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CAINOZOIC PALEOGEOGRAPHIC EVOLUTION OF THE AUSTRALIAN CONTINENTAL MARGIN

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CAINOZOIC PALAEOGEOGRAPHIC EVOLUTION OF THE AUSTRALIAN CONTINENTAL MARGIN

by

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Note

The following record on the palaeogeographic evolution of the Australian continental margin was submitted to the ANU as part requirement for a Graduate Dipolma in Science.

Several maps and charts that were prepared for the study, but are not incorporated in this record will be made available at a later date. These include a Cainozoic biostratigraphic chart, an Australian relief map, a lithostratigraphic correlation chart, and a series of data maps.

ABSTRACT

This study is a synthesis of the palaeogeographic evolution of the Australian continental margin. The present configuration of the margin is largely a result of processes acting throughout the Cainozoic. These processes include lateral and vertical movements of the continental crust, fluctuations in sea level, volcanism, and major oceanographic, climatic and vegetation changes. The present day coastline formed in the Holocene, although a similar pattern had probably emerged in the Pliocene.

To synthesize the Cainozoic evolution of the continental margin, a series of lithostratigraphic summary columns and eight palaeogeographic interpretation maps depicting changes in the distribution of depositional environments throughout the period have been compiled. A structural map which indicates structures that were active during the Cainozoic and the thickness of preserved Cainozoic sediment.

The time slices selected to represent major events and changes in palaeogeography are: Paleocene-Early Eocene; Middle-Late Eocene; Early Oligocene; Late Oligocene-Middle Miocene; Late Miocene; Pliocene; Pleistocene; and Holocene.

A marked decrease in clastic sedimentation, in response to a gradual increase in aridity and low erosion rates, characterises the Cainozoic offshore sequences. Prograding carbonate deposition dominates most of the present continental shelf, with widespread (tropical) coral reefs along the northern margin and (temperate) bryozoan colonies in the south. The carbonate material is dominated by skeletal debris comprising abraded molluscs, foraminifera, bryozoans, echinoids, calcareous algae and corals. This sedimentation pattern probably began during the Miocene and possibly even earlier. Major marine regressions during the earliest Paleocene, Early-Middle Eocene, Early Oligocene, Late Miocene and Quaternary have produced widespread unconformity surfaces in the shallow shelf sequences around most of the present day continental shelf.

INTRODUCTION

The purpose of this study is to present a summary of the geological evolution of the Australian continental margin during the Cainozoic period. To provide such a summary, a series of eight palaeographic maps at various time intervals throughout the Cainozoic have been produced.

The work was carried out during the joint Bureau of Mineral Resources - Australian Petroleum Industry Research Association Phanerozoic Palaeogeographic Maps of Australia project. The aim of this study was to produce a series of 1 :10 000 000 scale time slice palaeogeographic maps depicting the Phanerozoic development of the Australian continent.

In order to complete such a task, data on lithological sequences throughout the Phanerozoic was compiled and palaeogeographic interpretation maps of approximately 60 time intervals were produced.

The Cainozoic component of the project was undertaken by G.E. Wilford and myself. G.E. Wilford was responsible for research and compilation on inland sequences and I was responsible for the marginal marine and marine sequences.

The geochronological framework was provided by E.M. Truswell with the aid of various biostratigraphers throughout Australia (Truswell, in prep.). The timescale of Berggren et al. (1985) was chosen and various local biostratigraphic zonations were correlated to the international record, with planktonic foraminiferal zones providing the main tie-points.

The method used in conducting the Cainozoic study was to initially compile an Australia-wide lithostratigraphic correlation chart from available data sources. In the case of the continental margin and offshore regions, chronological control on sequences is relatively well constrained, especially on the southern and western margins.

Due to the lack of chronological control on the continental sequences and widespread duricrust formation, a Cainozoic model (Wilford, in prep.) was devised based on four episodes of sedimentary accumulation (McGowran, 1979), to fit the poorly dated inland units. The model is based on palaeoclimatic, geomorphic and pedologic considerations.

Having compiled the lithostratigraphic correlation chart, the second step was to select time slice intervals which would illustrate major changes in palaeogeography. Criteria such as widespread stratal breaks, periods of marine inundation, tectonic activity, and palaeoceanographic and palaeoclimatic changes determined the time intervals chosen. The time slices selected were:

1. Palaeocene - Early Eocene (66.4 - 52.0 Ma)
2. Middle - Late Eocene (52.0 - 36.6 Ma)
3. Early Oligocene (36.6 - 30.0 Ma)
4. Late Oligocene - Middle Miocene (30.0 -10.4 Ma)
5. Late Miocene (10.4 - 5.3 Ma)
6. Pliocene (5.3 - 1.6 Ma)
7. Pleistocene (1.6 Ma - 10 ka)
8. Holocene (10ka - present day)

To compile the interpretative palaeogeographic maps, a data map of each time interval was produced, depicting lithologies and approximate thicknesses of strata deposited during each time slice. Structural information, (such as active faults, folds and volcanism) was also plotted on a separate Cainozoic structural map.

The palaeogeographic maps illustrate a summary of the geography of the respective time intervals and hence do not depict an actual "snap-shot" in time. The maps are also compiled to be published at a scale of 1 : 10 000 000 and are necessarily generalised. A fuller explanation of each time slice map is given later.

A series of cross-sections are provided to illustrate the structural and stratigraphic relationship of Cainozoic strata, in areas of relatively well defined geology.

This study will concentrate on the continental margin development with passing reference to inland sequences.

PREVIOUS WORK ON CAINOZOIC PALAEOGEOGRAPHY

The first Australia-wide maps of Cainozoic data (extent of basins and strata) were published in 1968 (Brown et al., 1968). Palaeogeographic maps for Western Australia (Paleocene-Eocene, Miocene) were published in 1974 (Quilty, 1974) and 1975 (Playford et al., 1975), and in 1976 Abele et al. discussed the Cainozoic depositional history for Victoria. Kemp (1978) produced a series of regional palaeogeographic and palaeocirculation maps for the Paleocene, Eocene, Oligocene, and Middle and Late

Miocene. Seven time slice maps for Queensland were published in 1983 (Day et al., 1983), and Australia-wide palaeogeographic maps (Early Tertiary, Late Tertiary, and Pleistocene) at about 1:30,000,000 scale were published in the BMR Atlas Series in the same year (Wilford, 1983). The most recent compilations are those of Quilty (1984), Jenkins (1984) and Veevers et al. (1984). Quilty (1984), published four continent wide palaeogeographic maps - Paleocene-Early Eocene, Mid-Late Eocene, Oligocene-Mid Miocene, and Mid Miocene-Pleistocene, and Jenkins (1984) produced generalised early and late Tertiary Australian palaeogeographic maps. Veevers et al. (1984) produced a synopsis of Cainozoic palaeogeographic evolution which included a series of eight regional plate tectonic reconstructions.

CAINOZOIC STRATIGRAPHIC CORRELATION

The state of stratigraphic definition and nomenclature varies in Australian Cainozoic marginal sequences, ranging from virtually undefined in parts of the eastern and northern margins, through to detailed description to member level in southeast Australia. Many offshore marine sequences are often not defined, and are referred to by their position relative to unconformity seismic reflector surfaces. The age of the unconformity horizons have been determined by, at times tenuous long distance correlation to petroleum exploration wells or DSDP wells. A series of stratigraphic summary columns (Plate 1), depicts the present state of knowledge of Cainozoic sequences. Note that in the Bonaparte Basin, informal Cainozoic stratigraphic nomenclature has been applied to basin ("Gannet, Hibernia and Fantome Formations"). This nomenclature is currently being reviewed by the Geological Survey of Western Australia.

Biostratigraphic correlation

Marine sequences are generally correlated by foraminiferal and nannofossil biostratigraphy. Foraminiferal correlation schemes at present, are a combination of local assemblage zones, including those of Ludbrook and Lindsay (1969) and Mallett (1977), and evolving lineages such as Globigerinoides sicanus > Orbulina universa.

Foraminiferal event datums, such as first and last appearances (McGowran, in press; Chaproniere, 1984), are also included in foraminiferal stratigraphies, and are widely used. (Truswell, in prep,).

The international planktonic foraminiferal P and N zones are often not recognised within Australia. Instead, local biostratigraphic successions are calibrated against the radiometrically calibrated P and N zones at the present best estimate (McGowran, in press). Accurate stratigraphic correlation is hampered in shallow marine sequences by the dominance of benthonic foraminiferid faunas which are often long ranging. Nonetheless, several species or groups of species of foraminifera are valuable palaeoenvironmental indicators (Hallock and Glen, 1986). Nannofossil biostratigraphy is becoming increasingly more important as a correlation tool.

Palynostratigraphy, applied to continental and marginal marine sequences outside of southern Australia is at present unreliable, due to the lack of correlation to well calibrated schemes in southern Australia (especially in the southeast region). Long distance correlation of terrestrial vegetation is tenuous in that climatic differences have a major effects on the nature of vegetation communities. For a detailed appraisal of Cainozoic biostratigraphy refer to Truswell (in prep).

Financial considerations in offshore drilling results in very poor sampling of the top part of the sequences intersected in petroleum exploration wells. Consequently, sometimes up to 500 metres is not sampled either by core or wireline logs and valuable data for many Neogene sequences is not available.

Time slice intervals

The limiting factor in the selection of Cainozoic time slices was the poor biostratigraphic control of the continental sequences. Without this, the more accurate foraminiferal biostratigraphic control in the marine sequences would have allowed for even finer subdivision.

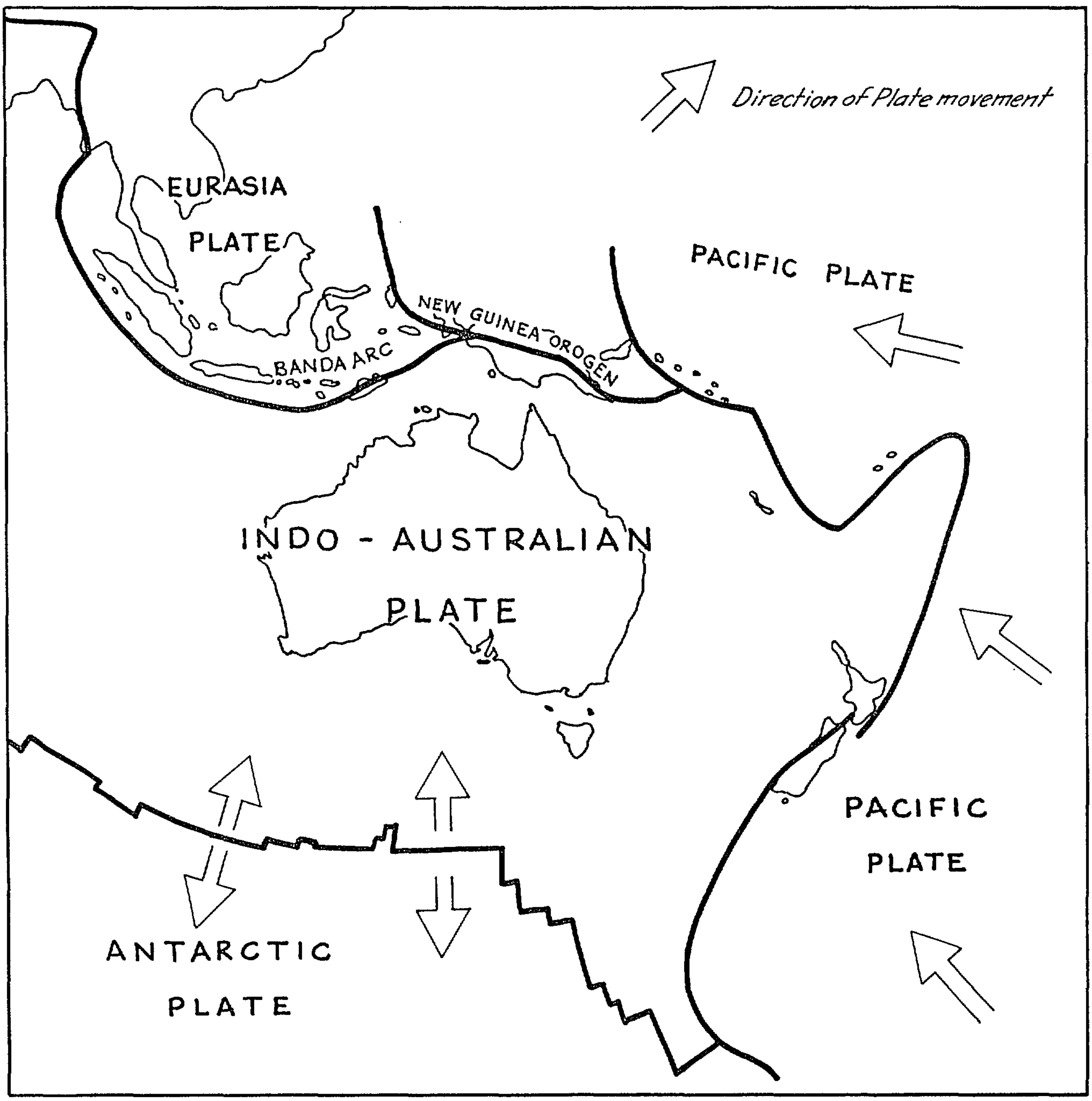


Fig.1 Simplified Plate Tectonic framework

TECTONIC FRAMEWORK

Three major crustal plates, the Antarctic, Pacific, and Eurasian plates, occur around the present-day margin of the Indo-Australian plate. Geologically, the Australian craton has divergent, passive continental margins on its southern, western, and eastern margins (Falvey & Mutter, 1981). The northern and northeastern margins form a complex convergent boundary between the Indo-Australian plate and the Eurasian and Pacific plates (Figure 1).

The northward drift of the Indo-Australia plate "carried" the Australian continent approximately 2000 kilometres during the Cainozoic (Figure 2). A change in plate motion during the Eocene is probably associated with a broader series of plate tectonic changes (McGowran, 1979; Idnum,1986), and an increased Antarctic - Australia spreading rate.

Northern margin

The New Guinea Orogen, on Australia's northern margin, has recently been interpreted (Pigram & Davies, 1987) to have formed as a result of Cainozoic collision and accretion of approximately thirty tectonostratigraphic terranes with the northern margin of the Australian craton. The western part of the northern margin is now generally recognized (Johnson & Bowin, 1981; Audley-Charles, 1986) as a Pliocene collision zone between the outermost edge of the Northwest Shelf and the Banda Arc subduction zone.

Western margin

The western continental margin was shaped by sea -floor spreading in the Indian Ocean during the Jurassic and Cretaceous periods (Johnson et al., 1973). Several marginal plateaus bounded by abyssal plains (the Scott, Exmouth, Wallaby, and Naturaliste Plateaus) resulted from the northeast trending spreading pattern, (Wilcox, 1981).

Southern margin

Modern tectonic trends on the southern margin are generally considered to have begun in the Jurassic, with sea-floor spreading between Australia and Antarctica beginning in the mid-Cretaceous (Cande & Mutter, 1982; Veevers, 1987). Thinning of the crust and

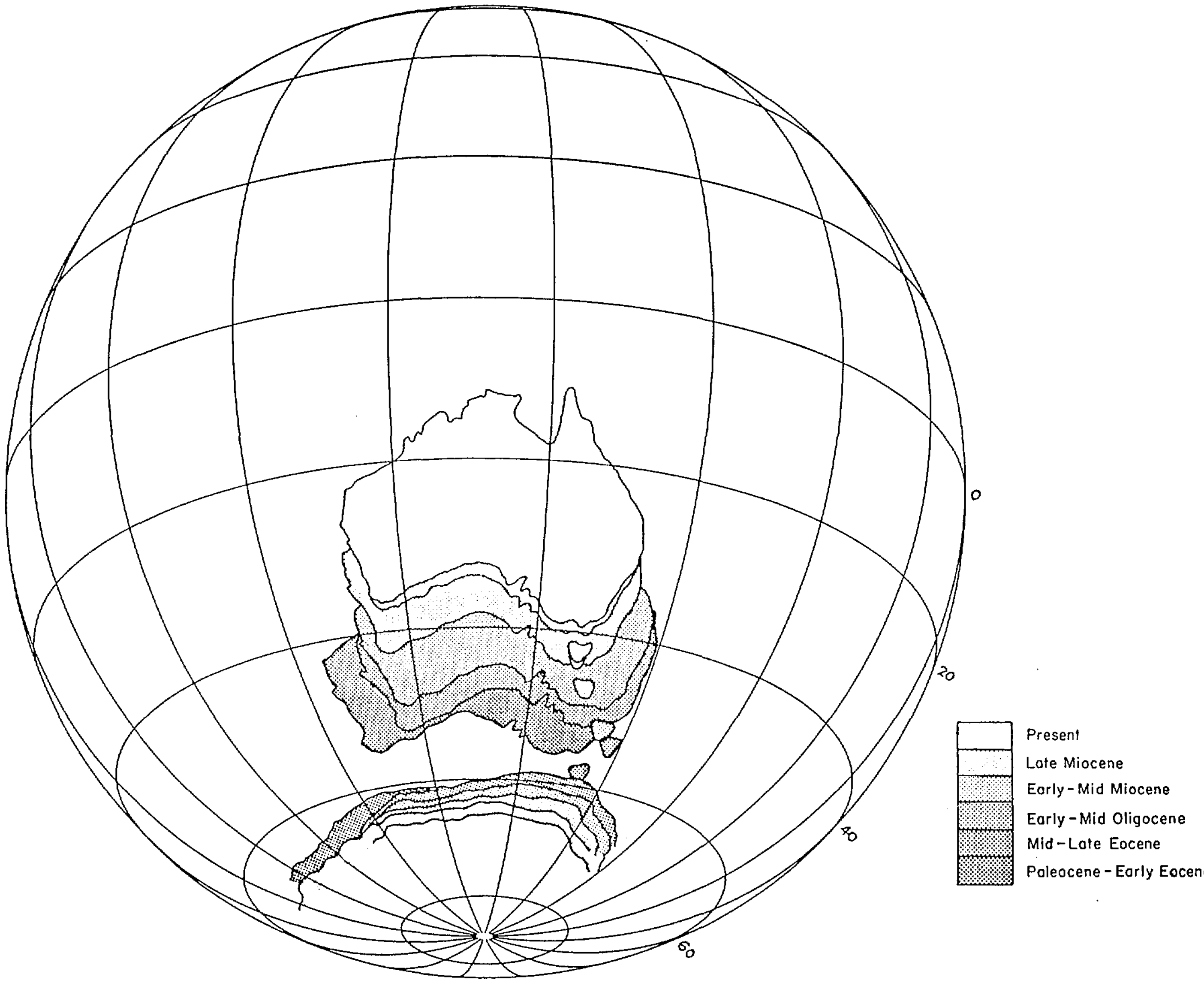


Fig. 2 Relative Cainozoic plate motion of Australia and Antarctica (Scotese, 1986)

subsidence of the Australian continental margin proceeded sea-floor spreading.

Eastern margin

The opening of the Tasman Sea, a marginal basin, between the Lord Howe Rise and the eastern Australian margin, has been dated by magnetic anomaly identification (Hayes & Ringis, 1973) as occurring from the Cenomanian to the Early Eocene (magnetic anomalies 33-24). Several spreading models based on different finite rotation poles and fault motions have since been proposed to account for the origin of the Tasman Sea, (Weissel & Hayes, 1977; Jongsma & Mutter, 1978; & Shaw, 1978.)

Northeastern margin

The northeastern margin is an extremely complex product of seafloor spreading, rifting and margin accretion. The opening of the Coral Sea Basin and associated rifting produced a network of troughs and marginal plateaus, and has been dated as occurring in the Paleocene (Weissel & Watts, 1979). However, more recent analysis (Symonds et al., 1984) implies an older, Late Cretaceous breakup age. Collision with the New Guinea Orogen during the Oligo-Miocene has produced foreland basins at the northern edge of the Australian plate (Pigram & Symonds, 1988).

STRUCTURAL HISTORY

The Cainozoic was a period of relative stability in the interior of the continent, with broad scale epeirogenic warping of the craton. Faulting and low-angle folding of sediments in the Eromanga Basin began in the mid Tertiary, and is continuing locally to the present day; tectonism is generally ascribed to compressive crustal shortening resulting in small scale movements on pre-existing faults (Krieg, 1982; Finlayson et al. 1988). Along the eastern Palaeozoic orogenic belt high-angle normal faults trending north to northwest, and local upwarping related to basaltic volcanic activity occur, (Wilford et al, in prep).

The Cainozoic structural features around the continental margin are primarily related to subsidence of the passive margin, except on the northern convergent margin. The different rates of subsidence of various basins are evident from the isopach on the structural map (Plate 2). A mid Tertiary ?compressive event appears to have led to widespread effects in various parts of the continent. There also appears to be a gradual uplift along parts of the southern margin, with a period of pronounced vertical tectonism along the northern margin,during the late Cainozoic.

<u>Southern margin</u>

Cainozoic sediments in the inshore Bremer Basin are flat lying, with no evidence of any structural movements. To the north on the Yilgarn Block, Late Eocene shallow marine sediments are locally at an altitude of 300 meters (Johnson et al., 1973). Equivalent sediments on the eastern side of the Eucla Basin are at a present elevation of 150 meters (Benbow et al., 1982). The difference in altitude may reflect uplift of the craton relative to the basin, or alternatively downwarp of the basin. Miocene limestones within the Eucla basin are also at a present elevation of up to 180 meters, indicating uplift: the magnitude of which is dependant on palaeobathymetry and post depositional erosion. Numerous fault scarps (Lowry, 1970), up to 160 kilometres long outcrop across the basin, and possibly are related to tilting and uplift.

The Early Tertiary in the Bight Basin was marked by the development of east-west trending, closely spaced normal faults on the southern flank of the basin (Boeuf & Doust, 1975; Frazer & Tilbury, 1979). Further east in the Duntroon Basin similar faulting with associated tilting and uplift of basement blocks took place. However, the timing of this tectonism is poorly known and the event is presumably related to post-rift subsidence of the outer continental margin. The Cainozoic sequences are generally undeformed throughout both basins, although local slumping has been recorded in the Duntroon Basin (Pattinson et al., 1976).

The intracratonic St Vincent Basin is separated from the southern continental margin by a basement high centred on Kangaroo Island. The basin formed during the Middle Eocene, possibly as a result of increased rate of Australia/Antarctica separation, and subsidence of the trailing plate margin. Movements along normal faults have controlled the basin sedimentation patterns throughout the Cainozoic (Stuart, 1970; Daily et al., 1976; Cooper, 1985). The faults reflect underlying basement structure established during the Early Palaeozoic Delamerian Orogeny. To the east of the basin, uplift at various times during the Cainozoic has brought the Flinders and Mount Lofty Ranges to their present elevation. The timing of uplift is poorly constrained, although the main period of uplift was probably during the Plio-Pleistocene (Wellman, in press). Uplift it probably continues today, as the region is one of the most seismically active areas in Australia (Denham, 1979).

The Cainozoic history of Spencer Gulf to the west is poorly known , however the northern part of the Gulf may have a similar history to that of St Vincents Basin, (Gostin et al., 1984). The southern area is underlain by shallow Precambrian basement.

The intracratonic Murray Basin developed as a result of eustatic sea level changes and related intrabasinal isostatic adjustments (Brown, 1985, Brown & Stephenson, 1986). Jones and Veevers (1982) have proposed an alternate model of tectonic cycles of uplift in the hinterland (Eastern Highlands) and/or subsidence of the basin. However both factors, eustatic and tectonic, have probably been involved in producing the thin (less than 600m) but widespread sedimentary record in the basin. Tertiary movement on underlying basement blocks has been recorded in the basin (C.M. Brown, pers. comm.), but generally conditions were relatively stable. Quaternary sedimentation was influenced by minor movements on pre-existing fault zones; the location of gypsum playas can be related to movements on the Hindmarsh and Danyo Faults (Lawrence, 1976), and the present course of the Murray River is largely structurally controlled (Twidale et al., 1978).

The structural evolution of the Bass, Gippsland, and Otway Basins has been extensively discussed (Carey, 1970; Falvey, 1974; Davidson, 1980; Etheridge et al., 1988). The stratigraphic similarity of the basins implies that they are inter-related. Agreement exists that their development is related to rifting of Australia and Antarctica and/or Lord Howe Rise/New Zealand during the Cretaceous and Early Tertiary. The structural development can be described in terms of early rifting and associated extension, followed by a subsidence sag phase, overprinted by a late stage compressional phase. The exact timing, mechanism and extent of the structural stages is complex and, at present, unclear, but the tectonism is probably a result of a northwest to southeast Eocene to Recent compressional stress field (Etheridge et al., 1985). The recently recognised basin forming, high-angle transfer faults which separate a series of orthogonal, lower-angle rotational normal faults into "compartments" (Etheridge et al., 1984) appear to extend a fundamental control on the geometry of the basins (Fig. 3).

The Portland Trough in the Otway Basin formed as a result of differential basement subsidence during the Cretaceous, and is a Cainozoic depocentre in the basin containing

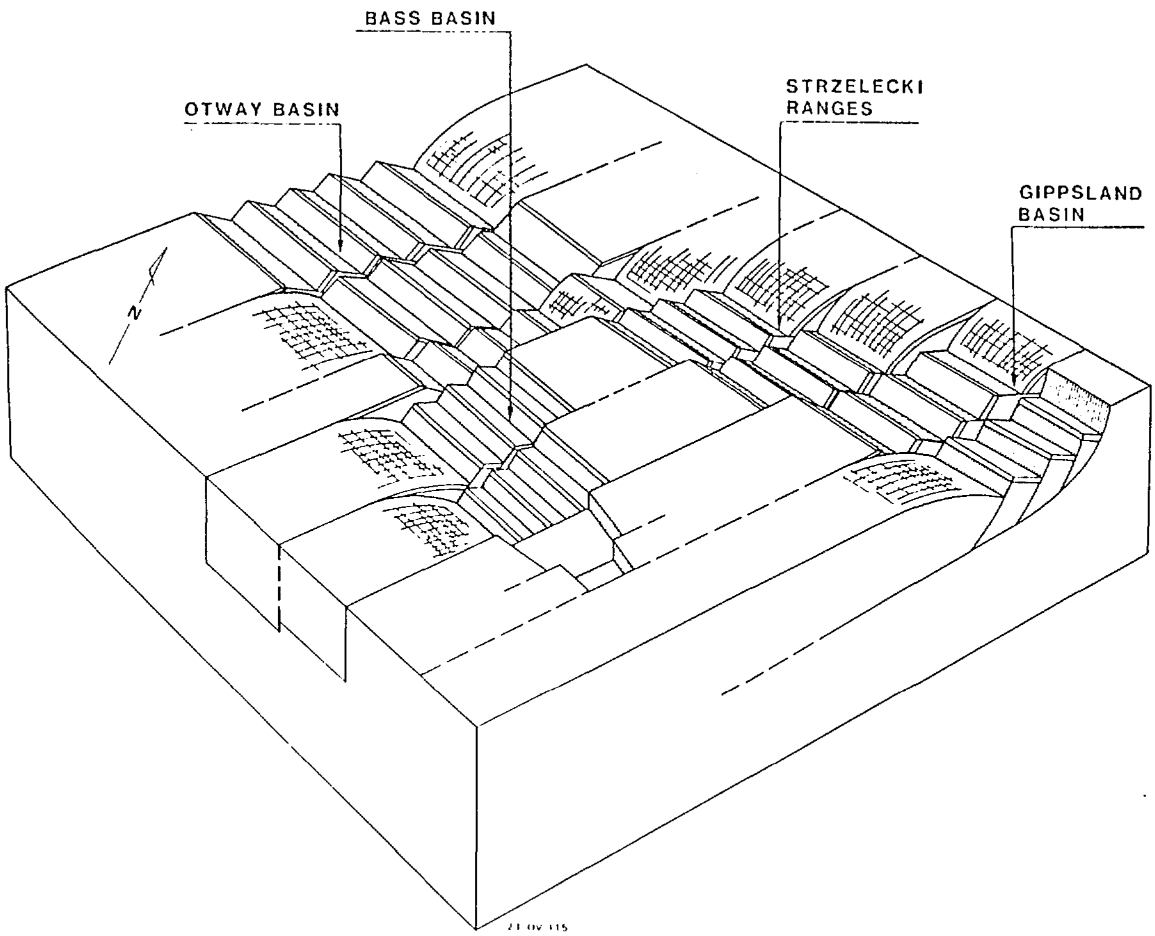


Fig.3 Schematic diagram of Cretaceous basin-forming structures in the Bass Strait area (Etheridge et al., 1987)

up to 2.5 kilometres thickness of sediment along its axis. The trough is a fault-bounded graben structure trending parallel to the coastline. Faults and structural highs bounding the trough were active during sedimentation in the Early Tertiary, and sedimentation rates were high, up to 280 m/Ma. Tectonic activity appears to have slowed down during the Late Tertiary concomitant with lower sedimentation rates of approximately 25 m/Ma (Holdgate et al., 1975). During the Middle to Late Eocene a period of right-lateral wrenching affected the Otway Basin, reversing the movement on some faults (e.g. Kanawincka Fault), uplifting basement blocks, and forming en-echelon northwest-trending anticlines (Megallaa, 1985). Condensed sequences accumulated on either side of the trough, and beyond the present day 2000m isobath the Tertiary thickness diminishes to less than 200m.

In the western part of the basin fault reactivation is present at the Eocene/Oligocene unconformity surface, forming antithetic block faults and rollover structures. The faults are reactivated rifting faults and trend parallel to the shelf; some are still active today. In contrast, fault activity on the offshore eastern side of the basin is very minor, mainly reflecting sedimentary drape over deeper rifts (Williamson et al., 1987). The edge of the present day continental slope appears to have collapsed since the Eocene with subsidence of up to 3000m occurring (Exon & Lee, 1987).

The Otway Basin was gradually uplifted from the Late Miocene to the Quaternary. Onshore faulting, widespread folding, volcanism and local monocline development were associated with this uplift (Abele et al., 1976). Differential uplift was presumably responsible for the differences in Late Cainozoic depositional history along the Victorian coast; the cliffed coastal physiography of the eastern Otway Basin area is in marked contrast to the sand barrier coasts of the Murray, Port Phillip and Gippsland Basins (Carter, 1985).

Along the southeastern part of the Otway Basin and further south into the Sorell Basin, tectonism is complex and not fully understood. Accelerated Australia-Antarctica separation appears to have been responsible for Eocene wrenching along the western Tasmanian shelf and slope (Hinz et al., 1985). This was followed by thermal subsidence and flexuring of the continental margin, as is evident along the shelf. Rapid post-Eocene subsidence of the outer continental shelf/slope region similar to that in the Otway Basin has occured.

The Torquay Basin was relatively stable during the Early Tertiary, but Late Tertiary tectonism produced faulting and folding of Miocene and older sequences, with progressively greater deformation at depth and towards bounding faults at the basin margins (Jones & Holdgate, 1980).

Early Tertiary subsidence with associated volcanism occured in the Ballan Graben, and also possibly in the Port Phillip Basin (Abele et al., 1976). The present day embayments of Port Phillip Bay, and to the east, Western Port Bay, were probably formed by compressive late Cainozoic graben development. Present day topography and seismicity in Victoria can be explained in terms of a dominant northwest - southeast stress component (Gibson, 1982).

In the Bass Basin, Cretaceous extensional faulting continued into the Early Tertiary, producing normal and minor reverse faulting within the Tertiary sequence due to displacement of basement blocks (Robinson, 1974; Williamson et al., 1987). This basin was the least affected by the late stage compressional tectonics, with reactivation of early faults forming local minor folds and faults.

Further east in the Gippsland Basin,the Early Tertiary structural history was that of mainly east-west trending, down-to-basin faulting (Jones & Evans, 1981; Abele et al., 1976; Threlfall et al., 1976). Compressive tectonic activity began during the Middle Eocene and has continued to the present day. Many of the major anticlines that dominate the basin today began growth in the Eocene and are related to movement on underlying faults. The timing of the development of the various anticlines is complex and uncertain, especially onshore (Brown, 1985; Etheridge et al., 1985). Offshore, basin subsidence during the Paleogene appears to have been greater than sediment supply; this relationship was reversed in the Neogene with the basin being infilled with prograding sediments (Hegarty et al., 1986).

Large scale N-NW trending grabens developed along the northern margin of Tasmania during the Cretaceous-Early Tertiary. These depressions formed major drainage outlets joining the Bass Basin and became the site for non-marine deposition. Vigorous mid-Cainozoic volcanism produced thick sequences of alkali and tholeiitic lavas that filled valley systems and upland troughs (Sutherland, 1974). A major graben on the west coast of Tasmania (Macquarie Harbour) possibly formed during the Early Tertiary. Other Tertiary faults have been recorded throughout Tasmania, although the age of movements are generally not well established. Emergent Quaternary shorelines provide evidence for recent uplift in Tasmania, however further investigations are required to substantiate uplift (Bowden & Colhoun, 1984).

Eastern margin

The plate separation that formed the Tasman Sea was apparently non-axial,with little seismic evidence for block faulting remaining on the Australian plate (Jongsma & Mutter, 1973). This accounts for the narrowness of the southeastern Australian continental shelf (less than 60 km), and the steepness of the continental slope. The spreading operated about a northwest orientated spreading axis, affecting the southern area earlier than the northern part. The northern margin (in the vicinity of latitude 28°-30° S), is probably the youngest part of the Australian margin and coincides with a seismic basement high beneath the shelf (Jones et al., 1975). The southern area possibly has a longer history of subsidence (Chapman et al., 1982).

Northeastern margin

Late Cretaceous to Paleocene rifting in northeast Australia produced fragmentation of the northeastern extension of the Tasman Fold Belt. This created a system of rift troughs -the Queensland, Townsville and Bligh Troughs, and Osprey Embayment (Taylor & Falvey, 1977; Mutter & Karner, 1980; Symonds et al., 1984). The westernmost rift basins and boundary faults have controlled the location and form of the present day continental shelf. Sea floor spreading in the Coral Sea began in the Late Cretaceous and was completed by the Early Eocene. Rotational opening of the Coral Sea Basin separated the Eastern and Papuan Plateaus from the Queensland Plateau. The Capricorn Basin to the south also appears to have formed at the same time in response to opening of the northern Tasman Basin (Marshall, 1977). Following the rift phase, vertical subsidence of the troughs and marginal plateaus continued throughout the Cainozoic period as the Indo-Australian Plate moved northwards. The structural style and relationships of the various structural elements in the region is complex.

The Queensland Trough structural development was controlled by pre-existing basement normal faults. The fault trend is north to northwest, affecting the Early Tertiary sequences; the post- Oligocene sequences are essentially undisturbed. The Townsville Trough structural style is at present not well understood. Cainozoic faulting on the

Queensland Plateau is restricted to small grabens and half grabens (Mutter, 1977), with subsidence affecting the outer edge of the Plateau more than the inner edge.

The western edge of the Eastern Plateau is defined by the fault controlled Pandora and Bligh Troughs. The Pandora Trough may have resulted from collision with the Papuan Plateau; the Bligh Trough is underlain by small tilted fault blocks. The western edge of the Osprey Embayment is probably rift related and of continental origin, whereas in the east it may be of oceanic origin (Davies et al., in prep.). Collision of the northern edge of the Eastern and Papuan Plateaus with the Papuan Peninsula during the Late Cainozoic produced deformational structures on the leading edge of the Moresby Trough, associated with foreland loading (Pigram & Symonds, 1988).

Northern margin

Cainozoic downwarping of the Gilbert-Mitchell Trough in the Karumba Basin led to the deposition and preservation of the maximum (250m) thickness of onshore sediment in the basin (Smart et al., 1980). Seismic data (Pinchin, 1973) indicates that Cainozoic sequences are about 300m thick in the Gulf of Carpentaria, and thicken northwards towards the Morehead Basin.

Faulting is evident in the Money Shoal Basin (Jongsma, 1974), which is outside the area covered by the accompanying structural map.

Western margin

The Cainozoic structural history of the North West Shelf is dominated by passive margin subsidence following Mesozoic rifting and transform faulting. However, the structural history of the northern part of the Shelf is more complex than that of a subsiding passive margin. The Early Tertiary flexure of the continental margin produced a prograding, northwest-thickening sediment wedge (Allen et al., 1978). This pattern continued until the Early Miocene when pre-existing faults in the Londonderry High area were reactivated, producing a complex pattern of antithetic faulting and horst/graben blocks in response to extensional deformation (Laws & Kraus, 1974, Hall, 1987). The Cartier Trough was reactivated, forming a symmetrical sag basin, which led to faulting on its marginal arches. This process has continued from the Miocene to the present day, and is reflected in the current sea floor morphology.

Rapid depression in the Scott Reef-Ashmore Block area began during the Early Miocene, and this epeirogeny has been attributed to the collision of the Northwest Shelf with the Banda Arc to the north (BOCAL, 1975). However, this interpretation is possibly not valid as the Timor orogeny is now recognised as a Pliocene event (Johnson & Bowin, 1981; Audley - Charles, 1986). Alternatively this epeirogeny may be related to a change in intraplate stress as proposed by Charlton (1986).

Deformation associated with Australia-Banda Arc collision is most intense at the foot of the inner slope of the Timor Trough. The deformation front is discontinuously advancing southwards as new thrust slices develop within the subducted Australian margin strata (Karig et al, 1987).

Along the rest of the shelf, a regional northwestward tilt began during the Early Tertiary and continued throughout the Cainozoic, aiding the development of closure on earlier formed draped anticlines (Barter et al., 1982). A thick prograding carbonate wedge (up to 3km thick) has obliterated most traces of any earlier basin configurations. The sedimentaton rate was greater than that of the slow, subsiding tilt along the hinge line parallel to the present coastline (Quilty, 1984).

The outer margin of the continental shelf underwent Late Tertiary normal faulting and gentle folding . The reason for the movements is unclear, and could be due to gravitational collapse, differential compaction, or related to the well- documentated Miocene tectonism (Jones, 1973, Playford et al., 1975). Fault structures on the outer edge of the Scott Plateau are most likely to be related to gravitational collapse. Further inshore, reactivated faulting adjacent to the Leveque Platform is probably due to movement along the inner hinge zone.

Miocene to Recent fault rejuvenation in the Carnarvon Basin disrupted the gradual subsidence pattern, producing several regional en echelon regional anticlines, and uplift of the eastern margin of the basin. The present day coastline is a result of these movements, evident in the Shark Bay area where emergent Late Quaternary coastal deposits are raised over anticlinal axes (Denman and van der Graff, 1976). High angle reverse faulting is a common feature of the southern part of the basin (Playford et al., 1975; Smith & Cowley, 1987) and has been related to compressive wrench-tectonics (Kopsen & McGann, 1985), which has important implications in oil migration paths. This reverse movement may be a result of late stage readjustments to the breakup and foundering of the western margin (Hocking et al., 1987). Subsidence of the outer margin has continued to the present day, reflected in high sedimentation rates especially during the Plio-Pleistocene.

The cooling oceanic crust surrounding the Exmouth Plateau continued to subside to abyssal depths , precipitating isostatic subsidence on the plateau (Barber, 1982). A broard anticlinal structure, the Exmouth Plateau Arch), probably dates from the Miocene (Exon & Wilcox, 1978), and is downwarped on its western and eastern sides. The Kangaroo Syncline to the east is underlain by an intensely faulted graben structure facilitating downwarping.

The subsidence of the surrounding abyssal plains was accommodated by faulting on the margin of the plateau, especially on the western side (Exon et al., 1982). Movement on some of these faults has continued through the late Cainozoic, and some penetrate through to the sea floor. A major hinge line structure on the northern side of the plateau and a northwestly trending arch are presumably related to subsidence. Low sedimentation rates have resulted in water depths of over 1500 metres overlying the Exmouth Plateau.

Faulting of deep sea turbidites has been recorded to the south in the Cuvier Abyssal Plain (Symonds & Cameron, 1977), and has been related to Miocene tectonism. The Pliocene to Recent sequences along the North West Shelf are generally flat lying or exhibit gentle depositional dips (Jones, 1973).

Present day seismicity

The present day seismicity of the Australian continent occurs in broard zones of prexisting weaknesses within the craton and is concentrated along the convergent northern margin of the continent. Widespread stress measurements (Denham 1979, 1981) indicate that a predominately compressive state exists in the Australian continent, and that stresses are being released only in the upper and middle regions of the crust. The axes of maximum compression vary considerably across the continent, and is related to intraplate stress, a phenomena not well understood, (Lambeck et al., 1984)

Weissel et al., (1980) demonstrated from studies of recent sediments, that the Indo-Australian plate has been undergoing deformation since the Late Miocene, possible due to changing boundary conditions along the northern margin .

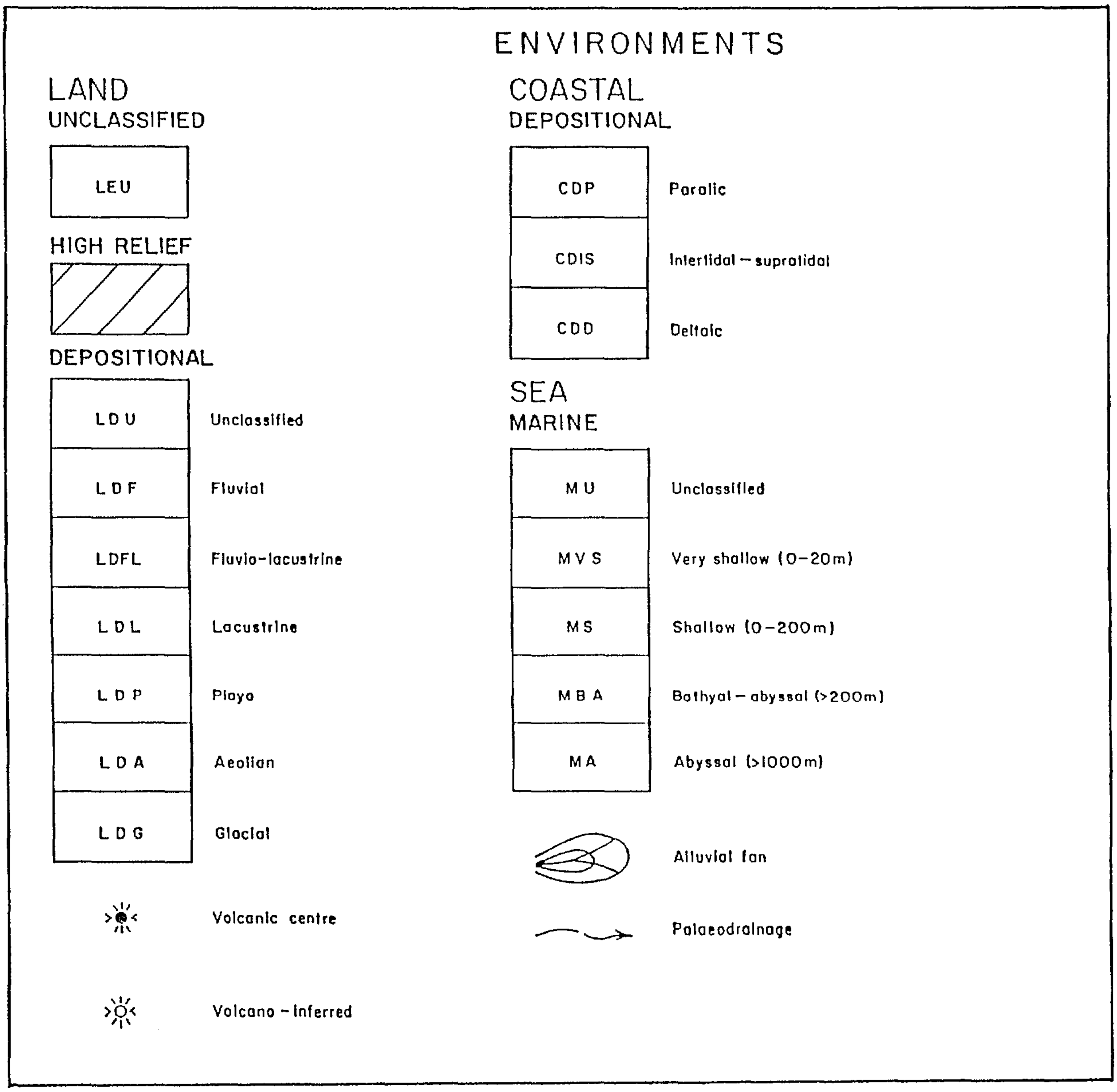


Fig. 4 Reference to environments


BMR – APIRA
PALAEOGEOGRAPHIC MAPS PROJECT
CAINOZOIC TIME SLICE I
INTERPRETATION
PALEOCENE TO EARLY EOCENE
66 – 51 Ma (Berggren et al., 1985)
INDIAN OCEAN
SOUTHERN OCEAN
CORAL SEA
SOUTH PACIFIC OCEAN
TASMAN SEA
SOLOMON SEA
TIMOR SEA

Figure 5

PALAEOGEOGRAPHY AT THE BEGINNING OF THE CAINOZOIC

At the beginning of the Cainozoic many of the major relief features present today were already in existence, the major exception being the Flinders-Mount Lofty Ranges which was a relatively low-lying terrain. In parts of the Eastern Highlands relief was probably similar to that of today. However, in areas of Cainozoic volcanism, local up-doming resulting from intrusion at depth, as well as lava accumulations at the surface have produced the present landscape. Drainage was totally external and approximated that shown in Figure 5. The general paucity of coarse clastics in most offshore areas (except in the tectonically active southeast corner) in latest Cretaceous and Early Cainozoic times indicates that much of the detritus being eroded from the deeply weathered mantle was being deposited on the low-lying continent, with mainly fine material reaching the sea. Wide, irregular valley systems had developed in the flatter part of the continent in the west, (Wilford et al, in prep).

The Cretaceous-Tertiary boundary is marked by a widespread hiatus along the western margin of the continent and in several areas on the southern margin. Global extinction of many genera of marine fauna especially shallow water biota occurred, reflecting a major oceanographic change possibly associated with a lowering of sea level. Many hypotheses, involving both terrestrial and extraterrestrial causes, have been proposed to explain this event and several other phenomena that occur at the end of the Cretaceous (Kennett, 1982; Berggren & van Couvering, 1984).

TIME SLICE 1: PALEOCENE - EARLY EOCENE (66-52 Ma)

The Paleocene to Early Eocene interval has been recognised by various workers (Quilty, 1977; McGowan, 1978a, 1979) as a distinct cycle of sedimentation in the Australian region, bracketed by regressions and hiatus at the Cretaceous-Tertiary and Early-Middle Eocene boundaries. During this interval the Australian continent lay between 30 and approximately 55° South. Sea floor spreading along the eastern margin ceased during this period while slow spreading continued along the southern margin. Fully marine conditions had been established on the western margin in the Indian Ocean.

The Southern Ocean was in an early stage of ocean basin evolution with restricted and somewhat sluggish deep water circulation depositing euxinic claystones (Andrews, 1975). Cretaceous to Early Eocene sea floor spreading half-rates between Australia and Antartica have been calculated at approximately 5km\Ma (Mutter et al., 1985). Surface water temperatures were high, in the vicinity of 20° C on the Campbell Plateau to the east (Shakleton & Kennett, 1979). There was probably a shallow strait connecting the Southern Ocean and the Tasman Sea.

The Great Australian Bight was a broad terrace with shallow marginal marine to lagoonal environments, on the landward side of which glauconitic and carbonaceous clastics and coals accumulated. The area was affected by seven marine transgressions (Deighton et al., 1976) and was characterised by slower subsidence and sediment accumulation than in the Cretaceous (Cande & Mutter, 1986).

In the Murray Basin spreads of coarse sand with minor lignite and fine clastics (Warina Sand), accumulated along ancestral courses of the Murray and Darling rivers. Borehole data indicates that the Warina Sand was deposited in braided-channel alluvial system with the lenticular finer sediment being deposited in lacustrine to flood-plain environments (Brown, 1985). The preserved sediment forms a major depocentre in the central part of the basin.

Sedimentation in the subsiding Otway Basin was essentially detrital (Wangerrip & Knight Groups), with a widespread hiatus occurring in the earliest Palaeocene. Locally, deposition of the Timboon Sand Member continued across the Cretaceous\Tertiary boundary (Abele et al., 1976).

Rising sea levels in the late Early Paleocene reworked lag gravels and sands with peletal shales to form restricted shallow marine iron-rich oolitic sediments of the Pebble Point Formation (Holdgate et al., 1987). The map shows two major deltas of a sequence of up to seven deltaic cycles (Holdgate, 1981) filling a rapidly subsiding Portland Trough. Initially, a thick prodelta sequence of pyritic, carbonaceous mudstones (Pember Mudstone) containing arenaceous foraminifera accumulated within the trough. This graded upwards through cycles of delta-slope and delta-plain clastics with minor coals of the Dilwyn Formation. The palaeo-rivers carrying detritus may have flowed from north of the present divide. Deltaic sedimentation ceased with uplift of local structural highs and inundation of marine shales (Burrugule Formation) during the latest Early Eocene.

Elsewhere in the Otway basin the Pember Mudstone and the Dilwyn Formation, which are in part time-transgressive, but are contemporaneous in other areas (Abele et al., 1976), formed in a variety of environments from continental to marine. Offshore barrier bars (Mussel Sandstone) have been recognised within the Pember Mudstone.

Onshore in the Otway and Torquay Basins, clastics and coals of the Eastern View Formation and equivalents were deposited in fluvial environments as basalts were locally extruded and intruded.

Off western Tasmania, non-marine to marginal marine conglomerates and sands of variable thickness have been intersected in petroleum exploration wells on the present day continental shelf. Peaty sands of Early Eocene age have been recovered from deeper parts of the Tasmanian continental slope (Hinz et al., 1986), indicating substantial post-Eocene subsidence. The arenaceous nature of sediments in the region is probably a result of provenace from Precambrian quartzites and early Palaeozoic clastics cropping out onshore.

Extensive alluvial floodplains with lakes occupied the Bass Basin. Minor uplift of basement blocks produced local highs which were actively eroded. Drainage was predominantly northwesterly, producing predominately sandy sequences in the south with argillaceous and coal-rich sediments in the centre and northwest of the basin.

In the Gippsland Basin, correlation of eustatic sea level curves (Steele, 1976; Partridge, 1976) with sedimentation patterns indicates a mainly eustatic control on depositional environments throughout the Cainozoic; climatic and tectonic factors appear to have played only a minor role (Loutit & Kennett, 1981).

A westward shoreline migration characterised this period especially in the northern part of the Basin. A linear coastal barrier was established, and periodic flooding occurred over a broad well-vegetated, coastal floodplain. In the central and southern parts of the basin, thick shales with coals up to 10 metres thick (Latrobe Group), accumulated in fluvial-deltaic environments, whereas towards the basin margin coarse alluvial sands were laid down (Bodard et al., 1986).

During a transgressive maximum in the Early Eocene, the Tuna- Flounder channel was incised in shallow to deep marine conditions in the easterly part of the basin. Prograding esturine sediments (Flounder Formation) infilled this and other similar channels with fine material that was locally re-worked from part of Latrobe Group sediments.

Off the eastern Australian margin, the Tasman Basin continued to open during this period (Hayes & Ringus, 1973). True oceanic conditions began in the south by the Middle Paleocene as the Lord Howe Rise continued to subside, reaching its present upper bathyal depth by the Early Eocene. The Lord Howe Rise appears to have been stable at its present depth since the Middle Eocene (Whitworth et al, 1985). Deposition of hemi-pelagic clay, silt and chert has been recorded in the Tasman Sea (DSDP site 283) during the Paleocene, with a hiatus during the Early Eocene.

Very poor control exists for the timing of marine shelf sedimentation along the eastern seaboard of the continent. However, margin subsidence rates, eustatic sea level positions, and offshore stratigraphic drilling in Queensland appear to favour a Miocene age (Chapman et al., 1982). Hence, during the early Tertiary, subaerial erosion occurred in the region, with only local fluvial-deltaic systems operating.

During this interval the Capricorn Basin was subsiding faster than the remainder of the shelf. Petroleum exploration wells have intersected conglomerate and red-bed sequences (Ericson, 1976),suggesting accumulation of fluvial and alluvial fan facies in continental environments within the basin.

The age and lithological control on early Tertiary sequences in offshore northeast Australia is tenuous as correlation relies heavily on long distance ties to two DSDP sites on the Queensland Plateau. However seismic studies (Taylor & Falvey, 1977, Symonds et al., 1984) suggest that in the subsiding Queensland Trough infilling of the trough occurred with deposition of fluvial to marginal marine sediments. Mutter (1977) concluded that in the Paleocene to Early Eocene the Queensland Plateau was above sea level. Further north, most of the Papuan Basin was emergent (Dow, 1977; Stewart & Durkee, 1985), with sedimentation restricted to the extremity of the basin where bathyal limestones, cherts and mudstones of the Port Moresby association and Paga beds were accumulating.

Along the Northwest Shelf, Cainozoic carbonates contain less siliciclastics than those of the Cretaceous (Laws & Kraus, 1974). However, the locally terrigenous nature of Early Tertiary sediments along the margin implies that rivers were flowing, carrying detritus derived from the weathered mantle of the Precambrian craton. Bottom currents probably carried fine sediment along the coastline.

In the Bonaparte Basin, relatively deepwater facies of fine grained marls and calcilutites, rich in planktonic foraminifera were deposited over most of the basin, with the terrigenous content decreasing upwards through the sequence. Restricted marine, lagoonal conditions are represented by terrigenous dolomitic sediments in the proximal parts of the basin. Similar marine conditions existed along the northwest margin, where the coastline was located approximately 150 kilometres west of its present position. On the landward side of the Browse Basin and southern Bonaparte Basin, sandstones up to 350 metres thick were deposited in continental to marine environments.

By the Early Tertiary the Exmouth Plateau had subsided to bathyal depths (Exon & Willcox, 1978,1980) and deposits of deep water marls and pelagic carbonates accumulated Current erosion and submarine slumping of the poorly consolidated pelagic oozes on the plateau has distributed the oozes onto the abyssal plains. This process has probably continued throughout the Cainozoic.

In the Carnarvon Basin, glauconitic clastics and bryzoal carbonates (Cardabia Calcarenite) were deposited during a major marine transgression. Open continental shelf conditions were established from Shark Bay to east of Barrow Island, with migrating shoals of calcarenites, in a generally calcilutite, calcisiltite sequence. The presence of glauconite and phosphate suggests that water depths were greater than 30 metres. Deep-water claystones and marls of outer shelf\slope facies were deposited further basinward. Detailed analysis of these units indicates that during the Paleocene there were distinct and rapid climatic fluctuations occured within the shelf\slope environment (Hocking et al., 1987). A widespread submarine erosion event has been identified as occurring in the Late Paleocene (Foram zone N7).

Further south, in the Perth area, a restricted marine embayment formed bordered by mangrove swamps in which glauconitic mudstones, with minor limestone (Kings Park Formation) accumulated, filling an old river-submarine valley system. As time progressed sediments in the northern part of the area became sandier and less marine while offshore, carbonate content increased. The presence of keeled Globorotaliae tend to indicate warm water conditions (Quilty, 1978).

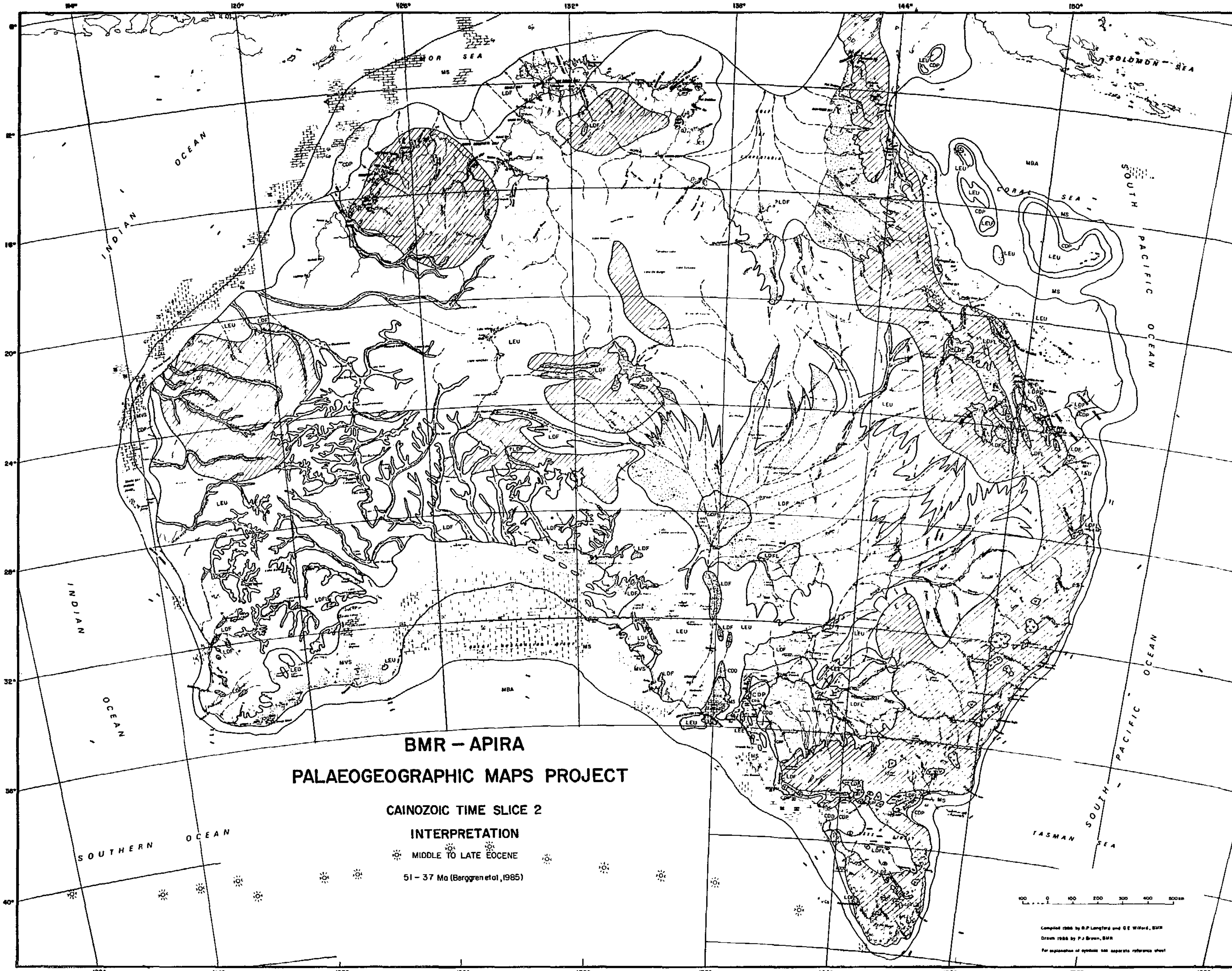

BMR – APIRA
PALAEOGEOGRAPHIC MAPS PROJECT
CAINOZOIC TIME SLICE 2
INTERPRETATION
MIDDLE TO LATE EOCENE
51 – 37 Ma (Berggren et al, 1985)
INDIAN OCEAN
SOUTHERN OCEAN
SOUTH PACIFIC OCEAN
CORAL SEA
TASMAN SEA
SOLOMON SEA
ARAFURA SEA

Figure 6

TIME SLICE 2: MIDDLE - LATE EOCENE (52-36 Ma)

Separation of Australia from Antartica accelerated during the Middle Eocene to an increased spreading half-rate of 23 km\Ma (Cande and Mutter, 1982, Veevers, 1987). By the end of the Eocene open marine conditions existed, as attested by coccolith bearing sediments in DSDP site 282 in the Southern Ocean (Kemp, 1978). A shelf carbonate regime was established on the southern margin for the first time since the Palaeozoic.

Four major transgressions have been recognized in southern Australia, and have been related to rapid shifts in water masses (Harris, 1985; McGowran, 1986). Figure 6 depicts the maximun penetration of shallow seas which occured in the latest Eocene (Foram zone P17). Sedimentation along the southern margin was probably eustatically controlled, occurring in an episodically subsiding regime.

Floral studies (Kemp, 1978; Harris, 1985), have revealed that sub-tropical rainforests were widespread along the entire southern margin. Transgressive phases during the Eocene covered lignite deposits, which had formed in basement depressions and along ancient shorelines. These coal bearing sediments are closely related to transgressive cycles. Climatic data would indicate high annual precipitation, probably in excess of 1000 mm, with a temperature trend showing a decline from high values during the Early Eocene to relatively cool conditions at the end of the Late Eocene (Harris, 1985).

Very shallow seas extended across the Bremer Basin forming a number of islands and promontaries, and deposited bryozoal carbonates and spongolites of the Plantagent and Eundynie Groups on an irregular Precambrian surface, sometimes overlapping non-marine sediments including lignites (Werillup Formation).

In the Eucla Basin, lignitic clastics (Pidinga Formation) accumulated on the basin margins; basinwards, sands (Hampton Sandstone), reflecting drainage from the hinterland, were followed by marls and eventually bryozoal carbonates of the Wilson Bluff Limestone, as water depths increased. In the southwest, the Toolina Limestone was deposited in high energy environmments (Lowry, 1970). Along the old coastline, a barrier bar/dune system, (Ooldea Sand) may have formed during transgressive/ regressive cycles, and remains on the present landscape as linear ranges (Benbow, 1986). Marine clastics and carbonates were deposited offshore in the Bight Basin in middle to outer neritic environments.

In the intracratonic, fault-controlled St Vincent Basin, the Eocene stratigraphic succesion resulted from an interplay of delta, pro-delta and interdistributary bay facies related to eustatic cycles (Harris, 1985). Initially, a thick flood of fluvial to paralic sands of the Maslin Sands filled fault-angle depressions on the eastern margin. The sea advanced and inundated low lying areas, depositing fossiliferous bioclastic carbonates (Kingscote, Tortichilla Limestones), except in the northern end where a delta supported peat accumulations (clastics and coals of the Clinton Formation). Marine influence extended into the gulf, represented by calcareous sands of the Muloowurtie Formation (Stuart, 1970), and cherts and carbonates of the Blanche Point Formation. A regressive period resulted in deposition of the lagoonal Throoka Silts in the west, and the Chinaman Gully Formation in the east. The following trangression deposited the Aldinga Member of the Port Wilunga Formation. Faunal studies (McGowran & Beecroft, 1986) have shown that at times, restricted circulation existed within the basin and distinctive chert horizons within the Blanche Point Formation possibly reflect repetative volcanism from an unknown source (Jones & Fitzgerald, 1984).

The Murray Basin was partially inundated in the Late Eocene and carbonates and marls (Buccleuch beds) were laid down. Inland, a thin blanket of unconsolidated, carbonaceous clastics (Renmark Group and Olney Formation) reflects an essentially fluvial - lacustrine environment. Local and regional hiatuses are marked by the presence of palaeosols within the succession.

In the Otway Basin thick paralic sequences (Dilwyn Formation) accumulated, with periodic marine ingressions. A major regression led to a large part of the the basin receiving no sediment during the late Early and early Middle Eocene. A diachronous marine transgression in the late Middle to Late Eocene inundated lignitic fluvial sediments along coastal areas, and marine embayments were established (Abele et al., 1976). In high energy littoral and shallow shelf environments, calcareous sands (Mepunga Formation) accumulated. With continuing transgression, fossiliferous marls of the Lacepede Formation and Narrawaturk marl were deposited.

Within the Bass Basin fluvial activity increased and sand-rich deposits built out across the basin from meandering river systems (Williamson et al, 1987b). Peats developed in swamps or marshy areas on the floodplain,and there were local extrusions of basaltic magmas. In the late Eocene,restricted marine conditions entered the northwestern part of the basin (Demons Bluff Formation), being the first marine influence in the area. In the Gippsland Basin, marine conditions became more permanently established with a coastline approximating its current position. Associated with the trangressive phase, a barrier system with lagoonal and marsh facies formed during periods of stillstand. The Latrobe sequences contain many channel, point-bar and barrier sand bodies which are the primary reservoirs of the petroleum resourses of the Gippsland Basin. During a low stand, the Marlin Channel was cut into Latrobe Group sediments and was later filled with marine fine clastics of the Turrum Formation during a time of high sea-level (Partridge, 1976).

A thin veneer of glauconitic clastics (Gurnard Formation) was deposited in condensed sequences throughout the early Tertiary, covering Latrobe Group sediments. Non-deposition and erosion characterised the central part of the basin during the Late Eocene, until later deposition of the Lakes Entrance Formation.

Landward of the shoreline, fluvio-deltaic sequences referable to the Latrobe Group accumulated (Smith, 1982). Further westward, thick accumulations of clastics and lignite (Taralgon Formation) spread across the basin, in fluvio/lacustrine systems.

Extensional tectonic movements possibly associated with sea floor spreading in the Coral Sea resulted in multiple trough formation along a zone parallel to the present Queensland coast. This resulted in a reversal of flow of the originally southwesterly flowing rivers there to form a rectilinear pattern linking a series of parallel lakes. These rapidly filled with sediment, much of it of algal origin (Noon, 1984).

The Queensland Plateau continued subsiding, and by the latest Eocene most of the plateau was below sea level (Mutter, 1977). Dredge samples from the northern end of the plateau (Chaponiere, 1983), recovered Eocene shallow marine limestones, which supports Mutter's hypothesis. Reef growth probabaly began during this interval on basement highs, although direct evidence is lacking (Davies et al., in prep.). Temperate, clastic, fluvial-deltaic and carbonate sedimentation probably developed along the continental margin (Davies et al., 1987).

Widespread carbonate platform sedimentation (Mendi Group) became established by the end of the Late Eocene in the Papuan Basin. A marine connection may have existed across the Torres Strait area, although no Eocene sediments are present except for littoral sequences to the northwest in the Morehead Basin.

Fluvial conditions may have been present in the Gulf of Carpentaria, although well control is extremely poor (Duyken No 1). Onshore in the Karumba Basin clastics of the Bulimba Cycle were deposited (Smart et al., 1980). Further west on Melville and Bathurst Islands, thin sands of the Van Dieman Sandstone were deposited. The age control of these sands is poor, and is based on plant macrofossil identification (Hughes, 1978).

Shallow water carbonates with transgressive clastics and minor anhydrite of the "Hibernia Formation" and equivalents were deposited in a wide shelf environment stretching over the present day Arafura and Timor Seas. The fossil fauna include abundant benthonic foraminifera, diverse shelly faunas with occasional corals. The Middle to Late Eocene sequence is generally fine grained, indicating quiet conditions, and is more siliclastic towards the basin margins.

Shelf conditions were well established by the Middle Eocene along the north-west shelf. In the Browse Basin area, marginal marine coal bearing sandstones were deposited in the east, and shelf clay and marl prograded northwestward. Middle and outer shelf carbonates were deposited in the southern and western area, while on the Scott Plateau, marl and calclutite were laid down. In the offshore Canning Basin, inner shelf barrier bars accumulated skeletal debris, and due to variations in sea level and basin subsidence, barred lagoons formed. The occurence of dolomite and gypsum may indicate chemical precipitation during periods of higher temperature (Forman & Wales, 1981).

Eocene high sea levels inundated the present onshore area of the Carnarvon Basin, and warm waters deposited Discocyclina-rich Giralia Calcarenite (Condon, 1969) in high energy environments. The marginal marine Merlinleigh Sandstone was deposited in the southern and eastern areas of the basin, with little terrigenous material escaping into the Giralia calcarenite. Outside these embayment, deep water carbonates, marls and cherts, rich in planktonic foraminifera (Walcott Formation), were deposited.

All samples recovered from the Exmouth Plateau consist of pelagic chalks or oozes (Exon et al., 1982), whereas on the surrounding abyssal plains thin deposits of deep sea oozes and clay with interbedded turbidites accumulated.

Renewed sedimentation in the Perth Basin initially re-excavated an embayment established in the Paleocene, and locally deposited clastics and carbonates. The presence of terrigenous material indicates significant drainage operating in the hinterland (Quilty, 1978).

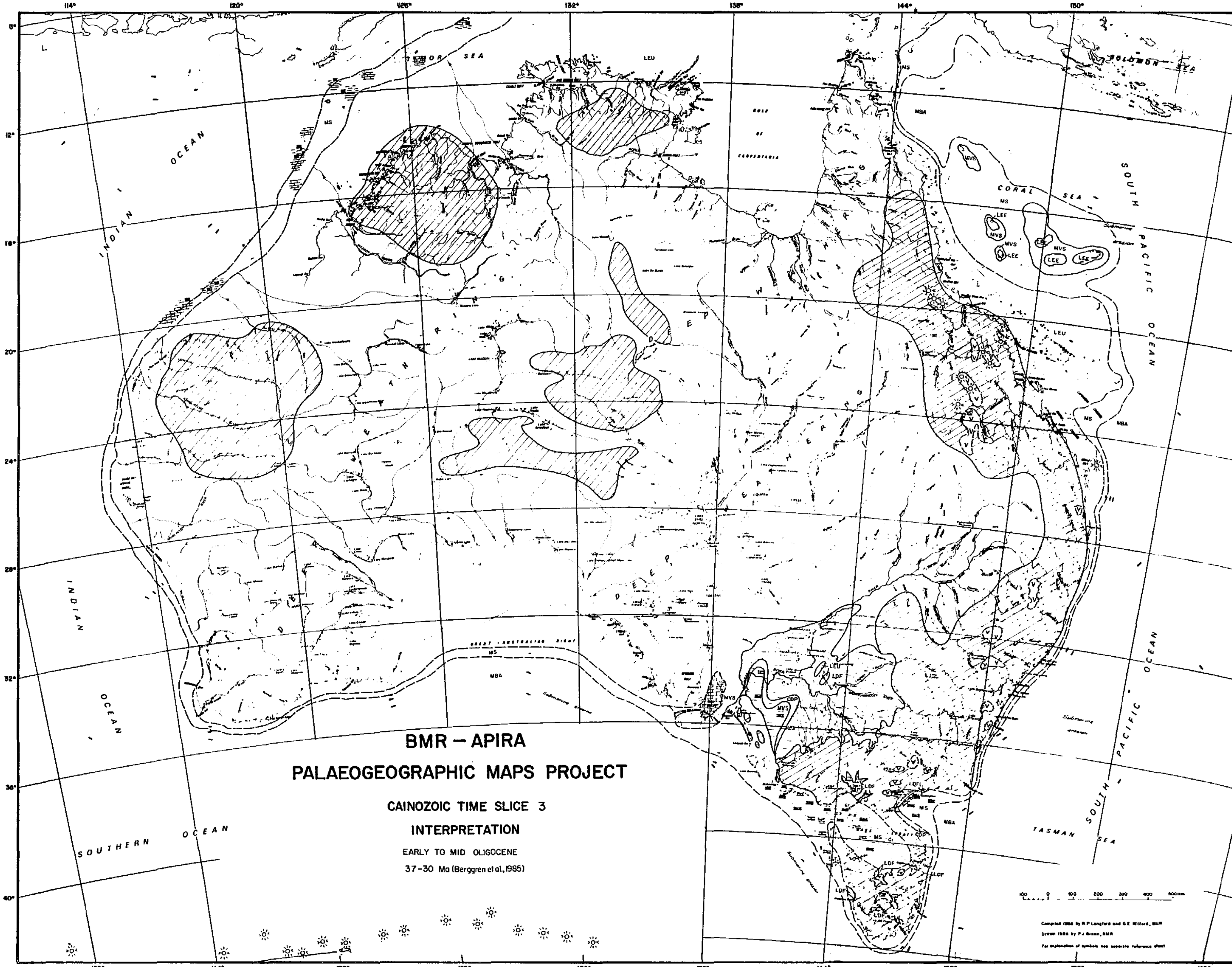

BMR – APIRA
PALAEOGEOGRAPHIC MAPS PROJECT
CAINOZOIC TIME SLICE 3
INTERPRETATION
EARLY TO MID OLIGOCENE
37-30 Ma (Berggren et al.,1985)
INDIAN OCEAN
SOUTHERN OCEAN
TIMOR SEA
CORAL SEA
SOUTH PACIFIC OCEAN
TASMAN SEA
SOLOMON SEA
GREAT AUSTRALIAN BIGHT

Figure 7

Chert concentrations within the Eocene carbonates around the Australian margin are noticably higher than in any other period during the Cainozoic. Similarly, cherts are present in deep sea sequences around the world, and their occurences are probably related to major paleaoceanographic changes (Kennett, 1982).

TIME SLICE 3: EARLY OLIGOCENE (36-30 Ma)

The marine gulf south of Australia continued to widen in the Oligocene, as the continent moved further north. A major reorganisation of water masses, with important climatic consequences, resulted from the opening of a deep seaway south of the South Tasman Rise, probably by the middle Oligocene (Kennett & von der Borch, 1985).

The Early Oligocene is characterised by very limited sedimentation on the continental margin, except in the tectonically subsiding southeast. It was also a period of widespread submarine erosion. Unconformities are widespread on the seafloor around Australia, and an unconformity surface occurs in shallow shelf sediments, including those now exposed on the continent itself. It is probably that these two sets of unconformities resulted from different and perhaps unrelated causes (Carter, 1978). The length of the hiatuses represented by seafloor unconformities tends to be irregular, suggesting that their origin lies in erosion and non-deposition by deep-sea currents (Keller et al., 1987). The best documented of these events is the Tasman/Coral Sea regional unconformity (Kennett et al., 1972), which may have formed by bottom waters flowing northwards through the Tasman Sea, due to palaeocirculation changes associated with the onset of Antartic glaciation. The Oligocene hiatus which is widespread in the abyssal plains sediments of the Indian Ocean has similarly been attributed to the effects of Antartic bottom waters (Davies et al., 1975).

Hiatuses in the continental shelf sequences may be related more to eustatic changes than to currents associated with climatic events. The global eustatic low sea level at the Early to Late Oligocene boundary is recognised around the continental margin. A widespread depositional cycle commences in the Late Oligocene.

In the Eucla Basin a period of non-deposition and erosion occurred, while further offshore, in the Great Australian Bight Basin minor marls and limestones accumulated.

In the main depocentres of the St Vincent Basin, cherty bryozoal limestones (Ruwarang Member of the Port Willunga Formation; Cooper, 1985) were deposited; at the basin margins thin paralic sands of the Rogue Formation and Pirramimma Sand accumulated. Local unconformities exist in marginal areas of the St Vincent Basin, although tectonism appears to have overprinted the regionally recognized middle Oligocene unconfomity.
In the southwest of the Murray Basin, a period of non-deposition produced the hiatus which separates the Buccleuch Beds from overlying strata. According to Lindsay (1985), this hiatus extends from the base of the Oligocene (Foram zone P17) to the end of the Early Oligocene (P21a). The subsequent transgression which deposited the Compton Conglomerate and marls of the Ettrick Formation was diachronous. This hiatus is difficult to detect in non-marine sections of the basin (Olney Formation), but Martin (1986), using palynological zonal sequences, has detected channelling and downcutting, presumedly in response to lowered base-level, at some time during the Oligocene.
In the Otway Basin, sedimentation and progradation of the Narrawaturk Marl continued until the mid-Oligocene, when a minor regression ended deposition in structurally high areas. In the subsiding Bass Basin , marine conditions were well established, and marls and clastics of the Torquay Group were deposited.
In the Torquay Basin, prodelta carbonaceous sands (Anglesea Sand) filled the subsiding embayment, while basinward, marls of the Jan Juc Formation were deposited. Nannofossil data from the Jan Juc and associated formations have been interpreted as representing cool water conditions, with temperatures similar to those in northern Bass Strait today, (between 12° and 17° C). A possible marine transgression has been identified between the Anglesea Sand and the overlying volcanogenic Angahook Formation (Reeckmann, 1986). In the Melbourne area, continental deposits of the Werribee formation accumulated.
Further west in the Gippsland Basin, advance of the sea caused coarse clastics of the Latrobe Group to be overlain by fine-grained deep-water marls and carbonates of the Lakes Entrance Formation. The clay material was possibly sourced from weathered Eocene basalts onshore. In onshore areas lignites and clastics of the Taralgon and Clifton Formations continued to accumulated (Abele et al., 1976).
No sediments of Early Oligocene age have been sampled along the northern and eastern margins of the continent. An unconformity is widespread in the plateaux and basins off northeastern Australia. At DSDP Site 209, on the eastern margin of the Queensland

Plateau, the depositional hiatus spans the Late Eocene to Late Oligocene; this hiatus can be matched to an unconformity that occurs on reflection profiles over most of the Queensland Plateau (Mutter & Karner, 1980). The unconformity has been recognized in the Capricorn Basin (Ericson, 1976); it occurs also in deeper areas such as the Coral Sea Basin where deposition was interrupted from the Late Eocene through to the Early Oligocene. The hiatuses on the northeastern margin have been variously attributed to Antarctic deep water production, or to commencement of a significant equatorial current pattern (Davies et al., in prep).

The Capricorn region may have been uplifted during intrusion of trachytic volcanics on Fraser Island (Grimes et al., 1984). The Oligocene was a period of tectonic uplift in the Papuan Basin (Dow, 1977), and erosion of Eocene shelf limestones occurred on the emergent landmass.

On the western margin of Australia, non-deposition in the Early and early Late Oligocene has been attributed to a major sea-level regression (Quilty, 1977), with retreat of the sea beyond the shelf edge exposing Eocene continental shelf sediments. Tectonic uplift has also been invoked to explain erosion on the northwest shelf (Barter et al., 1982) possibly associated with isostatic adjustment due to a major sea-level regression. Deposition of marls and carbonates occured only on the most distal parts of the shelf. A widespread hiatus is also recoginised on the Exmouth Plateau.

TIME SLICE 4: LATE OLIGOCENE - MIDDLE MIOCENE (30-10 Ma)

The northern margin of the Australian continent had moved considerably further north (ca. 20° S) into tropical realms during this time interval. The Circum-Antarctic current was well established and the seas surrounding Australia were warm. Faunas of larger foraminifera, notably Lepidocyclina and Cycloclypeus migrated as far south as Bass Strait. Marine sediments, were predominantly biogenic carbonates on a scale probably greater than at any other time in geologic history (Quilty, 1984).

This interval represents the most prominent episode of transgression during the Cainozoic, reaching a maximum at the Early/Middle Miocene boundary (foram zone N7-N8). Biostratigraphic evidence exists for an Australia-wide hiatus during the earliest


BMR — APIRA
PALAEOGEOGRAPHIC MAPS PROJECT
CAINOZOIC TIME SLICE 4
INTERPRETATION
LATE OLIGOCENE TO MIDDLE MIOCENE
30 - 10 Ma (Berggren et al., 1985)
INDIAN OCEAN
SOUTHERN OCEAN
CORAL SEA
SOUTH PACIFIC OCEAN
TASMAN SEA
SOLOMON SEA

Figure 8

Middle Miocene (N9), (McGowran, 1979) leading to widespread lithological changes in southeast Australia. A restricted sedimentary record concluded the latter part of the Middle Miocene. Figure 8 depicts the maximun marine inundation during the Middle Miocene.

In southern Australia, complex facies relationships are evident between continental sequences and widespread accumulation of bryozoan-rich carbonates. Planktonic foraminiferal faunas in northern Australia show marked tropical affinities (Quilty, 1984), and coral reefs developed along the northern margins of the continent.

Renewal of alluvial deposition occurred, with sluggish rivers and a proliferation of lake systems. Volcanism was widespread along the eastern margin while in the northeast, tectonic activity increased in the New Guinea Orogen.

In the very latest Oligocene (Foram Zone "N4") the sea inundated the Eucla Basin forming a broad open shelf. A bryozoan limestone (Abrakurrie Limestone, Lowry,1968) was deposited containing diverse faunas-echinoids, molluscs, brachiopods and benthonic foraminiferids; well sorted calcarenites, indicating that normal marine salinities and strong bottom currents were present.

A brief regression of approximately two million years saw a retreat of the sea, followed by a widespread transgression during which thin algal and foraminiferal limestone (Nullarbor Limestone, Lowry, 1970). Colonial corals have been reported in the north east part of the Eucla Basin (Lindsay & Harris, 1975), indicating the existence of offshore (patch) reefs. However, conditions in most of the basin were more suitable for the development of algal reefs.

In the marginal regions of the Eucla Basin thin calcareous sandstones (Colville Sandstone) were deposited indicating that local drainage channels were active (Jackson & Van de Graaff, 1981). Landward (northeast) of the Miocene coastline, clay and carbonate material (Garford Formation) accumulated in an extensive fluvio-lacustrine system behind a siliciclastic strandline sequence (Ooldea Sand - Benbow, 1986). The sea retreated during the early Middle Miocene, leaving a broad, flat, karstic land surface of indurated limestone which remains to the present day.

Extensive marine conditions existed in the southeast of South Australia. Five episodes of Miocene marine sedimentation, producing thin fossiliferous limestones (Melton Limestone - Lindsay, 1970), have been identified in the Spencer Gulf region. Similarly, isolated fossiliferous limestones on Kangaroo Island (Milnes et al., 1983) and within the

Myponga and Hindmarsh Tiers Basins are regarded as equivalent to early Middle Miocene sequences deposited during high sea level stands.

Bryozoal limestones and marls of the Port Willunga Formation continued to accumulate in the St Vincent Basin while, to the north, interbedded fluvio-lacustrine clastics (Snowtown Sands - Alley, 1973) were deposited.

During the initial Oligo-Miocene transgression in the Murray Basin, glauconitic marls of the diachronous Ettrick Formation (Ludbrook, 1961) accumulated over the western and central parts of the basin. With increasing relative sea-level rise, shallow marine calcarenites consisting of skeletal debris and quartz sand (Murray Group - Ludbrook,1961) were deposited in a broad marine embayment. Palaeogeographic reconstructions (Brown, 1985; Brown & Stephenson, in press) suggests that a very shallow (less than 20m depth) barrier shoal existed over the Padthaway ridge at the entrance to the basin. A shallow platform landward of the barrier shoal was flanked to the east and north by the restricted platform and lagoonal environments of the diachronous Ettrick and Winnambool Formations. Further landward the calcareous clays of the Ettrick/Winnambool Formations grade into an arcuate belt of carbonaceous silts and minor carbonates of the Geera Clay which formed in interdistributary bays and tidal flat environments. The marginal marine Geera Clay in turn interfingers with fluvio-lacustrine sands, silts, clays and peaty coals of the broadly dated Olney Formation.

In the Otway Basin, rapid marine transgression in the earliest Late Oligocene initiated sedimentation of the Heytesbury Group (Bock & Glenie, 1965). The basal bryozoan carbonates and sandstones (Clifton Formation) were deposited in littoral to shallow marine high-energy environments, while in deeper water, the fine grained clays and marls of the Gellibrand Marl accumulated. Transgression continued into the Miocene, with Gellibrand Marl and Gambier Limestone sedimentation proceeding in neritic environments with prolific growth of shelly marine organisms. Local basaltic activity (Abele et al., 1974) occurred in the eastern edge of the basin, while further offshore the fine grained Port Campbell Limestone prograded onto the slowly subsiding continental shelf and slope.

In the Late Oligocene a short period of marine regression accompanied an episode of basaltic activity on the margin of the Torquay Basin, producing a complex series of coastal sediments and volcanics (Angahook Member - Abele et al., 1976). Open marine conditions were then re-established and nearshore bryozoal calcarenite (Point Addis

Limestone Member - Abele et al., 1976) accumulated. In slightly deeper shelf waters the laterally equivalent Jan Juc Marl was deposited. A sequence stratigraphic analysis of Oligo-Miocene exposures in the Torquay area (Reeckmann et al., 1986) suggests that nine unconformity boundaries, representing falls in eustatic sea level, can be identified by detailed lithofacies analysis. These chronostratigraphic units cut across traditional formation boundaries. In the Early Miocene sea level rose,and calcareous clays and calcarenites of the Torquay Group (Puebla Formation) continued to be laid down until the early Middle Miocene.

Open shelf conditions persisted in the Bass Basin with carbonate deposition along the northwestern margin, and mixed carbonate and siliciclastic sediments filled the basin axis. Pre-existing faults acted as conduits for widespread intrusive and extrusive igneous bodies (Brown, 1976). Marine inundation occurred further south in northest Tasmania (Table Cape Group and equivalents - Quilty, 1972), and on Bass Strait islands, coincident with tholeiitic volcanism (Sutherland, 1973).

Marine sedimentation continued further east in the subsiding Gippsland Basin, and marls and limestones of the Lakes Entrance Formation and Gippsland Limestone were deposited. Landward of the Oligo-Miocene coastline, thick sequences of lignite (up to 160m) and clastics (Morwell and Yallourn Formations) accumulated in peat swamps. Basalts and tuffs (Thorpedale Volcanics) were locally extruded on the western margin of the basin. A dynamic model of a series of six major cycles of marine incursions has been proposed for the Morwell Formation, based on facies analysis and recent fossil discoveries (Holdgate and Sluiter, in prep.). Structural movements and sea level fluctuations produced massive submarine slumping and a multiplicity of submarine channels, which were subsequently filled by micritic limestones and coarse skeletal fragments. Similar channelling has been reported in the Otway Basin,and has been related to Indo-Pacific currents. Presumably widespread erosion along fault traces developed canyons as seen on the continental shelf and slope (Megallaa, 1985).

The Port Phillip Basin was connected to the Otway and Bass Basins during the Miocene (Mallett, 1978), with the thickest sequence (Fyansford Formation) accumulating in the Sorrento Graben, a north-south structure cutting across Port Phillip Bay. Sediments were deposited in water depths of up to 250m within the graben (McKenzie & Peypouquet, 1984). The Miocene Fyansford Formation embraces a variety of carbonate-rich lithologies in a gradual coarsening-upward sequence. The Batesford

Limestone (Abele et al., 1976), a sandy bryozoal calcarenite, was deposited in high energy, talus slope environments, in depths shallower than 30m in the western part of the basin.

Along the narrow eastern continental shelf, a northward dipping seismic reflector S1 (Davies, 1979) has recently been been postulated (Roy & Thom, in prep.) to be a time-transgressive seismic discontinuity ranging in age from 19-6 Ma. A model has been proposed that Miocene to Recent marine sedimentation gradually thickens to the north, in response to mantle "hot-spot" movement, sea-level fluctuations and passive margin subsidence (Roy & Thom, in prep).

In the Tasman Sea, the Tasmantid Seamounts erupted during the Miocene (McDougall & Duncan, 1988), rising from abyssal depths to near or above sea level. The seamounts were built subaerially and were subsequently eroded to sea level. They have subsided to depths ranging from 90m in the south to 400m in the north.

Sediments within the Capricorn Basin record a series of Oligo-Miocene marine transgressions (Ericson, 1976; Palmieri, 1984; Grimes et al., 1984). During the late Oligocene, a deltaic system near Fraser Island deposited lignitic clastics, which were overlain by Early Miocene shallow, warm water carbonates, and clastics. Anhydrite occurances within the sequence indicate that restricted lagoonal or sabka conditions probably existed. Open shelf conditions became established by the late Early Miocene and have continued until the present day. Silts and marls have filled the subsiding central part of the basin, with a mixed and alternating sequence of terrigenous and carbonate sediments being deposited on the marginal shelf. Microfauna and rare coral fragments provide evidence that isolated reefs may have been present in the area during the Miocene.

Seismic reflection studies (Symonds et al., 1984) conducted offshore from Townsville have revealed a series of alternating onlapping and progradational reflectors. At present no age or lithological control exists for these reflectors, however, Symonds et al. (1984) consider that the progradational units are probably Late Oligocene to Pleistocene fluvio-deltaic facies formed during times of low sea level. The onlapping reflectors are probably high sea level stand marine onlap facies. These sequences have controlled the present day morphology of the continental shelf.

Similar studies (Davies et al., in prep.) indicate that pelagic ooze and turbidite deposits have probably been accumulating in the Queensland and Townsville Troughs from the

Miocene to the present day. DSDP drilling (Burns et al., 1973) on the Queensland Plateau recovered almost pure biogenic ooze of Late Oligocene to Pleistocene age overlying neritic to upper bathyal Eocene deposits. The oozes were deposited at mid-bathyal depths, indicating post-Eocene subsidence. Seismic evidence (reefal structures - Mutter, 1977; Davies et al., in prep.) indicates that sub-tropical to tropical reef growth probably occurred on shallow basement highs on both the Queensland and Marion Plateaus, forming reef debris and shelf limestones. Sedimentation continued in the subsiding Coral Sea Basin, as attested by the presence of abyssal clays deposited below the carbonate compensation depth. These clays are thought to be sourced from the Papuan region.

Further north in the Papuan Basin, a broad shallow-water platform (Tallis, 1975; Dow, 1977; Stewart & Durkee, 1985) with a fringing barrier reef complex was established. Thick carbonates accumulated (Darai Limestone) whereas further east and north, limestones (Puri Limestone) and mixed clastic turbidites (Aure beds) of partly volcanic origin were deposited at bathyal depths in the Aure Trough. Isolated platform reefs grew on basement or volcanic highs in the present-day Gulf of Papua. Tectonism, possibly associated with terrane accretion (Pigram & Davies, 1987), produced widespread uplift during the Middle Miocene.

The Gulf of Carpentaria was probably inundated during the Miocene, based on recent drilling in the Gulf which recovered micritic limestones containing long-ranging Miocene to Recent foraminiferids (Ammonia beccari). Further south,marine influences have been reported in poorly dated clastics (Wyaaba beds) of the Karumba Basin (Smart et al., 1980).

Further west in the Bonaparte Basin, the sea advanced, recommencing deposition (Laws & Kraus, 1974), of predominately shallow-water carbonates and barrier/patch reef complexes ("Fantome Formation"). An extremely broad continental shelf was established with local reef development. Siliciclastic input was very minor, being restricted to the margins of the basin in the basal, thin Lower Miocene sandstones, shales and marls of the distal "Cartier Formation". Clastics were probably derived from reworking of shelf deposits and erosion of the exposed onshore craton. Extremely rapid carbonate sedimentation in neritic environments occurred during this period on the western side of the basin, indicating rapid local subsidence. Similar marine conditions existed along the rest of the north-west shelf, and a massive prograding carbonate wedge,

up to 3km thick, was deposited. The presence of reef dwelling foraminifera, and probable reef structures identified from seismic studies (Forman & Wales, 1981), suggest the presence of inner shelf shoals and reefs. Shelf atoll formation was initiated in the Middle Miocene (Wright, 1977) on the outer edge of the north-west shelf; some of these atolls still exist today (such as Scott and Seringapatam Reefs). Many of the foraminiferal species in these Miocene sediments are forms that live attached to sea-grasses, which were probably an important part of the benthic community. Oceanward of the shelf fine grained pelagic oozes accumulated on abyssal plains and marginal plateaus, with local turbidite deposition (Cook et al., 1978; Exon et al., 1982). On the eastern flank of the shelf, nearshore and intertidal conditions are indicated by coal-bearing sandstone, dolomite beds and presence of gypsum (Allen et al., 1978).
In the Carnarvon Basin, detailed studies (Condon, 1969; Chaponiere, 1975; Hocking et al., 1987) have revealed a series of shallowing upward sequences within the Cape Range Group of Condon (1965). The fossiliferous well-bedded Mandu Limestone is recognisable on and offshore, and forms a series of prograding sigmoidal reflections on seismic sections. Each sigmoidal reflection marks the shelf edge/slope at a point in time during this time interval. Environments of deposition vary from outer shelf to slope conditions with carbonates containing abundant planktonic foraminiferids, to very shallow conditions producing calcarenites rich in shallow water biota. The Bullara Limestone (Chaproniere, 1976) was deposited in high energy nearshore shoaling environments, with shoals forming on or around sea-grass banks and being constantly reworked by waves. The Tulki Limestone is a locally developed shallow water equivalent of the upper Mandu Limestone, probably deposited on shoals and banks. A disconformity is present beneath the Trealla Limestone spanning foram zone N7 and parts of N6 and N8 (Quilty, 1974).
The Trealla Limestone, containing distinctive compound corals, is a widespread unit deposited in a range of environments in an overall shoaling upwards sequence. Chaproniere (1975) noted that metahaline salinities were present in shallow water facies of the Trealla Limestone due to the presence of an oceanward shoaling sand bar or sand spit (Pilgramunna Formation) inhibiting water circulation. The Lamont and Vlaming Sandstones are quartzose calcarenites formed in isolated shoreline environments where terrigenous material was concentrated. The poorly dated Pindilya Formation is a thin, silicified fluvial unit of either Miocene or Eocene age and probably resulted from sheet

flood processes.

In the Perth Basin to the south, the presence of Oligo-Miocene sequences is not well documented, except for the calcarenites, dolomites and cherts of the Stark Bay Formation (Quilty, 1974).

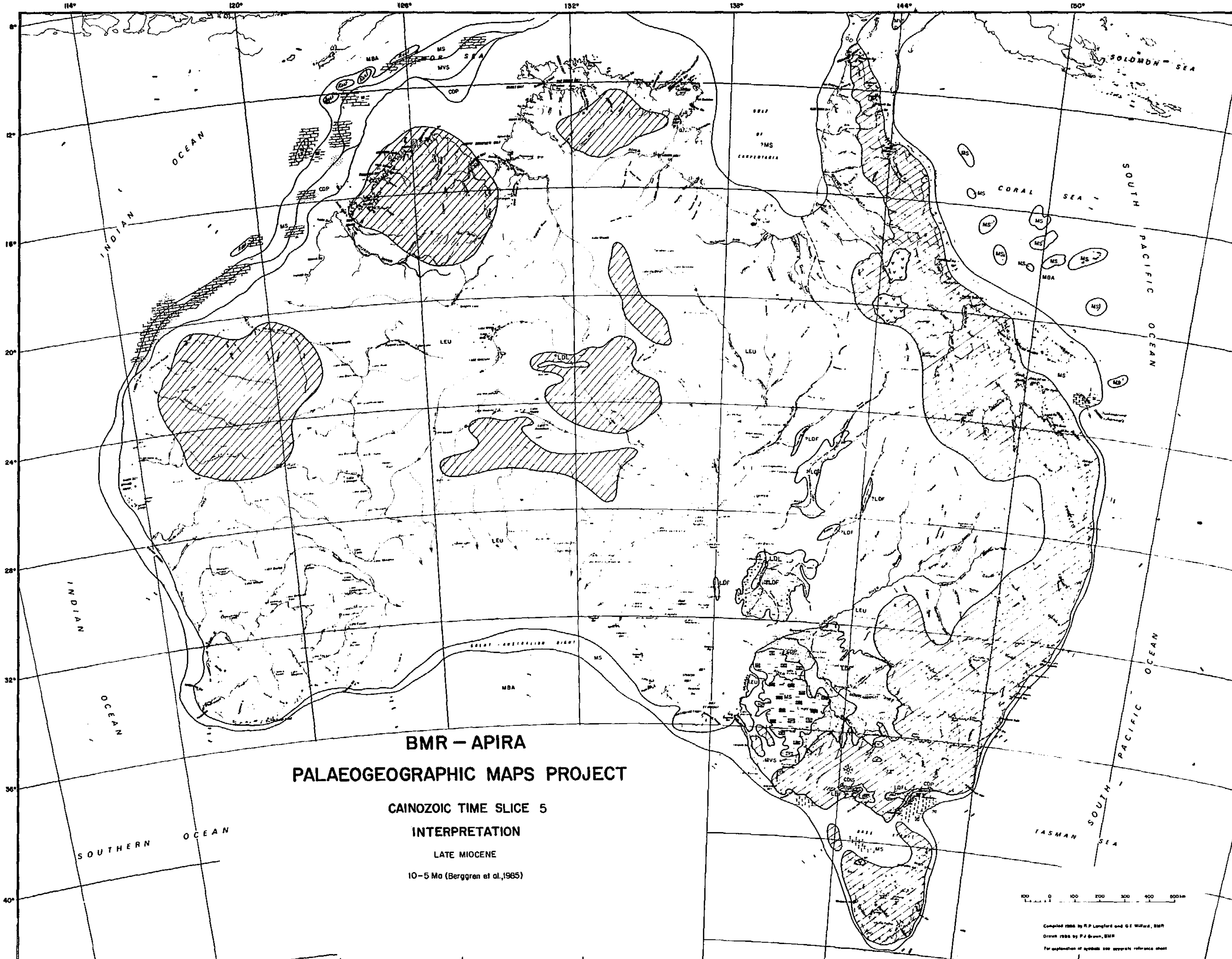
TIME SLICE 5: LATE MIOCENE (10-5 Ma)

Sedimentation was restricted during the Late Miocene, occurring primarily in offshore basins. The general cooling that prevailed during the Middle Miocene continued, reaching a maximum in the latest Miocene. A well-documented, dramatic lowering of sea level characterises this period (Adams, et al., 1977; Vail, et al., 1977; Mallet, 1978; Haq, et al., 1987). Figure 9 depicts the extent of this continent-wide sea level regression, except in the Murray Basin.

There was a major regression in the Murray Basin followed by a short lived marine incursion in the latest Miocene when thin marls and clays of the Bookpurnong beds were deposited. From the late Middle Miocene to the latest Miocene widespread weathering and erosion occurred, producing a planated land surface (Mologa Surface) and entrenchment of adjacent highland valleys (Macumber, 1978). Kaolinitic-rich material formed in central and eastern areas of the basin. This kaolin was later incorporated within sediments as matrix and thick intercalations in the granular, braided-fluvial sands of the Calival Formation (Brown, 1985).

Further south in the Otway Basin, sedimentation continued in a shallow and shrinking sea, whereas onshore erosion occurred, locally resulting in concentrations of quartz pebbles and phosphatic nodules (Abele, et al., 1976). Sedimentation continued in the subsiding Sorrento Graben (Fyansford Formation), with gradual shallowing culminating in coarse coquinas and nodule beds at the top of the sequence. Shelf calcarenites containing bryozoans, pelecypods and foraminiferal remains continued to accumulate in the Bass Basin.

During the Late Miocene the sea regressed eastwards in the Gippsland Basin, with glauconitic marls (Tambo River Formation) forming in marginal marine environments. Onshore, concomitant with uplift and changing climatic conditions, deposition of coarse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PALAEOGEOGRAPHIC MAPS PROJECT
CAINOZOIC TIME SLICE 5
INTERPRETATION
LATE MIOCENE
10–5 Ma (Berggren et al.,1985)
INDIAN OCEAN
INDIAN OCEAN
SOUTHERN OCEAN
CORAL SEA
SOLOMON SEA
SOUTH PACIFIC OCEAN
SOUTH PACIFIC OCEAN
TASMAN SEA
GREAT AUSTRALIAN BIGHT
GULF OF CARPENTARIA
LEU
MS
MBA
MVS
CDP
LDL
LDF

Figure 9

clastics (Haunted Hill Gravels) may have been initiated, although the age control is uncertain (Bolger, in prep). Offshore the Gippsland Limestone was deposited in quiet, shallow marine environments. Phosphatic nodule beds formed during this regression, probably slightly before maximum regression, as some nodules are abraded and encrusted with benthic organisms (Carter, 1985).

No record of sedimentation along the eastern margin exists, however deposition may have occurred in outer shelf/slope environments. Lord Howe Island in the Tasman Sea, a remnant of a large shield volcano, erupted during the latest Miocene (McDougall et al., 1981).

Sedimentation on the margin of the Capricorn Basin was disrupted by a marked sea level regression during the Late Miocene. Basinward, a prominent seismic reflector has been dated as Late Miocene (Marshall, 1977), and is related to a lithological change within the carbonate sequence. Palaeochannels within the basin can be delineated from a surface contour map of the reflector.

Iron-rich phosphate nodule beds (von der Borch, 1970) found on the eastern Australian continental margin are considered, on faunal evidence, to be coevalwith outcropping Late Miocene nodule beds in Victoria (Bowler, 1963). The nodules are considered to have been formed by winnowing of earlier formed, Miocene, phosphatic iron-rich concretions. A bacterial origin has been proposed for the initial concentration of phosphate, by assimilation of phosphorus from seawater in an area of restricted sedimentation (O'Brien et al., 1981).

Further north, subsidence continued on the offshore marginal plateaus (Mutter & Karner, 1980) counteracting the Late Miocene sea level fall and resulting in reef growth retreating to the summits of basement highs. Marine conditions may have continued in the Gulf of Carpentaria, however age control is virtually non-existent.

Further westward in the Money Shoal Basin, a strong and persistent reflector (S3 - Jongsma, 1974) has been correlated with a similar feature in the Timor Sea and Northwest Shelf. The age control in the Money Shoal Basin is tenuous, and it has been dated as Late Miocene to Pliocene. However, the strong acoustic contrast between the reflector and the overlying sequences suggests that the reflector is strongly indurated and could possibly be related to lowering of sea level and the formation of a widespread hardground.

Poor sampling of petroleum exploration wells on the Northwest Shelf has hampered environmental interpretation. However, evidence of a widespread erosion surface (Jones, 1973) of probable Late Miocene age, and a hiatus in Ashmore Reef No 1 petroleum exploration well (Chaproniere, 1984b), suggests that regressive conditions existed during this period. Sediments recovered along the shelf are sometimes dolomitic, implying the presence of a broad intertidal to supratidal environment on the inner side of the shelf. Reef atolls continued to develop in deeper waters, however growth of some reefs was apparently not sufficient to keep pace with subsidence, as evidenced by the presence of drowned reefs (Jones, 1973).

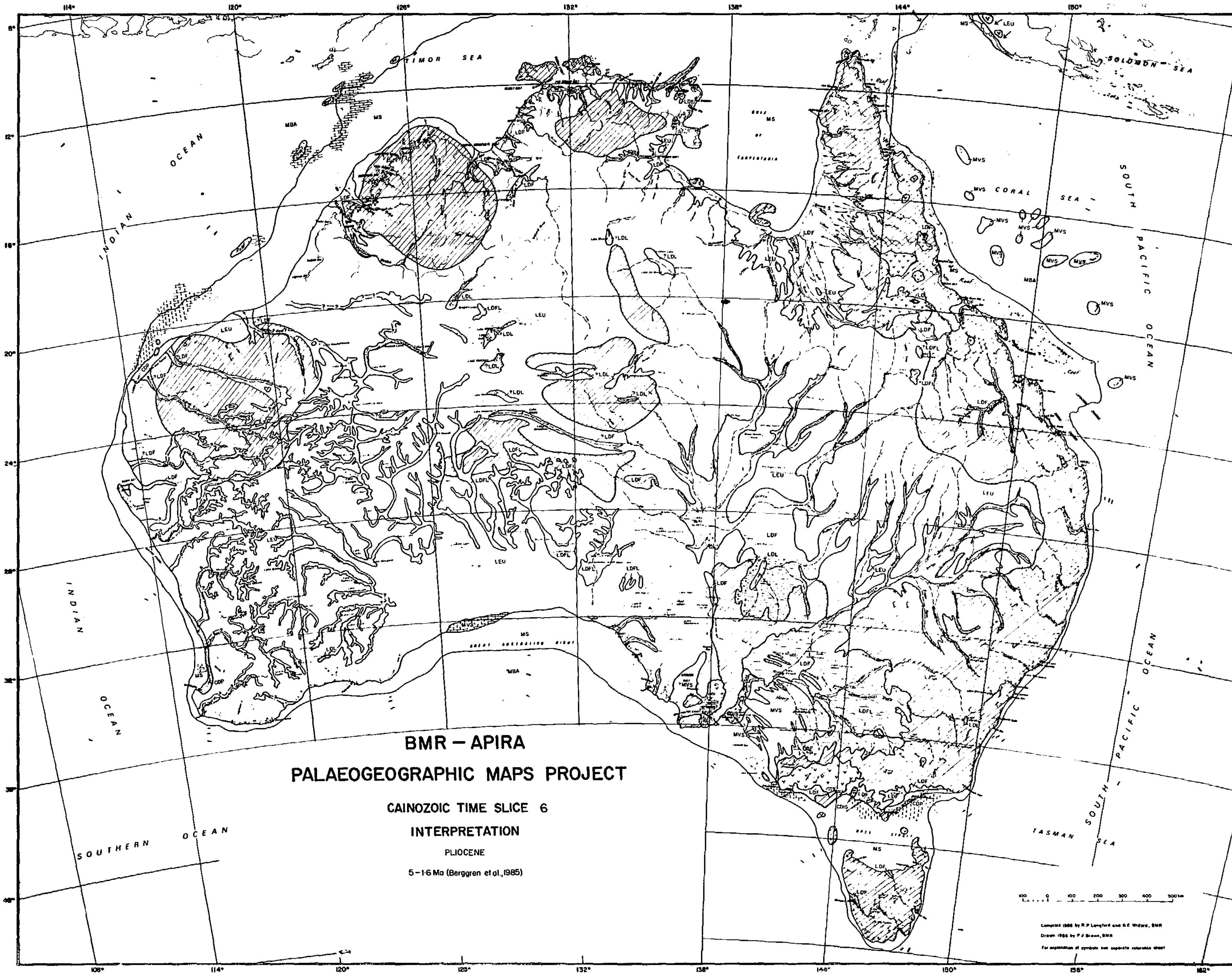
No onshore deposits of Late Miocene age are recorded in the Carnarvon Basin. Offshore, a mixed sandstone and carbonate sequence (Bare Formation) of probable Late Miocene age is recognised in the Rankin Platform area (GSWA, in prep.). The maturity of the sandstones suggests they represent beach or dune deposits, and the dolomitic intervals were possibly formed in highly saline lagoonal-intertidal areas.

TIME SLICE 6: PLIOCENE (5-1.6 Ma)

The Australian continent lay within 1°-2° latitude of its present position. Rejuvenation of drainage systems occurred during the Pliocene, as evidenced by a marked increase in terrigenous sedimentation. A rise in relative sea level from the Late Miocene resulted in a coastline similar to that of the present day.

Deposition recommenced in the Eucla Basin with the thin, very shallow, calcarenites of the ?Plio/Pleistocene Roe Calcarenite (Lowry, 1970) accumulating on a low-relief coastal plain. Strand line deposits associated with the calcarenites indicate fluctuating sea level during deposition. On the margins of the basin, fluvio-lacustrine conditions (Garford Formation) may have been re-established; the age constraints on this sequence are broad. Lacustrine clays (Ilkina Formation) which overlie the Garford Formation may also have a Pliocene age (M. Benbow, pers. comm.). Further east, on Yorke Peninsula fluvial sequences have been dated as Pliocene (Harris, 1979).

To the east, the sea entered the Gulf St Vincent, inundating low-lying areas of Kangaroo Island. Shelly Limestones were deposited in shallow waters, while on the margins of the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CAINOZOIC TIME SLICE 6
INTERPRETATION
PLIOCENE
5–1·6 Ma (Berggren et al., 1985)
TIMOR SEA
INDIAN OCEAN
SOUTHERN OCEAN
CORAL SEA
SOLOMON SEA
SOUTH PACIFIC OCEAN
TASMAN SEA

Figure 10

basin, marine to marginal marine calcareous sandstones accumulated (Hallett Cove Sandstone, Dry Creek Sands). These sands pass laterally and vertically into marine and non-marine Quaternary sequences.

Rising relative sea levels raised depositional base levels in the Murray Basin, diminishing the potential for erosion. Sediments backfilled the previously incised palaeovalleys, forming the youngest of several Tertiary deep-lead systems in northern Victoria. Subsequent Pliocene regression resulted in progradation of a series of strand plain and fluvial sand deposits (Loxton/Parilla Sands) over the Late Miocene to Pliocene marls and clays. The beach ridges and interfluves, composed of red sandstone, still remain on the present day landscape. Estuarine oyster beds in the Norwest Bend Formation delineate the position of the ancestral Murray River. Further east, fluvial aggradation in a flood plain environment occurred with clastics of the Shepparton Formation being deposited; this process has continued into the Quaternary, (Brown & Stephenson, in prep).

Volcanism was widespread in the Otway Basin with basalt flows, tuffs and scoria (Newer Volcanics) emanating from numerous eruption centres both on and offshore. Gradual uplift continued from the Late Miocene, with only minor transgressions depositing relatively thin limestones (Whalers Bluff Formation) at the western edge of the basin. Thick deposits of prograding marine carbonates accumulated on the outer continental shelf and slope in the central offshore part of the basin (Holdgate et al., 1985).

In the Melbourne area, renewed subsidence in the Sorrento Graben during the late Early Pliocene, allowed deposition and preservation of the marine calcarenites and clays of the Wannaeue Formation. Fluvial deposition of ferruginous sandstones (Baxter Sandstone - Abele et al., 1976) occurred in adjacent onshore areas.

High energy gravels and fine clastics (Haunted Hills Gravels) continued to accumulate in widespread braided river systems on the western side of the Gippsland Basin. In the seaward part of the basin, marine regression continued during the Pliocene, with limestones being deposited under neritic conditions in offshore areas. Coastal plain sediments containing various lithologies,rangeing from fossiliferous calcareoussands to carbonaceous clays (Jemmy Point and Boisdale Formations) were conformably deposited over similar Late Miocene sequences.

In the Capricorn Basin, reef growth became more common with increasing water temperature, as a consequence of the northward drift of the continent (Hekel, 1973).

Drilling confirms that a belt of terrigenous, fluvio-deltaic deposits occurred on the inner shelf, which migrated eastwards at times of low relative sea level. The outer shelf accumulated carbonate deposits as subsidence continued.

Similar conditions occurred north of the Capricorn Basin along the present day continental shelf. In the tectonically active Papuan Basin, the emergence of the central highlands (Stewart & Durkee, 1985) supplied vast amounts of clastic material, terminating carbonate deposition and associated reef growth. Fine marine clastics of the Orubadi beds and marginal marine to terrestial clastics of the Era beds blanketed the subsiding offshore area. This process of rapid subsidence and deposition has essentially continued to the present day (Davies et al., in prep.). Thenett flow of sediment is towards the Coral Sea Basin, depositing thick turbidites in the northeast area of the basin.

Following deep weathering and the formation of the lateritised Kendall Surface during the ?Late Miocene to Pliocene (Grimes, 1979), deposition recommenced in the onshore Karumba Basin. The sandy Campaspe beds accumulated around the margins of the basin in broad alluvial fans, a process which continues to the present day (Claraville cycle - Grimes & Doutch, 1978).

Pliocene sedimentation along the Northwest Shelf and the Arafura Shelf was in conditions probably similar to those of the present day. The Pliocene sediments recovered from several wells are carbonates containing little terrigenous material, suggesting that onshore drainage was minimal (Forman & Wales, 1981). Drilling in the Timor Trough on the leading edge of the Australian continent indicates that during the Late Pliocene, rapid deepening occurred from shelf to continental slope environments as a result of the plate entering a major subduction zone (Veevers et al., 1974; Johnson & Bowin, 1981).

In the Carnarvon Basin, foraminiferal assemblages within the offshore, fine-grained, calcareous sequence (Delambre Formation - Heath & Apthorpe, 1984) record a rapid transgressive episode over the clastic-dominated Bare Formation. Inner shelf benthic faunas were replaced by planktonic dominated middle shelf assemblages. On the Rankin Platform, faunas indicate deposition in continental slope environments (over 1000m) during the Early Pliocene. The water depth was reduced to shelf conditions (approximately 200m) by the end of the Pliocene as a result of rapid sedimentation rates associated with progradation of the shelf. Onshore, calcareous valley-fill deposits have

been tentatively dated as Pliocene to Pleistocene in age (Hocking, et al., 1987).
A thin sequence of Pliocene marine sediments unconformably overlies Paleogene and Cretaceous deposits in the Perth Basin. These sediments represent a barrier-bar systemwith carbonate and siliciclastic facies, which are referred to as the Ascot beds and Yoganup Formation respectively (Baxter & Hamilton, 1981). The latter sequence contains economic deposits of heavy minerals. Offshore, a transgressive, bryozoan-rich calcarenite of probable Pliocene age has been identified (Wadjemup Formation - formerly Rottnest Formation - Quilty, 1978).

TIME SLICE 7: PLEISTOCENE (1.6 Ma - 10 ka)

Reconnaissance surveys of the continental shelf , and detailed sedimentological studies have gradually revealed the Quaternary evolution of the continental margin (Marshall, 1977, 1980; Davies, 1979; Jones & Davies,1983; Exon & Lee, 1987; van Andel & Veevers, 1967; Jongsma, 1974; Jones, 1973; Blom, in press; Jones & Torgersen, in prep.; Chapman et al., 1982; Taylor, 1977; Lawrence et al., 1976; Flood, 1984; Baker et al., 1983; Belperio et al., 1984; Logan et al., 1970, 1974). The Pleistocene map (Figure 11) depicts the Australian coastline during the well-documented maximum-glacial low sea level of approximately ≈140m (Chappell, 1974,1983).

Along the southern margin at various times during the Pleistocene, shell debris from the exposed continental shelf was blown inland to form the bioclastic dune calcarenites which are a feature of the coastline in South Australia and Victoria. Previously dune deposits have been broadly related to the Pleistocene Bridgewater Formation (Boutakoff, 1963). However, recent microfossil studies (Milnes & Ludbrook, 1986) recovering only Middle Miocene faunas from some sequences in South Australia, suggest a wider time range, possibly dating from the Late Miocene. It is likely that aeolian reworking of former coastal dunes produced extensive inland blankets of carbonate sediments.
Sediment accumulation in Spencer Gulf and Gulf St Vincent was largely controlled by local biogenic production of cool-temperate carbonates. Renewed tectonism in the


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INTERPRETATION
CAINOZOIC 7b – PLEISTOCENE

Figure 11

Plio-Pleistocene was followed by widespread alluvial fan deposition (Hindmarsh Clay) around Spencer Gulf and Gulf St Vincent (Firman, 1965). Aeolian sand and clay pellets characteristic of clay lunettes, and playa lake gypsum deposits are also found in asociation with the alluvial deposits (Gostin et al., 1985).

Seagrass meadows on the margins of the gulfs trapped and bound biogenic sediment, whereas towards the centre of the basins reworked skeletal debris from diverse faunas makes up much of the sediment. During the last glacial maximum a large lake occupied the central depression in the St Vincent Basin (Belperio & Gostin, 1988). Quaternary sea level fluctuations (Fig 16), resulted in the deposition of shelly marine and marginal marine sediments in the Gulf St Vincent and Spencer Gulf, (Glanville and Mambray Formations). Periods marine sedimentation are seperated by long intervals of subaerial exposure and pedogenesis (Belperio, 1985; Billings, 1984).

In the Murray Basin tectonic damming of the ancestral Murray Basin led to the formation of a large lake (Lake Bungunnia - Firman, 1973; Stephenson, 1986) in the central area of the basin, in which a thin veneer of fluvio-lacustrine clays (Blanchetown Clay) and dolomitic carbonates (Bungunnia Limestone) accumulated. Lake Bungunnia dates from the Late Pliocene, with lacustrine conditions continuing into the Middle Pleistocene (0.7 Ma). Present day salt lakes in the region indicate that parts of the lake still exist today. The demise of the lake led to the formation of modern landforms in the basin with widespread deflation occurring in the semi-arid to arid climate. The basin is blanketed by extensive Pleistocene to Recent aeolian dune deposits with associated calcretes (Brown & Stephenson, in prep.). On the coastal margin of both the Murray and Otway basins a series of prograding beach ridge/dune complexes (Bridgewater Formation) and inter-ridge estuarine/lacustrine/lagoonal sequences (Padthaway Formation) record Pleistocene sea level fluctuations (Fig 16), in an area of regional Plio-Pleistocene uplift (Cook et al., 1977; Schwebet, 1984). The complex Quaternary evolution of the Murray Basin has been extensively studied and summaries are published by Firman (1973), Lawrence (1975), Bowler, (1982) and Brown and Stephenson (in prep.).

Volcanism (Newer Volcanics) continued throughout the Quaternary in the Otway Basin and high glacioeustatic sea level stands deposited the marls and clays of the Whalers Bluff Formation. Late Quaternary faunal and sedimentological studies in the Bass Basin (Blom, in press), indicate that during the last glacial maximum a shallow lake of variable salinity occupied the centre of the basin, surrounded by marshes and beaches. The basin was flooded from the west at approximately 11,000 BP, as evidenced by the destruction of lacustrine facies and incoming marine molluscs. This lake formed several times in the Pleistocene, although the present day Bass Strait probably dates from about 10,000 yr BP.

Fluvial deposition continued in the Gippsland Basin,with movements on fault blocks producing warping and tilting of the land surface, causing entrenchment of river systems and diversion of their channels. Several marine terraces and barrier systems were formed, and have generally been uplifted (Jenkins, 1968; Ward, 1986).

Along the southeastern continental shelf three broad Quaternary lithofacies are recognised: inner shelf and nearshore quartz-rich sands; mid-shelf muddy sands and muds; and outer shelf calcareous sand and and gravelly sand facies (Chapman, 1982; Davies, 1979). Glacioeustatic sea levels, migration of strandline sequences, and wave/current transport direction and velocity have been the main deposition mechanisms involved in producing this sediment pattern. Heavy mineral deposits are concentrated in the northern sector of the shelf, in response to northward long shore drift; a process that is still active today.

Extensive studies on the modern day Great Barrier Reef have shown that growth commenced in the Pleistocene on basement highs composed of clastic fluvial/deltaic sediments, during periods of high sea level. The reefs are composite features with continued recolonisation of the same sites throughout their growth history. Reefs were subaerially eroded during long periods of low sea level, and solution unconformity surfaces were produced (Davies et al., 1983; Davies & Hopley, 1983; Marshall, 1983).

Four stages of overlapping fan deposition have been recognised in the Gilbert and Mitchell River areas of the Karumba Basin, each related to a phase of erosion in the provenance area (Grimes & Doutch, 1978). These stages appear to have been controlled by Pleistocene climatic and sea level changes, with some tectonism associated with volcanicity in the southeast producing localised uplift of the source area.

Offshore, sediment sampling of surficial sediments of the Gulf of Carpentaria has revealed the late Quaternary history of the region (Smart, 1977; Jones & Torgersen, in prep.). A large, shallow, brackish "Lake Carpentaria" occupied the deepest part of the present day embayment during the last glacial maximum (approximately 18,000 BP). The existence of the lake is a result of channel erosion and back-filling of a ridge

(Arafura Sill) separating the basinal area of the Gulf, from the outer margin of the continental shelf to the northwest. The land link with Papua New Guinea was probably severed during the early Holocene.

In the Arafura Sea several notches, terraces and scarps have been identified and related to Pleistocene low sea levels (Jongsma, 1974). Dating of wood and coral samples supports this suggestion and a broad sequence of eustatic events has been established in the area. Quaternary sediments must have been extensively reworked during fluctuating sea levels, with coral reef development continuing during interglacial maxima (Jongsma, 1974).

Further west in the Timor Sea, sediment studies have shown that most of the Sahul Shelf was emergent during the last glacial maximum (20-18 ka), as indicated by widespread calcrete and pedogenic development (van Andel & Veevers, 1967). A shallow embayment (lagoon) which developed in the Bonaparte Depression had a narrow connection to the open sea. Precursors of modern day rivers flowed towards the lagoon. The emergent shelf possibly provided a land bridge, leading to the migration of various animal species, including humans.

Pleistocene sedimentation over most of the North West Shelf is thin (1-200m) except in shelf atolls (Jones, 1973). In contrast, high sedimentation rates of approximately 350m / million years have been recorded in the Timor Trough as a result of rapid vertical tectonics (Johnson & Bowin, 1981). Several submerged strandlines have been recorded along the continental shelf although their age is uncertain. However, the shallowest of these features is probably related to Plio-Pleistocene glacioeustatic sea levels.

Along the coastal margins of the Carnarvon and Perth Basins Pleistocene to Holocene carbonate-rich aeolianites (Tamala Limestone) dominate the present landscape. Shallow marine calcarenite to calcrudite and coquina deposits are widespread as are coral-reef and algal dominated bioherms. Some of these marine sequences were deposited during the late Pleistocene interglacial high sea level 120-130,000 BP. Associated with these marine deposits are numerous littoral and swamp deposits. Many of these marine and marginal marine units have been studied in detail (Logan et al., 1970; Semeniuk, 1983; Playford, 1983; Hocking, et al., 1987).

TIME SLICE 8: HOLOCENE (PRESENT DAY) (10 ka - present day)

The early Holocene was characterised by rising sea level from the last Pleistocene glacial maximum, (c. 18,000 BP), and has stabilised at its present position since about 6000 yr BP. Figure 12 depicts the extent and types of depositional systems active today. In offshore areas, sea bed lithologies (compiled from marine surveys) are shown, however the age of these sea floor deposits varies considerably, as large areas contain relict deposits due to erosion and non-deposition.

Extensive modern temperate - water carbonates are forming over the continental shelf south of approximately 24° South. These sediments are characterised by foramol assemblages in which the prominent constituents are foraminifera, molluscs, bryozoans, calcareous red algae and barnacles. North of about 24° South carbonates with tropical affinities (chlorozoan assemblages) contain diagnostic hermatypic corals and calcareous green algae are accumulating (Lees & Buller, 1972).

Widespread erosion is occurring around most of the Australian coastline at present, although some areas are prograding e.g. northern Australia (Bird, 1985). Figure 13 illustrates the different types of coasts around the continent and selected biogeographic features.

Along the southern margin, bay beaches between rocky promontaries are mainly either stable or retreating. The limestone cliffed coastline along the Eucla Basin is retreating, whereas to the east around the Eyre Peninsula there is evidence for recent coastline advances and progradation of sand spits (Bird, 1985).

Holocene studies of temperate sediments in Gulf St Vincent and Spencer Gulf have shown that the modern day gulfs were formed by the latest Holocene transgression at about 6000 BP (Belperio et al., 1984; Belperio, 1985). The coastal sediments studied in the Gulf St Vincent show no evidence of Holocene sea level having exceeded its present level; although in the Spencer Gulf marginal marine sedimentation (seagrass facies) appears to have occured at a relative sea level 2.5 m higher than at present. The differences in sea level flucuations are thought to be related to tectonic uplift. Minor changes have occurred on the shores of the gulfs since the major transgressive phase with erosion of cliffs and areas of local progradation.

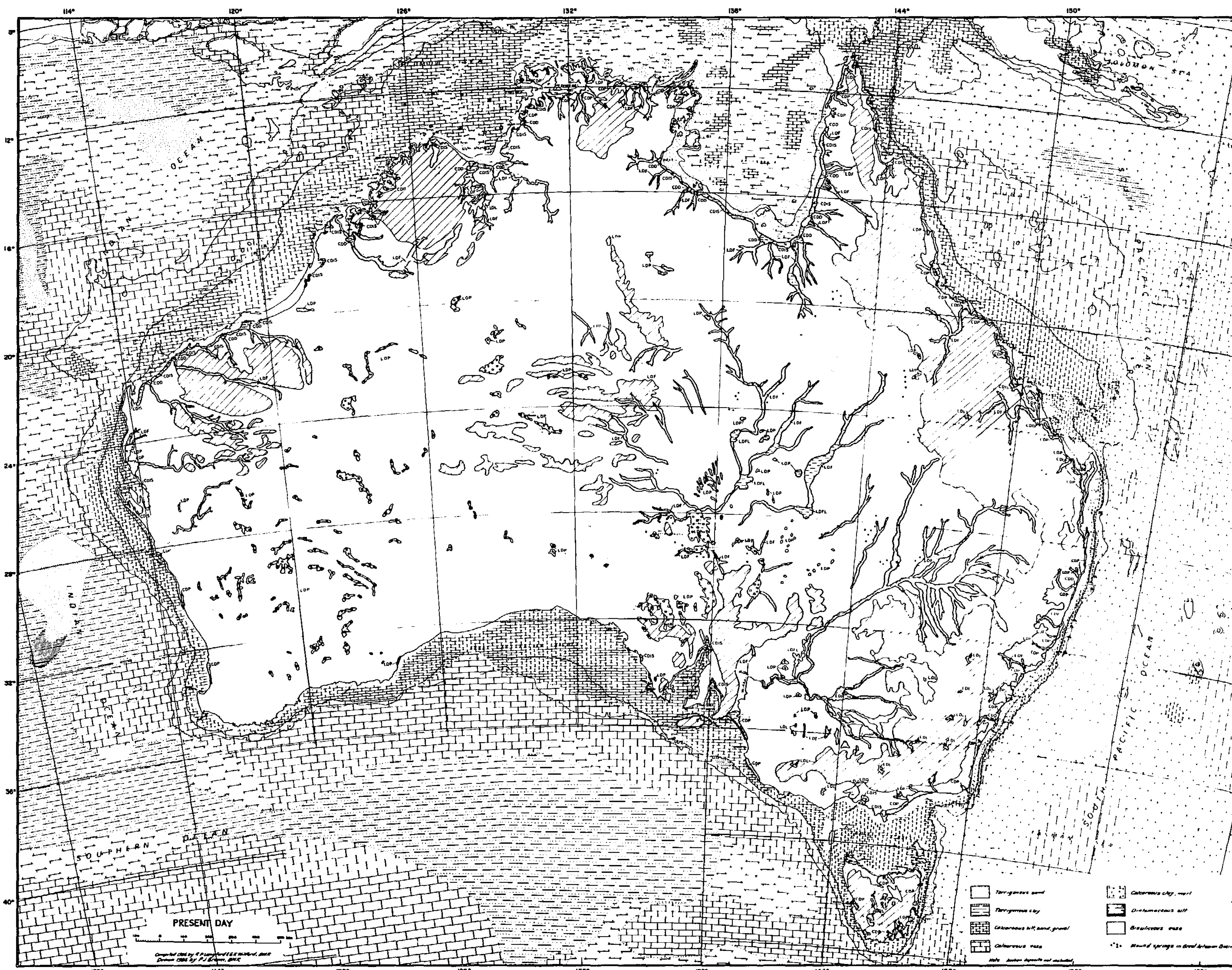

PRESENT DAY
INDIAN OCEAN
SOUTHERN OCEAN
SOUTH PACIFIC OCEAN
SOLOMON SEA
Terrigenous sand
Terrigenous clay
Calcareous silt, sand, gravel
Calcareous ooze
Calcareous clay, marl
Diatomaceous silt
Biosiliceous ooze
Mound springs in Great Artesian Basin

Figure 12

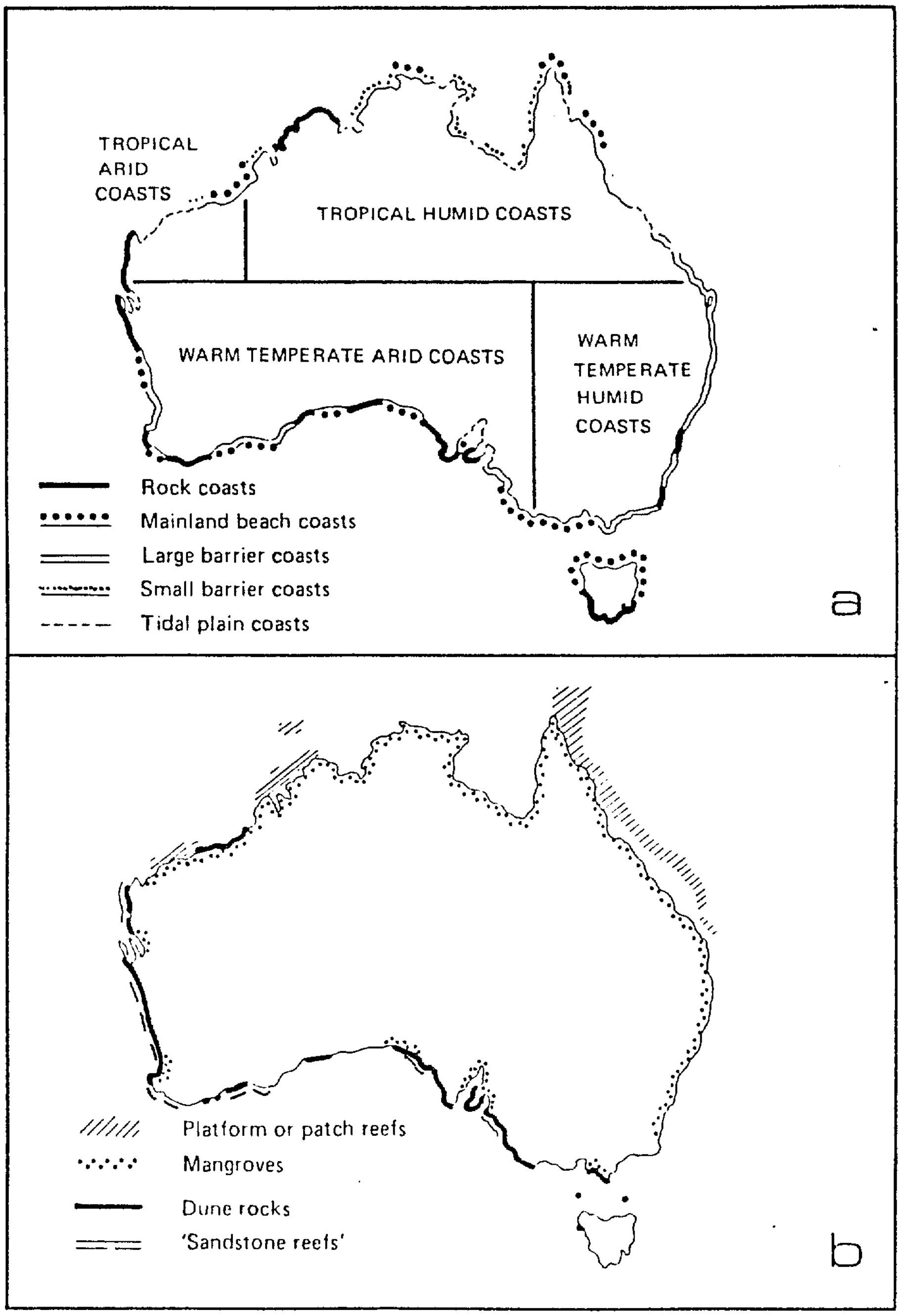


Fig. 13 Coastal types and selected features of the Australian coast (Thom, 1984)

In the Otway Basin, basaltic volcanism continued near Mt Gambier until approximately 1400 AD, and the area is a centre of present day seismicity (Firman, 1973). Onshore deposition continued in swamps and lakes, in topographic lows on a broad basaltic plain (Newer Volcanics). Along the coast, evidence indicates that Holocene sea levels oscillated, and at times flooded estuaries and calcareous dune deposits (Lawrance et al., 1975). Active sedimentation is currently occurring in Holocene barrier systems in moderate to high energy coastal environments (Short, 1988).

Behind these barrier systems, lagoonal (backbarrier) facies of fine clastics, biogenic and chemical sediments are accumulating. The character of these sediments varies greatly depending on embayment configuration, climate, river discharge, tidal range, vegetation and esturine organic assemblages. Washover sands were deposited into these shallow lagoons during the relatively rapid post glacial marine transgression.

Intertidal mudflats are currently forming in Westernport Bay and Corner Inlet. To the east, the Gippsland Basin is the site of one of the largest estuarine and sand barrier complexes in Australia (Jenkins, 1968; Thom, 1984).

Holocene sedimentation patterns along the southeastern seaboard have been well documented by Davies, 1979; Chapman et al. (1982), and Thom and Roy (1985). The rise in relative sea level to a peak at about 6,000 yr BP and its subsequent more or less stationary position (Holocene stillstand), has facilitated the growth of quartz-rich barriers along the eastern seaboard. Most of this sand has been derived from the reworking of inner shelf sand bodies. Widespread erosion of the south-eastern coastline is occurring at the present, with local sediment accumulation in areas adjacent to river mouths and protected embayments. Some terrigenous muds may be accumulating on the mid shelf region, although most of the material is probably being deposited on the floor of the Tasman Sea.

The modern day Great Barrier Reef began growth at about the same time (8-9000 yr BP), through out most of the province. Growth rates of framework corals varied from 1-16 m / 1000 yr and detrital carbonate facies were deposited at similar rates, in accordance with substate morphology, sea level and climatic changes. Initially, reef growth throughout wide areas lagged behind sea level rise, although once sea level stabilised (- 6000 yr BP), growth was outwards rather than upwards (Davies and Hopley, 1983). Landward of the reef, in the inner shelf and coast, sedimentation is dominated by terrigenous mud in water depths of 20-25 metres; mangrove dominated intertidal sedimentation and coastal progradation is widespread, with fluvial sands being largely contained at the coast (Cook and Mayo, 1970; Belperio, 1983). The efficient trapping of sediment by mangrove communities minimises offshore turbidity, therefore establishing ideal conditions for reef growth.

In the Gulf of Carpentaria, Holocene sedimentation is mainly confined to marginal areas of the gulf in proximity to onshore river sediment supply, and degree of exposure to wave and tidal activity. In deeper areas of the gulf, terrigenous muds and biogenic carbonate are slowly accumulating over relict fluvial and marine sediments (Jones, 1987). Along the coast of the gulf, chenier plains (low ridges seperated by broad wet flats), are prograding seawards (Rhodes, 1982). The low ridges are typically composed of molluscan debris with minor terrigenous material, whereas the interidge flats are mud rich with hypersaline deposits. Chenier plains are common hot-wet regions around northern Australia where rivers carry large quantities of fine sediment into low energy coastal provinces (Chappell & Grindrod, 1984).

No direct evidence of significant sedimentation since the Holocene transgression in the Arafura Sea exists, although shallow seismic sections and sampling suggest that fine grained sediment has accumulated on the middle shelf. On the inner shelf coarse grained sediment has been deposited, whereas near the shelf edge winnowing and erosion is the dominant process (Jongsma, 1974).

On the shelf edge in the Timor Sea numerous shoals and banks occur at a depth of approximately 20 metres below the surface; these features possibly originated as a barrier reef, or are a result of subaerial weathering. Foraminiferal calcarenites are forming on the outer shelf, with silty clays containing molluscan debris being deposited in sheltered areas. A blanket of terrigenous clay occurs in the Bonaparte Depression, and thin foraminiferal and algal calcirudites are slowly accumulating on shallow banks and rises. On the central and inner shelf relict transgressive deposits occur and sedimentation is slow, with evidence of intense burrowing and much of the skeletal material strongly glauconitised (van Andel & Veevers, 1967).

A distinct lobe of Recent, sand-sized sediment has prograded into the southern part of Joseph Bonaparte Gulf. This material is derived from the large Ord and Victoria Rivers deltas. The sub-aerial delta is composed of bare mud flats with local swamps, cheniers and small areas of stromatalite growth (Lees, 1984).

The present day North West Shelf is accumulating tropical to sub-tropical carbonate sediment at a very low rate. The broad shelf is dotted with reefs, banks and shoals including numerous coral fringed islands and reefs (Berry & Marsh, 1986). Fine grained terrigenous sediment occurs close inshore, and fine grained carbonates and Globigerina sands are being deposited near the outer edge of the shelf. A long (300km), low ridge is forming offshore from Broome near the edge of the shelf, due to the wide nature of the shelf and local sediment transport patterns; normally this material would prograde onto the slope as it does further south (Jones, 1973).

On the Scott Plateau and Rowley Shoals sedimentation is in relatively deep water with a strong pelagic influence. Plateau and abyssal sediments are generally very fine grained in contrast to the coarse, mud-free shelf sediments. The lower continental slope is virtually free of surficial sediments except in the north where the slope is more gentle (Stagg & Exon, 1981); the slope is probably swept clean by northward flowing contour currents.

Further south in the Perth area, Holocene sea level fluctuations and aeolin activity have formed a large barrier dune and lagoonal/estuarine system. Under the present day climatic and hydrologic regime, erosion and northward sediment migration is occurring along the barrier dune system, and a calcrete sheet is forming just above the water table (Semeniuk, 1983).

SEA LEVEL CHANGES

The history of global sea level changes during the Cainozoic was documented by Vail et al. (1977), and subsequently revised by Vail and Mitchum (1979) and Haq et al. (1987). The coastal onlap curve provided (Fig. 14,15) is based on modal averages from many areas around the world, as determined from seismic profiles calibrated to foraminiferal time stratigraphy across numerous continental shelves. Three major difficulties exist in constructing a eustatic sea level curve. These are: differentiating the effects of local tectonics; allowing for erosion of strata that was deposited during high stands of sea level; and accurately correlating sequence boundaries with geologic time scales (Steele, 1976).

The Paleogene time scales of Haq et al., and Berggren et al., vary considerably, and consequently problems exist in relating Haq et al., onlap curve with the Berggren et al., time scale, that has been used in this study. In contrast, the Neogene sequence and biostratigraphic boundaries are relatively consistant.

Tertiary sea level

The direct correlation of sea level fluctuations around the Australian continental margin with Vail and co-workers' sea level curves remains controversial, especially in regard to magnitude of the fluctuations. At present a general Cainozoic sea level curve for Australia is not available due to lack of control on the northern and eastern margins of the continent.

In regional studies McGowran (1978a, 1979) identified four major depositional sequences separated by unconformities on a generalised Australian margin. Quilty (1977, 1980) supported McGowran's studies by identifying similar cycles of sedimentation on the western margin of the continent. Bock and Glenie (1965) and Glenie et al. (1968) related sedimentary sequences in the Otway Basin and Adelaide area to major sea level fluctuations. Thompson (1986) has broadly related depositional sequences in southeast Australia to major sea level cycles proposed by Vail et al. (1977). Similarly, Steele (1976) and Partridge (1977) demonstrated correlation of seismic stratigraphic sequences within the Gippsland Basin to eustatic sea level stands; although, as Vail et al. noted, the amplitude of sea level variations is reduced due to the subsiding nature

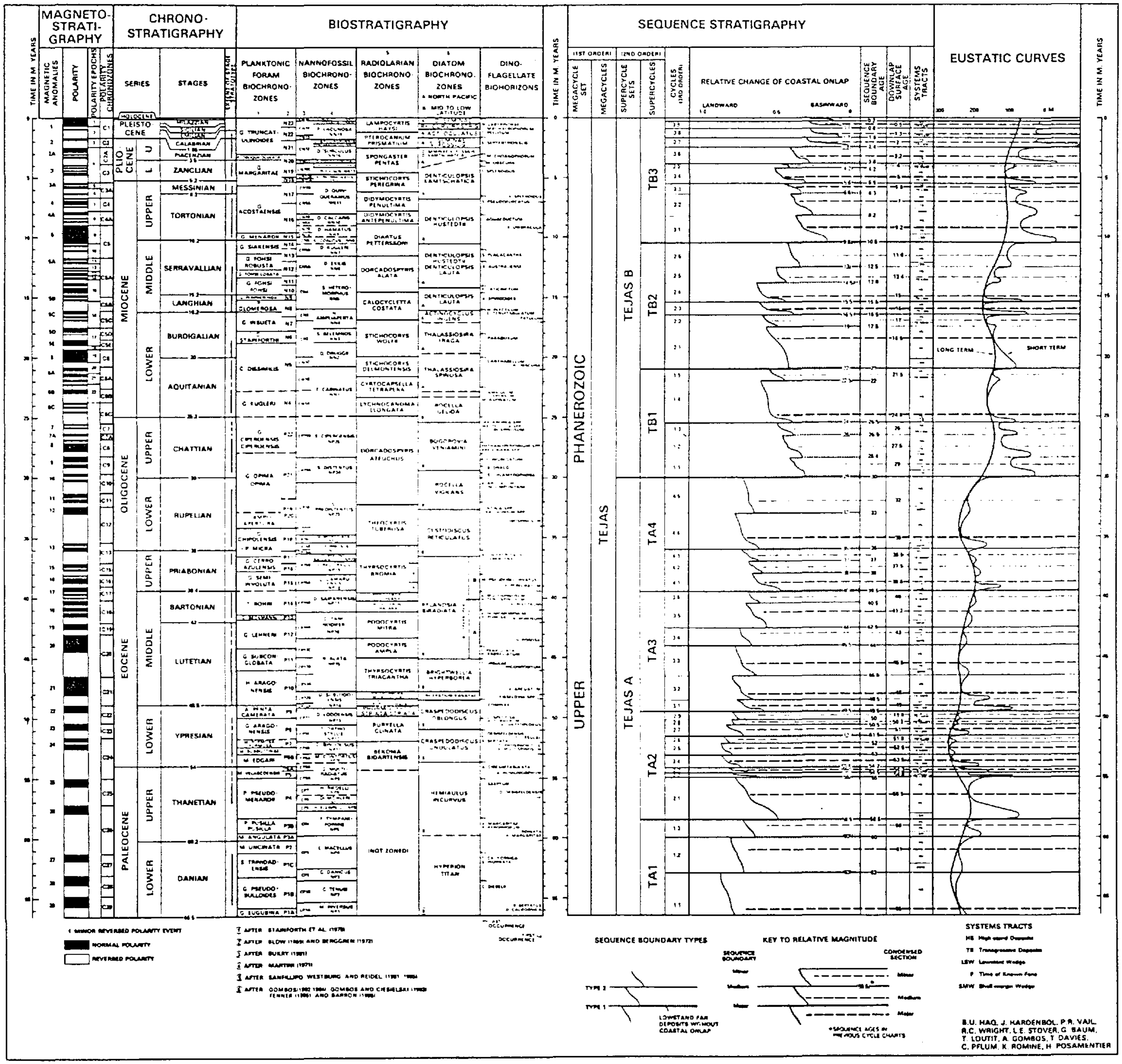


Fig. 14 Cainozoic sea level cycle chart (Haq et al., 1987)

of the Gippsland Basin. In studies of the Neogene of southern Victoria, Mallett (1978) related the distribution and lithologies of marine sediments to climatic events and associated sea level changes.

Loutit and Kennett (1981) concluded from studies of sedimentary cycles of the Tertiary of Australia that a good correlation exists between units identified and the second order supercycles of Vail et al. (1977) (Fig. 15). They also noted problems related to the length of time represented by unconformities in different regions of the continent. For example, hiatuses in the southern and western margin sequences are probably of a longer time duration than those in the southeast margin sequences as the former areas are in tectonically less active and more arid environments than the latter.

Another important observation was that a sea level hiatus can form at times of particularly high sea level (Vail et al., 1977). During a rapid rise in sea level terrigenous sediment can be trapped in estuaries and other nearshore environments leading to starvation of the continental shelf and ocean basins. Therefore periods of non-deposition or erosion can result in shallow marginal sequences. This may correspond to the well documented (Quilty, 1980, McGowan, 1979) hiatus occurring in the Middle Miocene (foram zone N8-N9). Glenie et al., (1968) also record minor sea level falls during the Middle Miocene and Middle Paleocene which may reflect short term sediment sediment starvation of the continental shelf region during high sea level stands (Loutit & Kennett, 1981).

In contrast to Loutit and Kennett's conclusions, Chappell (1984) indicated that transgressive and regressive cycles on the western margin correlate in only the most general way with Vail's curves, and that the trends are very different in detail.

In more recent studies, Brown (1985) has related sedimentation in the Murray Basin to the second order supercycles of Vail et al. (1977). Periods of sedimentation appear to correlate with high stands of sea level and hiatuses with low stands. Detailed third order cycles are rarely identified. The magnitude of sea level incursions in the basin has possibly been amplified by intrabasinal isostatic subsidence associated with sediment loading (Brown, 1985).

Data is constantly accumulating suggesting that depositional sequences within southeast Australia are directly related to eustatic sea level changes. Lindsay (1985) and Harris (1985) gave evidence for good local correlation between Eocene third order supercycles of Vail et al. (1977) and observed transgressions in the St Vincent and Otway Basins

(Thompson, 1986). Mallett and Holdgate (1985) have used Vail's onlap curve as a framework for considering local sequences in the Port Phillip Basin but note that better biostratigraphic control is required to establish correlations with global events, and that problems exist in relating marine temperature curves to Vail's curves.

However, a general pattern of Cainozoic relative sea level changes in the Australian region can be recognised. The Paleocene and Eocene were periods of relative high sea level, with a regressive period during the Early Eocene. A peak in sea level is recognised on the southern margin during the Late Eocene. The Early to Middle Oligocene was a relative low stand, followed by gradually rising relative sea level through to the Middle Miocene. The Late Miocene was a generally regressive period with higher relative sea levels during the Early Pliocene. The Late Pliocene was initially represented by lower relative sea level followed by rapid and extreme oscillations of climate and sea level which continue into the Pleistocene. A low sea level stand is apparent at about the Plio-Pleistocene boundary. The Holocene is characterised by gradually rising sea levels, from the last glacial maximum 20-16 ka to reach its present position approximately 6000 yr B.P. (Thom & Chappell, 1975).

Quaternary sea level

Glacio-eustacy, isostacy and local neotectonism are generally recognised as the main causes of Quaternary sea level changes. Separating these various components is complex, irrespective of scale (Hails et al., 1984). Eustacy is not necessarily a direct measure of glacial volume due to palaeogeoidal variation. This term was advanced by Morner (1976, 1981) to denote changes in the geoid. Morner suggested that due to palaeogeoidal variation sea level curves are only valid on a regional basis because of regional differences that result from changes in the geoid.

Ocean volume and temperature fluctuations throughout the Quaternary have been established from deep-sea and oxygen isotope records (Emiliani, 1972; Shackleton & Opdyke, 1973). Eustatic sea level maxima have been recorded in studies of emergent coral reefs, notably those of Chappell (1974, 1983a). High sea level stand deposits have been recognised in various locations around the continental margin (Fig 16). Pliocene studies are, in contrast, in a state of infancy (Quilty, 1984).

The Quaternary record of sea level and coastline changes in Australia have been extensively studied, although there is a need for more detailed regional studies (Thom,

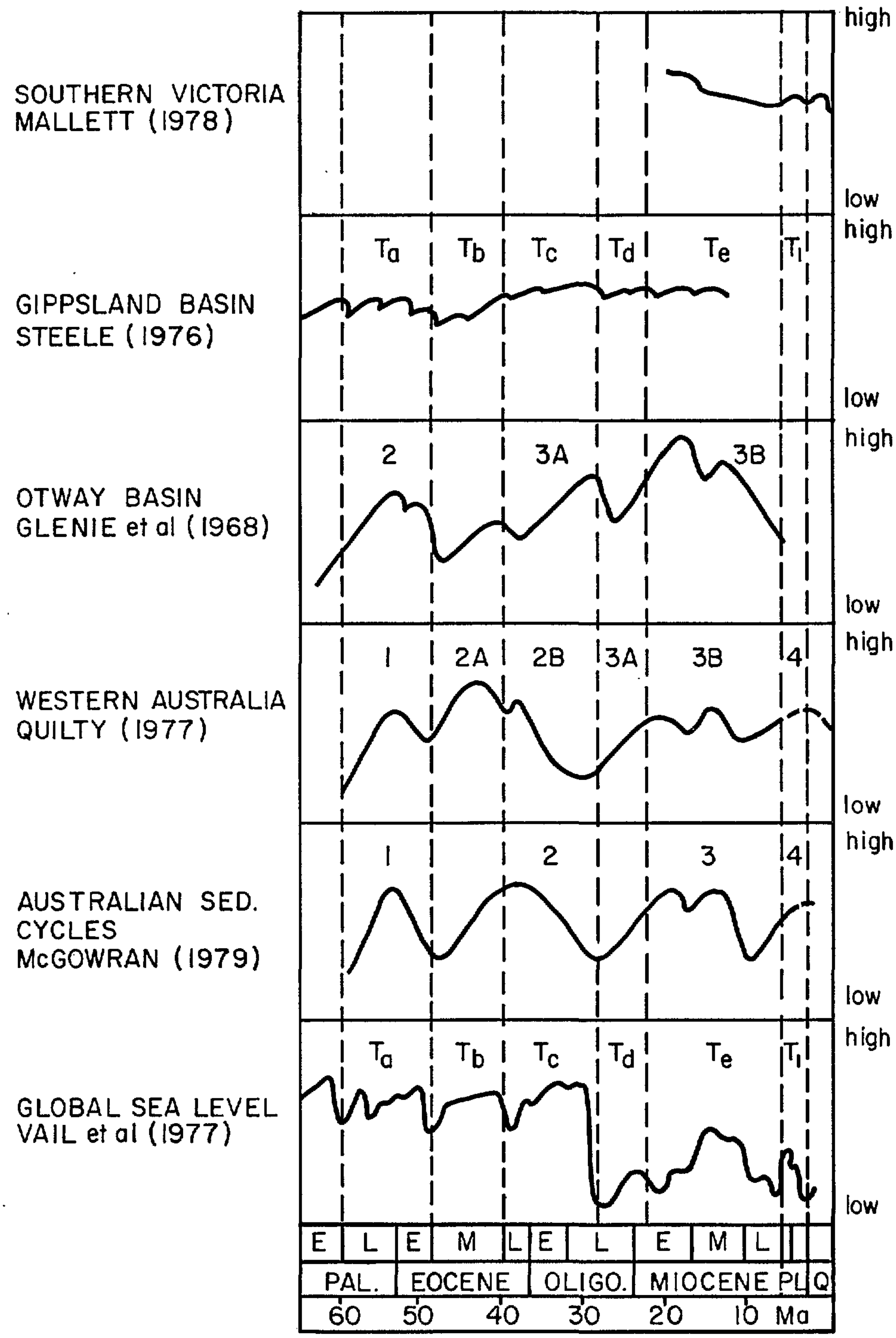


Fig.15 Correlation of several Australian sedimentary cycle histories

(Modified from Loutit & Kennett 1981)

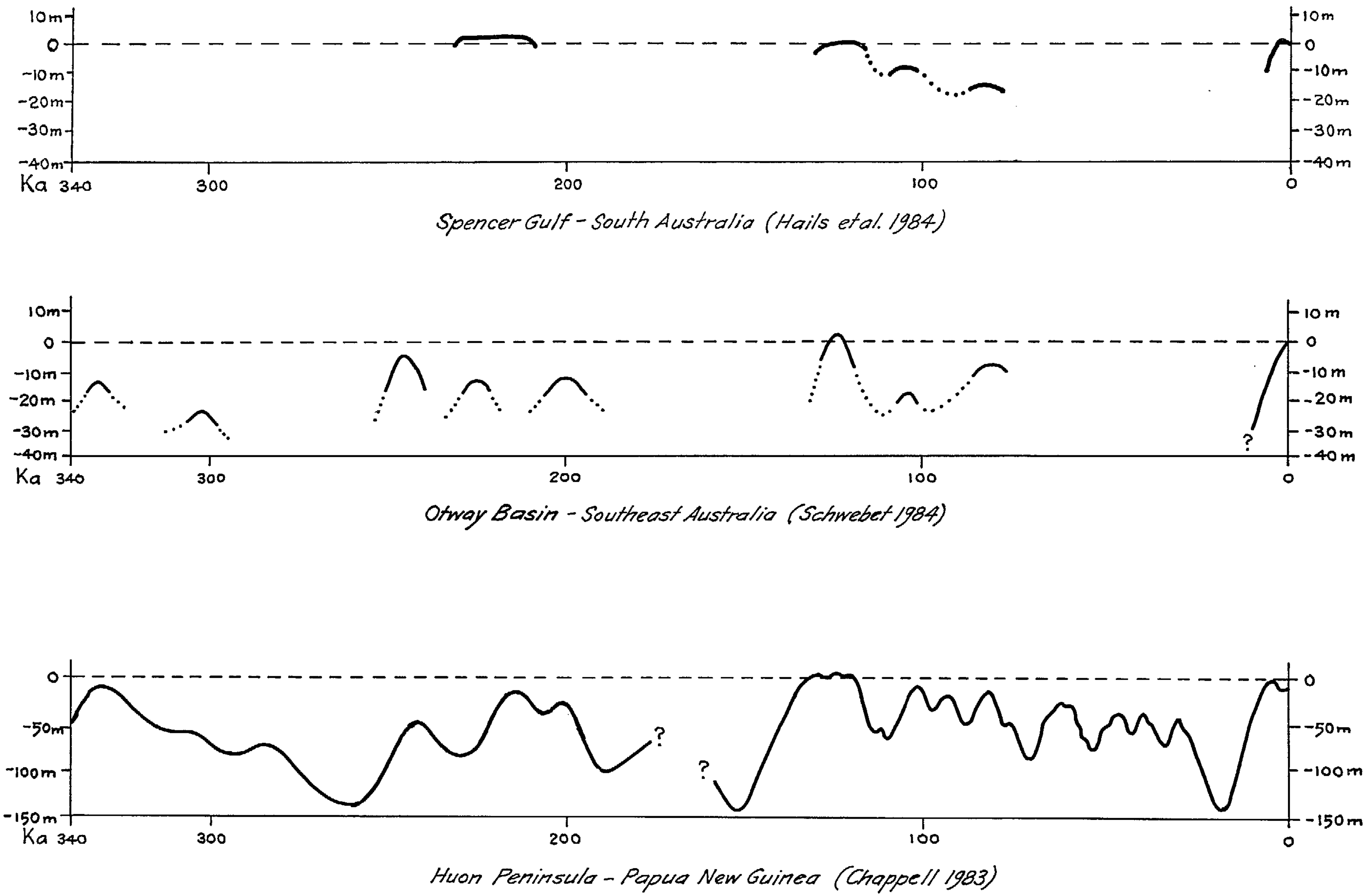


Fig. 16 Late Quaternary sea level curves

1984). It appears that the Australian craton is not as stable as initially envisaged but subject to subtle tectonic movements. Detailed published accounts have been presented by: Aubrey & Emery, 1986; Bird (1985); Belperio et al. (1984); Cann et al. (in prep.); Carter & Johnson (1986); Chapman et al. (1982); Chappell (1974, 1983), Davies & Hopley, (1983); Davies et al. (1985); Hopley and Thom (1983); Hocking et al. (1987); Pillans (1987); Semeniuk & Searle, (1986); Schwebel, (1983); Thom, (1984); Thom & Roy, (1985); and Ward (1985).

CAINOZOIC PALAEOCLIMATES

World-wide, Cainozoic climates show a progressive, stepped decline in temperature; probably reflecting major changes in the configuration of the ocean basins from the breakup of Gondwana to the establishment of the circum-Antarctic current. By the end of the Oligocene, the equable Cretaceous conditions had been replaced by a marked latitudinal thermal gradient which ranged, at least in the southern Hemisphere, from tropical equatorial to glacial polar. During the later Tertiary, this trend intensified, so that by the Pliocene the whole of Antartica was glaciated and the north polar glaciation was well advanced. This senerio has been deduced from DSDP and land - based studies (Kemp, 1978; Frakes, 1979; Grimes, 1980). Eustatic sea-level changes during the Neogene can be broadly linked to this thermal history, although the earlier eustatic events may have a tectonic origin (Veevers, 1984).

Paleogene

Oxygen isotope data reveals that the world's oceans in the Early Paleogene were warmer than at present, and also that the pole to equator temperature gradient was lower. Frakes (1979) estimated the gradient at about 4°-6° C during the Paleocene in the Pacific region ; this contrasts with the present gradient of about 12°-16° C. Isotope studies also suggest that the world's oceans were not markedly stratified (Fig 17), nor were vertical circulation and upwelling as intense as today. However, a degree of controversy remains concerning oxygen isotope interpretation, and there are several areas of uncertainty (Shackleton 1984).

In the Australian region, Paleogene isotopic data are restricted to DSDP sites on the Campbell Plateau, South Tasman Rise and the Tasman Sea. Evidence from these locations supports a low equator to pole temperature gradient (Shackleton & Kennett, 1975; Murphy & Kennett, 1985). Paleocene strata in Australia contain cosmopolitan marine faunas (McGowran, 1979), possibly reflecting the presence of a low gradient. Sea surface temperature values for the South Tasman Rise (Fig 18) were between 10°-20°C in the Paleogene and have declined in a series of steps to its present value of about 2°-5° C (Shackleton & Kennett, 1975, Kemp, 1978). Isotopic data is also available in the Otway Basin (Dorman, 1966), although recent work (Feary et al., in prep), indicates that these palaeotemperature determinations may only reflect local, nearshore conditions.

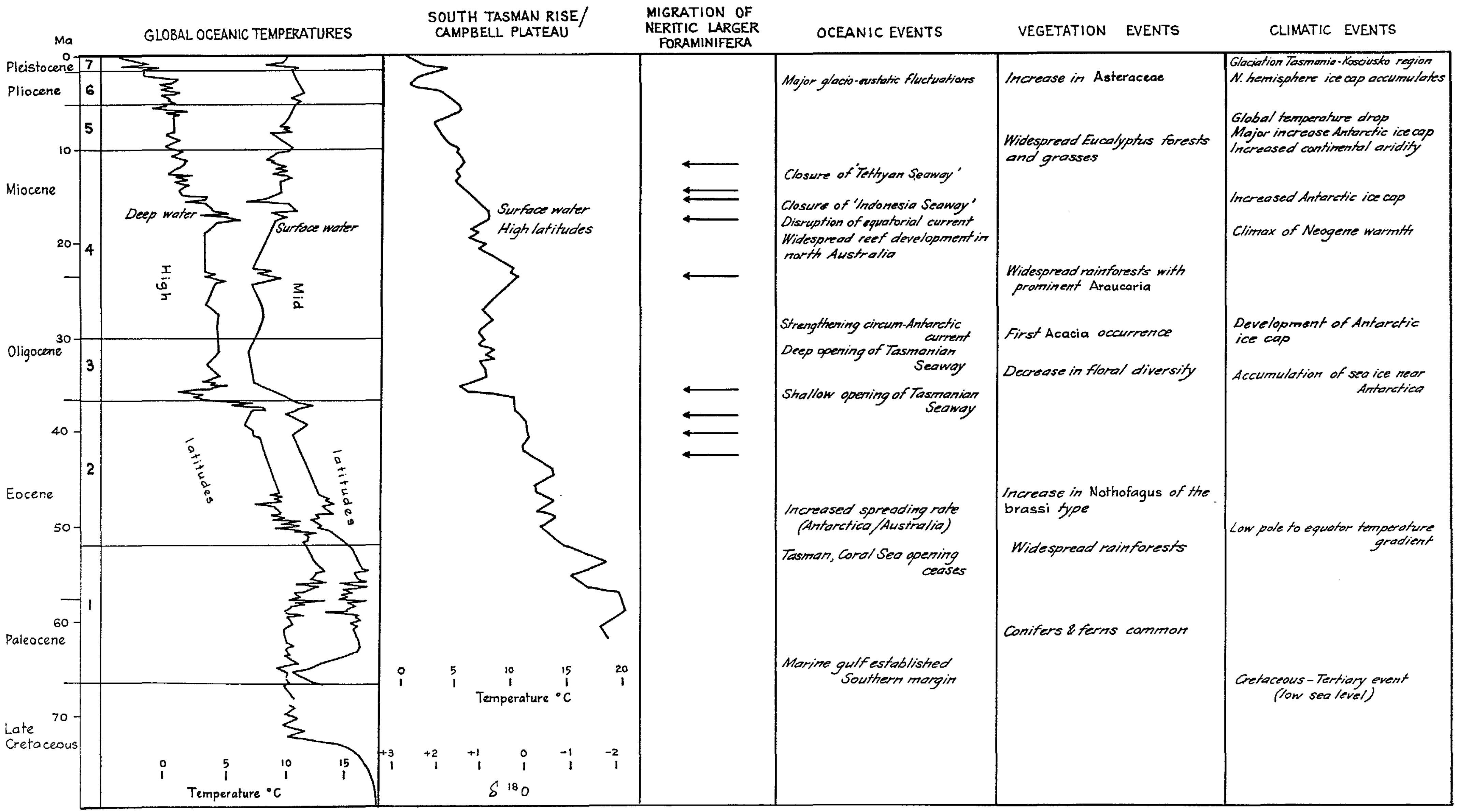
McGowran (1978; in prep) has documented several "excursions" of Indo-Pacific larger foraminifera to the Australian region during the Middle to Late Eocene (Fig 17). McGowran suggests that these extratropical excursions may reflect global changes in watermass shifts and major transgressions. Living species today inhabit shallow warm waters (18°-27° C - Wright, 1972), however the low diversity of Australian assemblages appears to represent the low end of the temperature spectrum (Chaproniere, pers comm).

Nannofossil studies along the Australian southern margin (Shafik, 1983; Exon & Lee, 1987), suggest temperate conditions during the Eocene, with an easterly decrease of temperature probably reflecting decreasing influence of warm Indian Ocean waters.

Higher sea-surface temperatures influenced climates on land, by producing high evaporation, leading to higher precipitation on continental masses (Kemp, 1978; Frakes, 1979). Palynological studies (Kemp, 1978) suggest that in the Paleogene temperate conditions with high rainfall (indicated by high fern diversity and presence of epiphytic fungi), produced extensive rainforests and Nothofagus and conifer-dominated closed forests along the southern margin. This vegetation pattern, with interspersed Eucalyptus species, may have extended into the interior, although data in parts of central and northern Australia is poor. The occurrence of Paleogene lignite on the southern margin and in the Browse Basin off northern Australia, as well as oil shale basins in the Eocene of Queensland, is further evidence for humid climates, at least on the margins of the continent.

Palaeoclimatic and sedimentological studies in offshore northeastern Australia suggest that during the Paleogene, temperate conditions were widespread. Carbonates similar

Fig.17 PALAEOCLIMATIC EVENTS



After Shackleton, 1984 — After Shackleton & Kennett, 1975 — After McGowran, 1979 — After Kemp, 1978; Kennett, 1982; Kennett et al., 1985; Kennet and von der Borch, 1985; Martin, 1986; Sluiter and Kershaw, 1982; Truswell et al., 1985 similar to those presently accumulating off southern Australia and along the Northwest Shelf were deposited in extensive shallow marine areas throughout the province. Reef growth may have briefly occurred during the Middle and early Late Eocene in response to warmer (>20° C) surface waters.

The most important event in Paleogene climatic development was the initiation of the circum-Antartic current during the very latest Eocene, which is reflected in a marked temperature drop, recorded in isotope data in the earliest Oligocene (Fig 17). Shallow breaching of the South Tasman Rise by the circum-Antarctic current resulted in decoupling of the warm subtropical South Pacific gyre, allowing the production of cold oceanic waters and sea ice close to Antartica (Kennett & von der Borch, 1985). Antartica became progressively colder, mountain glaciers formed, coalesced, and eventually grew into a major ice sheet. Since then the circum-Antarctic current has gradually strengthened to have a profound effect on the world's oceans and global climate; by causing deteriorating high latitude temperatures and reorganisation of the global heat budget (Kennett, 1982) .

Recent data from drillsites near Antartica (Barker, 1987), indicate that ice-rafting of sediment occurred in the early Oligocene (35 Ma). There is no indication, as yet, of the possible extent of an ice sheet on Antartica during the Oligocene, or when glaciation actually began.

A decline in sea-surface temperatures during the Oligocene may have lowered precipitation and temperatures on land. This is possibly reflected by the lack of sedimentation over much of the continent (McGowran, 1979; Grimes, 1980). The change in climate may have been associated with formation of silcretes (Wilford, in prep). Similarly, decline in temperature at the end of the Eocene was associated with a decrease in floral diversity (Kemp, 1978).

Neogene

The Early Miocene is characterised by increasing sea surface temperatures (Mallett, 1978; Kennett & Von der Borch, 1985) with a Neogene maximum in the Early to Middle Miocene (N7-N8). This is reflected by southerly migrations of larger foraminiferal genera (Chaproniere, 1980). Similarly a marked cooling in the Middle Miocene of sea surface temperatures, in higher latitudes, saw a retreat of larger foraminifera to equatorial regions. This decrease in temperatures was accompanied by an increase in the volume of Antarctic ice (Fig 17).

In the southeast of the continent pollen studies (Kemp, 1978; Kershaw & Sluiter, 1982; Martin, 1986) suggest that in the Early Miocene rainforests were still widespread, with high year-round precipitation rates locally exceeding 1500 mm. The presence of warm epicontinental seas in the Murray Basin would have contributed to this high rainfall. Temperatures are more difficult to assess, but were probably slightly warmer than at present. An altitudinal zonation of vegetation probably existed.

The southern margin would have been under the influence of westerly winds, whereas regions further north would have become increasingly arid. The increase of grass pollen during the Late Miocene reflects this aridity; the grasses would have also had an inhibiting effect on sediment movement (Quilty, 1984). Rainforest vegetation was gradually replaced by sclerophyll forest dominated by Eucalyptus and Acacia species as the continent moved northwards into drier climatic belts. Further inland, an increase in continental aridity is reflected offshore in clay mineralogy changes and terrigenous accumulation rates on the Lord Howe Rise (Stein & Roberts, 1985).

In northern Australia, Miocene sub-tropical to tropical reef growth was a consequence of continued northward drift into the tropics, and a marked increase in surface water temperatures (Davies et al., 1987; Feary et al., in prep.). Climatic and oceanic circulation patterns similar to those of the present day probably developed during the Late Miocene, result of this northward drift. Previously, equatorial circulation (Fig 19) was unhindered, with a continuous seaway (Indonesian Seaway) from the equatorial Pacific through the Tethyan and North Atlantic Oceans, but was closed during the Miocene (Kennett et al., 1985). The Late Miocene was generally a time of increasing continental aridity and cooler surface water temperatures.

Warm, wet conditions during the Pliocene are indicated by vertebrate faunas recovered in the Otway Basin, which contain species that are similar to those found living in Papua New Guinea today (Rich et al., 1980). Similarly, organic rich sediment from the Eyre Peninsula (Harris, 1979), and the presence of Lake Bungunnia in the Murray Basin reflect a wetter climate from that of the semi-arid conditions existing at present. Bowler (1982) suggested that late in the Pliocene, an earlier summer-dominated rainfall regime was replaced by cooler winter precipitation as a result of changes in atmospheric circulation. Bipolar glaciation was established during the Pliocene, which was accompanied by a further increase in latitudinal thermal gradients (Feary et al., in

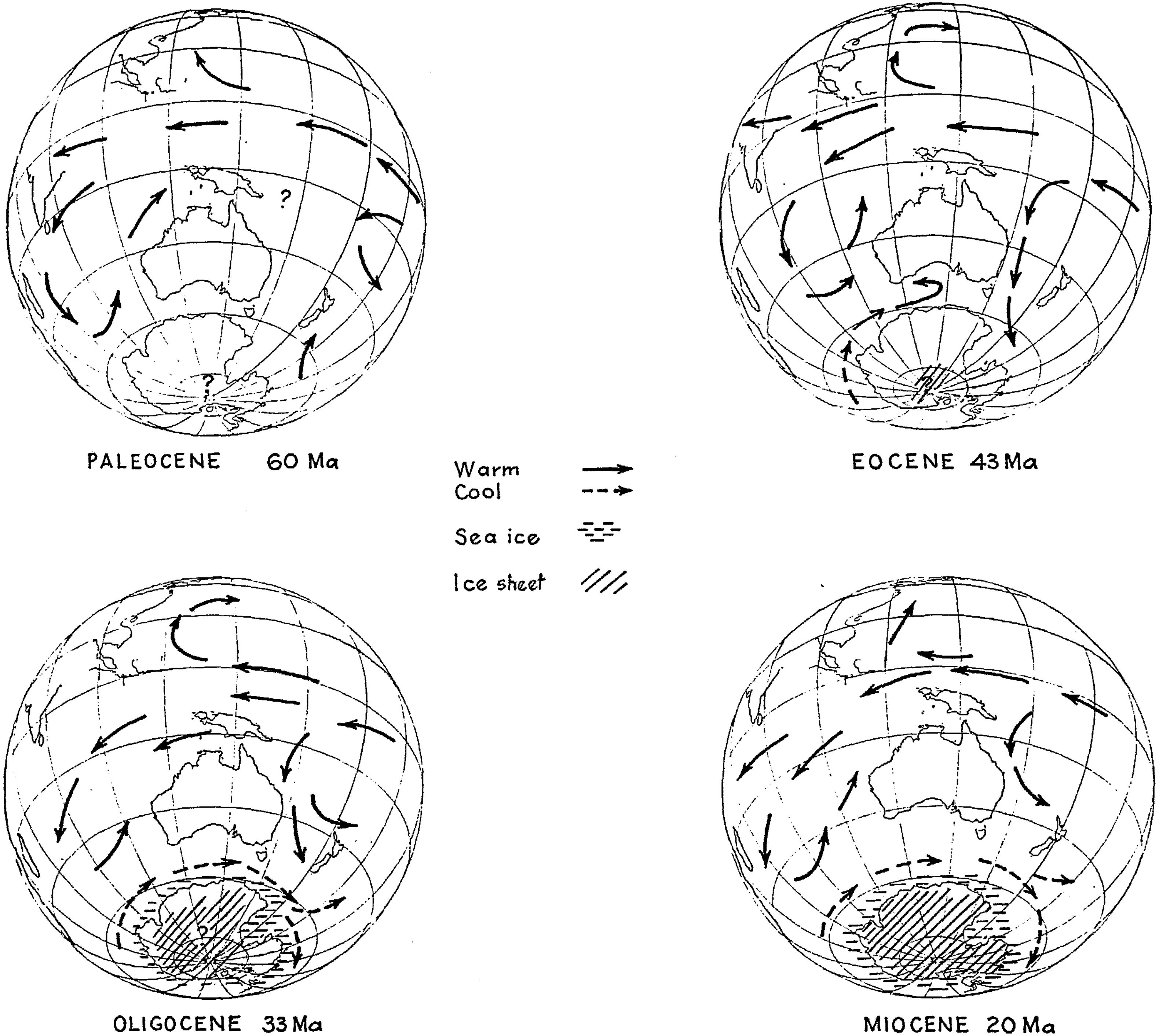


Fig. 18a Tentative surface circulation patterns

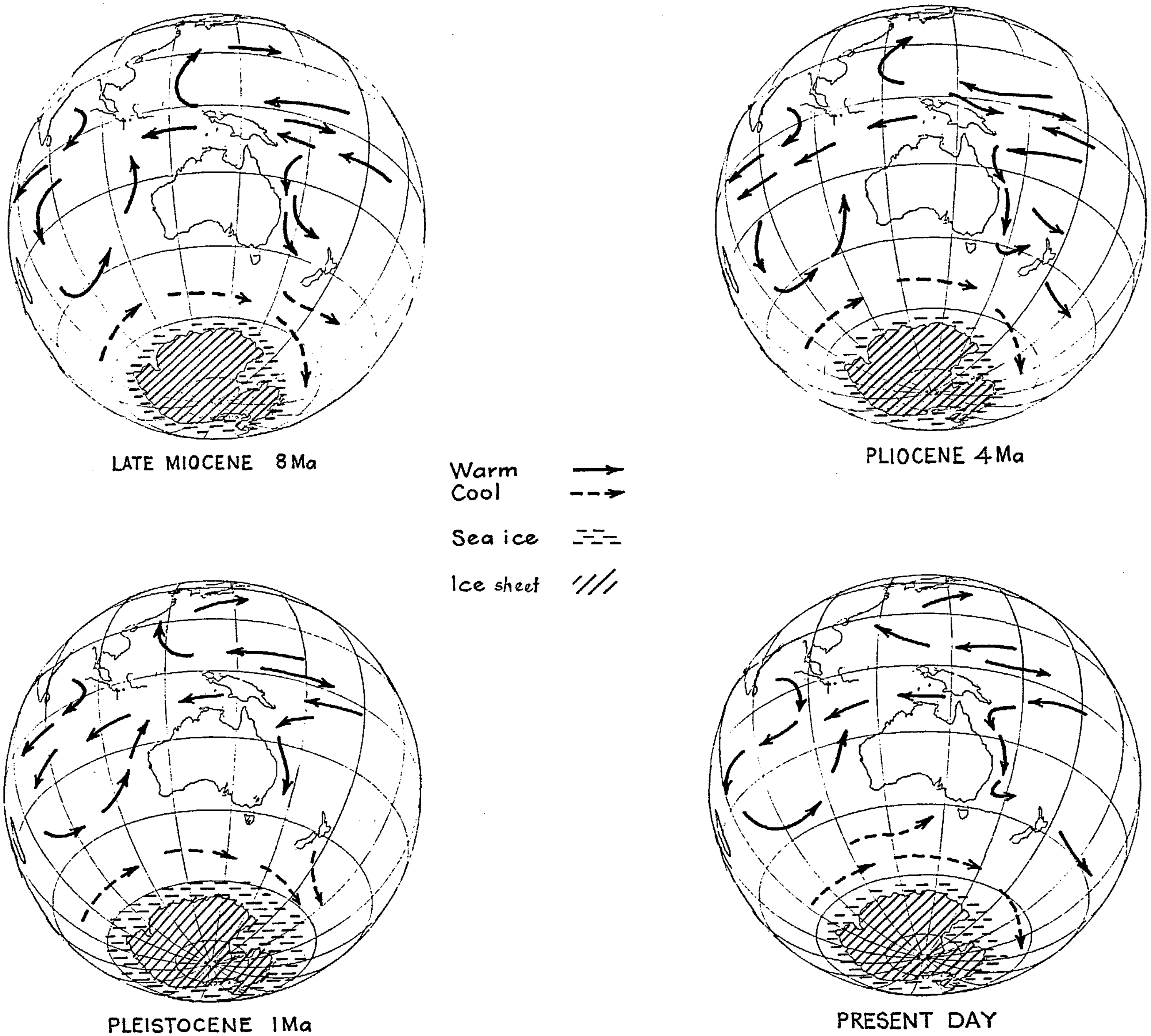


Fig. 18b Tentative surface circulation patterns

prep.).

Quaternary

Major fluctuation in sea level and climate during the Pleistocene resulted in alternating environments, ranging from wet lacustral phases to very arid conditions. At least 17 glacial-interglacial cycles, each of about 100 ka duration, have been recognised; in marked contrast to the relatively "slow" climatic oscillations of the Tertiary (Veevers, 1984). Glacial periods were characterised by lower sea levels and sea surface temperatures, and probably drier and windier conditions than today. Small areas of glacial ice were restricted to southeastern Australia, mainly in Tasmania. Intensified aeolin activity produced the present day extensive dunefields that dominate the Australian landscape (Bowler, 1982; Bowler & Wasson, 1984).

During interglacial periods, sea levels were high, rainfall increased, lake levels in wet areas rose, and forests expanded with a general reduction in continentality. The early Holocene climate was wetter than today, with higher temperatures and more evenly distributed rainfall (Williams, 1985).

CONCLUSION

The Cainozoic evolution of the Australian continental margin is a consequence of northward drift of the Indo-Australian plate, post-rift subsidence of the margin, sea level fluctuations, and major climatic and oceanographic changes. To document the Cainozoic development of the margin, a series of palaeogeographic maps portraying the changes in depositional environments throughout the period has been compiled. The selected time intervals and major features of the intervals are:

1. Paleocene - Early Eocene; Cessation of rifting along the eastern margin, restricted marine conditions along the southern margin, transgression in the west.
2. Middle - Late Eocene; Increased Australian/Antarctic spreading rate, major transgression along southern and western margin, widespread carbonaceous sedimentation.
3. Early Oligocene; Continent wide regession except in tectonically active southeast, widespread submarine erosion, ice development in Antarctica, strengthening of circum-Antartic current.
4. Late Oligocene - Middle Miocene; Continent wide transgression, highest Tertiary sea level, widespread carbonate deposition, reef development in northern Australia, collision with New Guinea Orogen.
5. Late Miocene; Continent wide regression, increase in continental aridity.
6. Pliocene; Transgressive period, widespread sedimentation, collision with Banda Arc, Arctic glaciation.
7. Pleistocene; Major sea level and climatic fluctuations, development of modern Great Barrier Reef, development of continental dune fields.
8. Holocene - Present Day; Rising sea level to approximate present day position at -6000 yr BP.

This set of palaeogeographic maps and stratigraphic correlation charts provides a useful framework for further, more detailed studies of the Cainozoic period in the Australian region, and for correlating the Australian record with other sequences world-wide.

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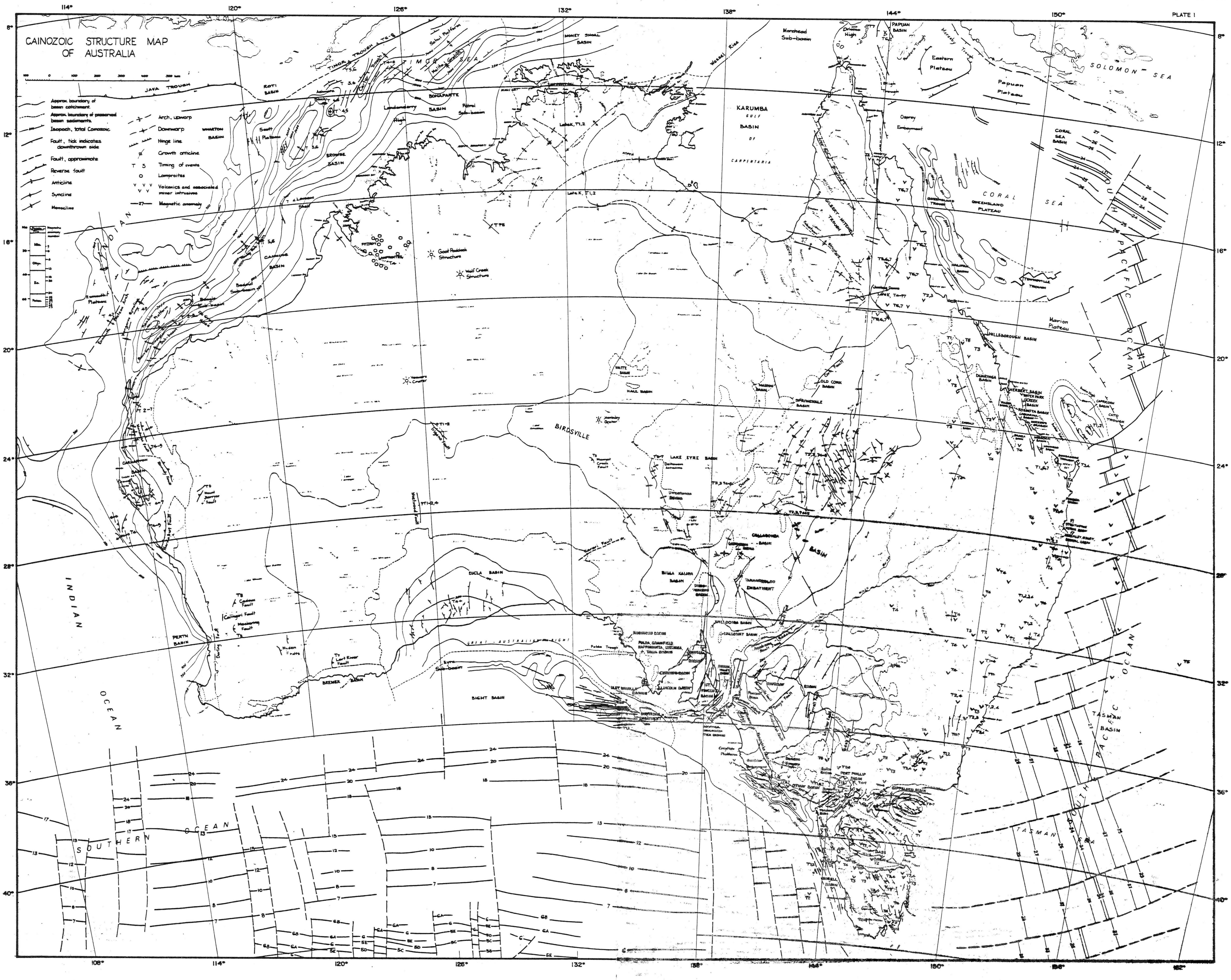
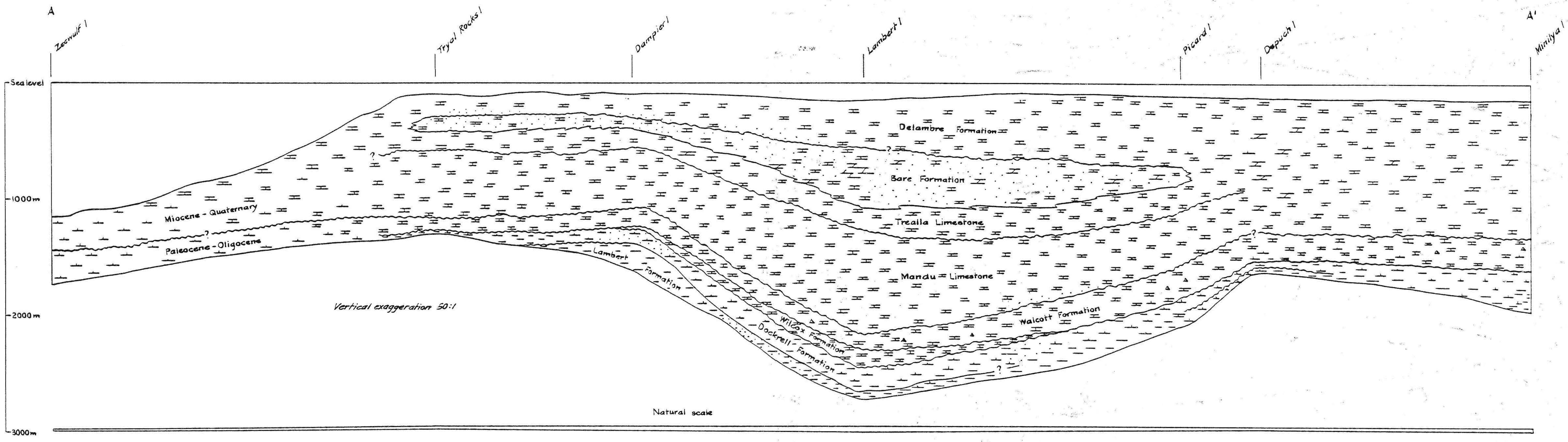
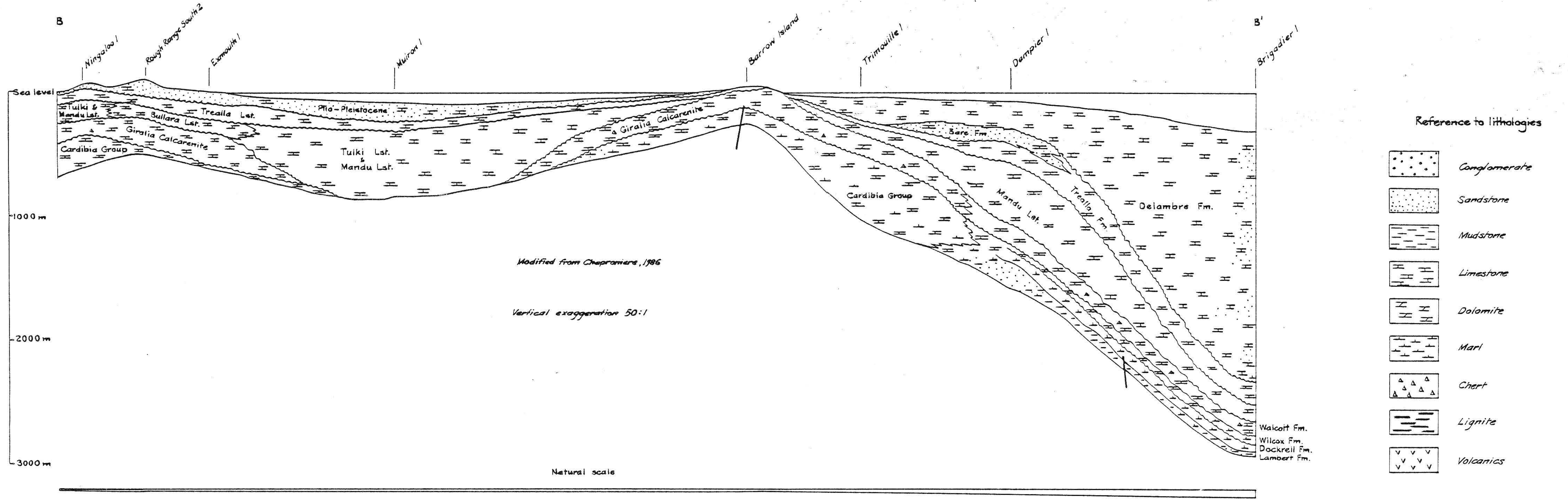
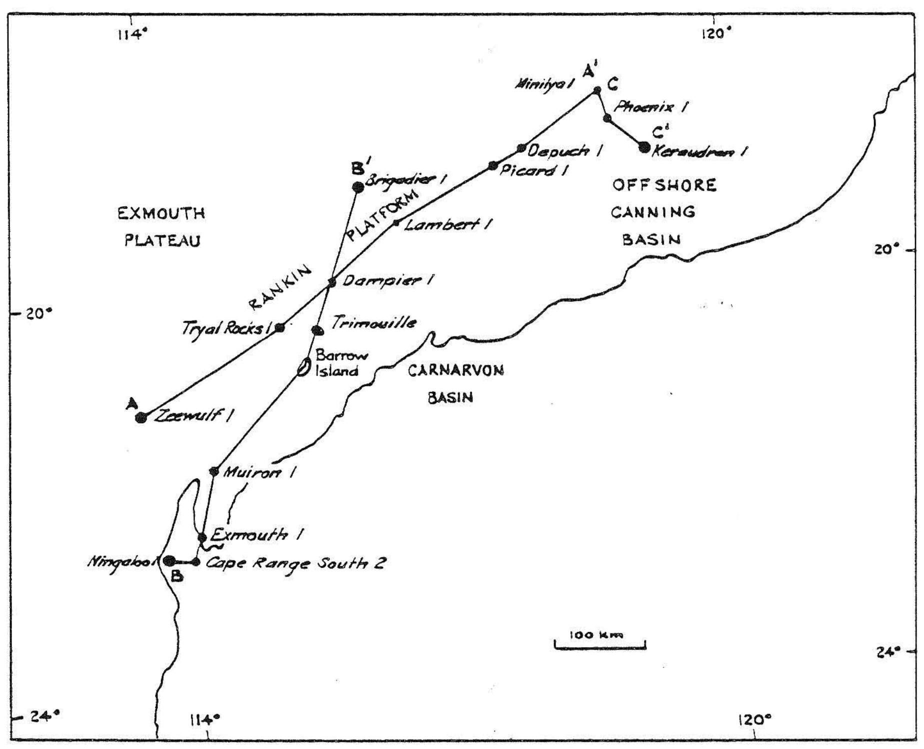
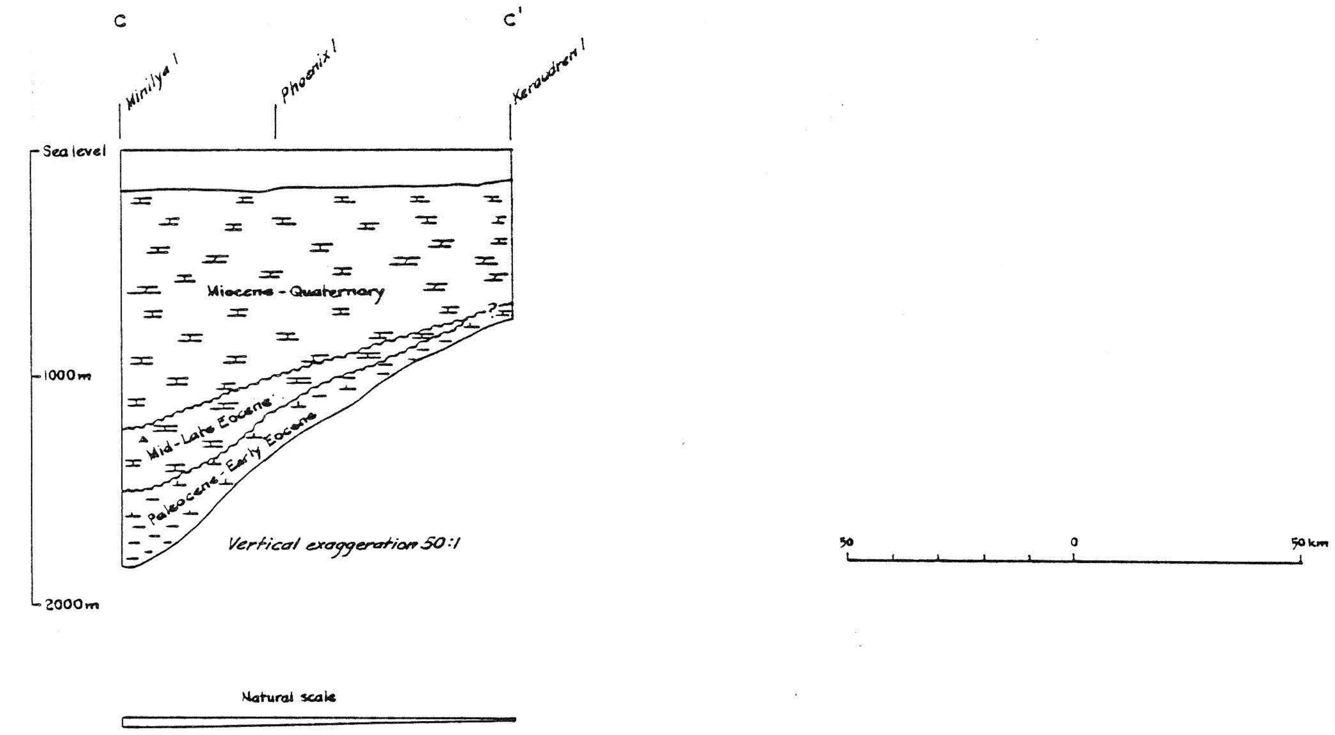
PLATE I


CAINOZOIC STRUCTURE MAP
OF AUSTRALIA
Approx. boundary of basin catchment
Approx. boundary of preserved basin sediments
Isopach, total Cainozoic
Fault, tick indicates downthrown side
Fault, approximate
Reverse fault
Anticline
Syncline
Monocline
Arch, upwarp
Downwarp
Hinge line
Growth anticline
Timing of events
Lamproites
Volcanics and associated minor intrusives
Magnetic anomaly
JAVA TROUGH
TIMOR TROUGH
TIMOR SEA
ROTI BASIN
BONAPARTE BASIN
Petrel Sub-basin
Londonderry High
WHARTON BASIN
Scott Plateau
BROWSE BASIN
CANNING BASIN
Bedout Sub-basin
Beagle Sub-basin
Exmouth Plateau
CARNARVON BASIN
PERTH BASIN
INDIAN OCEAN
SOUTHERN OCEAN
EUCLA BASIN
BREMER BASIN
BIGHT BASIN
Eyre Sub-basin
GREAT AUSTRALIAN BIGHT
Goat Paddock Structure
Wolf Creek Structure
BIRDSVILLE
LAKE EYRE BASIN
CALLABONNA BASIN
BILLA KALINA BASIN
KARUMBA BASIN
GULF OF CARPENTARIA
Morehead Sub-basin
PAPUAN BASIN
Eastern Plateau
Papuan Plateau
SOLOMON SEA
Oserey Embayment
CORAL SEA BASIN
CORAL SEA
QUEENSLAND PLATEAU
QUEENSLAND TROUGH
TOWNSVILLE TROUGH
Marion Plateau
HILLSBOROUGH BASIN
DUARINGA BASIN
HERBERT BASIN
CAPRICORN BASIN
CATO TROUGH
PACIFIC OCEAN
TASMAN BASIN
TASMAN SEA
SOUTH PACIFIC OCEAN
PORT PHILLIP BASIN
OTWAY BASIN
Wessel Rise
Money Shoal Basin
Sahul Platform

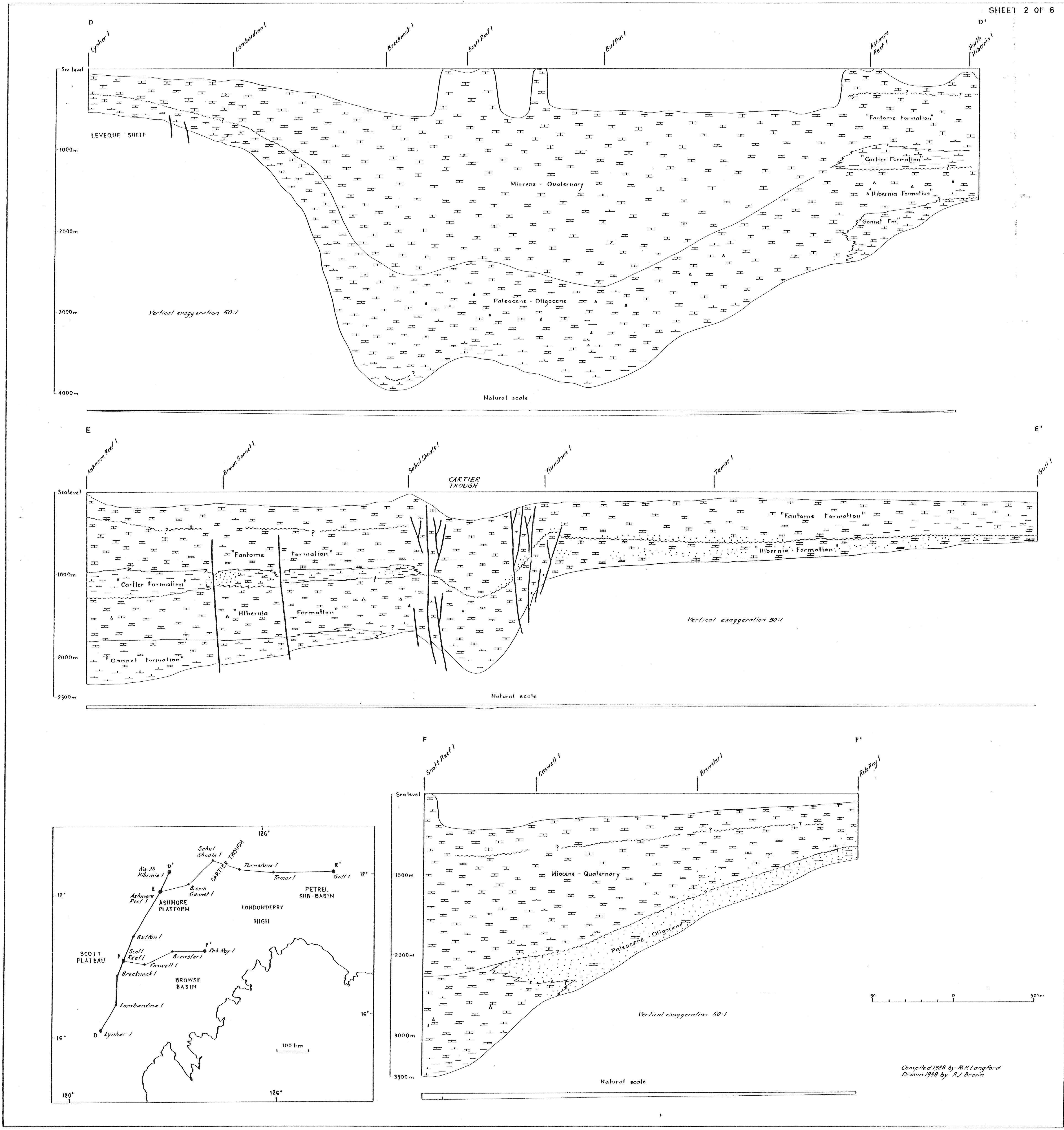








Compiled 1988 by R.P. Langford
Drawn 1988 by P.J. Brown


D
D'
Lynher 1
Lombardina 1
Brecknock 1
Scott Reef 1
Buffon 1
Ashmore Reef 1
North Hibernia 1
Sea level
1000m
2000m
3000m
4000m
LEVEQUE SHELF
"Fantome Formation"
"Cartier Formation"
"Hibernia Formation"
"Gannet Fm."
Miocene - Quaternary
Paleocene - Oligocene
Vertical exaggeration 50:1
Natural scale
E
E'
Ashmore Reef 1
Brown Gannet 1
Sahul Shoals 1
CARTIER TROUGH
Turnstone 1
Tamar 1
Gull 1
Sealevel
1000m
2000m
2500m
"Fantome Formation"
"Cartier Formation"
"Hibernia Formation"
"Gannet Formation"
Vertical exaggeration 50:1
Natural scale
F
F'
Scott Reef 1
Caswell 1
Brewster 1
Rob Roy 1
Sealevel
1000m
2000m
3000m
3500m
Miocene - Quaternary
Paleocene - Oligocene
Vertical exaggeration 50:1
Natural scale
50
0
50km
126°
12°
16°
120°
North Hibernia 1
Ashmore Reef 1
ASHMORE PLATFORM
Sahul Shoals 1
CARTIER TROUGH
Turnstone 1
Tamar 1
Gull 1
Brown Gannet 1
PETREL SUB-BASIN
LONDONDERRY HIGH
Buffon 1
SCOTT PLATEAU
Scott Reef 1
Brewster 1
Rob Roy 1
Caswell 1
Brecknock 1
BROWSE BASIN
Lombardina 1
Lynher 1
100 km
Compiled 1988 by R.P. Langford
Drawn 1988 by P.J. Brown

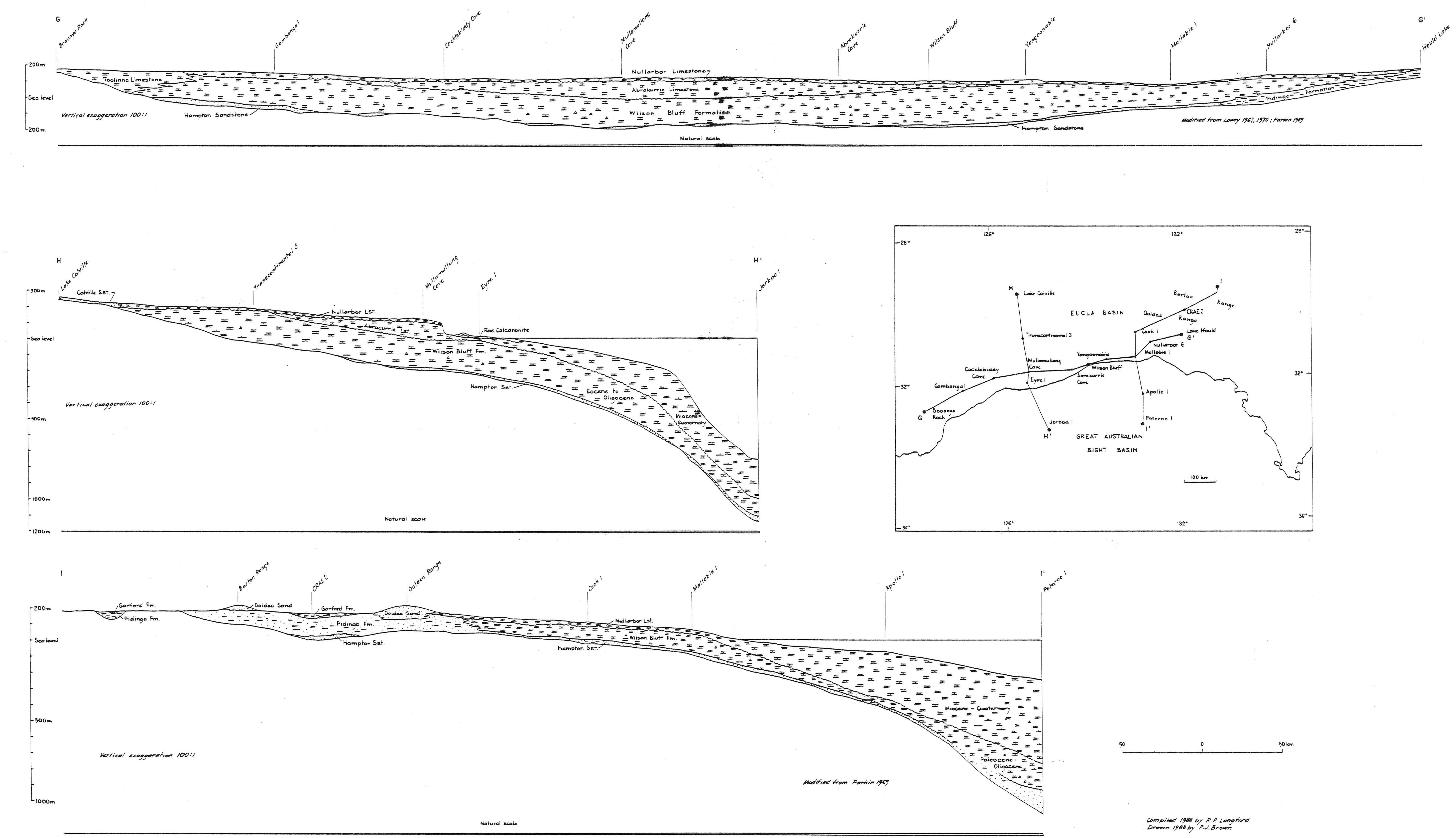
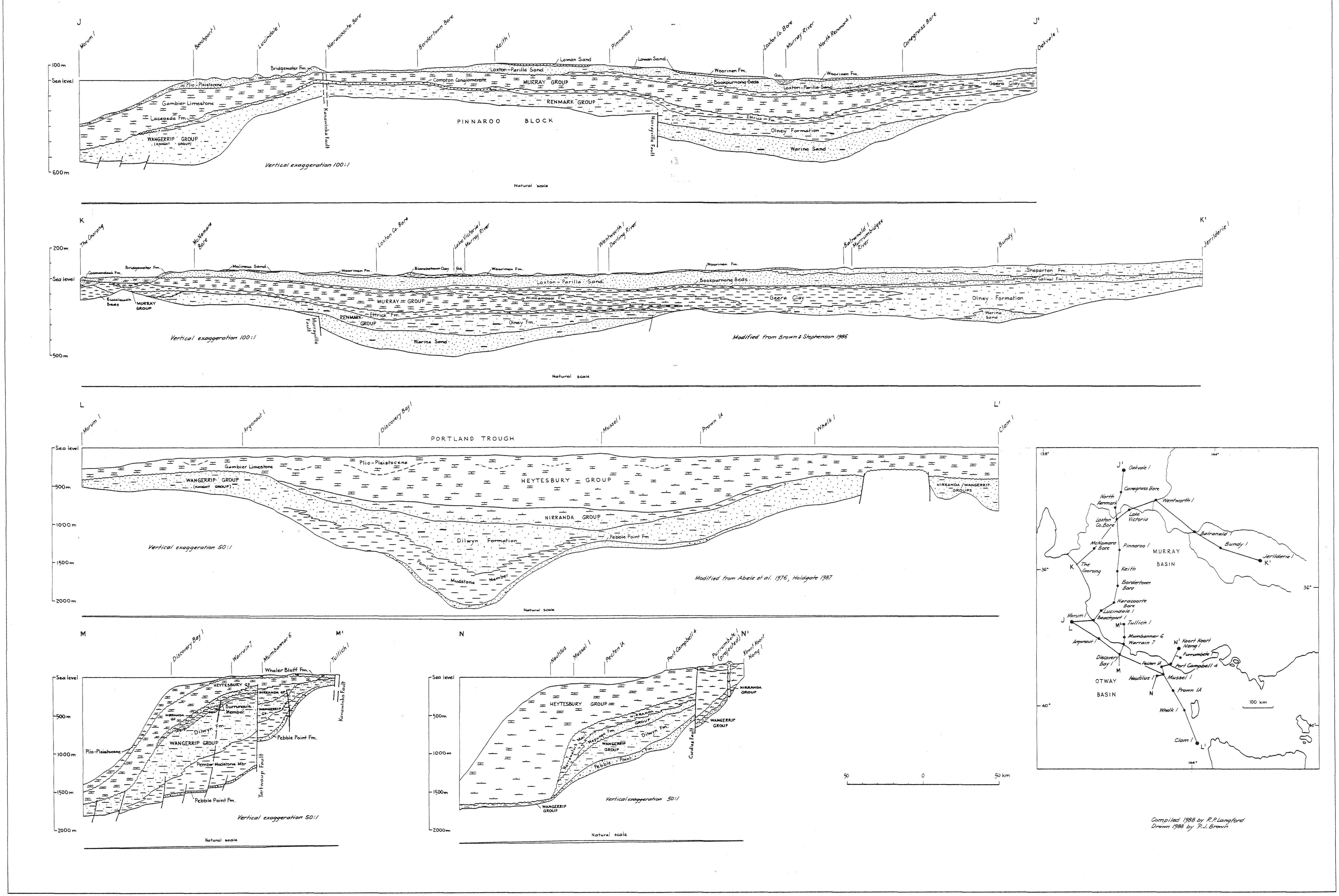
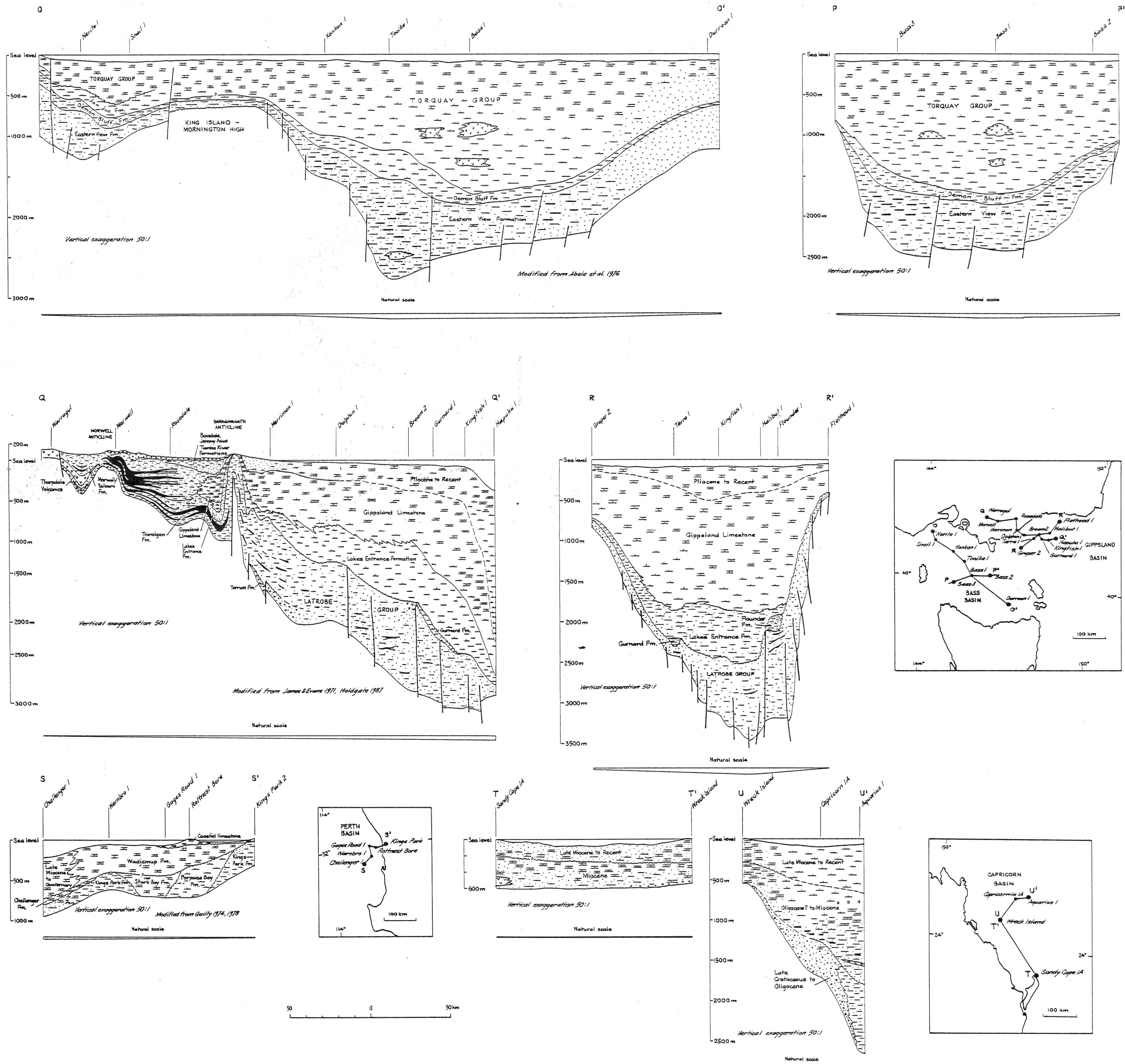
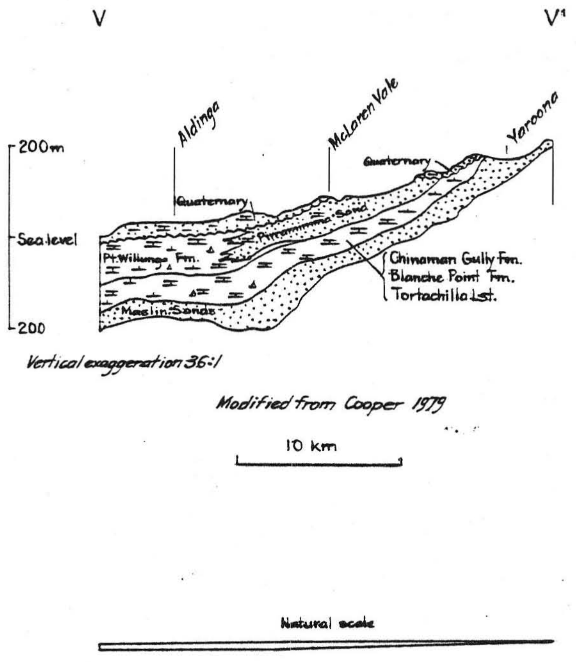

G
Boonyie Rock
Gambanga 1
Cocklebiddy Cave
Mullamullang Cave
Abrakurrie Cave
Wilson Bluff
Yangoonabie
Mallabie 1
Nullarbor 6
Ifould Lake
G'
200m
Sea level
200m
Toolinna Limestone
Nullarbor Limestone
Abrakurrie Limestone
Wilson Bluff Formation
Hampton Sandstone
Pidinga Formation
Vertical exaggeration 100:1
Modified from Lowry 1967, 1970 ; Parkin 1969
Natural scale
H
Lake Colville
Transcontinental 3
Mullamullang Cave
Eyre 1
Jerboa 1
H'
300m
Sea level
500m
1000m
1200m
Colville Sst.
Nullarbor Lst.
Abrakurrie Lst.
Roe Calcarenite
Wilson Bluff Fm.
Hampton Sst.
Eocene to Oligocene
Miocene - Quaternary
Vertical exaggeration 100:1
Natural scale
EUCLA BASIN
GREAT AUSTRALIAN BIGHT BASIN
Lake Colville
Transcontinental 3
Mullamullang Cave
Eyre 1
Jerboa 1
Cocklebiddy Cave
Gambanga 1
Booanya Rock
Yangoonabie
Wilson Bluff
Abrakurrie Cave
Ooldea
Barton Range
CRAE 2
Cook 1
Lake Ifould
Nullarbor 6
Mallabie 1
Apollo 1
Potoroo 1
100 km
126°
132°
28°
32°
36°
I
Barton Range
CRAE 2
Ooldea Range
Cook 1
Mallabie 1
Apollo 1
Potoroo 1
I'
200m
Sea level
500m
1000m
Garford Fm.
Pidinga Fm.
Ooldea Sand
Garford Fm.
Ooldea Sand
Pidinga Fm.
Hampton Sst.
Nullarbor Lst.
Wilson Bluff Fm.
Hampton Sst.
Miocene - Quaternary
Palaeocene - Oligocene
Vertical exaggeration 100:1
Modified from Parkin 1969
Natural scale
50
0
50 km
Compiled 1988 by R.P. Langford
Drawn 1988 by P.J. Brown

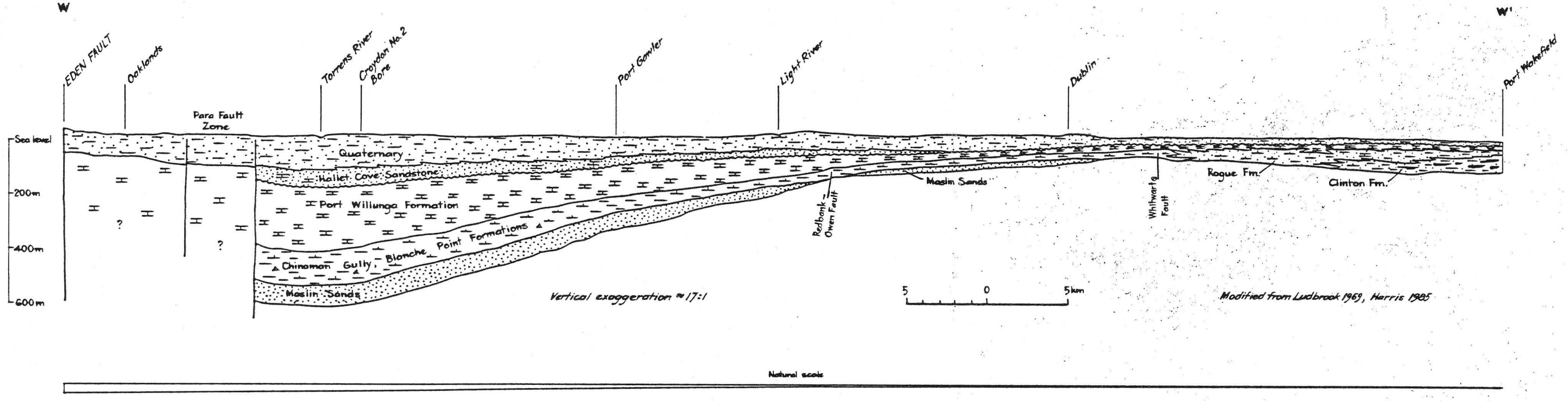
PLATE 5

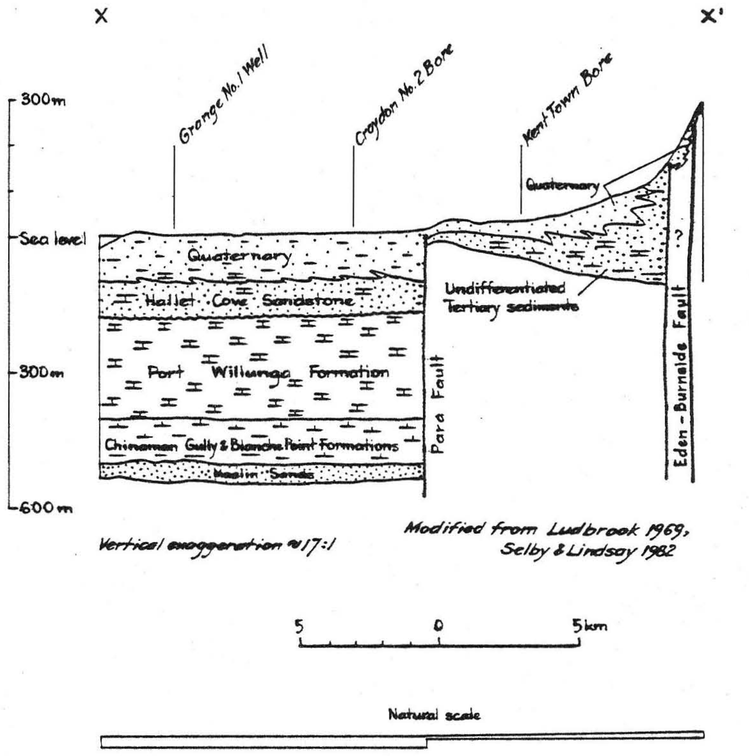
SHEET 4 OF 6

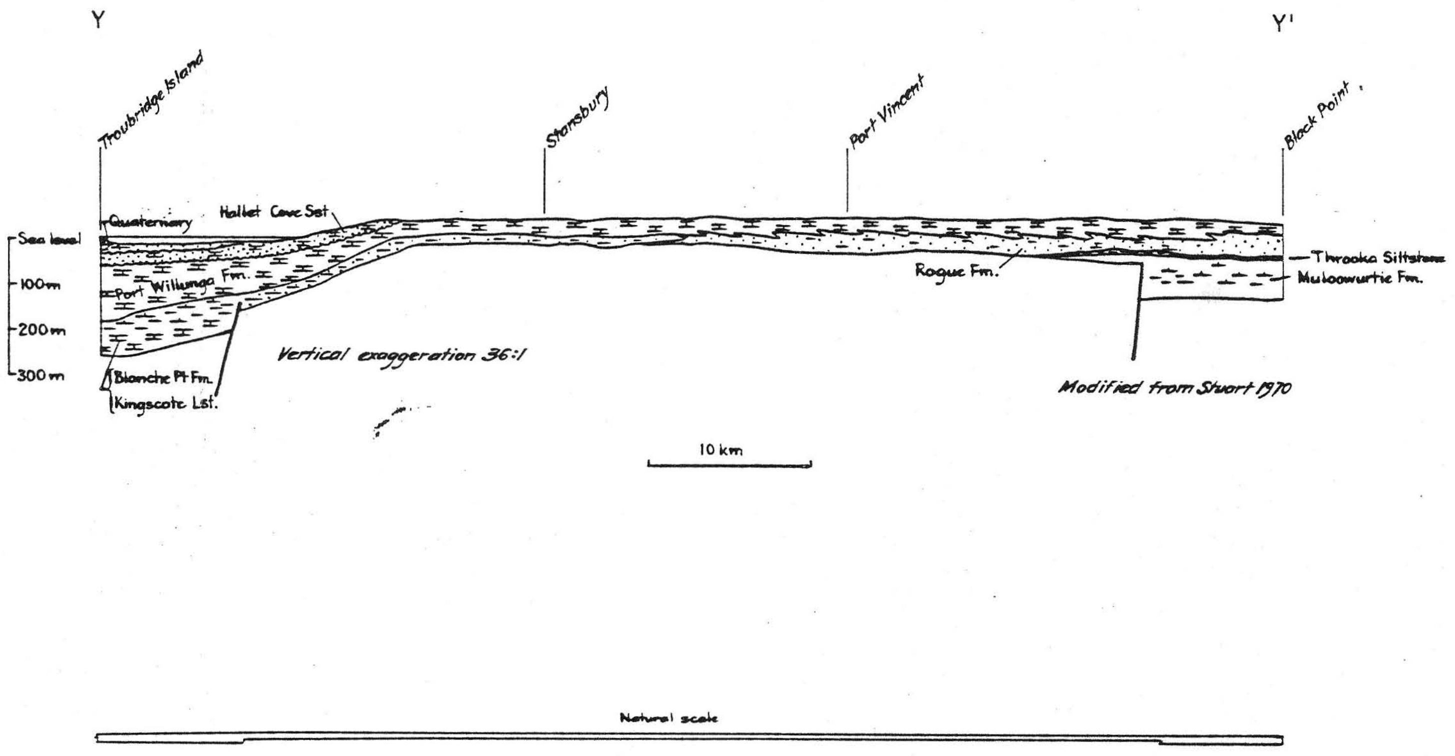


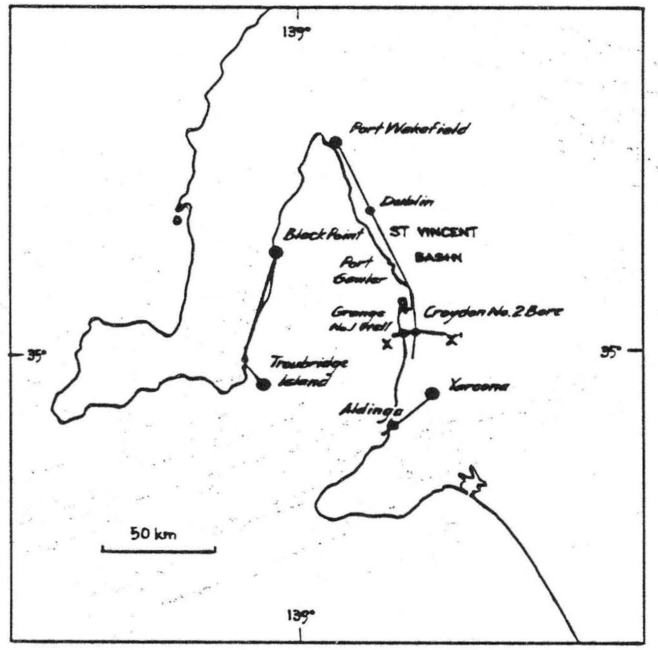

O
O'
Nerita 1
Snail 1
Konkon 1
Toolka 1
Bass 1
Durroon 1
Sea level
500 m
1000 m
2000 m
3000 m
TORQUAY GROUP
Jan Juc Fm.
Demon Bluff Fm.
Eastern View Fm.
KING ISLAND – MORNINGTON HIGH
TORQUAY – GROUP
Demon Bluff Fm
Eastern View Formation
Vertical exaggeration 50:1
Modified from Abele et al. 1976
Natural scale
P
P'
Bass 3
Bass 1
Bass 2
Sea level
500 m
1000 m
2000 m
2500 m
TORQUAY GROUP
Demon Bluff Fm.
Eastern View Fm.
Vertical exaggeration 50:1
Natural scale
Q
Q'
Warragul
MORWELL ANTICLINE
Morwell
Rosedale
BARRACOUTA ANTICLINE
Merriman 1
Dolphin 1
Bream 2
Gurnard 1
Kingfish 1
Hapuku 1
200 m
Sea level
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
Thorpdale Volcanics
Morwell Yallourn Fm.
Boisdale, Jeremy Point Tambo River Formations
Pliocene to Recent
Gippsland Limestone
Traralgon Fm.
Gippsland Limestone
Lakes Entrance Fm.
Lakes Entrance Formation
Yarram Fm.
LATROBE GROUP
Gurnard Fm.
Vertical exaggeration 50:1
Modified from James & Evans 1971, Holdgate 1987
Natural scale
R
R'
Groper 2
Tarra 1
Kingfish 1
Halibut 1
Flounder 1
Flathead 1
Sea level
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
Pliocene to Recent
Gippsland Limestone
Flounder Fm.
Lakes Entrance Fm.
Gurnard Fm.
LATROBE GROUP
Vertical exaggeration 50:1
Natural scale
144°
150°
Q Warragul
Rosedale
R' Flathead 1
Morwell
Merriman
Bream 2
Halibut 1
Dolphin
Tarra 1
Q' Hapuku 1
Kingfish 1
GIPPSLAND BASIN
R Groper 2
Gurnard 1
O Nerita 1
Snail 1
Konkon 1
Toolka 1
Bass 1
P' Bass 2
P Bass 3
40°
BASS BASIN
Durroon 1
O'
100 km
S
S'
Challenger 1
Warnbro 1
Gages Road 1
Rottnest Bore
Kings Park 2
Sea level
500 m
1000 m
Coastal limestone
Wadjemup Fm.
Kings Park Fm.
Late Miocene to Quaternary
Kings Park Fm.
Shark Bay Fm.
Porpoise Bay Fm.
Challenger Fm.
Vertical exaggeration 50:1
Modified from Quilty 1974, 1978
Natural scale
116°
PERTH BASIN
S'
Kings Park
Gages Road 1
32°
Warnbro 1
Rottnest Bore
Challenger 1
S
100 km
50
0
50 km
T
T'
Sandy Cape 1A
Wreck Island
Sea level
500 m
Late Miocene to Recent
Miocene
Vertical exaggeration 50:1
Natural scale
U
U'
Wreck Island
Capricorn 1A
Aquarius 1
Sea level
500 m
1000 m
1500 m
2000 m
2500 m
Late Miocene to Recent
Oligocene? to Miocene
Late Cretaceous to Oligocene
Vertical exaggeration 50:1
Natural scale
150°
CAPRICORN BASIN
Capricornia 1A
U'
Aquarius 1
U
T'
Wreck Island
24°
T
Sandy Cape 1A
100 km











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