

Phanerozoic History of Australia
Project 175A

SOUTHERN MARGIN BASINS BIOSTRATIGRAPHY

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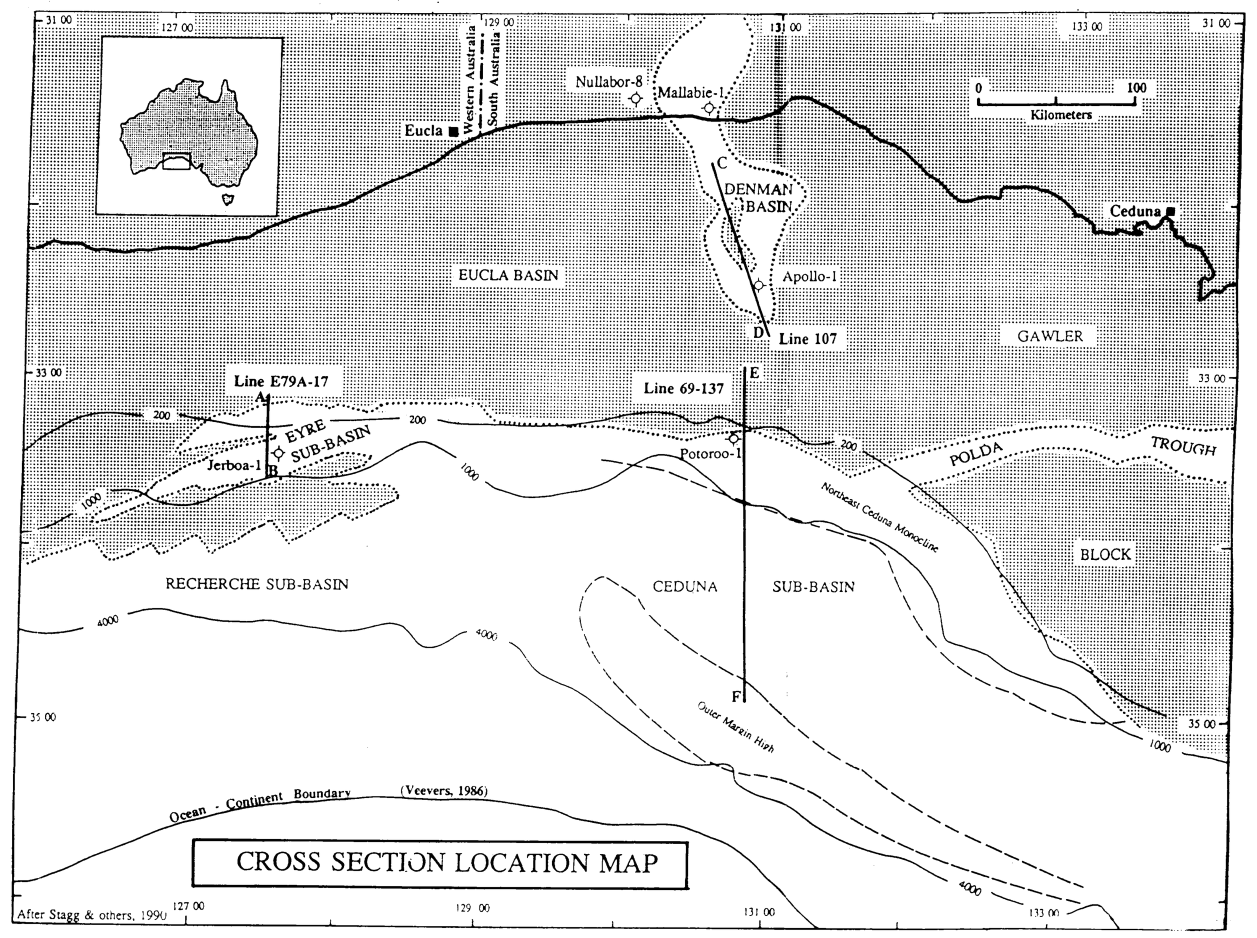
PLATE 2

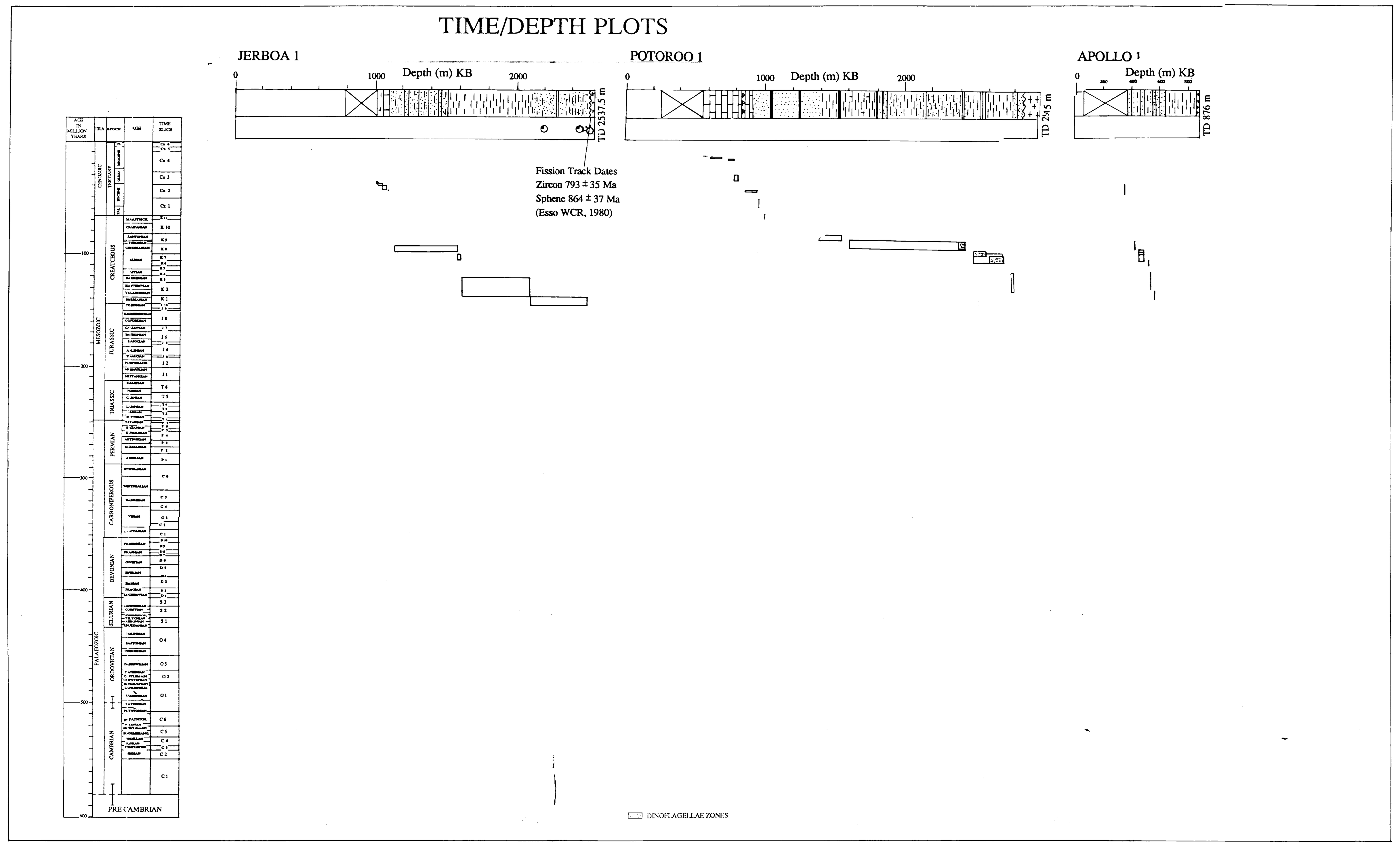


CROSS SECTION LOCATION MAP

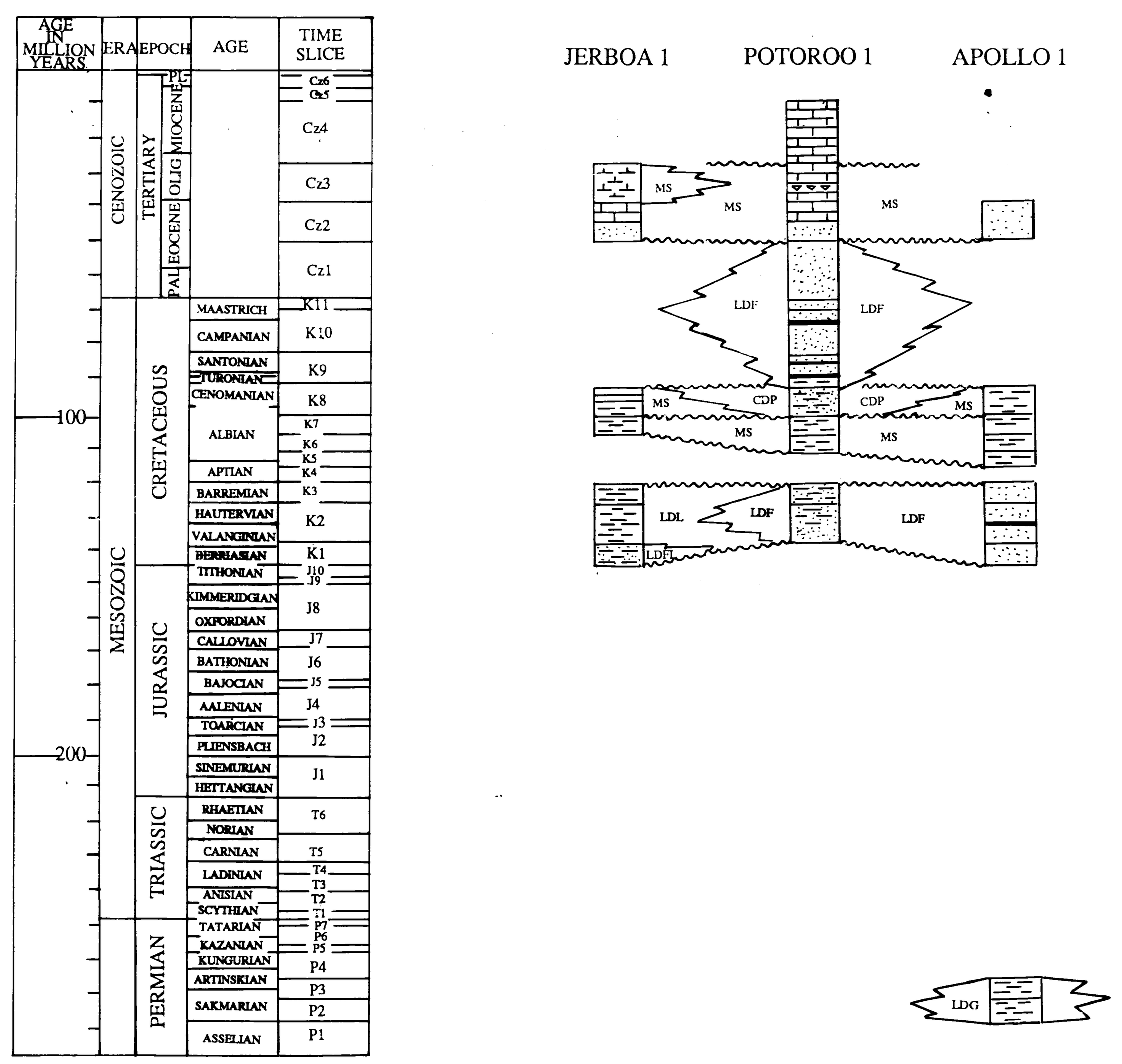
LITHOLOGICAL SYMBOLS

- MARL
- LIMESTONE
- SANDSTONE
- SILTSTONE
- COAL
- CHERT NODULES
- IGNEOUS

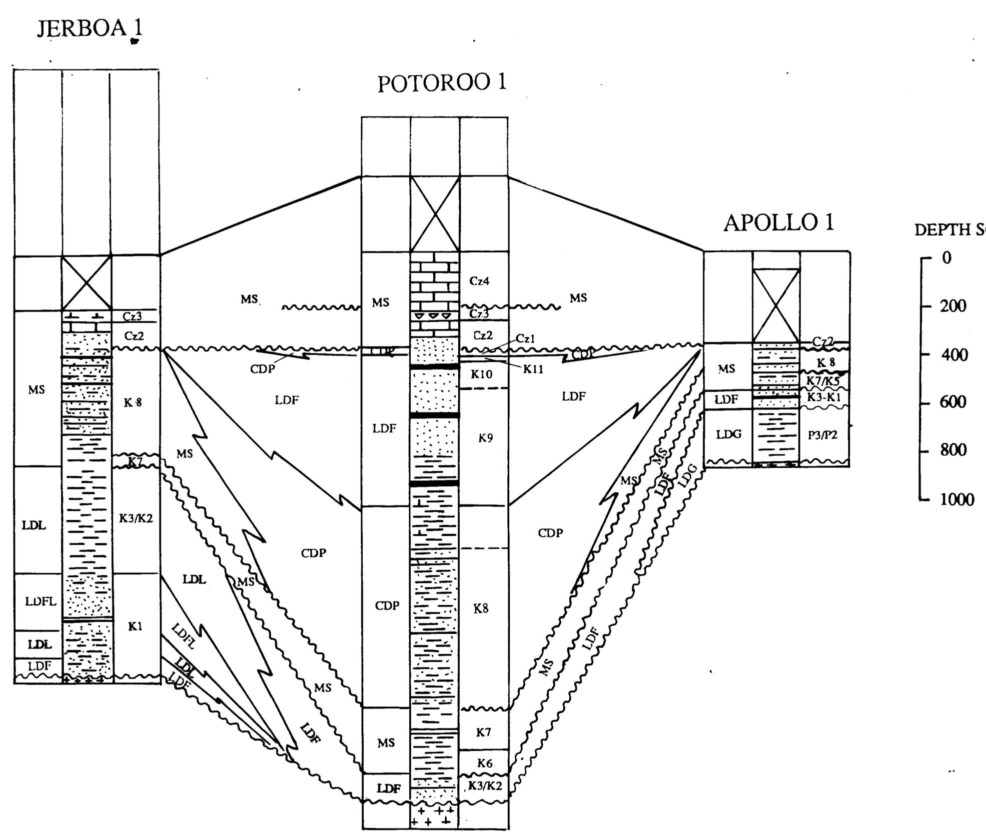
TIME/DEPTH PLOTS



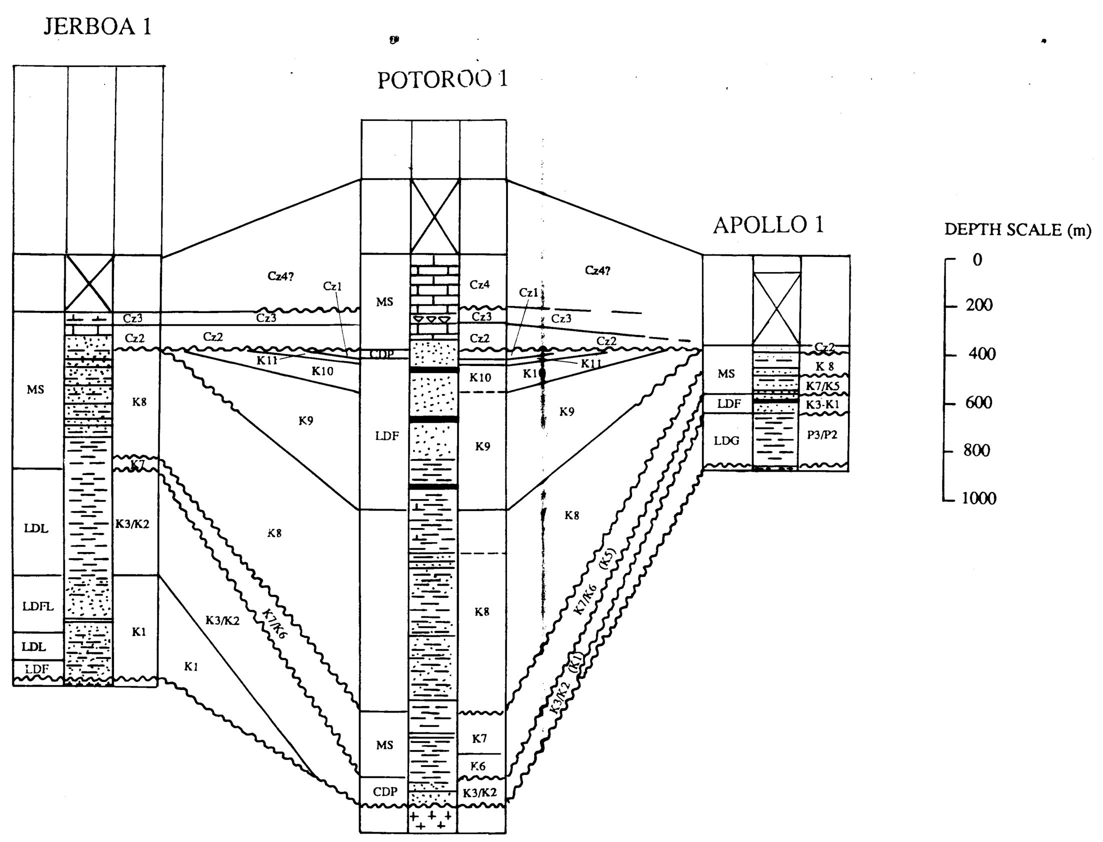
TIME SPACE



TIME-SLICE FACIES



TIME-SLICE CORRELATION



ENVIRONMENTS OF DEPOSITION

MS	MARINE SHALLOW
CDP	COASTAL DEPOSITION PARALIC
LDFL	LAND DEPOSITION FLUVIAL LACUSTRINE
LDF	LAND DEPOSITION FLUVIAL
LDG	LAND DEPOSITION GLACIAL
LDL	LAND DEPOSITION LACUSTRINE

Drafted by Scott Edgecombe

Version 1 November, 1990

(Palaeogeographic Maps Project -Phase 2)

Phanerozoic History of Australia
Project 175A

R9101302

PSLA NO: 19

SOUTHERN MARGIN BASINS EYRE SUB-BASIN

PLATE 3

INTERPRETED SEISMIC LINE E79A-17

PSLA NO:

SOUTHERN MARGIN BASINS

EYRE SUB-BASIN

PLATE 4

UNINTERPRETED SEISMIC LINE E79A-17

FIELD RECORDING
GROUPS/INTERVAL/LENGTH 48/50/50M.
POP INTERVAL 25M AV OFFSET TO GP48 223M.
AIR GUNS 28 GUNS/1450 CU IN.
INSTRUMENTS DFS V FORMAT SEG-B
RECORD LENGTH/SAMPLE 6.0SEC./4MS.
FIELD FILTER 8-128HZ SLOPE 18-72DB/OCT.
RECORDED BY G.S.I. DATE NOV 1979

LINE E79A-17 -M4A
SP 3126-1944 (FILE 2)

GEOPHYSICAL SERVICE
PROCESSING SEQ
PRE DECONVOLUTION RAMP
VELOCITY FILTERING
DBS DESIGNATURE
SBS 1X300,3X1000MS GATES RE
NMO VELSCANS AT DISCRETE LO
DPS 48 FOLD COVERAGE
TVF 10-90HZ. WB 10-
5-50HZ. WB+2000MS 5-
SAS 300MS TO BASEMENT 1000M
DATE PROCESSED DE

E79A-17 -M4C
076-3076 (FILE 1)

GEOPHYSICAL SERVICE INTERNATIONAL
PROCESSING SEQUENCE

SOUTH

NORTH

2.5 KILOMETRES

SOUTHERN MARGIN BASINS DENMAN BASIN PLATE 5

INTERPRETED SEISMIC LINE 107

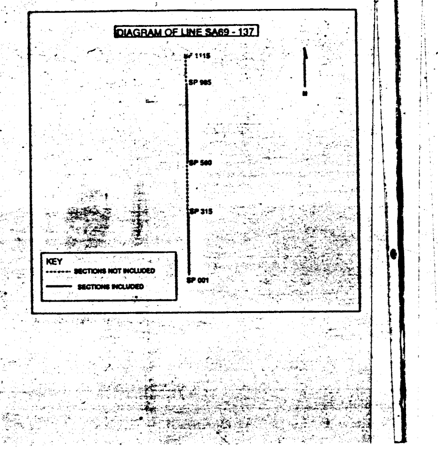
SOUTHERN MARGIN BASINS DENMAN BASIN PLATE 6

UNINTERPRETED SEISMIC LINE 107

SOUTHERN MARGIN BASINS

CEDUNA SUB - BASIN
INTERPRETED SEISMIC LINE SA69 - 137

PLATE 7

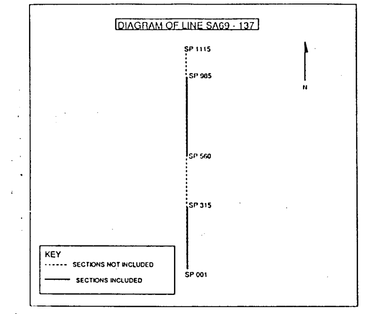


SOUTHERN MARGIN BASINS

CEDUNA SUB - BASIN

PLATE 8

UNINTERPRETED SEISMIC LINE SA69 - 137



SOUTHERN MARGIN BASINS

CEDUNA SUB - BASIN

UNINTERPRETED SEISMIC LINE SA69 - 137

PLATE 8

NOTE : Seismic Intervals SP 1115 - 985 and SP 560 - 315 are not included.