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A REVIEW OF THE STRUCTURE, GEOLOGY AND HYDROCARBON POTENTIAL OF THE OTWAY BASIN IN SOUTH AUSTRALIA

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1. TECTONIC HISTORY OF THE OTWAY BASIN REGION

(D.I. Gravestock)

Sedimentary history of the Otway Basin *sensu stricto* is provided by the Mesozoic and Cainozoic stratigraphic record, but tectonic history of the region is intimately linked with Gondwanan events spanning at least the Phanerozoic. Palaeozoic history of the Otway Basin region is so poorly known that opinions are polarized as to the fundamental continental or oceanic nature of the underlying crust, extent and direction of major strike-slip fault movements, and degree of rotational displacement between nascent continental blocks. Despite this uncertain foundation, the importance of older tectonic trends to younger graben-associated hydrocarbon provinces elsewhere, necessitates a brief review of the Palaeozoic as well as the Mesozoic and Cainozoic tectonic history of the Otway Basin region.

1.1 Early Palaeozoic

The Otway Basin region overlies the southern part of the Tasman Province (Rutland, 1976), southeast of the Australian Craton and north of the Early Palaeozoic platform margin of the East Antarctic Craton (Fig. 1). Palaeomagnetic (McElhinny et al., 1974) and Cambrian faunal evidence suggest that the Australian and East Antarctic Cratons were closely juxtaposed, although problems remain in correlating sedimentary sequences and tectonic events betwen the two (Cooper & Grindley, 1982). The Otway Basin overlies an area critical to interpretation.

Sedimentary rocks of the Adelaide Geosyncline and Victoria Land (Fig. 1) were deposited in thick sequences marginal to the southeastern Australian and East Antarctic Cratons. The Adelaide Geosyncline is thought to have evolved through rift and post-rift stages as a passive continental margin, with the 'breakup unconformity' placed either at the Cambrian - Precambrian boundary (von der Borch, 1980) or within the Precambrian (Preiss, 1983).

The crustal substrate of the southern Tasman Province is considered to have been either:

1) oceanic, consisting of successively cratonized volcanic fore-arc terrains (Crook, 1980), or a mafic island arc and marginal sea becoming ensialic by the mid-Silurian (Powell, 1983),
2) continental, from crustal thickness data and the presence of stable platforms in New Zealand and elsewhere (Rutland, 1976), or
3) 'a mosaic of smaller blocks during the Palaeozoic' (Austin & Williams, 1978, p.3).

Common to most proposals and of direct concern is the fact that Late Proterozoic to Devonian tectonic trends are meridional or nearly so. The primary arcuate trend of the southern Adelaide Geosyncline towards east-west on Kangaroo Island (Fig. 1) is the only exception, but its effect on the tectonic history northwest of the Otway Basin region is unknown.

1.2 Late Palaeozoic

Occurrences of benthic foraminifera and phytoplankton in the Early Permian Arckaringa and Troubridge Basins and in troughs beneath the Eucla and Murray Basins led McGowran (1973) to suggest a brief marine ingression following deglaciation, entering an incipient rift from the west, prior to that formed in the Mesozoic. Though not widely accepted, marine ingressions during the Permian must nevertheless have crossed the Great Australian Bight region to reach the Troubridge Basin. In Victoria, Permian glacigene, fluvial and lacustrine sediments dominated, but marine fossils occur near Bacchus Marsh (Douglas & Ferguson, 1976). Connections with Troubridge and sub-Murray Basin marine rocks are unknown and Permian rocks have not been positively identified beneath the Otway Basin in South Australia.

Early Permian glacials were deposited on deeply eroded older rocks in presumed relatively stable basins on the Australian Craton. Wopfner (1981) has proposed greater structural control, arguing that dominant northeast and northwest trends resulted from plate convergence in the Tasman Province.

1.3 Triassic to Early Jurassic

The Triassic was probably a period of non-deposition in the Otway Basin region (Douglas & Ferguson, 1976); weathering surfaces are recorded to the west on Kangaroo Island, and on Fleurieu Peninsula south of Adelaide (Daily et al., 1974). There is no direct evidence of Early Jurassic deposition and it is difficult at present to accommodate any significant thicknesses of Triassic to Early Jurassic strata below Cretaceous graben fill on seismic sections offshore.

1.4 Middle to Late Jurassic

Kimberlitic intrusives predominantly of Middle to Late Jurassic age occur in the Adelaide Geosyncline, Victoria, New South Wales and Tasmania (Ferguson et al., 1979). South Australian occurrences lie on a modern seismic belt which coincides with northward projection of transform faults from the Antarctic Ridge, and all occurrences indicate anomalously high heat flow at the time of emplacement which was 'controlled by fracture systems that penetrate the lithospheric plate' (Ferguson et al., 1979, p.239).

The onset of Australo-Antarctic rifting signalled by initiation of deep crustal fractures, was accompanied by widespread dolerite extrusion and shallow intrusion in Tasmania and on the Pacific side of the East Antarctic Craton. The latter may have been associated in part with relative motion of Marie Byrd Land (Thomson, 1983). Middle Jurassic tholeiitic basalt on Kangaroo Island, probably a remnant of more widespread intrusion, forms the nearest known occurrence to the Otway Basin region. Middle to Late Jurassic sediments have not been penetrated, the closest of non-marine origin occur in the Great Australian Bight Basin (Bein & Taylor, 1981) and Polda Basin (Harris, 1964).

1.5 Cretaceous

The Otway Group comprises the first known rift-associated sediments within the basin. These were deposited in graben complexes in response to progressive west-east rift propagation between Australia and Antarctica. High initial basement subsidence rates and Early Cretaceous depositional rates are indicated by Falvey & Mutter (1981) and Mutter et al. (1985) for certain Great Australian Bight and Otway Basin wells. Seismic data from the Bass Basin indicate high initial, but low subsequent fault displacement, suggested by Etheridge et al. (1984) to represent extensional and subsidence phases, applicable to other extensional basins, including the Otway Basin. Contemporaneous effusive sources for the highly volcanogenic Otway Group sediments (Gleadow et al., 1983) are disputable, but if the Casterton Volcanics are Neocomian in age (see e.g. Ludbrook, 1978), one such source is indicated, implying a continuation of high heat flow from the Late Jurassic.

Early Cretaceous palynomorphs from Mertz Glacier (Truswell, 1982) suggest that Wilkes Basin sediments (Fig. 1) crop out on the northern continental shelf of the East Antarctic Craton. The Wilkes Basin trend, parallel to the Ross Orogen, may indicate subsidence in response to intracratonic fracture patterns (Drewry, 1976), although northwest trending faults are assumed by Robertson et al. (1978) to have modified the northern margin of the Wilkes Basin region. Structural relationships with the western Otway Basin remain obscure.

The Sherbrook Group was deposited during the Late Cretaceous as basement subsidence rates declined roughly exponentially (Falvey & Mutter, 1981) and as sea floor spreading commenced at or slightly before anomaly 34 time (Cande & Mutter, 1982). Propagation of oceanic crust appears to have been diachronous, younging eastward from 85 to 65 Ma B.P. (Mutter et al., 1985). With downward revision of breakup from 55 Ma B.P., and as a result of more recent drilling and seismic data from deeper parts of the Otway Basin, the perceived need for a breakup unconformity has diminished. Deposition between the Otway and Sherbrook Groups is likely to have varied from conformable in deeper parts of the basin, to unconformable locally, with angular discordance aided by fault block rotation closer to the northern basin margin. In contrast to major Late Cretaceous regressions from interior basins of the separating Australian continent, ingressions of limited duration and extent are recorded along the widening rift, perhaps opposed by continued high rates of deltaic sedimentation. Cande & Mutter (1982) and Mutter et al. (1985)

consider Late Cretaceous to Early Tertiary widening of the new marine basin to have been extremely slow, hence the balance between rates of subsidence and deposition was probably crucial to 'marineness' of sediments at any particular locality. Synsedimentary faults are associated with high rates of Sherbrook Group deposition, probably induced in part by gravitational instability and shear failure in undercompacted shales.

1.6 Cainozoic

Cainozoic tectonic subdivision of the Otway Basin into embayments separated by 'highs' or ridges is mainly applicable onshore; their identity being either largely lost offshore (Abele et al., 1976), or masked by the complexity of Cretaceous fault systems. Here it is considered that the meridional trends of Otway Basin embayments and ridges are controlled by re-emergence of the Early Palaeozoic Tasman Province 'grain' which is dominant north of the Otway Basin. It may become possible to more readily discern offshore extensions of Early Palaeozoic trends as updip closures and highly oblique linear zones of fault convergence on detailed seismic grids. The importance of these structures as hydrocarbon traps is outlined elsewhere. Significantly, modern earthquakes in southeast Australia appear to occur in cratonized Tasman Province basement rocks beneath sedimentary basins, rather than in the basins themselves. Further, faulting associated with earthquake activity is controlled by pre-existing zones of crustal weakness (Denham et al., 1981). Detailed accounts of the Cainozoic geology and geomorphology of Victoria (Kenley in Wopfner & Douglas, 1971; Jenkyn in Douglas & Ferguson, 1976) clearly indicate continuation of tectonic controls which in many instances appear to have been inherited from the Tasman Province.

2. STRUCTURAL DEVELOPMENT OF THE OTWAY BASIN IN SOUTH AUSTRALIA

(A.J. Hill)

2.1 Introduction

Limited useful seismic, aeromagnetic, and gravity data, particularly over the onshore portion of the Otway Basin, hampers structural definition of the basin. Detailed seismic offshore is sparse and tentative limits of the western and southern margins have been determined from the relatively few old seismic lines available. It is anticipated that the recently renewed phase of exploration within the basin should provide higher quality seismic data, enabling a more detailed understanding of the structure.

Earliest Cretaceous rocks are preserved in apparently isolated depressions whereas younger Early Cretaceous and Late Cretaceous rocks have more basin-wide stratal continuity, striking parallel with major fault trends. Isolation of the Gambier Embayment (Wopfner & Douglas, 1971) took place in the Tertiary, thus treatment of Cretaceous rocks in the context of separate embayments is illogical.

2.2 Structural Setting

The Padthaway Ridge, a partly exhumed Ordovician granitic complex (490-480 Ma B.P.) forms the northern margin of the Otway Basin. The granite was emplaced at a late stage of the Delamerian Orogeny and crops out intermittently, trending northeast from east of Cape Jaffa, then southeasterly parallel to the Kanawinka Fault (Fig. 2). The Padthaway Ridge forms a structural hingeline (Rochow, 1971) south of which the 'basement' plunges steeply.

The Otway Basin in South Australia can be effectively divided into northern and southern areas, resulting from the contrasting effects of structural features on loci of sedimentation in the Early and Late Cretaceous.

These areas are separated by the northwesterly trending Tartwaup Fault (Fig. 2). The effects of individual structural elements on patterns of sedimentation are discussed briefly below. A schematic cross section of the basin is presented in Figure 18.

(i) Northern Area

Beachport-Kalangadoo High

Previous workers (Wopfner & Douglas, 1971) commented on the high gravity anomaly that trends east-northeasterly from Beachport and then turns in an east-southeasterly direction parallel to the Padthaway Ridge. This anomaly corresponds also to a structurally high basement complex.

Subsidiary structural highs to the north and east including the Diamond Swamp High have been generally included, although saddles between isolated highs may have allowed interconnection between troughs at certain times during deposition.

Basement lies at 1 407 m KB in Beachport East 1 and at 1 465 m KB in Diamond Swamp 1. Basement was intersected at a depth of 2 059 m KB in Kalangadoo 1. The Early Cretaceous Pretty Hill Sandstone is absent over the Beachport-Kalangadoo High complex whilst at least 300 metres of upper Otway Group Eumeralla Formation occur over the entire structure, suggesting progressive burial during the Early Cretaceous. The absence of Pretty Hill Sandstone suggests either simple onlap or post-deposition erosion. No noticeable thinning or arching of sediments of the upper Otway Group is evident. The limit of thick Sherbrook Group is coincident with the northern margin of the Beachport-Kalangadoo High.

Lake Eliza High

The Lake Eliza High appears as a horst block with east-west bounding faults at the northern and southern margins. Substantial Otway Group thinning over the basement high suggests that it remained a positive feature throughout the Early Cretaceous.

Lucindale High

The Lucindale High was a similarly persistent basement inlier during depositon of the Otway Group. Lucindale No. 1 well intersected 229 m of Pretty Hill Sandstone, suggesting a less dominant basement topography in the Early Cretaceous. Rochow (1971) incorrectly surmised however that it was emergent during deposition of the Pretty Hill Sandstone.

Robe and Penola Troughs

In excess of 3 500 m of Early Cretaceous Otway Group sediments are present within the Robe and Penola Troughs. Gravity data have been used to define the orientation of the troughs (Fig. 2). The limited useful seismic data available demonstrate that the west-northwesterly trending Penola Trough is fault bounded by the Beachport-Kalangadoo High to the south and represents a half graben. A major fault complex (en echelon?) defines the southern flank with sediment thinning over a series of faults to a zero edge on the Padthaway Ridge.

The northern margin of the north-northeasterly trending Robe Trough is also defined by a series of faults which on seismic evidence have a combined throw exceeding 3 000 m. The southern margin of this trough is disrupted by younger northwest oriented faulting cutting across the east-west ?pre-Cretaceous trend.

(ii) Southern Area

Tartwaup Fault

The west-northwesterly trending Tartwaup Fault (Fig. 2) has a displacement at depth in excess of 500 m but is expressed as a monoclinal flexure in outcropping Tertiary sediments at Allen's Quarry, 10 km north-northwest of Mount Gambier. The Tartwaup Fault and associated parallel step faults to the south have a combined throw of 2 500 m. These faults provide the major structural control on the Late Cretaceous, with Sherbrook Group sediments reaching considerable thicknesses to the south. Poor seismic data in the vicinity of Geltwood Beach preclude confirmation that the laterally extensive Chama Fault (Davidson, 1980) is in fact the offshore extension of the Tartwaup Fault.

Thickness of Otway Group sediments offshore south of the Tartwaup Fault has not as yet been determined by drilling although both magnetic and seismic data indicate at least 2 500 m of Early Cretaceous sediments beneath the Sherbrook Group.

The 650 m Sherbrook Group isopach coincides with the Tartwaup Fault trend. A dramatic change in Early Cretaceous fault trends offshore is indicated directly to the west of Geltwood Beach 1. Early Cretaceous east-west structures are apparent both offshore and onshore to the north of the hingeline whilst northwesterly trending faults south of the hingeline are thought to be related to Late Cretaceous trends.

Burrungule Anticline Trend

Harrison (1984) recognized a persistent seismic rollover adjacent to the Tartwaup Fault on the downthrown side to the south. Further anticlinal trends parallel the Burrungule Anticline with a west-northwesterly trend.

Lake Bonney High Trend

A structural high bounded by eastwest trending vertical faults occurs east of Lake Bonney 1. This trend extends to Caroline-1 and easterly into Victoria.

Numerous anticlinal trends of east-west and northwest-southeast orientation are present south of the Tartwaup Fault; these include the Portland-Bridgewater and Voluta Highs located offshore in Victoria and extending west-northwesterly into South Australia.

2.3 Major Lineaments

Major lineaments visible on Landsat Satellite photographs (Bands 5 & 7; Run Nos 96-86, 95-86) are presented in Figure 3.

The north-northwesterly trending Kanawinka Fault or escarpment is displayed as a pronounced lineament which can be traced from east of Robertson 1, where it abutts the Padthaway Ridge, to the southeast where it parallels the Dundas Ridge and Merino Uplift near Casterton 1 in Victoria. The Kanwinka escarpment forms a physiographic boundary between the coastal plains of southeastern South Australia and the uplifted region to the east. Boutakoff & Sprigg (1953) considered that it was a controlling factor in the development of the Gambier Embayment with a southwest downthrow of 600-900 m.

Reynolds (1971) recognised the lineament as a basement fault reflected by scarps formed in the Tertiary Gambier Limestone. The southeastern portion of the lineament appears erosional (Brown, 1965). To the west and parallel to the Kanawinka lineament, lie series of stranded Pleistocene dunes, remnants of fossil shorelines.

A major lineament extends north of Portland in a west-northwesterly trend to Diamond Swamp 1. Bathymetry maps reveal extension of this feature offshore to the east of Portland.

Structural features in the northern area are less apparent at the surface indicating either post Cretaceous structural quiescence north of the Tartwaup Fault, or masking by the arcuate Pleistocene dune system. However, a zone of disruption in Pleistocene dunes west of Lucindale 1 and coincident with a northwesterly lineament suggest possible strike-slip displacement. The change in orientation between the Robe and Penola Troughs in addition to shifts in direction of the Beachport-Kalangadoo, Lake Eliza and Lucindale Highs and Padthaway Ridge (Fig. 2) may be related to strike slip movement.

Major lineaments extend for distances up to 140 km and predominantly trend west-northwesterly to northwesterly. A major north-northwesterly trending lineament dissecting the Grampians in Western Victoria and trending southwesterly to Portland, perhaps reflects Early Palaeozoic structural orientations. Likewise, a north-northwesterly lineament through Lake Bonney 1 and extending to the west of Penola may also be representative of Early Palaeozoic basement fault trends.

2.4 Tectonic History

The tectonic framework and depositional history of the Otway Basin are discussed here in relation to the entire southern passive continental margin of Australia. The Great Australian Bight, Duntroon, Otway, Bass and Gippsland Basins each owe their tectonic origins to the rifting and final breakup of the Australo-Antarctic supercontinent during the Early and Late Cretaceous. The Great Southern Rift System is introduced here to represent a Late Jurassic-Early Cretaceous rift complex within which these basins formed.

Some previous authors (Deighton et al., 1976; Boeuf & Doust, 1975) have proposed a 3 stage basin development consisting of infrarift, rift and breakup phases the latter two of which are discussed below.

Rift Phase - Early Cretaceous Otway Group

Crucial to our understanding of the rift phase is the temporal span of continental extension. A tentative 95±5 Ma breakup (Veevers, 1984; Weissel et al., 1982) provides the upper time limit of rift divergence. However, the paucity of deep wells throughout the northern portion of the Otway Basin prevents an estimation of rift onset. Cores from the Pretty Hill Sandstone reveal a volcaniclastic rich sequence suggestive of contemporaneous volcanism (Duddy, 1981; Gleadow et al., 1983), while interbedded olivine basalt and volcaniclastics of the underlying Casterton Volcanics are dated at 163±5 Ma B.P. (Harding, 1969). An anomalous 'reliable minimum' K/Ar age of 120±10 Ma B.P. was obtained and if this is correct, a Neocomian age can be assigned to the Casterton Volcanics (Ludbrook, 1978) which represent the oldest known Otway Group sediments. We may therefore suggest that crustal extension persisted for at least 35 million years and may have originated in the Late Jurassic.

The tectonic model adopted here is based on the Red Sea Rift System which is considered to be the modern analogue of the Early Cretaceous Otway Basin (Blake, 1985). To some extent, the East African Rift System displays certain tectonic similarities (Carey, 1969; Veevers, 1984). An appreciation of the scale involved is necessary if one is to draw conclusions arising from similarities between ancient and modern analogues and this is where difficulties arise. The precise location of the original oceanic/continental boundary between Australia and Antarctica is ill defined and the unique nature of the Magnetic Quiet Zone with its complex 'rift crust' consisting of a hybrid of both oceanic and continental crust (Talwani et al., 1979) further complicates the obscurity of the boundary. Recent seismic data acquired by the BMR (Willcox et al., 1985) along the offshore portions of the Otway Basin from South Australia to western Tasmania indicate an extensive rift divergence zone. Offshore seismic line 48/043 (Willcox et al., 1985) extends southerly from Argonaut A-1 for a distance of 175 km with no clear indication of the ocean/continent boundary and coupled with the onshore portion of the basin gives a cumulative basin width of at least 300 km. Depending upon the symmetrical relationship between the Great Southern Rift System and its conjugate in the Antarctic region, this would indicate a rifted arch in excess of 600 km wide and at least 3 000 km in length (Fig. 4). This is comparable with the modern East African Rift System. Cochran (1983) noted that the Red Sea Rift is composed of a central axial ridge representative of a sea floor spreading centre that has gradually extended itself both north and south with the northern section currently altering from the diffuse extension to the sea floor spreading mode of plate separation.

Uplifted plateaus at both extremes of the 2 700 km long Red Sea are inclined towards the centre of the axial trough, referred to as the Red Sea Saddle. Examination of magnetic anomalies (32-34) along the southern margin of Australia indicate maximum deflection within the central portion of the Ceduna Depocentre in contrast to a minimum deflection for anomalies 20-31, which remain at nearly constant latitude. The loss of anomaly 34 east of 131°30' (Mutter et al., 1985) against the Magnetic Quiet Zone and the merging of anomalies 32 and 33 to the east may be indicative of an initial sea floor spreading event restricted to the Ceduna Depocentre. The marked reduction in the width of the Magnetic Quiet Zone at both extremes of the Australian continent may support the concept of an initial maximum stress field at the centre of the rift valley with rapid propagation to the west. A marked hiatus to the east is apparent and only a more detailed study of magnetic anomalies eastward of 131°30'E will determine lateral continuity or absence of early seafloor spreading events along the offshore portions of the Otway Basin. In addition, close examination of magnetic anomalies over the broad Ceduna Depocentre may reveal anomalies that precede anomaly 34 (95 Ma BP). Breakup along the eastern Australian margin ranges from 160 Ma B.P. on the northwest margin and 128 Ma BP on the southwest margins and a sympathetic sea floor spreading event in the Early Cretaceous within the central portion of the Great Southern Rift System is conceivable. Little is known regarding the distribution of rift valley structures on the Antarctic conjugate basin, but based on the East African and French Massif Central rift systems, where it is established that the initial rifted arch is divided into two (Boillot, 1981), we can expect to find a simple half graben filled with rift valley and successive prograding deltaic sediments within the Antarctic conjugate half graben. By the same analogy the Australian conjugate half graben will be accompanied by an aborted graben system further landward. Along the onshore portion of the Otway Basin in South Australia, thick accumulations of terrestrial Otway Group sediments are preserved within the Robe, Penola and St. Clair troughs, in turn overlain by a condensed Late Cretaceous Sherbrook Group. These troughs are representative of an aborted rift complex (Griffiths, 1971) that extended westerly into the Duntroon Embayment and easterly into the Port Campbell Embayment (Fig. 5). To the south of the Beachport-Kalangadoo High, which forms the southern boundary of this aborted rift complex, a hingeline coincident with the Tartwaup Fault (Fig. 2) and a series of down to the basin faults marks the northern extremity of the dominant rift valley within the rifted arch. The aborted rift complex to the north of this hingeline became a classic bypass margin commencing in the Late Cretaceous (Fig. 5).

Structural Style

Northeast-southwest extension between the Australian and Antarctic plates in the Early Cretaceous initiated simple conjugate faults sets that dominated the subsequent tectonic development of the Otway Basin, (Blake, 1985). The west-northwest set controlled both the orientation of down to the basin and back to the coast faults, initiating development of the Penola Trough, whilst offsets to the west-northwest set by the north-northwest conjugate set resulted in left lateral offsets to the present day coastline at Portland (Blake, 1985). Tilted fault blocks show a progressive oceanwards increase in extension from 20 to 30 percent up to a maximum of 83 percent (Branson and Falvey, 1985).

Post Rift Phase - Sherbrook Group

The exact timing of sea floor spreading remains problematical. Veevers (1984) suggests a synchronous event at approximately the Cenomanian-Turonian boundary (95 Ma B.P.) for the entire southern margin of Australia whilst Mutter et al. (1985) propose a diachronous propagation younging from west to east (110-86 Ma B.P.). As to whether it was a multistage, multirate process or a single event (Willcox et al., 1985) remains unresolved. However, the marked contrast in sedimentation patterns between the volcaniclastic fluvio-lacustrine Otway Group and the quartzose marginal marine fluvio-deltaic Sherbrook Group would support a major change in tectonic regimes, at least in the Otway Basin, at the boundary of these two groups.

Two distinct rates of sea floor spreading exist. Veevers (1984) assumes a revised uniform slow spreading rate of 4.3 mm/year for the interval 95-44 Ma B.P. and 29 mm/year for the interval 44 Ma B.P. to the present following the work of Weissel & Hayes (1972) and Cande & Mutter (1982). Boeuf & Doust (1975) regarded the Early/Late Cretaceous boundary as the breakup unconformity but as there is no direct evidence for a widespread faunal/floral break, this unconformity is likely to be principally a structural response to plate divergence.

The development of an 'Outer Continental Margin Ridge, (Boeuf & Doust, 1975) at the inception of breakup created a rim basin (Veevers et al., 1982) that dominated for a duration of up to 40 million years. Onlap of prograding Late Cretaceous deltaic sediments against this outer rim within a restricted sea is suggested (Veevers, 1984).

Subsidence of this outer rim or series of rims approximately 40 million years after breakup (55 Ma B.P.) allowed connection of the entire southern margin with the open sea.

Structural Style

Major northwest-southeast trending synthetic growth faults formed in delta depocentres as a consequence of high rates of sedimentation. Delta front and prodelta deposits in excess of 3 km thick prograded into a juvenile ocean, south of the 'Tartwaup Hingezone'. Down to the basin slumping and gravity sliding due to synsedimentary deformation resulted from rapid rate of burial.

Individual faults, often concave to the basin, are of limited lateral persistence and are considered to have evolved independently from the Early Cretaceous back to the basin normal fault blocks. The likelihood of Early Cretaceous faults persisting into the Late Cretaceous is rare south of the Beachport-Kalangadoo High.

Development of the northwest trending Lake Bonney, Bridgewater and Voluta Highs (Fig. 2) resulted from rotation of the downthrown strata to form broad rollover anticlinal complexes as the depocentre of the delta complex rapidly migrated basinward. Regional warping has dominated over faulting since the close of deposition of the Sherbrook Group although numerous faults still displace the Gambier Limestone as evidenced on seismic sections. Sprigg (1952) recognised fold structures within Tertiary rocks and suggested that they were related to 'jostling' of blocks during differential faulting of the basement. Rochow (1971) suggested that post-depositional faults in Tertiary outcrops may be related to Late Tertiary uplift of the Adelaide Geosyncline.

The Nelson, Tartwaup and Kanawinka Faults and additional minor faults all show effects of draping and minor movement. Vertical displacemnt along the Kanawinka Fault has led to the development of a pronounced surface escarpment with up to 10 m of topographic expression (Boutakoff, 1963).

During the Oligocene, the 'Marshall Paraconformity' (Carter & Landis, 1972) developed. Widespread submarine erosion as a consequence of the development of circum-Pacific currents signalled the establishment of full ocean circulation between Australia, Antarctica and New Zealnd.

With the exception of volcanic activity during the Pliocene-Pleistocene and more recently in the Mount Gambier - Mount Schank regions (4 800 Ma BP), the South Australian portion of the Otway Basin has been relatively stable since regression of the sea at the close of the Miocene (Reynolds, 1971).

3. STRATIGRAPHY OF THE OTWAY BASIN IN SOUTH AUSTRALIA

(J.G.G. Morton)

3.1 Introduction

Formations of the Otway and Sherbrook Groups (Early Cretaceous to Late Cretaceous) comprise the major units studied in this report, although the Tertiary units are briefly discussed. Because of the difficulties in correlating to the type sections in Victoria, South Australian reference sections are defined for each formation and the simplified nomenclature for South Australia adopted in this report is shown in Fig. 6.

3.2 Problems of Correlation and Interpretation

There exists a plethora of names for stratigraphic units in the Otway Basin, which in the past has hampered detailed interpretation of the palaeoenvironmental history. Some of the reasons for this were noted by Glenie (1971), but there is still no single well-defined stratigraphic scheme for the Otway Basin. The reasons for this may be because:

i) There are strong facies changes basinward and nearly all major lithological unit boundaries are markedly diachronous. Care must be taken to clearly distinguish between rock units and time units. A simplistic "layer cake" stratigraphic scheme will not adequately classify the sequence. To some extent this can be rationalized by employing a minimal combination of names (Fig. 6).

ii) Palynological data have in the past been relied upon heavily for correlation and interpretation of the sequence. While such data are valuable for interpretation of unconformities, sedimentation rates and palaeoenvironments, they are less useful for correlation because of strong facies changes. Most authors, even very recently, have accepted palynological interpretations as indicators of absolute time (e.g. Mutter et al., 1985). Such confidence is unjustified as old data cannot be compared with more recent data because of revisions in zonation and taxonomy, and that even recently, experienced palynologists differ greatly on their zonations of the same well: e.g. Argonaut Al, Alley (1984) vs Morgan (1985) or Banyula 1, Harris & Foster (1982) vs Morgan (1985). Some workers is rely heavily on cuttings determination (particularly Morgan), which lithologically at least show contamination by younger units (see v below). These limitations should be considered when basing interpretations on palynological data.

iii) It is unlikely that regional unconformities will be differentiated from diastems of local extent from available petrophysical logs of a particular well. Angular unconformities are particularly difficult to differentiate from certain types of faults on dipmeter logs. Some unconformities assumed from available seismic data (much of which is of poor quality) may represent the top of prograding sequences, which give rise to the appearance of high angle discordance with overlying strata, where there is insufficient resolution to recognise the tangential onlapping foresets. Furthermore, where seismic data quality is fair to good "there is no obvious angular relationship" in the offshore western part of the Otway Basin, and "deposition ... appears to have been continuous" (Boeuf & Doust, 1975, p.38). In general, but particularly for prograding sequences, seismic reflectors are synchronous surfaces that are independent of facies changes and hence formation boundaries (Vail & Mitchum, 1977). New palynological data suggest that few of the presumed unconformities exist as major basin-wide time breaks. In fact, condensed sequences occur near the basin margins, whilst towards to deeper parts of the basin, nearer the main axis of rifting, sedimentation rates were an order of magnitude larger. For this reason the term 'Condensed Sherbrook Group' is introduced to represent a predominantly sandy sequence spanning the late Cretaceous to Early Tertiary.

iv) Many of the names previously applied to the Otway Basin have not been adequately defined; the type sections for some others have been changed so often that the nomenclature has become cumbersome and applicable to restricted localities only. There are problems, too, in extrapolating some surface units to the subsurface, partly because of basinward facies changes, and partly because criteria applied to recognition of weathered outcrops do not always apply in unweathered subsurface intersections.

v) In general, cuttings do not provide a useful indication of lithology, even within such consolidated units as the Otway Group. This can be demonstrated in wells where full-hole or sidewall cores were taken; muddy or silty units can appear very sandy due to either the preferential mud dispersion from cuttings or contamination by younger unconsolidated units. This was further demonstrated recently by Banyula 1. Petrophysically the Eumeralla Formation appears as a monotonous unit from 831-2 350 m, but cuttings show substantial sand from 831-1 552 m. Coincidentally, casing was set at this depth, preventing contamination of the Eumeralla cuttings by Sherbrook Group Sands below 1 552 m. In all wells drilled to date, the only continuous indication of the lithology is by means of petrophysical logs which, when calibrated against cores, provide the primary source of data for lithological correlation. Gamma Ray and Sonic logs, when digitized can be displayed in a variety of standardized formats and scales not previously possible, which has greatly facilitated correlation in this study. However, care must be taken to check scales on logs - even recently digitially recorded logs e.g. Breaksea Reef 1 would appear to have wrongly marked GR scales which had to be corrected before cross-sections were constructed.

The lack of understanding of the limitations of available data by modern authors is highlighted in a recent paper which discussed the time of onset of separation of Antarctica and Australia (Mutter et al., 1985). Their use in converting old palynological data to absolute time, their assumptions that unconformities were periods of non-deposition (i.e. no erosion of older sediments) and that wells with complete Early/Late Cretaceous sequence are biased to marginal areas of the main rift axis (i.e. there is strong N-S variation in sedimentation rates that was not taken into account) all suggests that their conclusions concerning the time of onset of drift at various locations along the southern margin may be unjustified.

3.3 Pre-Mesozoic Rocks

Only wells in the northern part of the onshore section of the Otway Basin have intersected pre-Mesozoic rocks. With one exception (Robertson 1) these consisted of steeply dipping quartzites, phyllites and argillites, which are in general of low metamorphic grade. These have been correlated with the Cambrian Kanmantoo Group, metamorphosed during the Delamerian Orogeny (Rodgers, 1980). However, Kalangadoo 1, core 14 (2150-2156 m) contains possible carbonized plant fragments suggesting a considerably younger age for part of the sequence in ths region. Robertson 1 intersected trachyte (keratophyre) which is tentatively correlated (based on petrographic similarity) with Ordovician acid volcanics associated with intrusives north of the Padthaway Ridge, and which were intruded during the late stages of the Delamerian Orogeny. This interpretation differs from the assumed Jurassic age of Milnes et al. (1982).

No definite Permian sediments are known from the Otway Basin in South Australia, however, Permian diamictites and glacio-marine sediments are known north of the Padthaway Ridge (near Kingston) in the Troubridge Basin, and may occur, at least in isolated depressions beneath the Otway Basin. In Lake Eliza 1 (1315 to 1390 m), hard carbonaceous brown mudstone, grey micaceous siltstone and sandstone were intersected, which from cuttings descriptions are lithologically similar to Permian sediments from the Kingston area (Ludbrook, 1961, 1971). Large areas of Permian sediments were probably present adjacent to the Otway Basin, and provided one source of sediment for the Mesozoic and younger sediments, as recycled Permian palynomorphs are often abundantly present in Late Cretaceous sediments (Alley, 1984; Morgan, 1985).

3.4 Otway Group

Sediments deposited at initial stages of rifting (the "Rift Valley") before oceanic basement was formed, have been termed the Otway Group in the Otway Basin, but correlatives occur in the Duntroon and Great Australian Bight Basins. The sequence consists of 2 main units - a lower braided fluviatile unit (Pretty Hill Sandstone), overlain by a shaly unit with minor fine sand and coal (Eumeralla Formation), probably deposited in meandering fluvial and floodplain environments. Palaeocurrent indications within the Pretty Hill Sandstone (Medwell, 1977; and Fig. 8) indicate an east to west flowing braided river complex. Furthermore, the Pretty Hill/Eumeralla Formation boundary youngs to the east, suggesting that sediment transport was predominantly along the axis of the rift valley, and that palaeotopographic gradients decreased to the west to a regional 'low' near the Great Australian Bight. In the Duntroon and Great Australian Bight Basins few wells have been drilled, but the meagre data available indicate a similar stratigraphy to the Otway Group, with the exception of the Duntroon Basin, where both wells found only shaly sediments with no apparent Pretty Hill Sandstone equivalents. Here and elsewhere outside the Otway Basin, no palaeocurrent data are available. The presence of rare acritarchs (Reynolds, 1971) particularly in the western Victorian portion of the Otway Basin, suggests at least a brackish water or even marginal marine influence and recent palaeogeographic reconstructions for Australia in the Early Cretaceous (e.g. Coleman, 1980) indicate that a widespread epeiric sea covered much of inland Australia and in the central part of the rift, to the west of the present limit of the Otway Basin in South Australia.

Although the available evidence is meagre at present, the following depositional model for the Otway Group is possible: 2 major braided to distally meandering river systems flowed from the east and west respectively into a saline lake or restricted sea near the central more rapidly subsiding part of the rift, near what is now the Great Australian Bight. There is one restriction to this interpretation which should be noted: all drilled sections of the complete Otway Group have only a thin overlying Sherbrook Group (described below) - hence all available data are biased to marginal areas of the rift system - in the main axis of the rift the Otway Group has not been penetrated due to the overlying 3 000-3 800 m of Sherbrook Group sediments. Thus we know very little about the Otway Group in areas that were on the main axis of the rift; conceivably sediments of different origin could exist to the south of the presently drilled areas.

i) <u>Casterton Volcanics</u>

A sequence of interbedded carbonaceous shale and minor feldspathic sandstone and siltstone, characterized by interbedded olivine basalt and volcaniclastics was intersected in the western Victorian well, Casterton 1 (2063 to 2445 m). This unit, of probable Late Jurassic age has not been formally defined because of its limited known occurrence, although it was recognized informally as 'Unit J' by Reynolds et al. (1966) and "Basal Unit" by Ellenor (1976). Other authors (Wopfner et al., 1971, Kenley, 1976) have used the name "Casterton beds" informally. It is suggested that the name be changed to Casterton Volcanics to reflect the essential volcanic character of the unit and to formally define the intersection from 2063 - 2445 m in Casterton 1 as the type section.

K-Ar dates of the basalt range from 153±5my (in Harding, 1969) to 120±10my (Reynolds, 1971), which correspond to a Late Jurassic to Early Cretaceous age. Middle Jurassic Wisanger Basalt from Kangaroo Island (Milnes et al., 1982) may be a correlative of the Casterton Volcanics. No definite Jurassic to Cretaceous volcanics have been intersected from wells in South Australia to date, however, they are interpreted to be present in deeper areas not yet penetrated.

ii) Pretty Hill Sandstone (Figs 7, 8)

a) Definition and nomenclature

An "unnamed sandstone" below the Eumeralla Formation, recognized by Bain (1962) was informally defined by Edworthy (1963), and subsequent authors (Reynolds et al., 1966; Wopfner et al., 1971; Reynolds, 1971; Ellenor, 1976; Abele et al., 1976) have used the name without formal definition. Reynolds et al (1966) maintained that the Pretty Hill Sandstone in Pretty Hill 1 was unique, and introduced the name "Geltwood Beach Formation" for the more lithic and shaly sandstone sequence intersected in other wells. This is unnecessary if a reasonable amount of lithological variation within the Pretty Hill Sandstone is allowed for (reflecting different source areas, but not different palaeoenvironments of deposition), and the name is here used for a predominantly sandstone sequence of the basal Otway Group.

b) Type Section

Not previously defined. Here proposed as Pretty Hill 1, 1817 to 2400 m (5964-7874'). The top is defined as the first major and consistent sandstone sequence below the Eumeralla Formation, which corresponds to a negative shift on the SP log and lower count level of the Gamma Ray log. The base is defined in the type section as the contact with an altered ultrabasic igneous rock, assumed to be a Cambrian basement complex, and which corresponds to a positive shift on the SP log (Bain, 1962).

c) South Australian Reference Section

Crayfish A1, 1597 to 3199 m, (5240-10 497'). Total depth was reached in Pretty Hill Sandstone, so the base is undefined in this well.

d) Lithology and Distribution

The unit consists of interbedded quartz-feldspar-lithic sandstone and carbonaceous siltstone and mudstone, which is confined to structurally low areas such as the Robe-Penola Trough. The quartz:feldspar ratio varies from 90:10 in the west (Crayfish A1) to 50:50 in the east (Banyula 1). Sedimentary structures in cores include high angle cross bedding (some with graded foresets) and climbing ripples. Slump features (interpreted to be bank slumps) are common throughout, and minor shale intraclast conglomerate is also present. In Diamond Swamp 1 and Beachport East 1, breccia, predominantly of basement clasts occurs together with sandstone. It is probably a proximal facies equivalent to the Pretty Hill sandstone which was deposited on the margins of basement highs and may have been deposited in an alluvial fan environment.

The formation thickens to the west, along the axis of the Robe-Penola Trough. Pretty Hill Sandstone is possibly also present south of the Beachport-Kalangadoo High, but only one well (Geltwood Beach 1:3490 m to TD) has penetrated this sequence.

e) Thickness

47 m (Diamond Swamp 1, breccia), to over 1585 m (Crayfish A1).

f) Age

Early Cretaceous, Neocomian to ?Aptian (C. stylosus Zone to D. speciosus zone - Lower C. hughesi subzone) in all wells with palynology (Harris & Foster, 1982; Dettmann, 1968; Evans & Mulholland, 1970a,c; Stover, 1974a,b).

In Chama 1A, it would appear that deposition of the Pretty Hill Sandstone in other wells was synchronous with the lowermost parts of the Eumeralla Formation (Evans, 1970) in this well.

g) Palaeoenvironment

The lithology and sedimentary structures suggest low sinuosity fluvial palaeoenvironment, similar to that proposed by Medwell (1977) for similar, although slightly younger, sediments in the Otway Group of the Otway Ranges, in the eastern Otway Basin. Palaeocurrent directions measured by Medwell (1977) suggest that low sinuousity, mixed load rivers fed a westward flowing river belt. A similar westerly palaeocurrent direction for the Pretty Hill Sandstone in the Robe and Penola Trough is demonstrated in palaeocurrent data derived from dipmeter logs (Fig. 8) and by the westward thickening of the formation (Fig. 7). The presence of rare acritarchs, noted by Reynolds (1971), in the western Victorian portion of the basin suggests proximity to more brackish facies or an ephemeral brackish influence.

iii) Eumeralla Formation (Fig. 9)

a) Definition and Nomenclature

Reynolds et al. (1966) proposed the name Eumeralla Formation for the monotonous sequence of chloritic siltstone, shale and subordinate sandstone of the Otway Group.

b) Type Section

Eumeralla 1, 947 to 2777 m.

c) South Australian Reference Section

Banyula 1, 830 to 2350 m.

d) Lithology and distribution

The Eumeralla Formation, which forms the major portion of upper Otway Group sediments, either unconformably overlies pre-Mesozoic basement or the Pretty Hill Sandstone. This latter contact may be conformable in the trough areas, but recent seismic data north of Banyula 1 near the margin of the trough suggest that below a prominent seismic marker horizon, (corresponding to a porous intra Eumeralla sandstone in Banyula 1), there appears to be a marked angular discordance between the Pretty Hill sandstone and the Eumeralla Formation. This 6 m thick sandstone has been tentatively correlated with the "Heathfield Sandstone" (informal) in Heathfield No. 1, western Victoria (Djokic & Chan, 1982).

The Formation consists of laminated medium greenish grey, micaceous, carbonaceous silty claystone, with interbeds of very fine sandstone, showing climbing ripples. Minor associated lithologies and sedimentary structures seen in cores include, well preserved plant fragments, slumped and contorted beds, rare bioturbation, massive medium grained sandstone, shale intraclast conglomerate, and thin coals.

f) Thickness

The Eumeralla Formation ranges from 467 m (Lucindale 1) to 2350 m (Geltwood Beach 1).

g) Age

Early Cretaceous Aptian Cenomanian, (D. speciosus zone, upper C. hughesi subzone to P. pannosus zone). In one well, Chama 1A, the Eumeralla Formation may range down to the Neocomian (C. stylosus zone) (Dettmann, 1965, 1968; Stover, 1974b; Evans, 1970; Harris & Foster, 1982; Evans & Mulholland, 1970a,b,c; Stover, 1974a,b).

h) Palaeoenvironment

The dominance of fine-grained lithologies (mudstone and siltstone) over coarser grained lithologies suggests a relatively low energy palaeoenvironment compared with the Pretty Hill Sandstone. The fine grained sandstones with climbing ripples and rare bank slump features suggest the presence of minor high sinuosity streams flowing over a wide floodplain. Lacustrine and back swamp environments were also probably present. The lack of any major sandstones from cores or logs suggests that there was no well-developed drainage system during deposition of the Eumeralla Formation.

3.5 Sherbrook Group

The thick post-rift progradational deltaic sequence (similar to the Niger delta, Evans et al., 1978) has been termed the Sherbrook Group, mostly of Late Cretaceous age. Mutter et al. (1985) recently revised the age of break up between Australia and Antarctica to possibly as old as 110 Ma B.P. (approximate to Early/Late Cretaceous boundary), a conclusion which is in close agreement with the sudden change in depositional style between the Otway and Sherbrook Groups. However, drifting proceeded at a slow rate for about 50 Ma (i.e. to about the Cretaceous/Tertiary boundary; which also corresponds to a change in depositional style. The Sherbrook Group is overlain by a thinner progradational sequence called the Wangerrip Group, of Early Tertiary age, so that for most of the Late Cretaceous, Australia and Antarctica were separated by a narrow rapidly subsiding basin. The depositional model is one of a large deep saline lake; probably connected with a restricted sea further east, with very large prograding deltas (comparable in size and sedimentation style to the Tertiary Niger Delta, Evans et al., 1978), feeding into the basin at right angles to the main axis of rifting. Areas to the north that were not underlain by thinned continental crust or new oceanic basement, and hence underwent much less subsidence, have a condensed Sherbrook Group sequence that is at least an order of magnitude thinner, and which is probably mostly of fluvial origin. Thus, sediment sourced in areas to the north, was 'by passing' this relatively stable marginal area to be 'dumped' in the rapidly deepening depocentre to the south. There is also an apparent east to west change in sedimentation style comparable to (but in an opposite sense from), that found in the Otway Group. There are clear indications of fully marine conditions in the eastern part of the basin in Victoria, which decrease westwards; the glauconitic Nullawarre Greensand Member is not found west of the Dartmoor Ridge, and marine molluscs and glauconite found in the Belfast Mudstone in Victoria are not found in the South Australian portion of the Otway Basin. This suggests that the deep east-west elongate basin was open to the east and restricted to the west. The black, pyritic nature of the Belfast mudstone strongly suggests that anoxic conditions existed within the Sherbrook Group, i.e. that the lake or restricted sea was stratified and non-circulating.

i) Flaxman Formation (Fig. 10)

a) Definition and Nomenclature

Bain & McQueen (1964) first published the name "Flaxmans Beds", nominating Port Campbell 2 as the type well, but no interval was specified as the type section. Bock & Glenie (1965) applied the term Flaxman Formation to a unit transitional between the sandy Waarre Sandstone and the Belfast Mudstone. The name is used in South Australia for the sandy sequence below the Belfast Mudstone, and above the Eumeralla Formation i.e. the Waarre Sandstone is not recognized as a separate unit.

b) Type Section

Port Campbell 2, 2340 to 2494 m as redefined by Glenie (1971). However, the type section has been defined for 7 different intervals in this well by previous authors (as reviewed by Glenie 1971, p.201). It is questionable whether Port Campbell 2 should be the type section at all. As noted by Glenie (1971) the interval in Flaxmans 1, 1984 to 2096 m provides a better example of the Formation, and it is suggested that this interval be defined as the type section, to correspond to the original concept. There seems little justification for retaining Port Campbell 2 as the type section, particularly as Bain & McQueen (1964) stated that there is evidence for an unconformity at the contact with the Belfast Mudstone, in contrast to Flaxmans 1. Furthermore, the obvious confusion by past authors over the Port Campbell 2 section warrants the change to Flaxmans 1, which is better documented (Bain, 1961).

c) South Australian Reference Section

Caroline 1, 2466 to 2841 m (8090 to 9320').

d) Lithology and distribution

The formation is restricted to the southern portion of the Otway Basin but because of the great thickness of the Sherbrook Group relatively few wells have fully penetrated this unit. To the north it probably passes laterally into a condensed Sherbrook Group Sequence. On petrophysical logs the Formation appears as an interbedded sequence of "coarsening-upward" sandstones and fine grained units. In cores the unit consists of ubiquitously bioturbated fine sandstone interbedded with carbonaceous micaceous muddy siltstone. Associated sedimentary structures include slumped beds, climbing ripples, rare pillar structures and some red oxidation of the sandstones. The formation is probably conformable on the Eumeralla Formation, and conformable with the overlying Belfast Mudstone. Where the Belfast Mudstone is absent the Flaxman Formation is not differentiable from the Paaratte Formation.

e) Thickness

Thickness in Caroline 1 is 375 m, the only well to have fully penetrated the Formation in South Australia.

f) Age

Palynological age determinations for the Formation in South Australia are from Argonaut Al and Breaksea Reef 1 which indicate Late Cretaceous, Turonian (*A. distocarinatus* to *C. Triplex* zone) Alley (1984), (Morgan) 1985.

g) Palaeoenvironment

The Flaxman Formation was deposited during the first phase of a deltaic depositional regime which extended into the Early Tertiary. The 'coarsing upward' sandstones were deposited by laterally migrating delta distributaries on the lower delta plain, and the ubiquitous bioturbation in this unit implies deposition near a large, permanent body of water, possibly marine to restricted marine (Reynolds, 1971; Glenie, 1971; Ellenor, 1976). This sudden change in depositional environment at the base of the formation reflects broadening of the Palaeo-rift between southern Australia and Antarctica.

ii) Belfast Mudstone (Fig. 11)

a) Definition and Nomenclature

The name was first published by McQueen (1961) for black glauconitic mudstone overlying the Waarre Formation and underlying the Paaratte Formation. He noted that it had been first discovered in Belfast 4, but did not nominate a type section. Bain & McQueen (1964) nominated Port Campbell 1 as type section. Bock & Glenie (1965) changed the unit's status to a member of the Paaratte Formation, which has been adopted by most later workers (Glenie, 1971; Douglas, 1976; Ellenor, 1976). However, Reynolds (1971) reinstated the Belfast Mudstone as a Formation, and I concur with this practice. The unit is widespread and mappable over much of the basin, and is genetically related to the deltaic sequence, as is the Paaratte Formation.

b) Type Section

Port Campbell 1, 1501 to 1685 m, as redefined by Glenie (1971). As for the Flaxman Formation, the Belfast Mudstone has had numerous different intervals designated by previous authors for the type section. This confusion may be a result of too rigid a concept for the Belfast Mudstone. The unit intercalates to a degree with the sandy Paaratte and Flaxman Formations. The definition of the unit in South Australia is expanded to be that interval of predominantly black siltstone and mudstone, with subordinate sandstone, between the Flaxman and Paaratte Formations, i.e. the Belfast Mudstone is that interval where fine-grained lithologies dominate over sandy lithologies.

c) South Australian Reference Section

Caroline 1, 2161 to 2466 m (7090 to 8090')

d) Lithology and distribution

The Belfast Mudstone is restricted to the southern area of thick Sherbrook Group deposition; to the north it pinches out and the Paaratte and Flaxman Formations become undifferentiable.

On petrophysical logs the unit has a monotonous high Gamma Ray signature, with some sandstone interbeds of Flaxman/Paaratte Formations aspect. Core recoveries are in general low from the Belfast Mudstone, but where recovered it consists of black, massive, very carbonaceous mudstone. Sedimentary structures in the very fine-grained sandstone to siltstone beds include climbing ripples, and ubiquitous bioturbation, identical to those of the Flaxman and Paaratte Formations. The upper and lower contacts are conformable and strongly diachronous, younging away from the basin margin.

e) Thickness

Penetrated thickness ranges to over 1355 m in Breaksea Reef 1. The unit thickens to the south.

f) Age

Late Cretaceous, Cenomanian to Santonian, (A. distocarinatus to T. pachyexinus zones) (Alley, 1984; Partridge, 1975).

g) Palaeoenvironment

The Belfast Mudstone is a complex of upper prodelta, slope, deltafront and inter-distributary deposits, and upper delta-front deposits (cf. delta-top (lower delta plain) deposits of Flaxman and Paaratte Formations). The highly carbonaceous and pyritic lithology suggests deposition in either a marine or brackish body of standing water. The most landward occurrence may correspond to a transgressive maximum, due either to eustatic sea level rise, or a phase of maximum subsidence within the main rift. However, unequivocal evidence of marine sediments is lacking in South Australia.

iii) Paaratte Formation (Fig. 12)

a) Definition and Nomenclature

The name was first published by McQueen (1961, p.11) for the formation above the Belfast Mudstone "consisting of interbedded sandstone siltstone and mudstone, dolomitic and pyritic in parts and containing marine fossils". Bock & Glenie (1965) included the Belfast Mudstone, Nullawarre Greensand, and Timboon Sand as members within this formation. However, in South Australia, use is restricted to the original concept of McQueen (1961); i.e. an interbedded sequence transitional between the Belfast Mudstone and the Timboon Sand.

b) Type Section

Port Campbell 1, 1295 to 1501 m; the Paaratte Formation sensu stricto as redefined by Glenie (1971). As with the Flaxman Formation and Belfast Mudstone many different intervals have been proposed for the type section by previous authors.

c) South Australian Reference Section

Caroline 1, 1740 to 2161 m (5710 to 7090').

d) Lithology and Distribution

The Formation thickens to the south; to the north it passes laterally into the Timboon Sand and further north into a condensed Sherbrook Group Sequence. Both the upper and lower contacts of the formation are strongly diachronous.

In cores the formation consists of an interbedded sequence of black carbonaceous shale and bioturbated fine to coarse quartz-rich sandstone. The sandstone beds have a coarsing upward gamma ray log signature, similar to the Flaxman Formation, and contain siderite concretions and carbonized wood fragments. The upper contact is either conformable, passing into the Timboon Sand, or unconformable with the Dilwyn Formation.

e) Thickness

The penetrated thickness ranges from 421 m (Caroline 1) to 1439 m (Morum 1).

f) Age

Late Cretaceous, Turonian, to Maestrichtian (C. triplex zone to T. lillei zone), (Alley, 1984; Partridge, 1975; Evans, 1963).

g) Palaeoenvironment

The Paaratte Formation was deposited in a lower delta-plain environment; distributaries prograded south over the delta-front and interdistributary sediments of the Belfast Mudstone. Lagoonal and marginal shoreface environments are also probably represented by the Paaratte Formation (Reynolds, 1971).

iv) Timboon Sand (Fig. 13)

a) Definition and Nomenclature

Initially proposed as a member of the Paaratte Formation by Bock & Glenie (1965) for a largely non-marine quartz sandstone unit above the Paaratte Formation sensu stricto and below the Pebble Point Formation. Glenie (1971) further defined the unit, and suggested Port Campbell 1 as the type section. In this study it includes facies of the Pebble Point Formation, i.e. the Timboon Sand is used for the entire sandstone sequence above the Paaratte Formation and below the Dilwyn Formation.

b) Type Section

Port Campbell 1, 886 to 1295 m (2906 to 4250').

c) South Australian Reference Section

Caroline 1, 892 to 1740 m (2928-5710').

d) Lithology and Distribution

The Timboon Sand is distributed as a relatively narrow band of thick sand over the nearshore area of thick Sherbrook Group deposits. To the south the unit passes laterally into the Paaratte Formation, and to the north passes into part of the condensed sequence. The Gamma Ray log signature through this sequence is a typical of a clean sandstone, with relatively minor shale interbeds. In cores the unit consists of medium to coarse massive quartz sandstone often with ferruginous cement and oöliths, with minor ripple cross-laminated fine sandstone and siltstone. This is interbedded with black to brown very micaceous silty mudstone, commonly bioturbated. The upper contact with the Dilwyn Formation is unconformable.

e) Thickness

656 m (2151') in Burrungule 1 to 1590 m (5218') in Argonaut A1.

f) Age

Late Cretaceous, Coniacian, to Tertiary, Paleocene (*T. pachyexinus* zone to *T. longus* zone) (Alley, 1984; Partridge, 1975; Evans, 1963).

g) Palaeoenvironment

The Timboon Sand is normally regarded as a regressive unit deposited on the upper delta plain during the last phase of the prograding deltaic sequence of the upper Sherbrook Group. It was presumably formed in a non-marine environment, but bioturbation present in cores suggests an intermittent marginal-marine influence.

Cores from the Pebble Point Formation facies indicate slow sedimentation in an environment of sufficiently low energy to permit growth of large (several mm) solitary and composite chamosite rich, ooid-like concretions, and poorly sorted quartz clasts (fine sand to granule size), floating in a muddy matrix of in situ iron rich spherulites. These are considered to have formed in interdistributary bay muds on the lower delta plain during an episode of reduced detrital sedimentation, analogous to chamositic oolites in the Guayabo Group, northeastern Colombia (James & van Houten, 1979).

v) 'Condensed Sherbrook Group' (Fig. 14)

a) Definition

The name is used informally for that Late Cretaceous to Early Tertiary, sandy lateral equivalent of the thick Flaxman Formation to Timboon Sand sequence found south of the Tartwaup hingeline. It is a condensed sequence that is not lithologically differentiable into the recognized Sherbrook Group Formations (at least on Gamma-Ray and Sonic logs).

b) South Australian Reference Section

Kalangadoo 1, 544 to 765 m (1785-2510').

c) Lithology and Distribution

This unit is mapped beyond the area of thick Sherbrook Group deposition (north of the Tartwaup hingeline), but approaching the northern margin; of the Otway Basin, particularly over the Robe-Penola Trough it passes laterally into presently undifferentiated Wangerrip/Sherbrook Group sequences.

Very few cores have been cut and cuttings indicate a predominantly sandy lithology, but in Kalangadoo, core 1, 607 to 612 m, ferruginous oolitic sandy mudstone, characteristic of the Pebble Point Formation facies, was recovered. This is overlain by brown grey micaceous silty mudstone, characteristic of the Dilwyn Formation (Pember Mudstone Member). The upper contact with the Wangerrip Group appears to be transitional and palynology indicates no significant time break, hence the Sherbrook/Wangerrip Groups may be conformable in onshore areas of the Otway Basin. There is a sharp lithological change at the basal contact with the Eumeralla Formation which may be unconformable.

d) Thickness

82 m (Lake George 1) to 588 m (Geltwood Beach 1).

e) Age

Late Cretaceous, Cenomanian, to Early Tertiary, Paleocene. (A. distocarinatus zone to L. balmei zone (Harris & Foster, 1982; Evans & Mulholland, 1970b)). Similar ages are recorded for the undifferentiated Wangerrip/Sherbrook Groups. There appear to be palynological zones missing in some wells on available data, however, due to the condensed nature of the sequences, this is probably due to insufficient close spacing of sample points, but local hiati may exist.

f) Palaeoenvironment

As few cores have been taken in this formation, very little can be inferred about the palaeoenvironment. The origin of the Pebble Point Formation facies has been discussed above.

The 'Condensed Sherbrook Group' was probably generally deposited in an upper deltaic floodplain (i.e. dominantly fluvial environment), of the prograding deltaic regime represented by the thick Sherbrook Group further south. Sedimentation rates for the Sherbrook group are at least an order of magnitude lower north of the Tartwaup hingeline than to the south probably because the area mapped as 'Condensed Sherbrook Group' was a relatively stable area, largely "by passed" by sediments which were ultimately deposited in the rapidly subsiding basin to the south.

3.6 Wangerrip Group

Dilwyn Formation (Fig. 15)

a) Definition and Nomenclature

The unit was first named Dilwyn Clay by Baker (1953). Bock & Glenie (1965) changed the name to Dilwyn Formation and differentiated the Pember Mudstone Member. Abele *et al.* (1976) regarded the Dartmoor Formation of Boutakoff & Sprigg (1953) as a junior synonym of the Dilwyn Formation. I regard the Lacepede Formation, Kongorong Sand, and Tartwaup Formation (including the Burrungule Member), proposed by Ludbrook (1971), as junior synonyms of the Dilwyn Formation. The fine-grained Burrungule Member is probably a junior synonym of the Pember Mudstone Member.

b) Type Section

Pebble Point, 2.4 km southeast of the mouth of the Gellibrand River as summarized by Glenie (1971).

No subsurface reference section has been designated, although Bock & Glenie (1965) and Glenie (1971) stated that the Pember Mudstone Member is easier to differentiate in La Trobe 1 than in the type section. Blake (1980) informally defined the Mussel Sandstone, here regarded as a member of the Dilwyn Formation.

c) South Australian Reference Section

Beachport East 1, 191 to 404 m (625-1325'). The Pember Mudstone Member occurs from 351 to 404 m (1150-1325').

d) Lithology and Distribution

Two broad facies assemblages characterize the Dilwyn Formation on petrophysical logs: 1) a landward assemblage, consisting of the Pember Mudstone Member overlain by a sandy sequence (Dilwyn Formation *sensu stricto*), which is partly Late Cretaceous in age and more closely related to the Sherbrook Group than Wangerrip Group. 2) a basinward sequence of more mixed lithology. These can be further subdivided into deltaic cycles (Holdgate, 1982). The Formation was extensively cored in Caroline 1; cores 2-9 (213 m to 828 m). The sandy upper part of the Dilwyn Formation has low core recoveries, but appears to consist of a coarse, ferruginous sandstone with minor carbonaceous micaceous mudstone and siltstone. The Pember Mudstone Member is a monotonous sequence of very well-laminated silty mudstone, carbonaceous and micaceous with thin wispy very fine sandstone interbeds. The Mussel Sandstone Member, characterized by very low gamma ray values appears as a blocky, clean sand on logs. It has not been cored in S.A. at present. The upper contact with the Gambier Limestone is unconformable.

e) Thickness

The thickness of the Dilwyn Formation ranges from 101 m (Beachport 1) to 818 m (Kentgrove 1). The Pember Mudstone Member ranges from 49 m (Diamond Swamp 1) to 102 m (Argonaut A1). The Mussel Sandstone is 310 m thick in Breaksea Reef 1.

f) Age

Middle Paleocene, to Late Eocene (*L. balmei* zone to *M. diversus* zone) (Alley, 1984; Harris & Foster, 1982; Harris, 1973; Evans, 1963; Evans & Mulholland, 1970b).

g) Palaeoenvironment

Blake (1980) and Holdgate (1982) gave a detailed palaeo-environmental analysis for the range of facies assemblages within the Dilwyn Formation. The Dilwyn Formation (*sensu stricto*), onshore facies was probably deposited as fluvial and delta distributary channels, the Pember Mudstone Member as interdistributary bay muds.

In the offshore facies assemblages the Dilwyn Formation was deposited in prodelta and interdistributary bay environments, with the 'Mussel Sandstone' being deposited as offshore barrier bars (Blake, 1980).

3.7 Younger Sediments

i) Gambier Limestone

Most sections in South Australia are covered by the Gambier Limestone, a glauconitic bioclastic calcarenite which can range up to 400 m thick offshore. A basal glauconitic marl referable to the Gellibrand Marl (Abele et al., 1976) occurs in some wells. The Limestone was unconformably deposited on the Wangerip Group as a marine prograding sequence during the Oligocene and Miocene. This unconformity, the "Marshall Paraconformity" of Carter and Landis (1972) records the final phase of separation of Antarctica from Australia and the establishment of an erosive Circum-Antarctic current (Carter & Norris, 1976). The top of the Gambier Limestone is usually eroded except in distal offshore areas.

ii) Pliocene? to Recent sediments

A prograding sequence of sediments present on seismic sections, unconformably overlies and is clearly younger than the Gambier Limestone. It most probably represents Pliocene to Recent sediments, possibly deposited during low sea levels.

4. PLAY CONCEPTS
(D.I. Gravestock)

Hydrocarbon plays in the South Australian portion of the Otway Basin are assessed with reference to the two most prospective capped reservoir facies complexes. The first is the Early Cretaceous Otway Group (Pretty Hill Sandstone in particular), fluvial dominated and principally confined to the area of the Penola and Robe Troughs north of the Tartwaup Fault. The second is the Late Cretaceous Sherbrook Group, dominantly deltaic and principally located south of the Tartwaup Fault, but probably extending offshore, northwest to latitude 37°30'S. Both facies complexes occur at depths in which drilled source rocks are oil-mature (1 000 - 4 000 m), based on vitrinite reflectance data (Cook, 1980; Felton & Jackson, 1985, in press; Holdgate et al., 1985; Struckmeyer, 1985a,b; 1986a,b,c).

Inadequate depth of burial and lack of effective seal downgrade the generative and trap potential of the Early Tertiary (Wangerrip Group) in South Australia and although hydrocarbon migration along faults or updip from deeper source rocks is likely (Tabassi & Davey, 1985), lack of data precludes discussion. Blake (1980) and Holdgate (1982) have described the Tertiary deltaic sequence in Victoria; Holdgate et al. (1985) have assessed hydrocarbon prospects in the vicinity of the Portland Trough.

4.1 Early Cretaceous (Otway Group) Fluvial facies complex

Stacked fluvial deposits of the Pretty Hill Sandstone are attributed to bedload-dominated low sinuosity streams discharging into a major river system presumed to flow west to northwest through the Penola and Robe Troughs (Fig. 8). These form the northernmost pair of a series of subparallel troughs which may at times have been interconnected, and which possibly intersected the major Australo-Antarctic Rift. Local alluvial fan deposits (Diamond Swamp 1, Beachport East 1) indicate proximity to scarps of moderate relief on the southern margin of the Penola and Robe Troughs, while infill from the gentler northern margin onshore (Padthaway Ridge) allowed accumulation of fluvial sediments of different provenance.

The Pretty Hill Sandstone (Fig. 7) and Eumeralla Formation (Fig. 9) have thickest intersections offshore in the vicinity of Crayfish A1 and Chama 1 respectively, but maintain the trough-like configuration. Further west it is likely that major fluvial systems discharged down the palaeoslope into an as yet undrilled rift-basin enclosing ?marine or lacustrine environments via deltaic complexes. Certainly a large volume of sediment was transported in a westerly direction. Extensive, organic rich lacustrine source rocks may be present downdip, ideally placed to charge fluvial (?and deltaic) reservoirs in the Otway Basin (McKirdy, 1985; McKirdy et al., 1986).

A number of wells (e.g. Crayfish A1, Lake Eliza 1, 2, Trumpet 1) have demonstrated that the Pretty Hill Sandstone has good reservoir characteristics where the quartz:lithic ratio is high and carbonate cement minimal, but variable porosities and permeabilities from cores recovered to date (Table 2), render reservoir quality unpredictable. In these wells the 'quartz-rich facies' was encountered on (present day) structural highs, but regional distribution is unknown; possibly the 'quartz-rich facies' underlies volcanogenic sands in structurally lower areas.

In the Penola and Robe Troughs, subordinate overbank mudrocks and diagenetically altered, tight volcanogenic sandstones provide intraformational seals, while the heterolithic Eumeralla Formation in particular, forms a regional seal. The Eumeralla Formation was deposited in dominantly floodplain and possibly lacustrine environments, the former poorly drained by small mixed-load streams. Thin sections of cuttings from Banyula 1 indicate that sandstone is fine grained and often cemented by carbonate. Permeability is low, based on limited core data (Kalangadoo 1, Table 2).

Diagenesis

An extremely high proportion of fresh volcanogenic detritus (Boeuf & Doust, 1975; Duddy, 1981; Gleadow et al., 1983) indicates erosion of contemporaneous trachytic volcanic rocks which Bhatia (1982) has shown are mineralogically distinct from those expected from an eastern magmatic arc provenance (cf. Veevers et al., 1982). Whatever the origin of the feldspar (dominantly plagioclase) which comprises up to 50 per cent of framework grains, diagenetic alteration has considerably reduced primary porosity and permeability in potential sandstone reservoirs.

Removal of feldspar alteration products; chlorite which coats framework grains, interstitial zeolite and locally abundant carbonate (Rochow, 1971; Bhatia, 1982), is required to create secondary porosity in the worst affected sandstones. Bhatia (1982) has suggested that secondary porosity could develop by alteration of laumontite (zeolite) to calcite plus kaolinite, and has observed secondary porosity due to calcite dissolution in cores from Banyula 1. Creation of secondary porosity by calcite dissolution and enhancement of permeability by dolomitization of remnant calcite offer the best chances of improving reservoir quality in such sandstones, while plays which avoid the volcanogenic facies are obviously preferred. Detailed analysis of dipmeter data together with petrological study of cores and cuttings may provide a means of locating the source direction of volcanogenic detritus.

Structural controls

Poor seismic quality and low regional coverage north of the Tartwaup Fault preclude accurate forecasts of structural controls on hydrocarbon trap formation. Were it otherwise, commercial discoveries would probably have been made by now in the Otway Group in South Australia. Lack of factual data provides scope for wide speculation on structural styles anticipated in an extensional tectonic regime associated with the early stages of Cretaceous rifting between Australia and Antarctica, but structural controls are undoubtedly complex and partly dependent on the Palaeozoic history of the region as found elsewhere (Kent, 1973).

On the assumption that magnetic anomalies in this region reflect Early Palaeozoic structural trends parallel to those in western Victoria (e.g. Crook, 1980; Powell, 1983), there is likely to be a degree of overprint on Cretaceous and Tertiary structuring. Possibly, dominant east-west Early Cretaceous rift-associated fault trends became relatively quiescent after Late Cretaceous continental separation, while Early Palaeozoic faults were reactivated. Such effects would be more apparent north of the limit of thick Sherbrook Group deposition on the Beachport-Kalangadoo High, towards the Padthaway Ridge and in the vicinity of the Kanawinka Fault as noted by Kenley (1971). Etheridge et al. (1984a,b) have recognized on seismic data from the Bass Basin transform-like transverse faults trending 020° to 030°, which in that basin are restricted to Early Cretaceous or older rocks. Nevertheless, the same authors recognise the effects of tectonic overprint, discussed later.

The first well specifically drilled on a wrench-associated fault block was Trumpet 1 (Eyles, 1974), offshore immediately south of the Padthaway Ridge. Right-lateral divergent wrenching was indicated from seismic data. Banyula 1 was similarly drilled on an anticline between two en echelon faults presumed to be related to wrench movement on the southern margin of the Penola Trough (Djokic & Chan, 1982). McPhee (1975) and Blake (1980) have ascribed en echelon anticlines in the eastern Otway and Gippsland Basins to Early Cretaceous right-lateral wrenching.

Such structures are proven hydrocarbon traps elsewhere (Wilcox et al., 1973; Harding, 1974), but both the magnitude and style (divergent, convergent) of strike-slip displacements control the geometry of individual anticlines. Small-scale lateral displacements (5 km or less) are unlikely to affect anticlines more than 5 to 10 km away from wrench zones, and since seismic lines in the Penola and Robe Troughs are at best 5 km apart, discussion of detailed trap geometry related to wrenching would be premature. However, available data do suggest that this structural style may have operated in the Cretaceous, perhaps associated with continental rifting (and rotation?) of Australia relative to Antarctica.

4.2 Late Cretaceous (Sherbrook Group)
Deltaic facies complex

The Sherbrook Group delta complex in South Australia forms an east-southeast striking sedimentary wedge which thickens rapidly south of the Tartwaup Fault to exceed 3 000 m, but maximum thickness is unknown. Nine wells have partly or fully pentrated the sequence which comprises in ascending order: delta front muddy or silty sandstone (Flaxman Formation); prodelta slope/delta front silty mudstone (Belfast Mudstone) and delta front/lower delta plain variably quartz-rich to lithic sandstone interbedded with shale (Paaratte Formation). Strike length of the sequence including the Sherbrook Group in the Portland Trough area (Holdgate et al., 1985) is at least 270 km.

Three major controls on hydrocarbon trap formation likely to have been both laterally and vertically variable are:

1) rates of sedimentation and subsidence,
2) structural movements associated with continental rifting and breakup,
3) structural movements inherited from Palaeozoic or older tectonic provinces.

By reference to maturely explored deltas elsewhere these controls can be assessed for the Sherbrook Group.

Rates of sedimentation and subsidence

Superimposed on basinward progradation of major deltas are variations in sediment input rate due either to extrinsic tectonic controls in source areas or to intrinsic factors such as delta lobe abandonment in favour of other sites. Hence 'marineness' of the offshore slope to lower delta plain varies with time and location. Rates of sediment supply can locally be large enough to severely limit marine incursions e.g. Norias delta system on the Texas Gulf coastal plain (Galloway et al., 1982), as also suggested for the Otway Basin by Deighton et al. (1976, p.27). In contrast, continued subsidence on abandoned delta lobes and on delta flanks allows coastal processes to modify nearshore environments, not only allowing development of potential sandstone reservoirs, but also giving rise to variable 'indices of marineness' as found in the Belfast Mudstone and Paaratte Formation. Petrological study of the Paaratte Formation from Mt. Salt 1 and Argonaut A1 cores shows significant variations in grain size, sorting, mineralogical maturity and degree of cementation of the sandstone, but core-derived porosities and permeabilities are less variable than for the Otway Group (Table 2). However, this may reflect insufficient samples for proper comparison. Potential exists for structural and stratigraphic traps in upper Belfast and lower Paaratte sands, and fears of poor reservoir quality due to choking of pore throats by clay products of feldspar alteration are unwarranted (cf. Pretty Hill Sandstone volcanogenic facies above). Secondary porosity due to leaching of carbonate cement is significant in Argonaut Al and variable in Mt. Salt 1 cores. On the Texas Gulf Coast, lithic, feldspathic sands have significant proven oil, gas and condensate reserves in stratigraphic and structural traps (Gordon, 1982; Galloway et al., 1982).

Too few wells have sufficiently penetrated the Flaxman Formation to provide meaningful reservoir data, despite the fact that it has been a primary target offshore. Lack of an overlying Tertiary regional seal has downgraded trap potential of the Paaratte Formation, but as shown below, syndepositional structuring is likely to produce local traps and seals at the Belfast/Paaratte interface and may allow reservoir development within the Belfast Mudstone, which itself forms a widespread seal for the underlying Flaxman Formation.

Intraformational traps are anticipated for the Belfast Mudstone where prodelta slope deposits accumulated most rapidly, allowing downslope mass movement from gravitaional instability or shear failure in undercompacted shales. Growth faults, rollovers and shale anticlines, illustrated for the Triassic of Svalbard by Edwards (1976) are typical for deltaic sediments. In Argonaut Al the Paaratte Formation consists of stacked distributaries forming a 'point source of a major Upper Cretaceous delta' (James, 1968). There the bulk of the Paaratte Formation occurs in the *C. triplex* Zone (Fig. 17), which is wholly within the Belfast Mudstone in Voluta 1 (Dettman, 1968). Similar time and rock relationships to Voluta 1 are expected downdip from Argonaut Al, hence sands distributed over the prodelta slope could form reservoirs *within* the Belfast Mudstone under appropriate conditions of sedimentation.

Rift and breakup-associated structure

The Sherbrook Group was deposited as cumulative subsidence decreased roughly exponentially through the Cretaceous (Falvey & Mutter, 1981; Cande & Mutter, 1982; Mutter et al., 1985). The Flaxman Formation and part of the Belfast Mudstone were thus probably deposited while subsidence was still substantial. Structural style is dominated by north-northeast dipping rotated blocks bounded by closely spaced rift-parallel and oblique faults, few of which extended into the Tertiary (Boeuf & Doust, 1975). The high sides of rotated blocks may have been preserved or eroded depending on the timing of rotation relative to subsidence and the degree of scarp relief. Hydrocarbon traps known to be productive elsewhere (Harding, 1984) principally arise from high-side sandstone reservoir truncation, flexure, rollover and fault-seal.

The upper Belfast Mudstone and Paaratte Formation were deposited as cumulative subsidence lessened during a period of extremely slow initial continental drift (Cande & Mutter, 1982; Mutter, 1985). The balance between deposition and subsidence rates, and frequency of through-going faults will have been critical to stratigraphic and structural trap formation.

Reactivation of older structures

As shown for the Penola and Robe Troughs, reactivation of Early Palaeozoic northerly structural trends may have overprinted margin-parallel rift and post-rift structural trends. Although the degree and extent of overprint are poorly identified south of the Tartwaup Fault, significant control has been shown to affect rift-associated deltaic sediments, as found in the East Shetland Basin (Kirk, 1980; Harding, 1984). This has also been suggested for the Gippsland Basin (Etheridge et al., 1984a). The principal effect of oblique cross-faults is to markedly increase updip closure and strike closure at fault junctions, enhancing existing traps. New traps may be created in younger sediments where dip variations are created at the junctions of cross-faults and normal faults. As post-rift faulting became minimal in the Late Cretaceous and Tertiary, effects of Early Palaeozoic overprinting are likely to have become correspondingly more pronounced.

4.3 Conclusions

Early Cretaceous

Major horst blocks flanking the Penola and Robe Troughs (Lake Eliza, Lucindale) have been drilled without encouragement beyond gas-cut formation water (Table 3). Poor seismic control makes the location of these wells uncertain with respect to structural closure. Post-drill interpretation of the Crayfish structure resulted in loss of most of the closure (James, 1968). However, a number of ill-defined horsts are known. Plays on the flanks of these horsts (alluvial fans, reservoir subcrops) as well as the flanks of structures bald of Pretty Hill Sandstone (e.g. Beachport High) require further investigation.

Late Cretaceous

Lack of closely spaced seismic grids raises doubts as to whether or not the crests of structural closures were drilled. Nevertheless, three onshore wells have demonstrated trap potential of the Flaxman (Waarre) and Paaratte Formations: Burrungule 1, Mt. Salt 1 (highly saline formation water from log analysis and drillstem test respectively), and Caroline 1 (commercial CO_2 production) (Table 3); remaining onshore wells south of the Tartwaup Fault lacked structural closure. Only three wells have been drilled offshore on seismically defined structures with Late Cretaceous targets (Argonaut A1, Morum 1, Breaksea Reef 1) with no significant hydrocarbon shows. In each case the validity of the closure at the target horizon is suspect.

Considering the unpredictable nature of lower Paaratte shale trends from current data, the principal target in the Sherbrook Group at present is the Flaxman Formation sealed by the Belfast Mudstone. Potentially significant targets for future exploration are intra-Belfast sandstone reservoirs. In view of the structural complexity of the region, the key to successful drilling will rely most heavily on seismic-stratigraphic techniques.

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Table 1: Otway Basin, South Australia Formation tops, KB depths (metres)

Well	Gambier	Gelibrand	Dilwyn ((onshore)	Pember	Dilwyn (offshore)	Wang/ Sherb.	Cond. Sherb.	Tim.	Parr.	Belf.	Flax.	Eum.	Pretty Hill	Base.
Argonaut A1	105		311	625?				727	2317	3063	3542			
Banyula 1	0		266	565			660					831	2350	
Beachport 1	85	250	294	294			369					573		
Beachport East 1	0		191	351			404					587	1381	1407
Breaksea Reef 1	112				510				1013	2849				
Burrungule 1	0				103			651	1306	1981	2126	2300		
Caroline 1	3				195			892	1740	2161	2466	2841		
Chama 1A	113					370?						803		
Crayfish A1	78?	333?				347						477	1597	
Diamond Swamp 1	0		235	454			503					625	1417	1465
Douglas Pt. 1	0	321			337			1014						
Geltwood Bch 1	18				277		552					1140	3490?	
Lake Bonney 1	5		238	652				747	1623	2355	2534	2720		
Lake Eliza 1	0	256				262						392	1068	1315
Lake George 1	12	246			264		406					578		1248
Lucindale 1	46					162						267	733	962
Kalangadoo 1	0		96	449			544					765		2062
Kentgrove 1	0				63?			881						
Morum 1	286								427?	1866				
Mt. Salt 1	0	146			163			954	2271?					
Neptune 1	45					357						490	1422	
Penola 1	11					76						317		
Robertson 1	5	64				79						317		1765
Robertson 2	5					129						246		1456
Trumpet 1	59											427	1303	

UNIT	WELL	POROSITY (per cent)	HORIZONTAL AIR PERMEABILITY (millidarcies)
Paaratte Fm.	Argonaut Al	25	230
	Morum 1	23	294
	Mt. Salt 1	6-25	3-407
Flaxman Fm.	Argonaut Al	10-15	0
Eumeralla Fm.	Kalangadoo 1	10-32	0-65
	Banyula 1	18-22	35-504
	Penola 1	16-32	0-40
Pretty Hill Sst.	Banyula 1	5-20	0-1
	Lake Eliza 1	17-27	0-793
	Lucindale 1	11-33	2-950
	Neptune 1	7-15	0
	Trumpet 1	22-26	136-670
	Crayfish Al	5-27	0-660

Table 2: Selected core data from wells in the Otway Basin, South Australia.

UNIT	WELL	TEST	TEST INTERVAL (metres)	FLOW (x 1 000 m^3)	RECOVERY	REMARKS
Paaratte Fm.	Mt. Salt 1	DST 1	2991-3015	NFTS	1241 m SW + WC	Tool closed early.
Flaxman Fm.	Caroline 1	DST 4	2516-2570	est. 56.7-85.0	1321 m SW	CO_2
Eumeralla Fm.	Banyula 1	DST 1	1990-2011	NFTS	1750 m SW	Nil.
	Geltwood Beach 1	DSTs 1-4	1176-1854	NFTS	SW, SGCM	NaCl equiv. 15-26 000 ppm
	Robertson 1	DST 2	988-996	NFTS	480 m SW	NaCl equiv. 24 000 ppm
	"	DST 3	1577-1599	NFTS	527 m v.gassy SW	predom. methane (corr. for air contam.)
Pretty Hill Sst.	Crayfish A	Production Test	1597-1599	NFTS	203 bbl SW, 32 bbl WC	NaCl equiv. 26 000 ppm
	"	FIT 4	2783	-	0.35 l gas, 17.4 l SW	7-10% v/v methane
	Lake Eliza 1	DST 2	1067-1071	RTSTM	876 m gas cut SW	NaCl equiv. 26 600 ppm, predom. methane
Basement	Kalangadoo 1	DST 14	2051-2137	up to 75.9 (unstabilized)	51 m gassy mud	CO_2 from fractured basement.

Table 3: Mechanically valid test data from wells in the Otway Basin, South Australia.
Abbreviations: DST - drillstem test; FIT - formation interval test;
NFTS - no fluid to surface; RTSTM - rate too small to measure;
SW - salt water; WC - water cushion; SGCM - slightly gas cut mud.

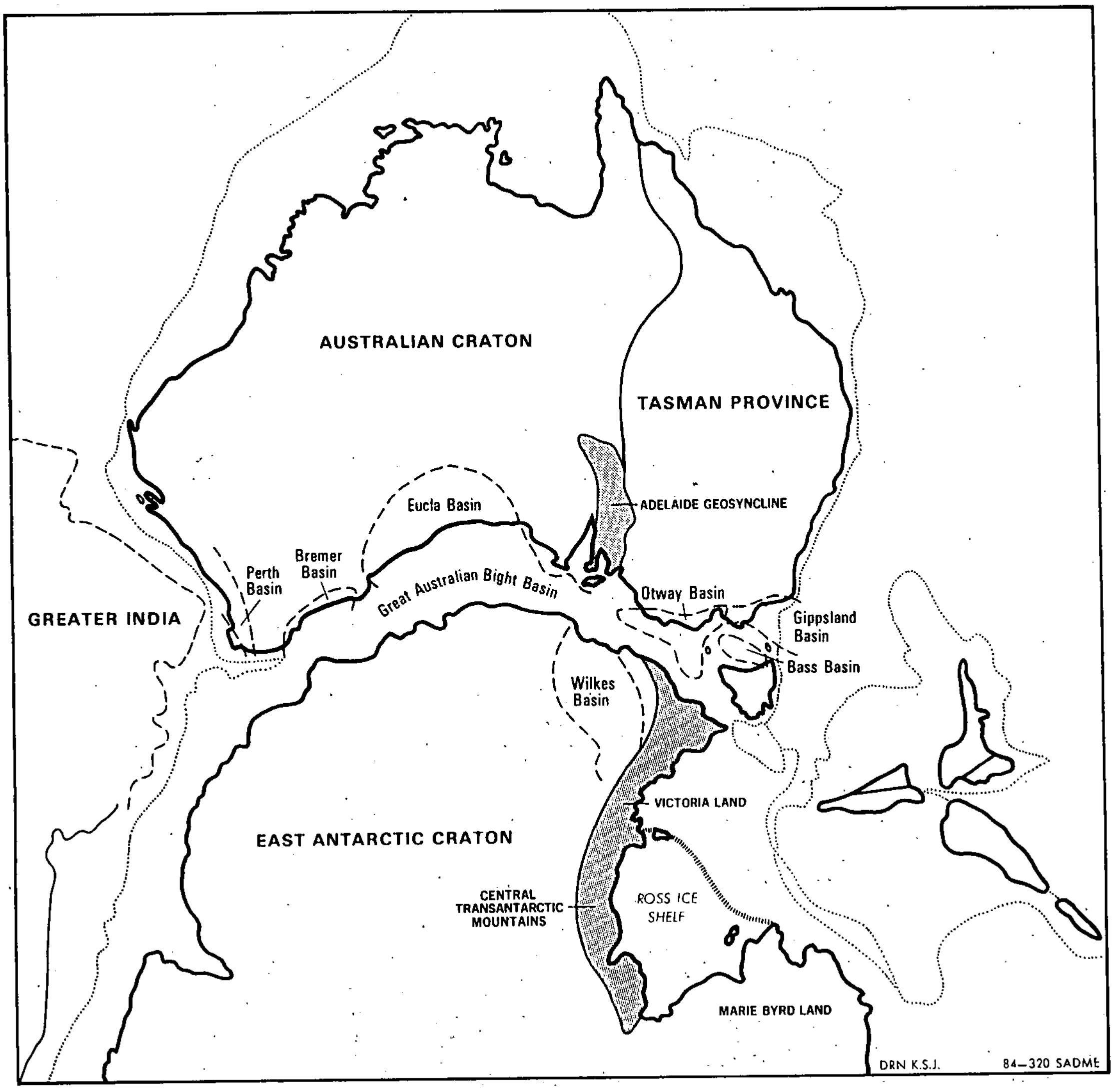


Fig. 1. Gondwanaland reconstruction showing principal Palaeozoic provinces and continental margin sedimentary basins. After Cooper & Grindley (1982), Truswell (1982).

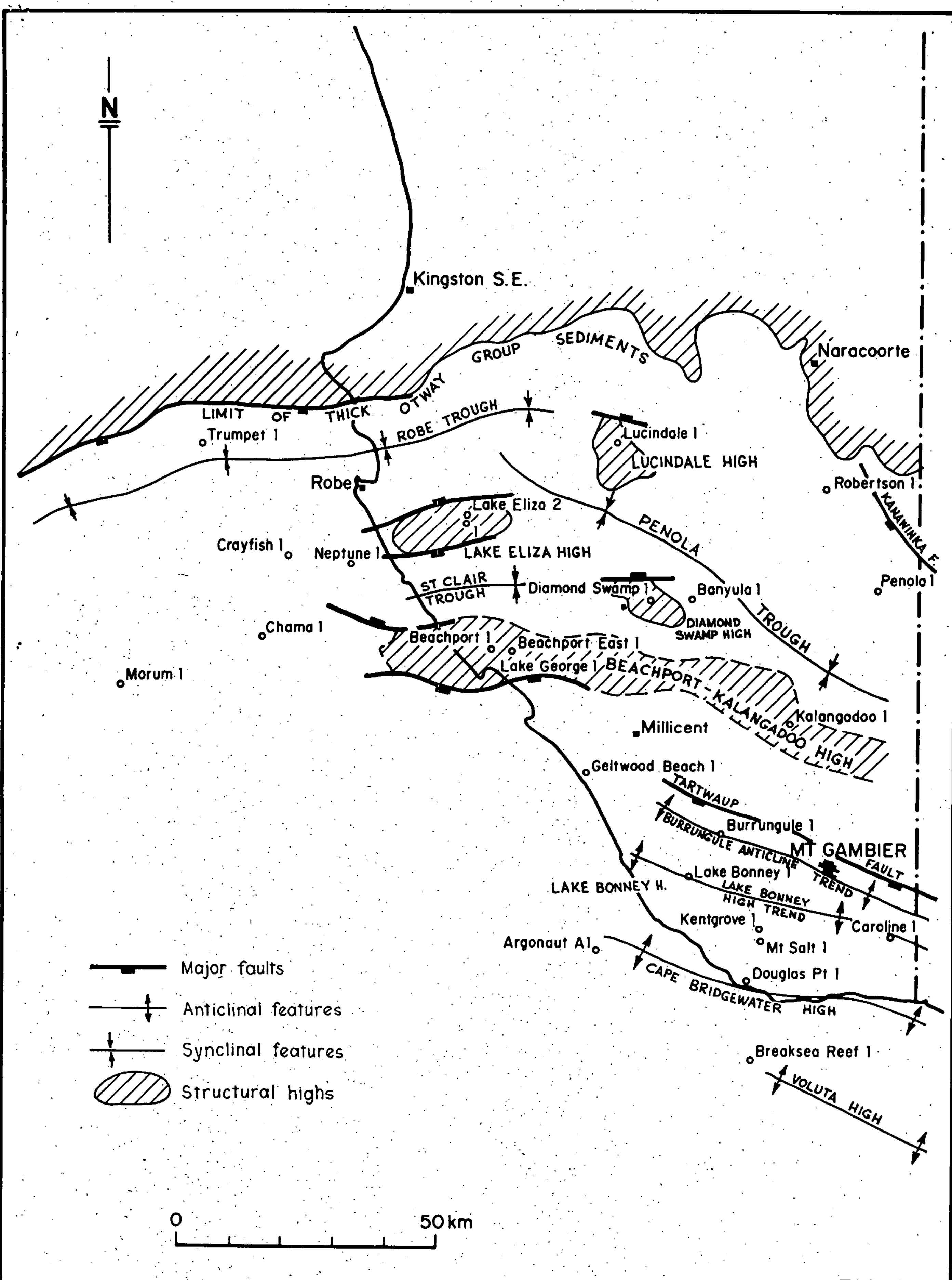
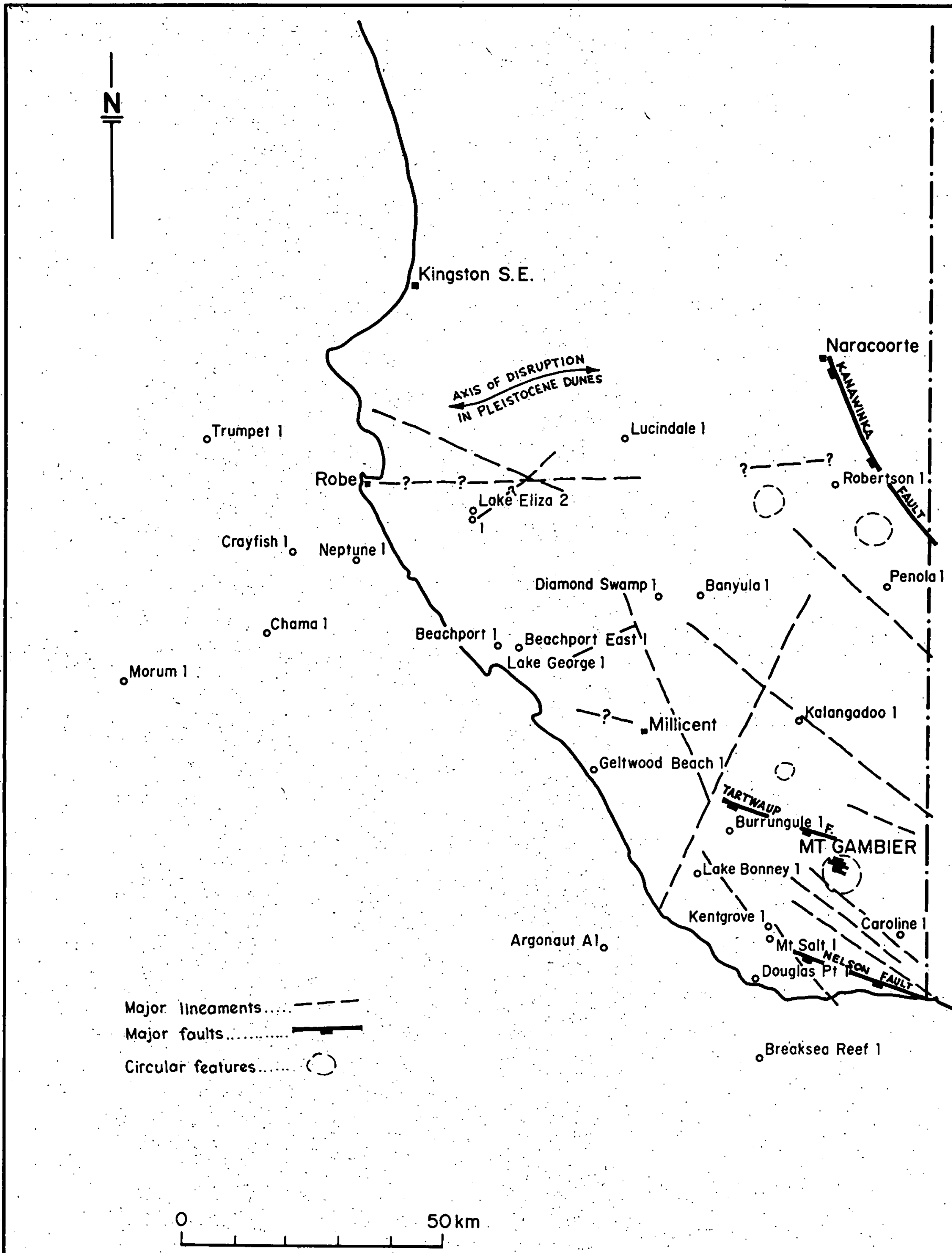


FIG. 2

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA	COMPILED A.H.	CDO 9.4.86 DATE
OTWAY BASIN - SOUTH AUSTRALIA	DRAWN A.F.	SCALE 1:1000000
MAJOR STRUCTURAL FEATURES	DATE 1-8-84	PLAN NUMBER S17410
	CHECKED	

3566



Data based on ERTS imagery

FIG. 3

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

OTWAY BASIN - SOUTH AUSTRALIA

MAJOR LINEAMENTS

COMPILED A.H.	CDO	9.4.86 DATE	
DRAWN A.F.	SCALE 1:1000000		
DATE July '84	PLAN NUMBER S18287		
CHECKED			

3566

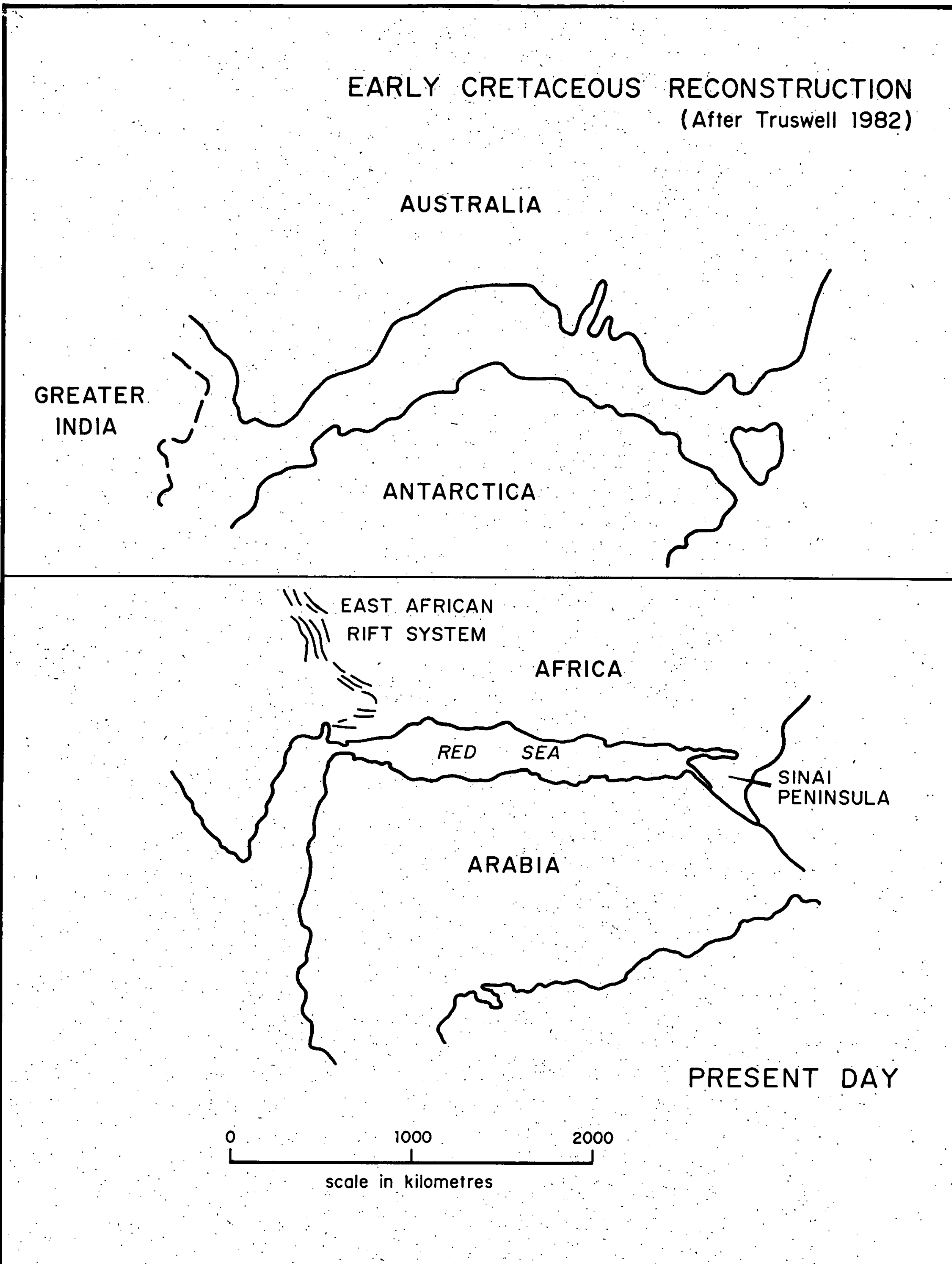


Figure..... 4

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

COMPARISON BETWEEN RED SEA AND GREAT SOUTHERN RIFT SYSTEMS

COMPILED A. Hill	C.D.O.	DATE
DRAWN A.F.	SCALE As shown	
DATE 11-6-86	PLAN NUMBER	
CHECKED	S 18935	

3566

3566

CONFIGURATION OF GREAT SOUTHERN RIFT SYSTEM - OTWAY BASIN

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

COMPILED A. Hill	C.D.O. DATE
DRAWN A.F.	SCALE As shown
DATE 11-6-86 CHECKED	PLAN NUMBER S 18936

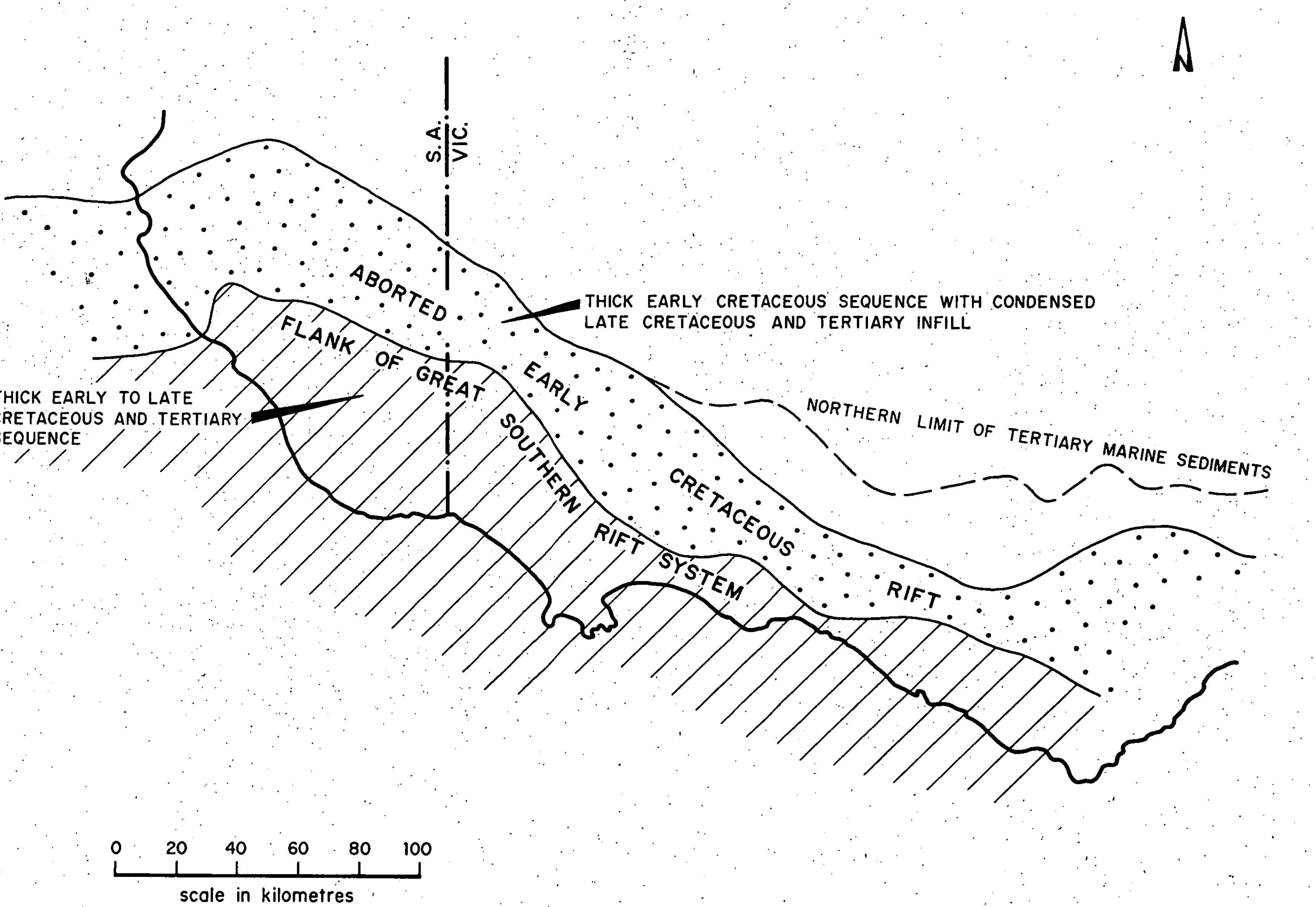


Figure.....5

STRATIGRAPHIC RELATIONSHIPS

OTWAY BASIN – SOUTH-SOUTH AUSTRALIA

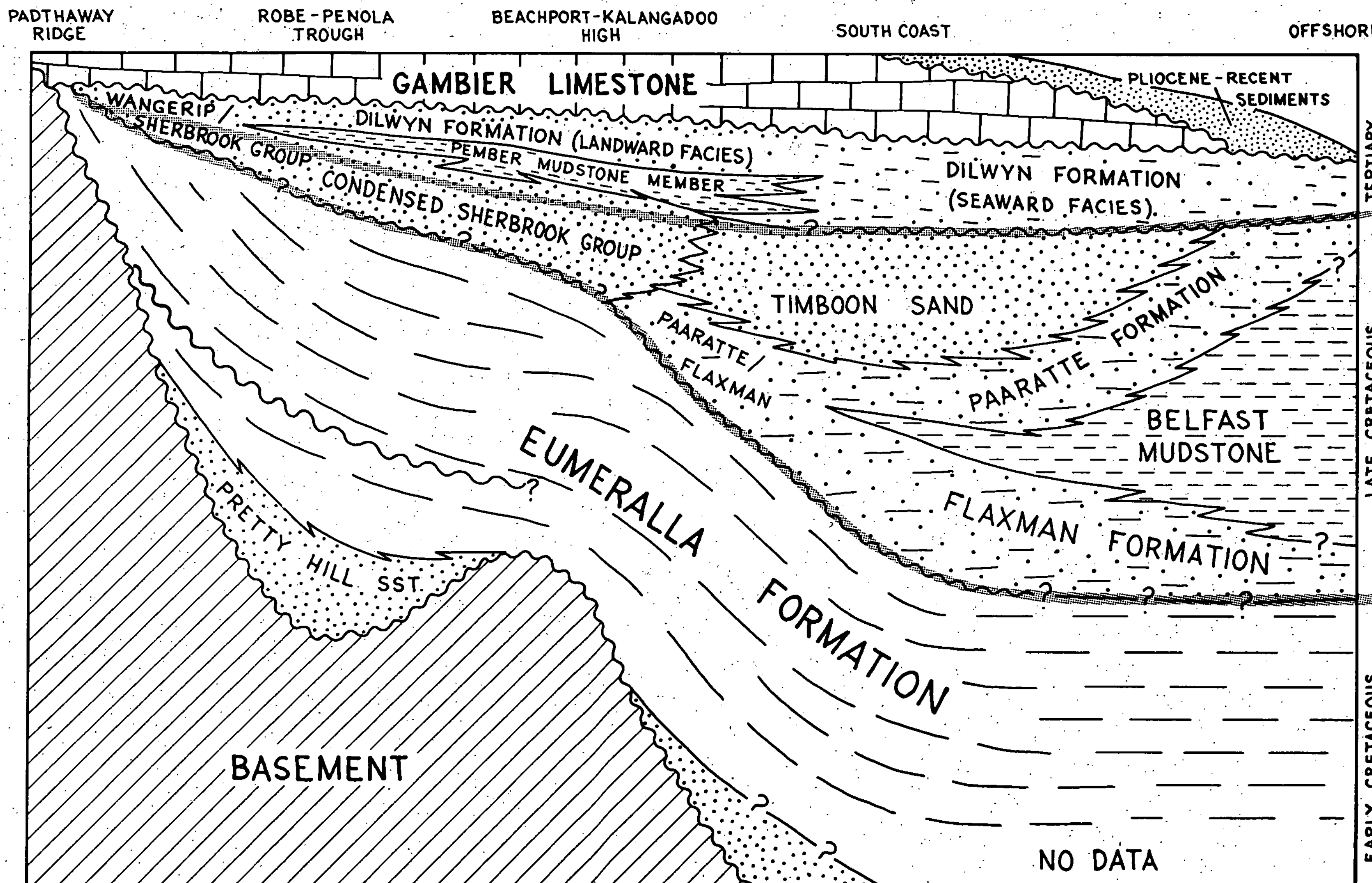


FIG. 6

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

COMPILED J. Morton	C D O	DATE 9.4.86
DRAWN A.F.	SCALE	
DATE 20-6-84		
CHECKED	PLAN NUMBER	S17409

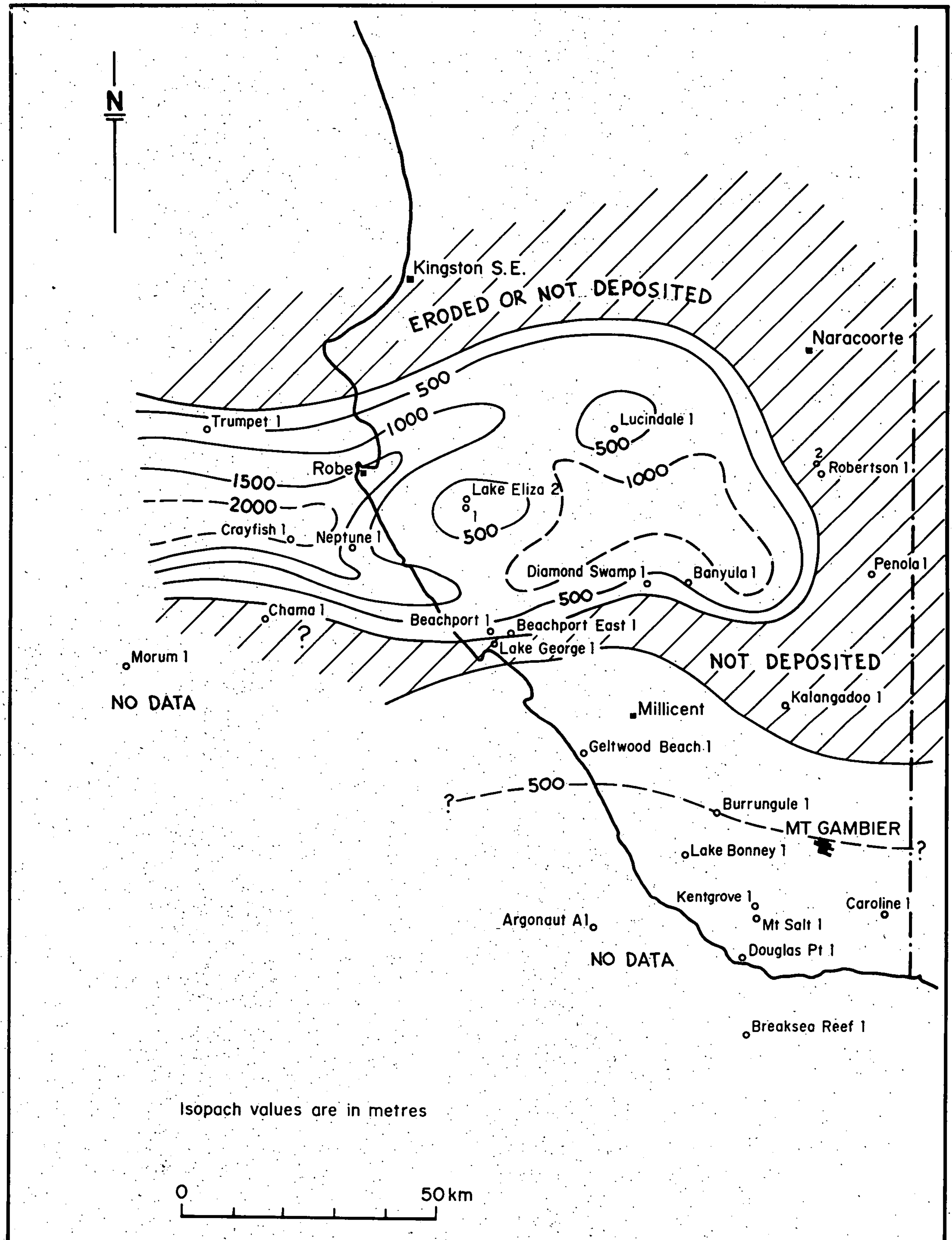


FIG. 7

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

OTWAY BASIN - SOUTH AUSTRALIA
PRETTY HILL SANDSTONE
ISOPACH MAP

COMPILED J. Morton	CDO 9·4·86 DATE
DRAWN A.F.	SCALE 1:1000000
DATE 20-6-84	PLAN NUMBER
CHECKED	S 17411

3566

3566

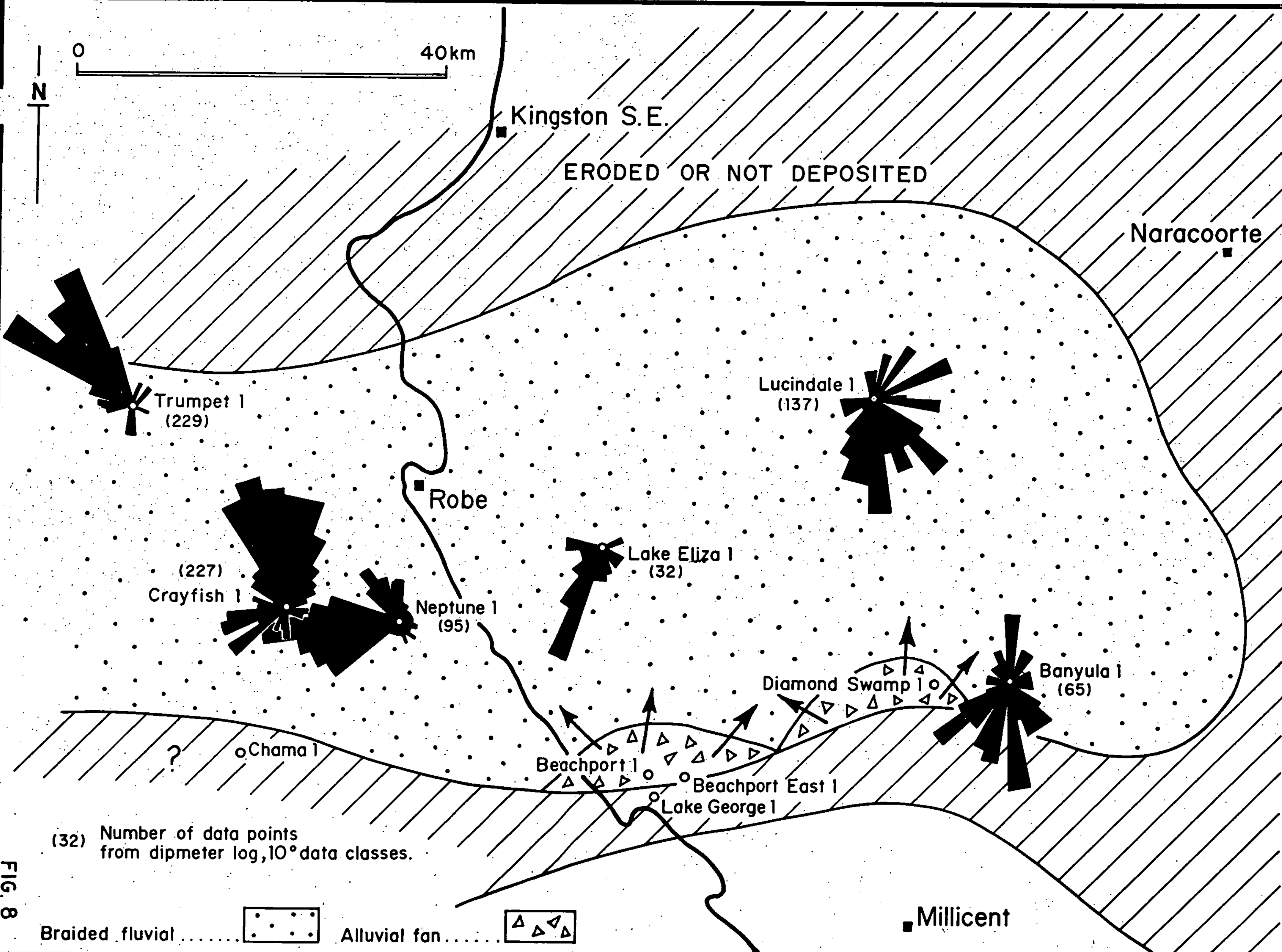


FIG. 8

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

OTWAY BASIN - SOUTH AUSTRALIA
PRETTY HILL SANDSTONE
INTERPRETED PALAEOENVIRONMENTS AND PALAEOCURRENTS

COMPILED J.M.	C.D.O.	9. 4. 86 DATE
DRAWN A.F.	SCALE	
DATE 31.7.84		
CHECKED	PLAN NUMBER S17459	

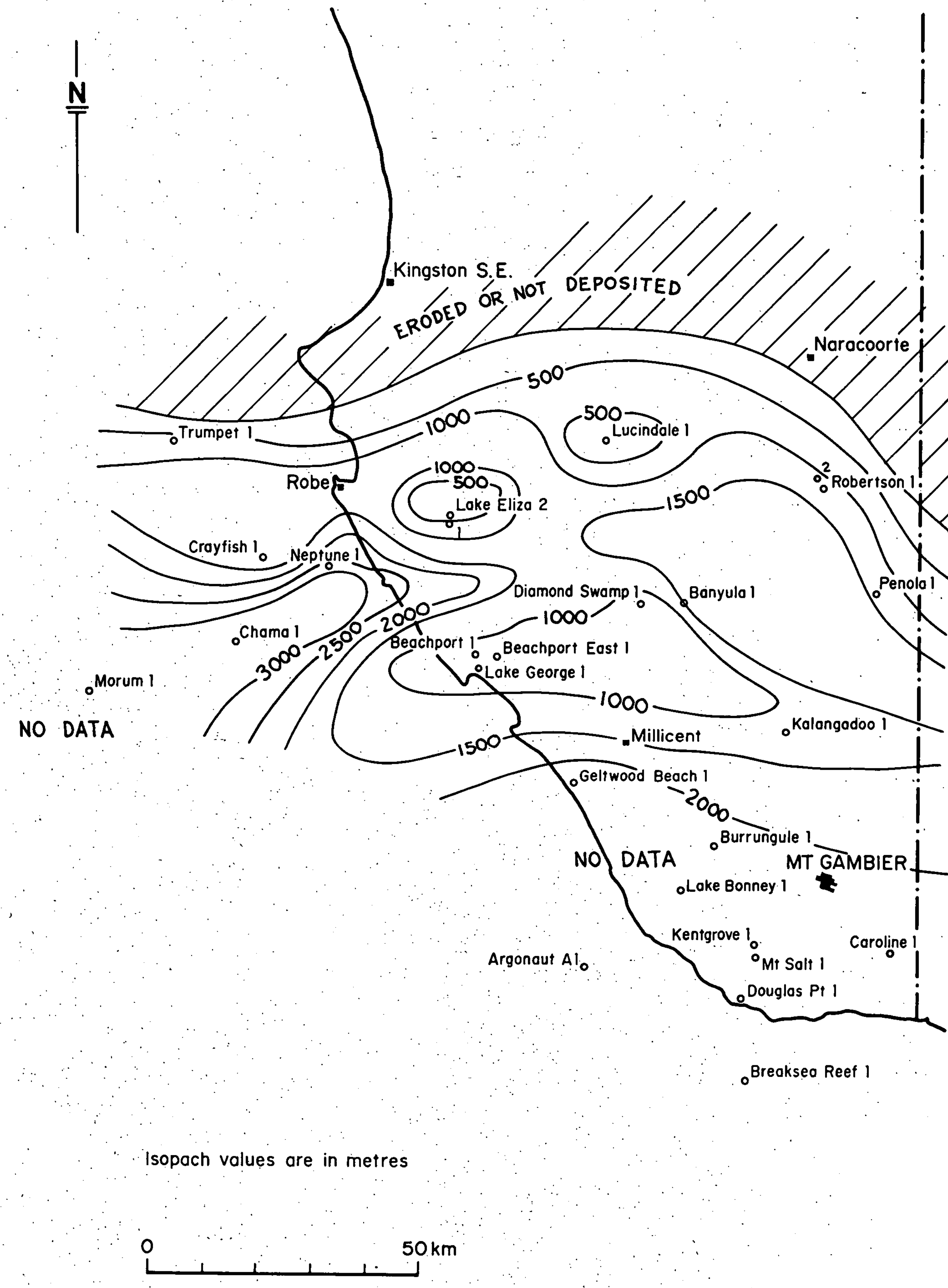


FIG. 9

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

OTWAY BASIN - SOUTH AUSTRALIA
EUMERALLA FORMATION

ISOPACH MAP

COMPILED J. Morton	CDO	DATE 9.4.86
DRAWN A.F.	SCALE 1:1000000	
DATE 20-6-84	PLAN NUMBER	
CHECKED	S17412	

3566

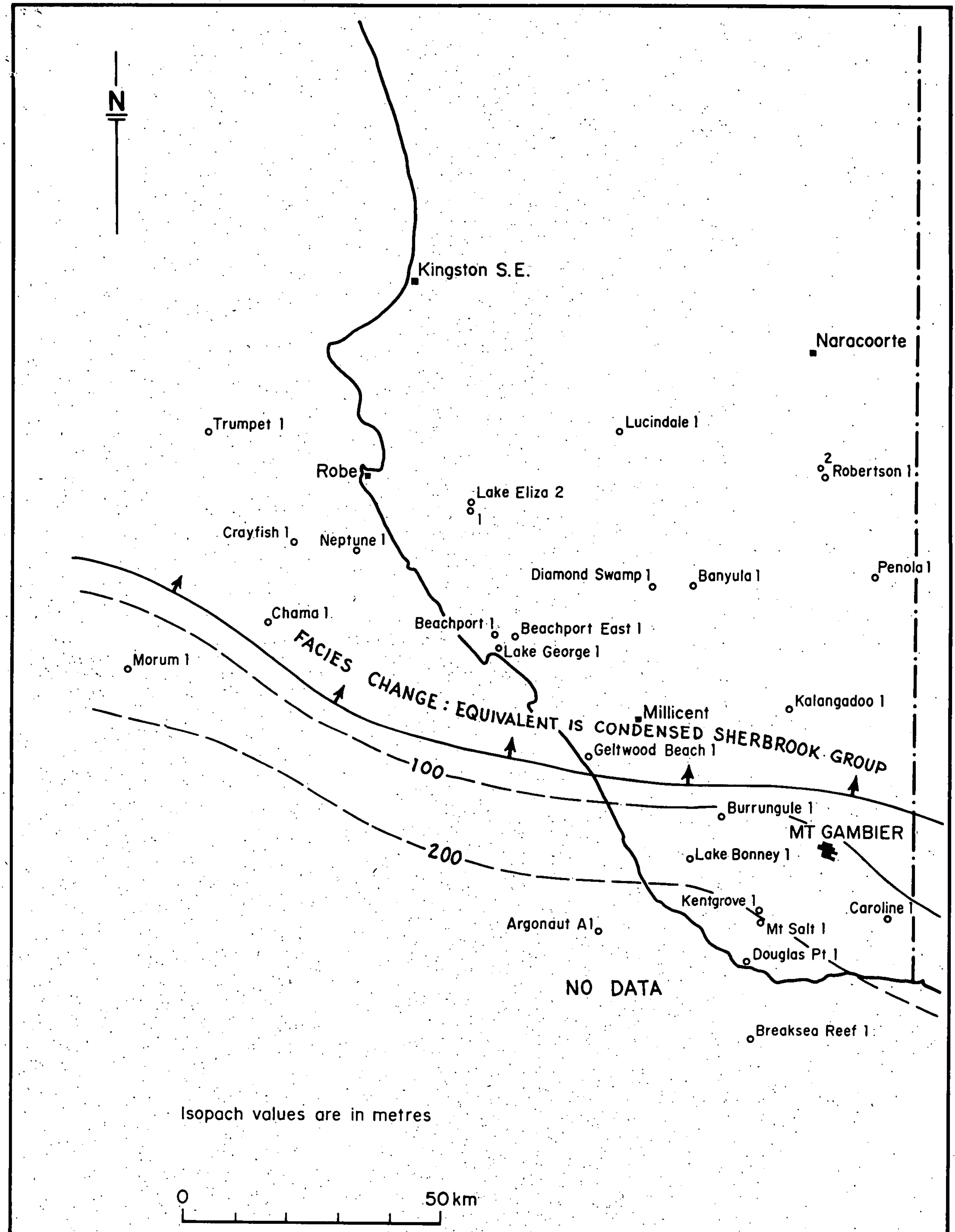


FIG. 10

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

OTWAY BASIN - SOUTH AUSTRALIA
FLAXMAN FORMATION
ISOPACH MAP

COMPILED J. Morton	CDO	DATE 9·4·86
DRAWN A.F.	SCALE 1:1000000	
DATE 20-6-84	PLAN NUMBER S 17415	
CHECKED		

3566

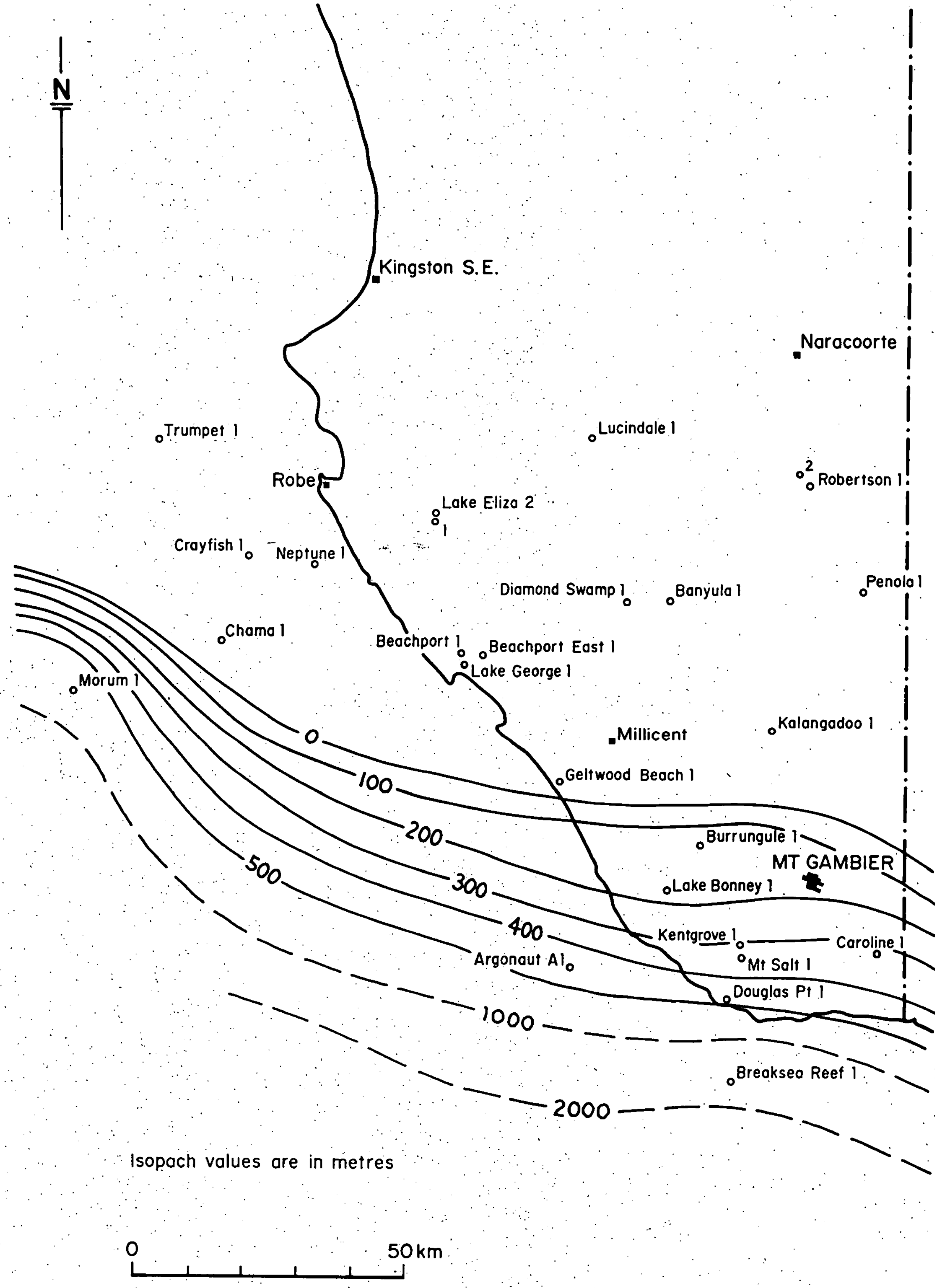


FIG. 11

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

OTWAY BASIN – SOUTH AUSTRALIA
BELFAST MUDSTONE
ISOPACH MAP

COMPILED J. Morton	CDO 9·4·86 DATE
DRAWN A.F.	SCALE 1:1000000
DATE 20-6-84	PLAN NUMBER S17416
CHECKED	

3566

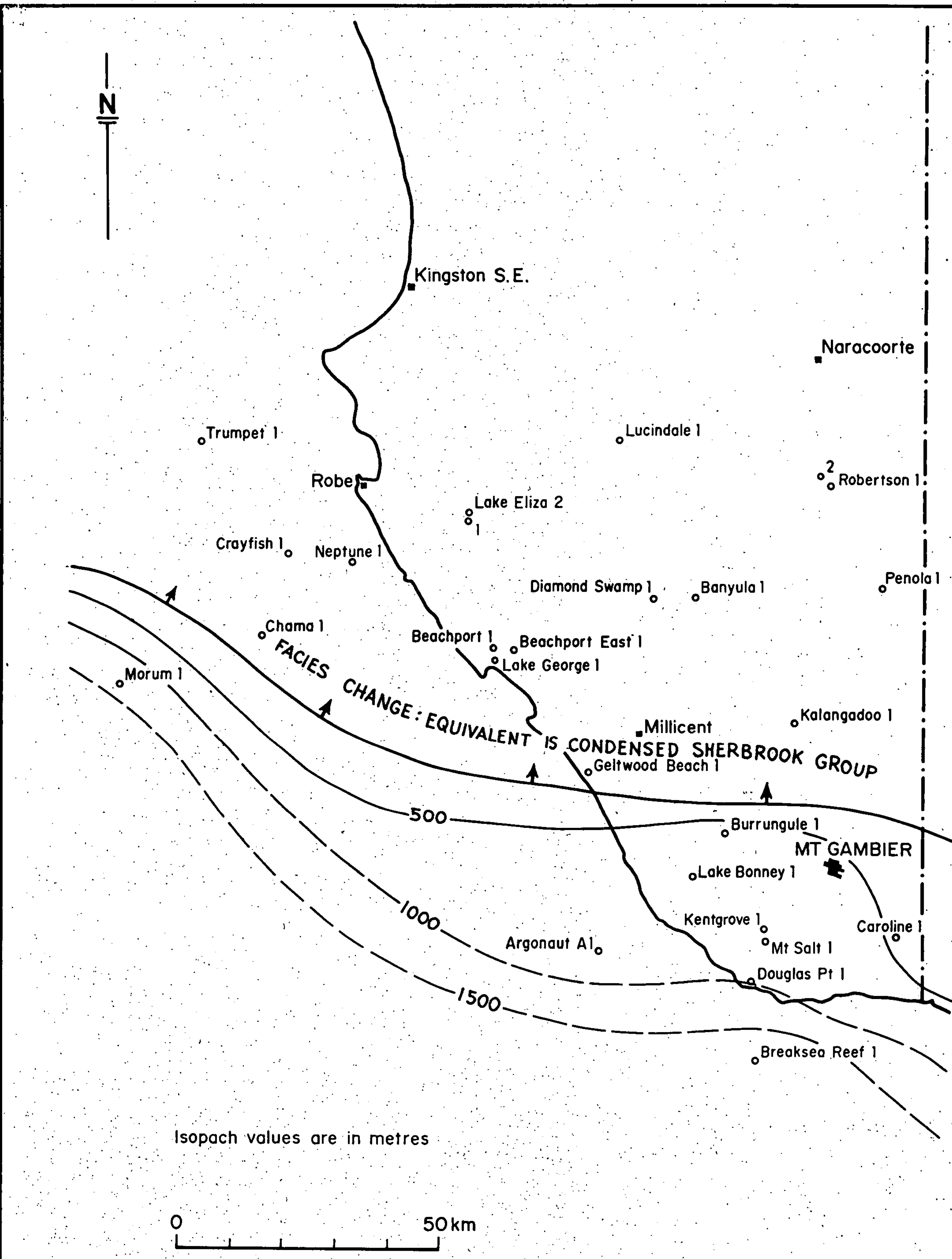


FIG. 12

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

OTWAY BASIN – SOUTH AUSTRALIA

PAARATTE FORMATION ISOPACH MAP

COMPILED J. Morton	CDO	9·4·86	DATE
DRAWN A.F.	SCALE 1:1000 000		
DATE 20-6-84	PLAN NUMBER S 17417		
CHECKED			

3566

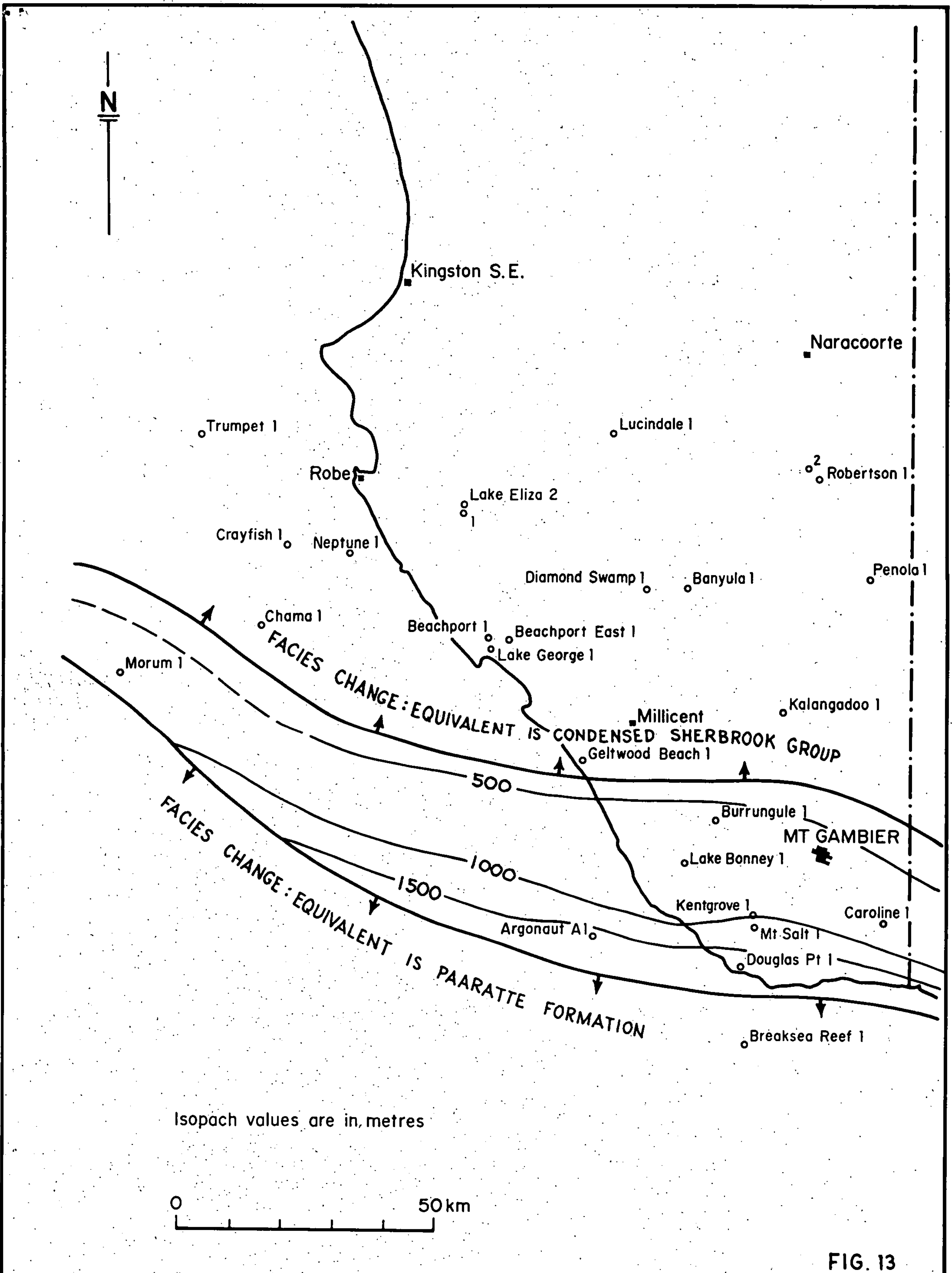


FIG. 13

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

OTWAY BASIN - SOUTH AUSTRALIA
TIMBOON SANDSTONE
ISOPACH MAP

COMPILED J. Morton	CDO 9 · 4 · 86 DATE	
DRAWN A.F.	SCALE 1:1000000	
DATE 20-6-84	PLAN NUMBER	S17418
CHECKED		

3566

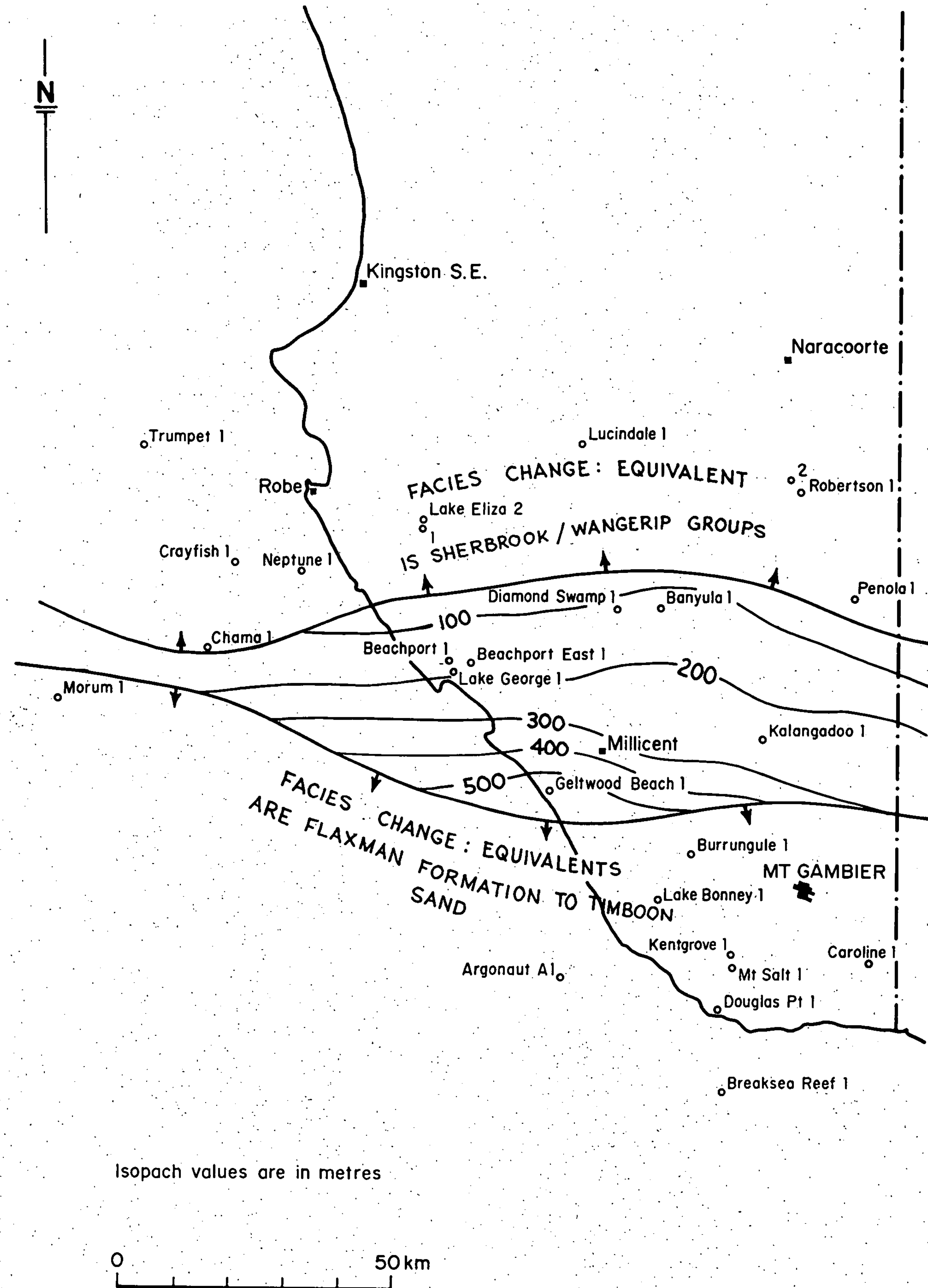


FIG.14

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

OTWAY BASIN - SOUTH AUSTRALIA
CONDENSED SHERBROOK GROUP
ISOPACH MAP

COMPILED J. Morton	CDO	9·4·86 DATE
DRAWN A.F.	SCALE 1:1000000	
DATE 20-6-84	PLAN NUMBER S 17419	
CHECKED		

3566

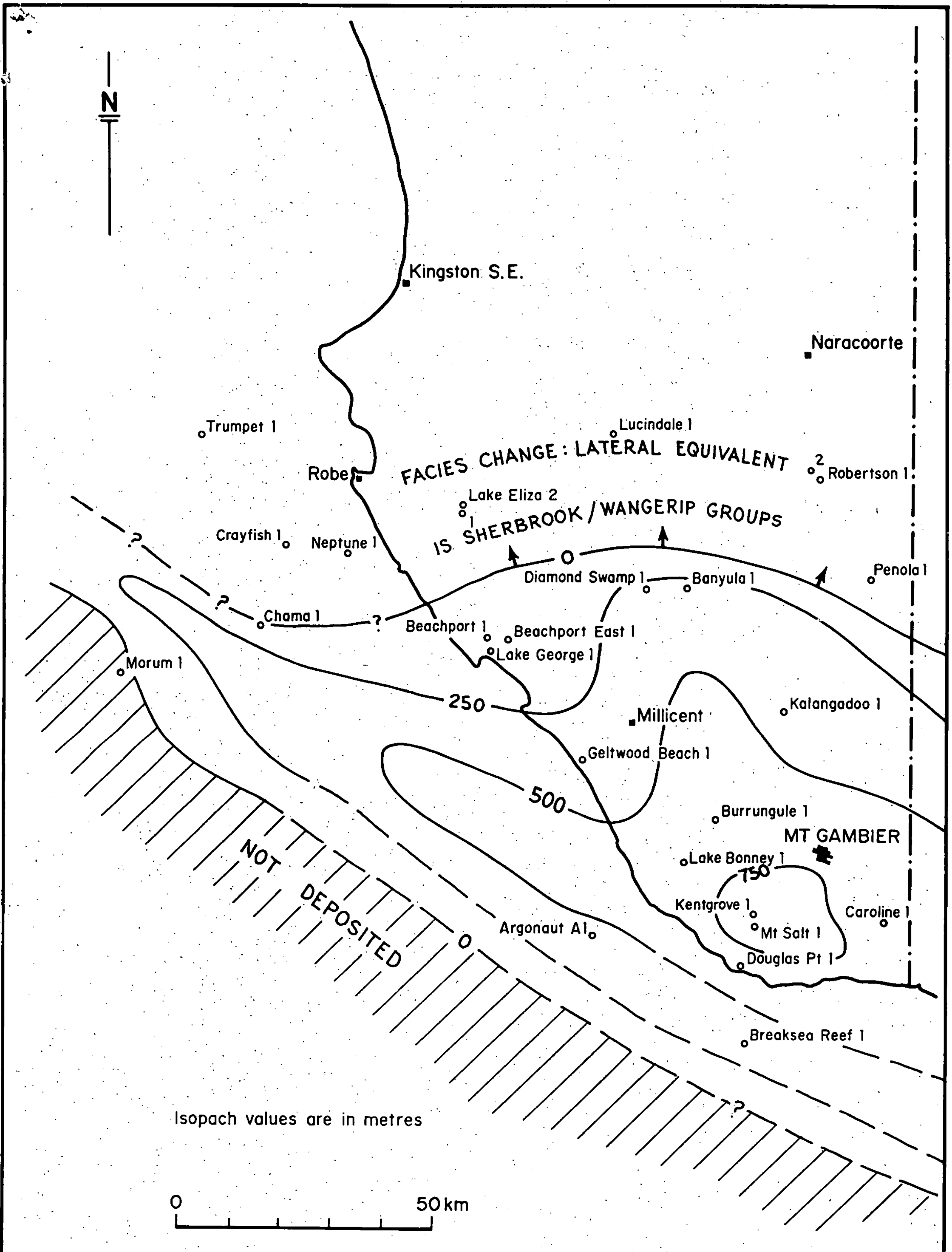


FIG. 15

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

OTWAY BASIN - SOUTH AUSTRALIA

DILWYN FORMATION
(INCLUDING PEMBER MUDSTONE MEMBER)
ISOPACH MAP

COMPILED J. Morton	CDO 3·4·86 DATE
DRAWN A.F.	SCALE 1:1000000
DATE 20-6-84	PLAN NUMBER
CHECKED	S17420

3566

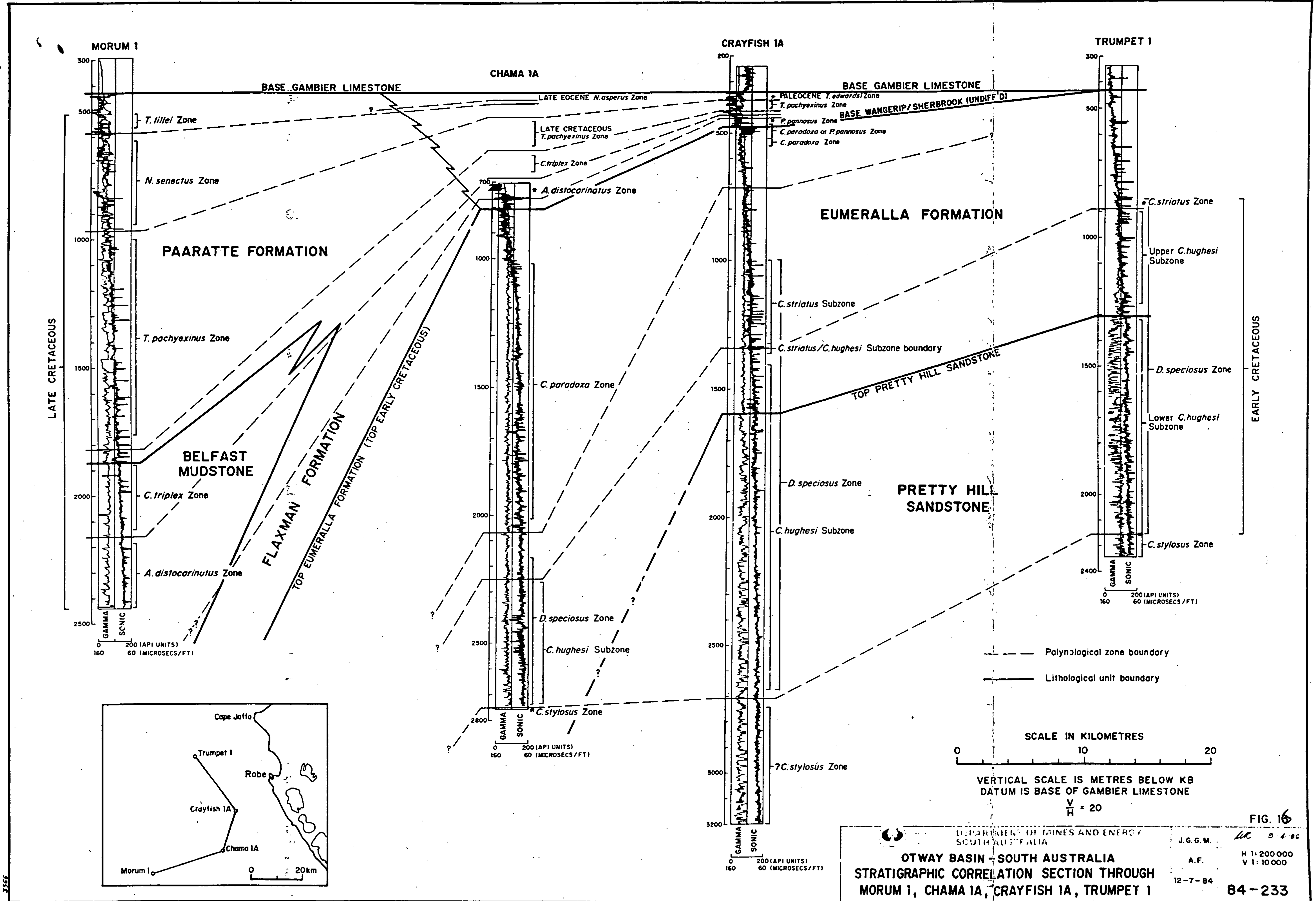


FIG. 16

OTWAY BASIN - SOUTH AUSTRALIA
STRATIGRAPHIC CORRELATION SECTION THROUGH
MORUM 1, CHAMA 1A, CRAYFISH 1A, TRUMPET 1

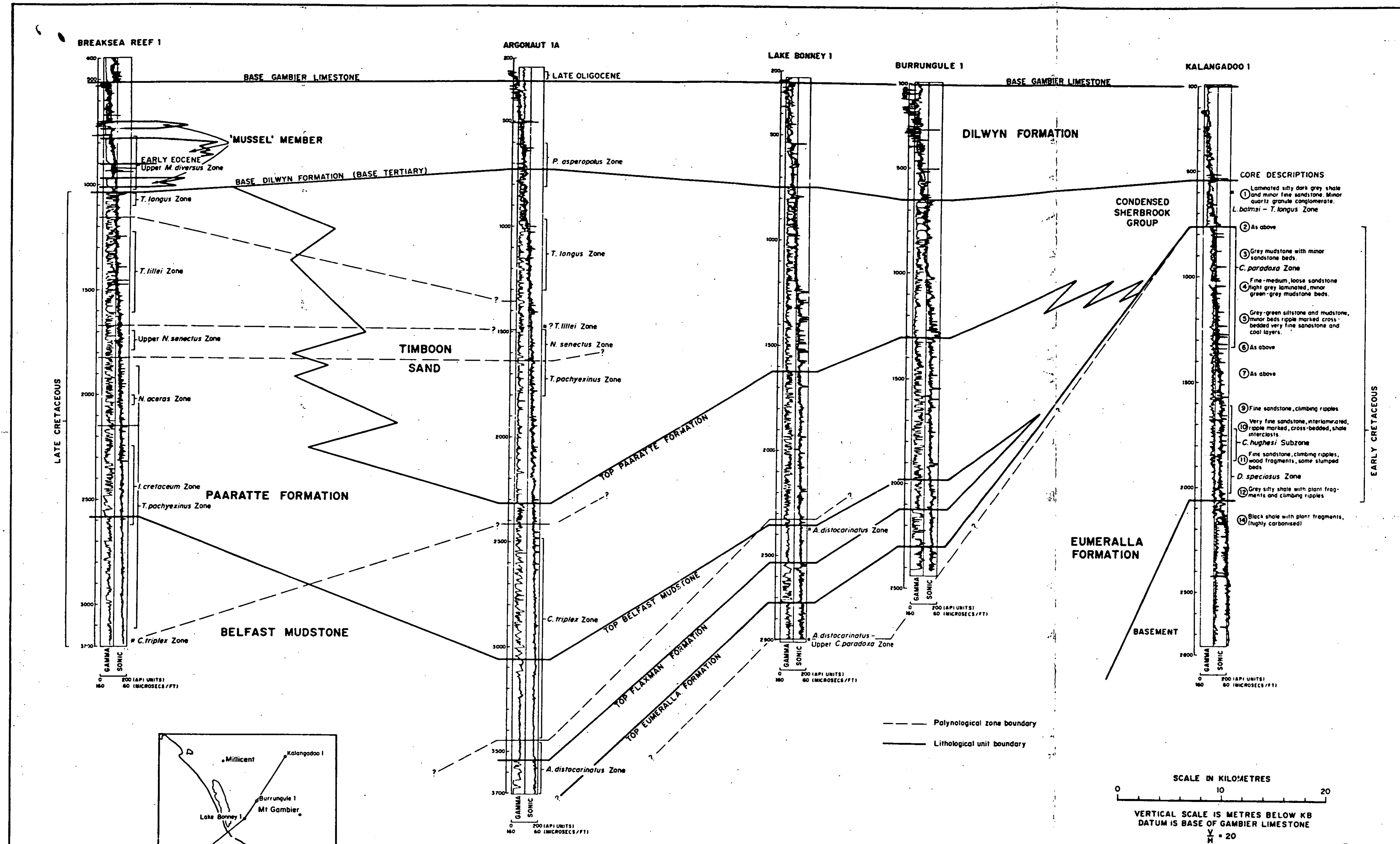


Fig. 17

OTWAY BASIN - SOUTH AUSTRALIA

CROSS SECTION BREAKSEA REEF 1 - KALANGADOO 1

DEPARTMENT OF MINES AND ENERGY - SOUTH AUST. 86-254

4087

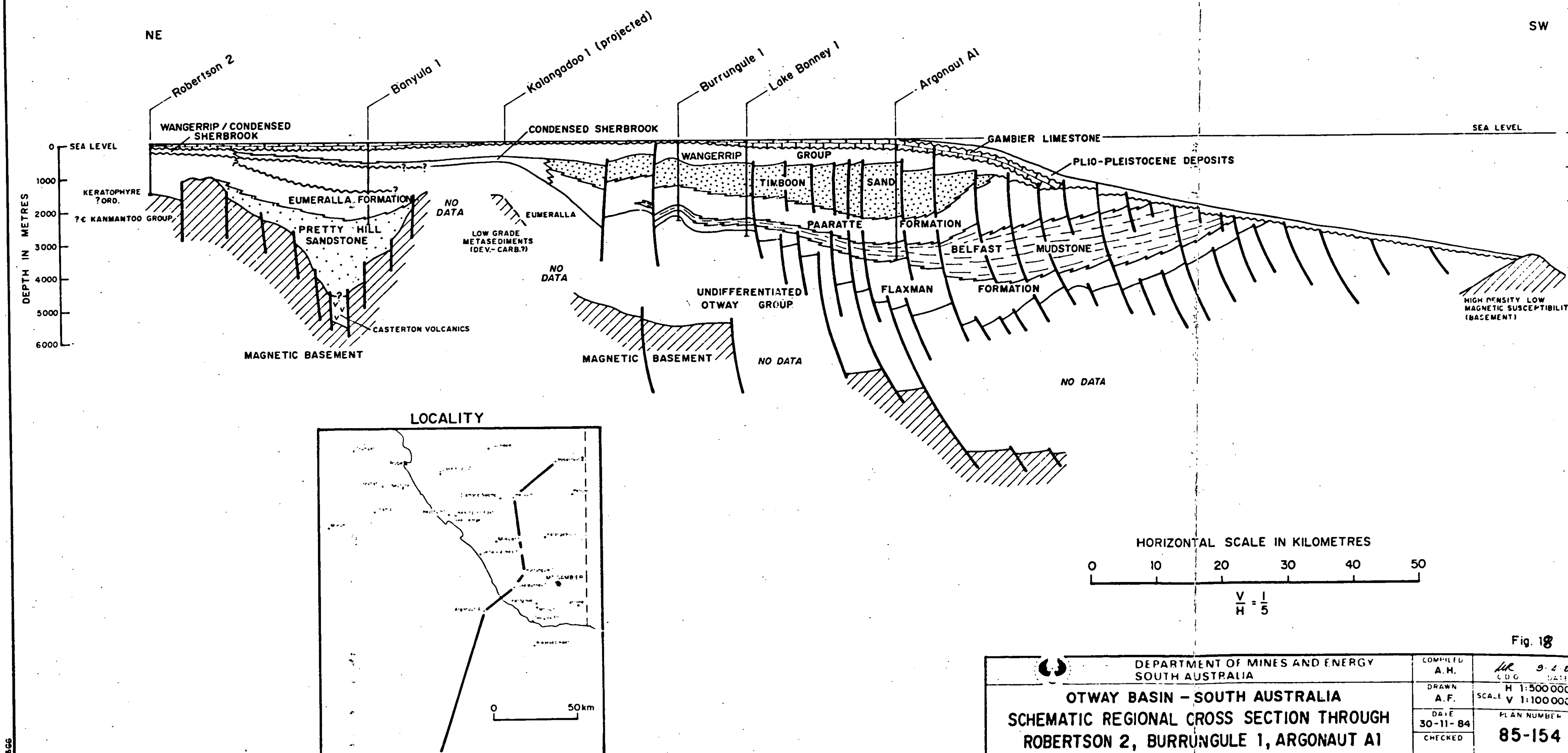


Fig. 18

DEPARTMENT OF MINES AND ENERGY SOUTH AUSTRALIA

OTWAY BASIN – SOUTH AUSTRALIA
SCHEMATIC REGIONAL CROSS SECTION THROUGH ROBERTSON 2, BURRUNGULE 1, ARGONAUT A1

COMPILED	A.H.	C.D.O.	9.4.86
DRAWN	A.F.	SCALE	H 1:500 000 V 1:100 000
DATE	30-11-84	PLAN NUMBER	85-154
CHECKED			