PALAEOGEOGRAPHY 19

AUSTRALIA

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ONSHORE SEDIMENTARY & PETROLEUM GEOLOGY

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PHANEROZOIC PALÆOGEOGRAPHIC MAPS OF AUSTRALIA PROJECT

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CONTENTS

SUMMARY

Australian environmental reconstructions have been prepared for seven Permian time slices, as part of the Phanerozoic Palæogeographic Maps of Australia Project, funded jointly by the Bureau of Mineral Resources and the Petroleum division of the Australian Mineral Industry Research Association (APIRA). The maps were compiled from well and outcrop information for both onshore and offshore Australia. Correlation was mainly based on palynological zonation, supplemented by faunal palæontology and isotopic dating. The time scale used was that of Harland & others (1982).

Permian sediments were deposited in over two dozen basins distributed across the continent, at a time when it was part of eastern Gondwana and bordered on most sides by other land masses. The basins on the western and northern Australian margins developed in extensional regimes that may have been related to the rifting of some continental blocks from the nearby Gondwanan margin. The evolution of many of the basins in central and eastern Australia are also related to stresses generated along the continental margin. The Sydney-Bowen Basin was initiated in the Early Permian by backarc extension or transtension, and was later affected by compressional or transpressional tectonism. A change in relative plate motions on the eastern Australian margin in the latest Carboniferous or Early Permian resulted in a large double orocline in the New England Orogen and the migration eastwards of the southern portion of its magmatic arc. Although most igneous intrusive and extrusive activity took place in eastern Australia, there was some in other areas, such as the extension-related intrusives of the Carnarvon and Canning Basins.

The changing pattern of environments was controlled by sea level, tectonic regime, global climate, and the continent's palæogeographic location in high southerly latitudes. Glaciation affecting large areas was at its climax at the start of the Permian, but ended rapidly. There was a brief return of local glaciation in the mid-Permian. Despite global warming, the climate did not become warmer than cold temperate, except in the Tethys-facing northwestern basins. Marine onlap peaked in the earliest Permian, and then showed a general decline. The sea level trend in the earliest Permian, except for the Sydney - Bowen Basin, departed markedly from the global trend, due to isostatic depression of the crust by the nearby large ice caps. Volcanism was also greatest in the early Permian, then declined in the mid-Permian, to be followed later by a resurgence. Most of Australia's black coal was formed in this Period, strikingly most of it in just two interludes, and particularly in the Late Permian.

FOREWORD

Palæogeographic maps are one of the most widely used techniques by which geological data are summarised. They are commonly employed by research and teaching institutions as a method for presenting concepts on the geological evolution of a region, and are widely used by the petroleum and minerals industry as a aid to exploration. Also, they are used by both government and industry as a basis for the broadscale assessment of undiscovered resources. Despite this importance, there has been no comprehensive series of Phanerozoic palæogeographic maps for Australia as a whole. To fill this gap, a palæogeographic project was initiated in 1984 within the Division of Continental Geology of the Bureau of Mineral Resources, Geology and Geophysics (BMR), though drawing on the expertise in other sections of the Bureau, particularly the compilation and drafting skills in the Cartographic Services Unit. In addition, industry support for this project was sought through the Australian Mineral Industry Research Association (AMIRA). A total of 14 companies agreed to provide financial support through AMIRA, thus enabling us to take on extra staff for this project. The direct involvement of the exploration industry has also provided geoscientific input into the project from many company geologists with specialist knowledge of particular areas. Additional vital input has been provided by geoscientists in the State and Territory Geological Surveys, and the universities. We have endeavoured to summarise the wealth of knowledge from these various organisations, individual geologists, and published and unpublished information, in the best possible way, but of course it is not always feasible to get all geologists to agree on how the data should be interpreted. Therefore we have, where feasible, clearly separated facts from interpretation, thus leaving the map user not only with a clear indication of what our interpretations are based on, but also giving the user the opportunity to make new interpretations based on existing data.

The intention from the start of the project has been to produce a series of maps which together summarise the Phanerozoic palæogeographic history of Australia, with one or more authors reponsible for each Period. To minimize the length of time taken to release information to the public, maps for a particular Period will be published as soon as they become available, but the final product of the project will be an integrated series of Phanerozoic maps, each with a common legend, while still allowing authors to place their own interpretation(s) on the data. For each Period the same approach has been taken. This consists in every case of a series of discrete steps which clearly document both the data and the reasons why a particular interpretation has been favored. The various steps involved in the preparation of the maps were as follows: -

1. Compilation of information

Inevitably, this was one of the most protracted phases of the project, requiring the perusal and summarisation of many publications, and the preparation of a comprehensive bibliography. For the most part the data used are in the public domain, but where previously confidential information was released to the project, then this too has been incorporated into our data base. Well completion reports were consulted wherever possible, and a summary of subsurface data prepared.

2. Detailed stratigraphic data columns

The purpose in compiling stratigraphic data columns was to summarise the detailed stratigraphic information for each basin in a uniform manner. Rather than trying to compile the maximum number of stratigraphic columns possible, this phase of the project was aimed at using the minimum number of columns required to characterise the stratigraphy of a basin as well as the continent as a whole. Two types of information were compiled for each column: basic data and interpretive criteria. The basic data compiled included the name and location of the section, name of formation, thickness, grain size, lithology, sedimentary structures, fossil assemblages, and biochronological age.

The interpretive criteria compiled included depositional environment, provenance, tectonic environment, intensity of orogenesis, sea level change, energy level of deposition (quiescent to vigorous), and palæocurrent directions.

Intervals or "time slices", rather than "snap shots", were used as the basis for all the palæogeographic maps. The difference in the two approaches is that in the case of the snap shot the palæogeographic map attempts to represent the geography at an instant in time rather than the summation of an interval. Provided that precise correlations are possible for Australia as a whole, the snap shot approach gives far greater precision and a far more accurate representation of the palæogeography than is possible with the time slice approach. However, it suffers from the major disadvantage that data between snap shots are essentially lost. For this reason, and also because of the imprecision of a number of the Phanerozoic time lines, the time slice approach was taken. Ideally, to obtain the greatest possible resolution with the time slices, they should cover the minimum time span that our present knowledge allows. Nevertheless there is a practical limit to the number of time slices possible, and in a number of cases significant but very short-lived highstands and lowstands of relative sea level cannot be shown. Where several rapidly changing environments have succeeded each other in the same area within a time slice, only one can be shown, and where environments in different areas developed at different times, they have to be shown as contemporaneous. These differences between necessarily generalised time slices and snap shots must constantly be borne in mind by users.

3. Summary stratigraphic chart

The stratigraphic units, their thicknesses, and lithologies, from each of the detailed stratigraphic data columns, were compiled into single lithostratigraphic columns, which were assembled to form a summary chart using biochronologic and isotopic ages. The interpreted depositional environments were then added. It should be noted that the biochronology of the different Periods, and of the basins within the same Period, is of variable quality, and some difficulty was also experienced in deciding which time scales to use. The Harland & others (1982) scale was selected because this was the most up-to-date available when the project began, though it was necessary at times to modify the epoch/stage nomenclature for Australia. The summary chart was used not only for inter- and intra-basinal correlations, but also to establish where major time breaks were or where major changes in sedimentation or tectonism took place. These were then used to determine the sedimentologically significant time intervals in each Period. The result is that a summary stratigraphic chart, which includes biochronologic and isotopic time scales, and the selected times slices, is provided for the whole continent for each Phanerozoic Period.

4. Data maps

With the time slices established, it was possible to compile data maps for each at a scale of 1:5 million, summarising the most important sedimentological data. These include areas of outcrop, subcrop (where established by drilling), and inferred subcrop of the rocks within each time slice; well sites, lithology (using the standard symbols already used for the stratigraphic columns), and the presence of such environmentally significant minerals as halite, sulfates, carbonate evaporites (trona, etc.), collophane (phosporites), glauconite, chert, and organic matter. Where available, measured palæocurrent directions are indicated. In addition, spot thicknesses are given. Early in the project the decision was made that these and all other maps would be compiled and drawn using computer-assisted drafing techniques, so that the maps can be readily upgraded in the future as new data become available.

5. Structure map

Maps showing the structural features of each Period were compiled, because major tectonic features were likely to have influenced the sedimentation, and therefore the palæogeography. The Permian structure map shows basinal features (including depocentres) and major structural features (e.g. faults and folds) that were active during the Permian, as well as Permian intrusive and extrusive rocks and areas of metamorphism.

6. Palæogeographic maps

For each Period the final stage is the construction of palæogeographic maps for each of the time slices. Again, lithology is represented by the symbols used on the summary stratigraphic chart and the data maps. Environmental interpretation is indicated by colour, but there is obviously some overlap of these various environments in reality. Inferred palæocurrent directions, submarine fans, ocean floor basalts, and continental basalts are also shown. Control points are not indicated on the palæogeographic maps, but can be discerned by overlaying the palæogeographic onto the corresponding data map.

Inferred, and in some cases, rather speculative tectonic features such as zones of crustal extension, volcanic arcs, subduction zones, directions of subducting, transform margins, and fore-arc basins, are included on some of the maps. At the start of the project, an executive decision was made that palinspastic reconstructions would not be used because of the lack of an accepted set of Phanerozoic reconstructions. However, a small scale reconstruction showing fits of Australia to adjacent continental fragments has been incorporated into the Permian text (see Fig. 5).

Finally, for each Period and for the time slices within that Period, a short text is provided which highlights some important features and discusses some of the shortcomings in the existing data.

In conclusion then, it is our hope that this series of stratigraphic charts, data maps, tectonic maps, palæogeographic maps, and associated text provides a new account of the Phanerozoic history of Australia which is not only comprehensive and informative, but is also a valuable aid in the search for and assessment of our mineral and energy resources.

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The affiliations of some of the above have changed over the duration of the project. Also, in a project of such wide scope, it is impossible to acknowledge everyone with whom we discussed the work, or who rendered some assistance. To those not mentioned we are nevertheless grateful, and hope that they will accept this as a suitable expression of our thanks.

INTRODUCTION

This set of Permian palæogeographic maps is one of a series which together summarises the Phanerozoic evolution of Australia. There have been only a few previous attempts to compile Permian palæogeographic maps for the continent as a whole, for example the generalised maps by Wade (1939), Brown & others (1968), Crowell & Frakes (1971), Blayden (1975), Veevers (1984), and the Early and Late Permian 1:30 000 000 scale maps by Wilford (1983). Preliminary versions of some of the maps presented here have been published by Brakel & Totterdell (1988, 1990, & in press), and parts of the maps dealing with the Northwest Shelf have appeared in simplified form in Yeates & others (1987), and Bradshaw & others (1988). A number of previous Permian palæogeographic compilations have also been done for specific regions, such as Western Australia (Playford & others, 1975a), the Cooper Basin (Thornton, 1978, 1979), Queensland (Day & others, 1983), New South Wales (Degeling & others, 1986), the Sydney Basin (Herbert, 1980), and Tasmania (Banks & Clarke, 1987; Clarke & Forsyth, 1989).

There is considerable interest in the Permian from both an economic and scientific point of view. The Permian is Australia's main source of black coal, which not only provides the lion's share of the nation's energy requirement, but is currently (1989/90) Australia's leading export earner. This coal occurs in all states, except Victoria and the onshore Northern Territory. Economic oil and gas fields have been delineated in Permian rocks in the Cooper Basin and southwestern Bowen Basin, and small gas accumulations have been found in the Bonaparte Basin. Permian coal-bearing

<table>
<tr><th colspan="2">AGE</th><th colspan="2">PRICE (1983)</th><th colspan="3">PRICE (1985)</th></tr>
<tr><td rowspan="14">PERMIAN</td><td rowspan="3">TATARIAN</td><td>UNIT TR1A</td><td></td><td>PP6</td><td></td><td></td></tr>
<tr><td rowspan="3">UPPER STAGE 5</td><td>U5C</td><td rowspan="3">PP5</td><td rowspan="2">PP5.2</td><td rowspan="2"></td></tr>
<tr><td>U5B</td></tr>
<tr><td rowspan="4">KAZANIAN</td><td>U5A</td><td>PP5.1</td><td></td></tr>
<tr><td rowspan="3">LOWER STAGE 5</td><td>L5C</td><td rowspan="3">PP4</td><td>PP4.3</td><td></td></tr>
<tr><td>L5B</td><td>PP4.2</td><td></td></tr>
<tr><td>L5A</td><td>PP4.1</td><td></td></tr>
<tr><td rowspan="2">KUNGURIAN</td><td rowspan="3">UPPER STAGE 4</td><td rowspan="2">U4B</td><td rowspan="4">PP3</td><td rowspan="2">PP3.3</td><td>PP3.3.2</td></tr>
<tr><td>PP3.3.1</td></tr>
<tr><td rowspan="2">ARTINSKIAN</td><td>U4A</td><td>PP3.2</td><td></td></tr>
<tr><td>LOWER STAGE 4</td><td>L4</td><td>PP3.1</td><td></td></tr>
<tr><td rowspan="2">SAKMARIAN</td><td rowspan="2">STAGE 3</td><td>3B</td><td rowspan="2">PP2</td><td>PP2.2</td><td></td></tr>
<tr><td>3A</td><td>PP2.1</td><td></td></tr>
<tr><td>ASSELIAN</td><td>STAGE 2</td><td></td><td>PP1</td><td></td><td></td></tr>
</table>

Figure 1. Price's (1985) recommended palynological interval zones for the Australian Permian, compared to previous usage.

sequences underlying parts of the Surat and Eromanga Basins are source rocks for hydrocarbon plays in the younger cover. In addition, Permian igneous rocks have yielded gold, silver, copper, lead, zinc, tin, wolfram, bismuth, molybdenum, and other metals. From a scientific viewpoint, the climate of Permian Australia, the Early Permian glaciation, and the widespread coal accumulation of the Period, have always claimed major attention internationally. Most of these features and resources are directly related to the Permian palæogeography. Although it is not the intention of these maps to examine in detail the palæogeographic distribution of the mineral and energy resources, the maps obviously provide an opportunity for carrying out such an evaluation, and will be very useful as the basis for exploration models.

CORRELATIONS

The primary biostratigraphic scales used for the main Permian correlation chart are the palynological stages of Price (1983), and the Western Australian palynological stages of Balme (in Kemp & others, 1977). Price & others (1985) have since revised the former scale, but their changes mostly involve renumbering of the stages, and have not yet been used extensively by others (Fig. 1); other changes are the subdivision of upper Stage 4b into two zones, and the merging of upper Stages 5b and 5c because the putative "index" fossil *Microreticulatisporites bitriangularis* is now known to make its first appearance at different times in various basins.

A plethora of faunal zones, often competing, have been set up for various local regions and different faunal groups, and many conflicting correlation schemes have been published for these zones and the stratigraphy. The disageements among faunal palæontologists are such that it was decided to adopt palynological stages as the primary biostratigraphic reference for the main correlation chart, because these are less controversial and seem to be more reliable; they also offer a wider coverage across the continent than the more parochial faunal zones. Palynology does have its own limitations, however, not the least of these being that in some areas palynomorphs are not preserved, or lack sufficient diversity. In such areas, faunal zones can have an important role. A faunal zones chart, explained in detail by Brakel (in preparation), relates the faunas and the various interpretations of different workers to the palynological stages. The zonations applicable to various regions are those of Dickins (1963) and Archbold (1982) for Western Australia, Palmieri (1983), Dickins (1964, 1968), Dear (1972), and McClung (1981a) for the Bowen Basin, Runnegar (1969) for the Sydney Basin, Clarke & Banks (1975) and Clarke & Farmer (1976) for the Tasmania Basin, and Runnegar & McClung (1975) and Runnegar & Campbell (1976) for eastern Australia generally.

Isotopic dating has been confined largely to New South Wales and Queensland. Most of the analyses have been done on plutons in the New England Orogen, but results have also been obtained for adjacent areas, such as northeast Queensland and volcanogenic rocks in the Sydney - Bowen Basin. In Western Australia, mafic intrusives and some possible volcanic rocks intersected in offshore wells in the Canning and Carnarvon basins have been dated (e.g. Reeckmann & Mebberson, 1984). In addition, a kimberlitic dyke and breccia pipe 180 km NNE of Broken Hill has yielded 260-264 Ma ages by Rb-Sr and fission track methods (Gleadow & Edwards, 1978). The bulk of the isotopic dates are K-Ar ages, with some Rb-Sr, fission track, Nd-Sm, and Ar-Ar ages. Where the same pluton has been dated by both K-Ar and Rb-Sr methods, the latter are always significantly older, commonly by some tens of millions of years. In such cases, the Rb-Sr age is interpreted as the date of emplacement of the intrusion, while the K-Ar number records the date of cooling below the blocking temperature of white mica either after the intrusion, or after a later heating event. What is also uncertain is whether K-Ar isotopic systems reset by heating have been completely reset, thus recording the actual date of the heating event, or have only been partially reset to give an apparent age intermediate between emplacement and later heating. This double ambiguity afflicts all K-Ar dates obtained from plutons, posing a serious interpretation difficulty for the palæogeographic maps. In general, we have assumed that these dates represent either cooling or reheating, and probably indicate times of elevated topography. The affected areas are portrayed on the maps as erosional.

The ages of the upper or lower boundaries of many stratigraphic units are poorly controlled or unknown, and are shown on the summary stratigraphic chart by "?". Where the extent of a particular unit into a particular time slice is uncertain, the widest range of reasonable possibilities is generally shown on the chart. A few units have no age control at all, and a best estimate of age based on geological reasoning has been used to place them. An example of poor age control is the section in the Duck Bay 1 bore in eastern Victoria (not a primary control point and not shown on the stratigraphic chart), which is an Early Permian (Stage 3 or younger) possibly deltaic - near marine sequence (Bowen & Thomas, 1976). These deposits seemed to fit best into Time Slice 2, possibly recording a post-glacial rise in sea level, and accordingly they have influenced the palæogeographic interpretation on map P2 for that region. An example of an occurrence which may not even be Permian is the 174 metres of possible glacial deposits intersected in the Burketown 1 bore. These beds have failed to produce any fossils and are thus undated, but the lithology suggests a correlation with the earliest Permian glacial event (Burgess, 1984), and they have been tentatively assigned to Time Slice 1. Other workers, however, have assigned them to the Cambrian, based on the underlying dolomite, which may be a correlate of the Georgina Basin sequence (Ingram, 1973a).

The boundaries of the Australian Permian have long been debated. In Australia, the start of the period was a time of glaciation, with the palæopole being located in a broad band west of Tasmania (Embleton, 1973; McElhinny, 1973; Klootwijk & Giddings, 1988). As a result, the biota were largely endemic, and are difficult to correlate with those of Europe, where the System and Period were defined. The end of the Period occurred at a time of low sea level, when terrestrial sequences were being deposited, with few exceptions, on all the continents. The lack of marine fauna at this level again hinders correlation with the outside world.

No international boundary stratotype for the base of the Permian has yet been chosen. The Permo-Carboniferous boundary in Australia has traditionally been placed at the first appearance of either the Glossopteris flora or the Eurydesma fauna. There are however some ambiguous localities from Gondwana, where the highest occurrences of the typically Carboniferous rhacopterid flora overlie the first Glossopteris or first

Eurydesma occurrences, suggesting that the rhacopterid - glossopterid boundary may be somewhat time-transgressive. Palynologically, positions that have been suggested for the base of the Permian are the base of Stage 1 (Helby, 1969), now no longer advocated; the base of Stage 2 (Evans, 1969; Archbold, 1982; Foster, 1983b); a level within Stage 2 (E. Truswell, pers. comm.); the base of Unit III / Stage 3a (Kemp & others, 1977; Balme, 1980; Cooper, 1981); and the boundary between Stages 3a and "3a-3b" / Unit III (Powis, 1984). Comments we have solicited from around Australia indicate that the bases of Stages 2 and 3a each have their strong proponents. Those in favor of the base of Stage 3a position point to an increase in the abundance and diversity of gymnosperm pollen at this level in Gondwana, comparable in magnitude to similar changes in microfloras at the base of the Permian on other continents. Others favoring the base of Stage 2 argue that because of Gondwana's circumpolar position, this change in diversity was delayed here until the climate ameliorated. We have chosen the latter, taking into account the practical consideration that some Stage 2 units, such as the Bacchus Marsh Formation (Victoria) and the Paterson Formation (Officer Basin, W.A.), regarded as Permian on most maps and by most geologists, would then appear on the summary stratigraphic chart and maps where most users would expect to find them. One of the reasons for selecting the Stage 2 interval as a time slice was to bracket the area of disagreement, so that those who prefer to regard it as latest Carboniferous can relabel it as such, without any other changes being necessary to the maps.

The Permo-Triassic boundary has also been the subject of some dispute. Most workers place it between the Tatarian and Griesbachian stages of the northern hemisphere, and that is the position we have followed. The absence of a marine section at this level in Perm, U.S.S.R., and the scarcity of contemporaneous marine sections elsewhere in the world, mean however, that correlations usually rely on palynology. In Australia, this boundary is identified as the top of the *Protohaploxypinus reticulatus* ("Tr1a") zone (Balme, 1969; Kemp & others, 1977) and its equivalents. Waterhouse (1976), however, would extend the Permian to the top of the Griesbachian, and this usage has been followed in recent publications of the Geological Survey of Queensland, such as Foster (1979) and Day & others (1983), with the result that their "Middle Permian" includes the Late Permian of other workers.

At an early stage in the Australian Palæogeographic Maps Project, a decision was made to use the time scale of Harland & others (1982) for all periods, because this was then the most up-to-date one available. Inevitably, other time scales have since been published, but by the time they appeared, it was no longer practicable to change the scale of our stratigraphic chart, despite misgivings we had by then about some aspects of the Harland & others scale. Thus the following numerical dates have been used: base of Permian (Asselian) - 286 Ma; base of Sakmarian - 277 Ma; base of Artinskian - 268 Ma; base of Kungurian - 263 Ma; base of Kazanian - 258 Ma; base of Tatarian - 253 Ma; and top of Permian - 248 Ma. A scale proposed by Forster & Warrington (1985) gives the ages of these boundaries respectively as 290, 290, 280, 270, 260, 255, and 250 Ma (they did not recognise the Asselian as separate from the Sakmarian, and extended the latter down to the base of the Permian). Note that the two middle Permian epochs have been doubled in length. A 10- million-year length for the Artinskian would fit our own data better, because on the present chart many units such as the Wooramel Group, Greta Coal Measures, and the Fauna II biozone have to be forced into unrealistically short spans of time.

De Souza (1982) and Forster & Warrington (1985) increase the age estimate of the base of the Permian to 290 Ma, and Jones (1988) takes it further to 295 Ma. Indeed, some workers, such as Lippolt & Hess (1985) prefer a 300 Ma age. The 295 Ma figure of Jones (1988) agrees with the date of 296±6 Ma calculated by Carr & others (1984) using a linear regression model of isotopic ages (excluding glauconite dates) fitted on biostratigraphic data. Thus the consensus of opinion seems to be shifting in the direction of an older Permian base.

At the other end of the Permian, there is a corresponding trend towards an older Permian top. Young dates, such as the 236±9 Ma of Carr & others (1984), are being increasingly questioned. Hellman & Lippolt (1981) and Forster & Warrington (1985) advocate a 250 Ma age. Most recently, a highly precise U-Pb zircon age of 256±4 Ma, obtained by Gulson & others (1990) from a tuff close to the top of the Newcastle Coal Measures, suggests an even older age for the boundary of perhaps 255 Ma. Another less certain U-Pb zircon date of 266±0.4 Ma, from a tuff near the middle of the Tomago Coal Measures, implies that an even more drastic revision of the ages of the Tatarian-Kazanian and some lower epoch boundaries may be necessary. These latest results are discordant with K-Ar dates of 253±5 Ma from latite flows near the base of the Illawarra Coal Measures (Facer & Carr, 1979), and 244±7 Ma from a tuff in the Kaloola Member, well below the top of the Permian in the Bowen Basin (Webb & McDougall, 1967; Green & Webb, 1974), on which the relevant part of the present summary stratigraphic chart was based. Clearly, K-Ar results have to be regarded as minimum ages only in most cases.

The European stage names used by Harland & others (1982) have been used on our chart also, because Australian sequences are most commonly referred to them (less commonly to the Pakistani stages). An exception is the Ufimian, which is difficult to recognise in Australia and has generally been included with the Kazanian. The local Tasmanian stage names of Clarke & Farmer (1976) have not been applied on the mainland, except in South Australia. Significant disadvantages of the latter scheme are

TABLE 1

Permian time slices (absolute ages based on the time scale of Harland & others, 1982)

No.	*Age (Ma)*	*International Age*
P1	286-277	Asselian
P2	277-ca.271	early-middle Sakmarian
P3	ca.271-266	late Sakmarian-middle Artinskian
P4	266-258	middle Artinskian-Kungurian
P5	258-ca.256	early Kazanian
P6	ca.256-250	middle Kazanian-middle Tatarian
P7	250-248	late Tatarian

that the Lymingtonian stage embraces a wide interval from the late Artinskian to the Tatarian; the non-marine top of the Permian is apparently not included; and the Tasmanian Late Permian palynofloras are so impoverished (Calver & others, 1984) as to render them unhelpful for correlation with the rest of the continent.

The summary stratigraphic chart is based on columns for 52 areas, and also includes isotopic dates for intrusives in the New England, northeastern Queensland, and southeastern Queensland regions. Seven time slices were delineated, varying in length from 9 m.y. (Permian 1) to about 1.7 m.y. (Permian 5) (Table 1). For the most part, the boundaries of the time slices are based on the presence of significant breaks or changes in sedimentation. The Period is divisible into three major intervals: Permian 1-3, characterised by greater than average non-marine sedimentation; Permian 4-5, with above average marine deposition; and Permian 6-7, which saw the re-assertion of a long-term progradational trend. The Permian 1-2 boundary is the alternative position for the base of the Permian at the base of Stage 3a, advocated by several workers, while the Permian 2-3 boundary lies at the top of Stage 3a and corresponds to depositional changes in some local areas. The short Permian 5 interval marks a major transgression following tectonism and a hiatus in much of eastern Australia. Permian 7 represents the culmination of the Late Permian progradation, when very little marine deposition was taking place. The continental time slice division is necessarily a compromise in places, and as expected it is not the most suitable for some particular basins; for example, Banks & Clarke (1987) selected different time intervals for Tasmania, and Permian 3 covers a variety of events in the Carnarvon Basin (shallow marine, subaerial erosion, marine transgression, delta construction, and shallow marine again), only one of which can be shown on the map.

TECTONICS

The depositional areas and structural elements that were active during the Permian are shown on the Permian structure map, and the timing of both deposition and deformation is indicated in terms of the time slices used for the Permian palæogeographic maps. Basins are classified as intracratonic, marginal (or back-arc), or polyhistory extensional/foreland basins, the latter category referring specifically to the Sydney-Bowen Basin. An additional category is provided for parts of the New England Orogen that contain scattered areas, some only fault slivers, of Permian sediments; this category includes small depositional basins and erosional remnants of formerly more extensive deposits. Also shown on the map are Permian intrusive and extrusive rocks, and ultramafic bodies. Structural features include faults (the nature of which is indicated where known), folds, depocentre axes and trend lines. Areas which have undergone metamorphism during the Permian are also indicated.

The basin classifications used are described in Totterdell (1990), from which this Tectonics section is derived.

NORTHERN AND WESTERN AUSTRALIA

Arafura Basin

Early Permian (Stage 2) sediments have been intersected in two wells in the Goulburn Graben of the Palæozoic - Early Mesozoic Arafura Basin (McLennan & others, 1990; Bradshaw & others, 1990), although, on seismic evidence, Permian sediments appear to be more widespread. R.J.H. Loosveld (BMR, pers. comm., 1989) proposed that the graben developed as the result of transtensional movement on northwest-southeast striking bounding faults, possibly in the latest Carboniferous - Early Permian, and suggested that the graben may have been a failed arm of the rift between Australia and Sibumasu* (Metcalfe, 1988 - see Browse Basin section below). This age is supported by a K-Ar date of 293±3 Ma on a dolerite sill in Kulka 1 well. Bradshaw and others (1990) argued that the graben developed later, sometime in the Permian-Triassic, because on seismic evidence, the Cambrian-Carboniferous section appears to be laterally continuous and shows no thickening into the major faults. Alternatively, McLennan and others (1990) proposed that the Carboniferous-Permian sequence in the western part of the Goulburn Graben represents an intracratonic sag phase of basin development following a Late Devonian - Early Carboniferous rifting event.

Bonaparte Basin

The Cambrian-Mesozoic Bonaparte Basin in northwestern Australia contains a thick, probably complete, Permian section. During the Permian, the Petrel Sub-basin was the major depocentre of the basin; Mory (1988) suggested that the Permian-Carboniferous succession was the result of a reactivation of rifting along the northwest oriented Petrel Sub-basin. In the Late Carboniferous-Early Permian, subsidence and faulting took place in the Moogarooga Depression and Burt Range Syncline. Large normal faults in the eastern part of the basin formed during the Permian (Veevers & Roberts, 1968). Deltaic progradation of the Cape Hay Member of the Late Permian Hyland Bay Formation may have been a result of movement along the Halls Creek Mobile Zone (Bhatia & others, 1984). At the end of the Permian, pre-breakup thermal doming resulted in crustal upwarping and initiation of block faulting, accompanied by a major marine transgression in the Triassic (Brown, 1980).

Browse Basin

Based on seismic and limited drilling evidence, the intracratonic Browse Basin appears to contain a thick succession (up to 4000 m) of Carboniferous-Permian sediments; the basin developed during an extensional phase at the end of the Carboniferous (Allen & others, 1978), termed the 'infra-rift' stage by Veevers (1984). This phase is possibly related to the break-up of Australia and Sibumasu, which is believed by some authors to have occurred in the late Early Permian (Metcalfe, 1988). The timing of break-up

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*A terrane composed of the Shan states of Burma, northwestern Thailand, peninsula Burma and Thailand, western Malaya, and northwestern Sumatra.

is constrained by the presence in parts of Sibumasu of Early Permian glacial-marine sediments and cold-water faunas with affinities to northwestern Australia, and middle Permian warm water Tethyan faunas (Archbold & others, 1982; Metcalfe, 1988). A further extensional tectonic regime appears to have been initiated in the Late Permian. Powell (1976a) considered that many of the structural trends which were active throughout the Mesozoic were initiated during a block faulting phase at the end of the Permian. The northwestern margin of the Scott Plateau (the subsided, oceanward margin of the basin) may have been uplifted at this time. The Ashmore-Sahul Block and Scott Reef areas however, have a thick Permo-Triassic section suggestive of graben fill (Powell, 1976a).

Canning Basin

The intracratonic Ordovician-Mesozoic Canning Basin contains up to approximately 2800 m of Permian sediments. In the Canning Basin, the Permian was a time of relative tectonic inactivity compared with the Carboniferous. Basin-wide subsidence occurred from the latest Carboniferous until the late Triassic. In the Late Carboniferous-Early Permian, gentle downwarping occurred in the Kidson and Willara Sub-basins. In the Fitzroy Graben, where subsidence was facilitated by limited growth faulting, the major depocentres were the Fitzroy and Gregory Sub-basins. Subsidence on the Broome Arch was less than in adjacent sub-basins (Yeates & others, 1984). The Early Permian was a time of minor faulting, folding and erosion with movement along the Pinnacle and Fenton Fault Systems and the Stansmore Fault, and the development of an unconformity between the Grant Group and the Poole Sandstone (Towner & Gibson, 1983a). During the Late Permian, deposition became confined to the region north of the Fenton Fault System (the Fitzroy Graben). Subsidence here involved limited down-to-basin faulting. In the latest Permian - earliest Triassic there was only minor deformation and erosion, with a low-angle unconformity between the Late Permian and Early Triassic units restricted to the Fitzroy Sub-basin (Yeates & others, 1984). Minor subsidence in the Wallal and Samphire Embayments during the latest Permian may have been related to the pre-breakup extensional regime that existed at this time.

Mafic intrusions of tholeiitic affinity have been intersected in several wells in the northwestern Canning Basin. Although dated as Late Carboniferous to Jurassic they are believed, on fission track, stratigraphic and structural evidence, to be Late Permian to Triassic in age (Reeckmann & Mebberson, 1984). These, and similar intrusions in the northern Carnarvon Basin, are believed to be related to the initiation of extensional tectonics at the beginning of rifting of the northwestern continental margin (Reeckmann & Mebberson, 1984; Gleadow & Duddy, 1984). Alternatively, they may represent the actual breakup of Australia and Sibumasu.

Carnarvon Basin

The Carnarvon Basin is an intracratonic basin on the west coast of Australia containing sediments of Silurian to Tertiary age, including a thick section of Late Carboniferous to Permian rocks. During the Early Permian, uplift of the Precambrian shield area to the east of the Merlinleigh Sub-basin led to the development of an elongate, north-south-trending trough. The northern end of the Darling Fault was possibly active at this time, in the area of the Byro and Coolcalalaya Sub-basins (Moore, Denman & Hocking, 1980). After the deposition of the Callytharra Formation (Permian 3), there was a period of regional uplift and subaerial erosion, with locally important faulting and karst development. Movement took place on faults in the area of the Carrandibby Inlier during the deposition of the Wooramel Group (van de Graaff & others, 1977). Relative uplift of basin margins and adjacent source areas took place intermittently from the late Early Permian to the Late Permian during deposition of the Byro and Kennedy Groups (Moore & others, 1980a,b). During deposition of the Kennedy Group, the rate of basin subsidence lessened. There was syndepositional movement (down to the east) on parts of the Kennedy Fault System during this period (Hocking & others, 1987).

In the northern offshore section of the basin, there was mid-Late Permian faulting on the Sholl Island and Mermaid Faults (Kopsen & McGann, 1985). In the Exmouth Plateau area, seismic studies indicate the presence of a 3000 m thick Permian to mid-Jurassic section. A period of gentle folding, block faulting and erosion took place in the Late Permian, coinciding with the block faulting in the inner Browse Basin, and marking the beginning of Gondwanan breakup. The unconformity marking this event is not everywhere apparent, however, and locally the Permian-Triassic boundary is conformable or merely disconformable (Exon & Willcox, 1978).

Perth Basin

The Perth Basin is an intracratonic rift basin in southwestern Australia. According to Marshall and Lee (1987), two separate phases of extension occurred in the northern Perth Basin during the Permian. The first phase, during the Early Permian, involved east-west-directed extension on a series of shallow-dipping rotational faults that dip eastward on the Edel Platform. In the early Late Permian (Permian 5-6), rifting took place in the Abrolhos Sub-basin to the west on low-angle east-dipping extensional faults. Rifting appears to have occurred along a roughly north-south axis landward of the present shelf. Basal synrift sediments are presumed to be equivalents of the Wagina Sandstone. Marshall and Lee (1987) suggested that the northern Perth Basin exhibits similarities to regions such as the San Andreas Fault System at the present time, where, in places, extension is accompanied by a substantial component of strike-slip motion, i.e. transtension (see Harding & others, 1985), and further suggest that, for part of its existence, the Darling Fault underwent more of an oblique-slip motion than the usually assumed normal displacement.

There was probably minor movement on the Darling and Urella Faults in the northern Perth Basin during the Early Permian. The Beagle Ridge and Northampton Block were positive features in the Early Permian, but the Beagle Ridge subsided along with the rest of the basin during the late Sakmarian and Artinskian (Playford & others, 1976). In the southern Perth Basin, the Darling Fault was probably active at times during the Permian, but sedimentation is believed to have extended east of the fault (Playford & others, 1976; Backhouse, 1990).

Permian igneous activity in the Perth Basin is limited to the undersaturated alkali volcanics penetrated in Edel 1, which have been dated, using K-Ar on biotite, at 261 ± 5 - 267 ± 5 Ma (Ocean Ventures Pty Ltd, 1972; Le Maitre, 1975). Similar rocks have been found elsewhere in the world (Cape Verde Islands, Canary Islands, and off the coast of Brazil) in extensional tectonic settings on continental margins (Le Maitre, 1975).

Collie and Wilga Basins

The Collie Basin is a small, intracratonic, fault-bounded basin in southwestern Australia. It consists of two sub-basins, the Cardiff and Muja Sub-basins, separated by the fault-bounded Stockton Ridge. During the Early Permian, deposition appears to have been widespread in the region of the Collie Basin and was probably continuous with deposition in the southern Perth Basin (Backhouse & Wilson, 1989; Wilson, 1989). Localised downwarping and minor faulting led to deposition of a thicker section in the Cardiff Sub-basin (Lowry, 1976). In the Late Permian, large, normal faults within and bounding the basin were active, and had a controlling influence on sedimentation, possibly restricting deposition to the Cardiff and Muja Sub-basins (Park, 1982; Lowry, 1976), although Wilson (1989) proposed that the larger depositional area may have persisted. The smaller Wilga Basin, 25 km to the south, probably shares a similar structural history.

Officer Basin

The Officer Basin is a large intracratonic basin in eastern Western Australia and western South Australia. The Permian succession consists of a thin, flat-lying veneer of glacigenic rocks that covers virtually the entire basin (Jackson & van de Graaff, 1981a). There appears to have been very little tectonic activity in the area during the Permian.

SOUTHERN AND CENTRAL AUSTRALIA

Mallabie Depression

Permian sediments have been intersected in only three drillholes in the Mallabie Depression. From this limited evidence, there is no indication of tectonic activity during the Permian.

Polda Basin

The Polda Basin, an elongate, east-west trending trough on the Eyre Peninsula in South Australia, has been the site of periodic sedimentation and mild tectonism since the Middle Proterozoic (Cooper & Gatehouse, 1983). The Permian sediments in the Polda Basin may represent a downfaulted remnant of a once more extensive deposit of glacial and glacially-derived sediments, although Cooper and Gatehouse (1983) suggested that sediments were deposited in the trough during periods of maximum tectonic instability and were subsequently preserved.

Troubridge Basin

The Troubridge Basin in southeastern South Australia contains a thin but extensive succession of Early Permian glacigene sediments. Foster (1974) considered that the sediments were deposited in graben structures formed by syndepositional faulting. This fault movement, particularly relative uplift during deglaciation, led to a rejuvenation of erosion and an increase in sedimentation rates. Some workers (e.g. McGowran, 1973) have suggested that this tectonic activity was related to initial rifting between Australia and Antarctica.

Arckaringa Basin

The Arckaringa Basin is an arcuate, Permian intracratonic basin in central South Australia. During the Late Carboniferous - Early Permian, reactivation of older faults led to the resumption of sedimentation in the Boorthanna and Tallaringa grabens, and the development of the Wallira and Phillipson Troughs and the broad central northern depression. The Coober Pedy - Mount Woods trend, the Mabel Creek High and the Peake and Denison Ranges became positive topographic features providing sediment to the basin. Faulting continued through the earliest Permian glacial and post-glacial periods and may have been responsible for the generation of turbidity currents which deposited much of the upper Boorthanna Formation (Townsend, 1976). The overlying Stuart Range Formation and Mount Toondina beds appear to have been deposited under much quieter tectonic conditions.

The Mulgathing Trough, to the south of the Arckaringa Basin, is a narrow, fault-bounded trough closely resembling the Wallira Trough (Nelson, 1976). It contains up to 500 m of presumed Permian sediments.

Pedirka Basin

The Pedirka Basin is an intracratonic basin north of the Arckaringa Basin, in central Australia. The basin can be divided into western and eastern sub-basins along the McDills Trend, a roughly northeasterly-trending pattern of gravity anomalies. In South Australia the McDills Trend runs northwesterly, and appears to be associated with the Peake and Denison Ranges trend. Faults are generally aligned NNE/SSW and folding is relatively gentle. The eastern sub-basin contains a much thicker latest Carboniferous-Permian and Triassic section (Youngs, 1976) than the western sub-basin.

Deposition of the glacial Crown Point Formation was followed by a short period of erosion in the early Sakmarian. During the Artinskian, terrestrial sedimentation was accompanied by growth faulting (Youngs, 1976). A phase of Early Permian extensional faulting is evident from seismic data (Moore, 1986). Deposition ceased by the late Artinskian and the basin was affected by a period of Late Permian structuring, as indicated by erosion of the sequence in structurally high positions, and the large time break separating these deposits from the overlying Triassic and Jurassic sediments.

CENTRAL-EASTERN AND NORTHEASTERN AUSTRALIA

Cooper Basin

The intracratonic Cooper Basin, which straddles the South Australia-Queensland border, was initiated in the earliest Permian and contains a thick Permian to Triassic section. The mechanism for the formation of the Cooper Basin is still debated, with views ranging from the widely accepted, dominantly extensional model (Heath, 1989), to one of strike-slip movement and compression (Kuang, 1985). Kantsler and others (1983) proposed that an early phase of extension created a series of half-grabens and that subsequent dextral strike-slip movements controlled Permian structural development. These strike-slip movements can be attributed to an east-west oriented stress regime, probably related to continent-wide intraplate stresses (Middleton & Hunt, 1989). The Cooper Basin can be divided into six major structural zones: the Gidgealpa-Merrimelia-Innamincka (GMI) and Murteree-Nappacoongee (MN) anticlinal trends, the Patchawarra, Nappamerri and Tennapera Troughs, and the extensive but poorly studied northern Cooper Basin.

The GMI and MN anticlinal trends are composed of a number of individual, *en echelon* anticlines, most of which are associated with large, high-angle, normal and reverse faults that were active during Permian deposition (Thornton, 1979; Kantsler & others, 1983). Many of these faults show evidence of structural inversion. For example, structure contour and isopach maps show that there was a change from normal to reverse movement on faults in the Big Lake area between early Gidgealpa Group time and Toolachee Formation time. During this period, basin-wide deformation resulted in the cessation of deposition and relative uplift along the anticlinal trends (Heath, 1989). At the northwestern ends of the GMI and MN trends are the west-northwesterly-oriented anticlinal trends, the Karmona, and Wolgolla and Tickalara Trends (Thornton, 1979).

The anticlinal trends divide the basin into the deep synclinal zones that were the locus of deposition. The Patchawarra Trough roughly parallels the GMI trend and contains up to 900 m of sediment. The Nappamerri Trough, which is also sub-parallel to the GMI trend, is the major depocentre of the basin and contains a sedimentary section well in excess of 1000 m. The Tennapera Trough, along the southern margin of the basin, contains up to approximately 500 m of sediment. The Karmona anticlinal trend divides the basin into northern and southern segments. The southern flank of the Karmona trend is in part fault-controlled with a throw of 500 m at the 'P' Horizon (near top Permian) level (Thornton, 1979). Deposition north of the Karmona trend was much more restricted than in the south. The condensed section in the northern Cooper Basin indicates the presence of a stable, shelf-like margin in the east, with slow but discontinuous sediment accumulation. A substantial hiatus comprising the entire palynological Stage 4 and much of Stage 5 occurs in the northern Cooper Basin

(Senior, 1975).

The GMI trend probably only became a positive feature during deposition of the Patchawarra Formation, as it is covered by a relatively thick layer of Tirrawarra Sandstone. Thickness variations along the GMI trend indicate that fault movement took place during deposition of the Patchawarra Formation (Thornton, 1979). The high degree of parallelism between the 'P' Horizon structure contour map and the Gidgealpa Group isopach map presented by Thornton (1979) is also evidence for structural growth during Gidgealpa Group deposition. This growth was due to both structural movements, and differential compaction of the coal-rich sediments (Thornton, 1979).

Galilee Basin

The Galilee Basin is a thin but extensive Late Carboniferous to Middle Triassic intracratonic basin which covers an area of about 230 000 km^2 in central Queensland. It is continuous with the Bowen Basin across the Springsure Shelf and Nebine Ridge and is probably continuous with the Cooper Basin across the Canaway Ridge. Structural evolution of the Galilee Basin was controlled largely by northeasterly-trending faults and lineaments in Early Palæozoic rocks of the Thomson Orogen (e.g. Cork Fault, Wetherby Structure, Beryl Ridge, and Pleasant Creek Arch) (Hawkins, 1978).

The Cork Fault - Wetherby Structure in the western Galilee Basin (Lovelle Depression) forms an important tectonic boundary between the Precambrian Mount Isa Inlier and the Palæozoic Thomson Orogen, coinciding with abrupt changes in magnetic and gravity patterns between the two provinces (Murray & others, 1989b). In the northern part of the Lovelle Depression, deposition was largely controlled by movement on the reactivated Cork Fault in the Early Permian (Permian 2-3), and then again in the Late Permian (Hawkins & Harrison, 1978). The Koburra Trough in the eastern part of the basin was initiated in the Late Carboniferous by reactivation of basement faults and accompanying subsidence. The mid-Carboniferous orogeny which affected the Drummond Basin exerted a controlling influence on the north-northwesterly orientation of the Koburra Trough (Hawkins, 1978). The Koburra Trough and Lovelle Depression were the principle depocentres in the Galilee Basin during the Permian. Deposition was more or less continuous from the Late Carboniferous to the middle Permian (Permian 3). The basin then experienced a prolonged period of non-deposition and/or gentle uplift and erosion before deposition recommenced in the Late Permian (as in the northern Cooper Basin). North-northeasterly-trending folds in the southern Galilee Basin are probably an expression of basement structures, which continued to grow intermittently from the Carboniferous to the Cretaceous (Exon & others, 1972).

Northern Queensland Basins and Coastal Ranges Igneous Province

The Olive River Basin is a small, roughly circular, intracratonic basin in the far north of Queensland. The basin contains a thin succession of Carboniferous and Permian sediments which are overlain by Jurassic-Cretaceous rocks of the Carpentaria Basin. A fault on the eastern side of the basin appears to have controlled deposition during the Permian, however, the Permo-Carboniferous section now has a shallow westerly dip (Wells, 1989b).

Permian rocks crop out in fault blocks in the Mesozoic Laura Basin in the Little River and Normanby River areas, and have been intersected in two petroleum exploration wells. The Permian rocks were subjected to block faulting with some associated tilting before the Jurassic. They are now preserved in graben or half-graben structures (Wells, 1989d).

Mount Mulligan is a fault block of Permian-Triassic coal measures and conglomerates, located approximately 100 km west of Cairns. The nature of the sediments suggests rapid deposition in a small extensional basin (Wells, 1989c).

Carboniferous and Permian volcanics and related granitoids of the Coastal Ranges Igneous Province (Henderson, 1980) are widespread in northern Queensland. Oversby and others (1980) considered that these rocks constitute the surficial expression of a post-orogenic ('transitional') volcano-plutonic province. Bailey and others (1982) and Murray (1986) argued that the volcanic rocks formed at an active, continental margin above a westward-dipping subduction zone. Oversby (1987), however, proposed that they are the product of an extensional tectonic regime. The palæogeographic maps for Permian 1-3 portray a scenario following Scheibner (1976), in which extension took place in the Ayr Volcanic Rift, west of a subduction zone lying off the coast. In the western part of the Province, the Permian magmatism was more mafic and less voluminous than the extensive, Carboniferous felsic ignimbrite dominated magmatism; the Permian rocks range from basalt and andesite, through granodiorite and dacite to rhyolite (Mackenzie, 1987a,b). Mackenzie (1987a) considered the basaltic-andesitic rocks to be typical intra-plate transitional alkaline rocks, genetically unrelated to the more felsic rocks. The Permian magmatism was related to northeast-southwest tension, apparently controlled by dominantly northwesterly-trending faults. Conversely, in the Featherbed Volcanic Field further east, the latest Carboniferous - Early Permian volcanic rocks are more voluminous and more felsic (dominantly rhyolitic ignimbrites and rhyolites) than the earlier Carboniferous volcanic rocks. The Featherbed Volcanics and associated intrusive rocks may be the result of extensional tectonism related to sinistral strike-slip movement on the Palmerville Fault during the Late Carboniferous - Early Permian (Mackenzie, 1990 and pers. comm.). Magmatism probably ceased in the Coastal Ranges Igneous Province by the mid-Permian (Oversby, 1987).

SOUTHEASTERN AUSTRALIA

Oaklands Basin/Ovens Graben and Murray Infrabasins

The Oaklands Basin/Ovens Graben is one of at least nine Palæozoic-Mesozoic infrabasins beneath the Cainozoic Murray Basin. It is an elongate, north-northwest to south-southeast-trending, fault-bounded trough over 200 km long that is located in southern New South Wales and northern Victoria. The northern part of the trough (Oaklands Basin) contains a thick (approximately 900 m) section of Early Permian glacial sediments (Urana Formation), unconformably overlain by the Late Permian

Coorabin Coal Measures (O'Brien, 1986a; Standing Committee on Coalfield Geology of New South Wales, 1978). The southern part of the trough (Ovens Graben) contains a slightly older succession of Early Carboniferous red beds, Late Carboniferous conglomerates, and Late Carboniferous - Early Permian Urana Formation (Holdgate, 1986). In the Ovens Graben, the Urana Formation may thicken slightly towards the eastern boundary faults, indicating some syndepositional fault movement (Holdgate, 1986). During deposition of the coal measures, the Oaklands Basin underwent very slow, intermittent subsidence. The Coorabin Coal Measures are probably an erosional remnant of a once more extensive fluvial deposit, preserved in the Oaklands Basin due to subsidence caused by compaction of the underlying Urana Formation and some minor fault movements (O'Brien, 1989b).

Permo-Carboniferous glacial sediments are preserved in a number of other infrabasins beneath the Murray Basin, including the Paringa Embayment and the Renmark, Tararra, Blantyre, Wentworth, Ivanhoe and Numurkah Troughs. These infrabasins are believed to have formed in the Devonian during late-orogenic tensional deformation (Brown & others, 1988). The Permian sediments preserved in these troughs are erosional remnants of formerly more extensive platform cover deposits (Brown & others, 1988).

A middle Permian age has been determined for the Kayrunnera kimberlitic diatreme in northwestern New South Wales (Edwards & Neef, 1979). A fission-track date on sphene of 264±18 Ma for the age of emplacement of the diatreme agrees closely with a Rb-Sr determination of 260±67 Ma (Gleadow & Edwards, 1978). The emplacement of the diatreme appears to have been controlled by an east-southeasterly trending fault (Edwards & Neef, 1979).

Victoria

Isolated outcrops of Early Permian glacial deposits occur in northeastern, central and western Victoria. In the Bacchus Marsh region, there is evidence of syndepositional fault movement (Bowen & Thomas, 1976), but generally structural information is sparse.

Tasmania Basin

The Tasmania Basin contains a Late Carboniferous - Late Triassic succession of sub-horizontal sediments named the Parmeener Supergroup (Clarke & Banks, 1975; Forsyth & others, 1974). Deposition of much of the Permian succession was concentrated in a north-northwest to south-southeast-trending trough, the axis of which coincides with the older Tamar Fracture System (Banks & Clarke, 1987); the sediment distribution pattern implies some growth faulting along this feature during deposition of the Parmeener Supergroup. The axial region of the trough was sourced by areas to the southwest, northwest and northeast at different times throughout the Permian (Clarke & Forsyth, 1989). A short lived marine incursion in the southeast and central parts of the basin during the Early Bernacchian (palynological Stage 3b) may have been caused by an increased rate of subsidence rather than a eustatic rise of sea level; the only documented Permian faulting in the Tasmania Basin (near Latrobe in northern Tasmania) occurred at this time (Banks & Clarke, 1987). The late Early Permian-early Late Permian (Permian 4-5) appears to have been a time of relative tectonic instability, as the sediments show rapid and frequent facies changes (Clarke & Forsyth, 1989). Possible Late Permian volcanism in the region is indicated by a high proportion of silicic volcanic ash in parts of the Risdon Sandstone south of Hobart. Relative uplift of source areas to the west in the latest Permian is indicated by the encroachment of coarse grained sediments over a low-energy fluvial system (Banks & Clarke, 1987). This coarse detritus may be the first evidence in the Tasmania Basin of foreland folding and thrusting along the palæo-Pacific margin of the Antarctic-Tasmanian sector of Gondwana (Collinson, 1991).

SYDNEY-BOWEN BASIN AND RELATED BASINS

A widely accepted model for the origin of the Sydney-Gunnedah-Bowen basin system is that it is a foreland basin to the New England Orogen (see e.g. Murray, 1985; Fielding & others, 1990). Murray (1985) argued that the Bowen Basin was a retroarc foreland basin, with initial subsidence due, not to loading of the crust by the foreland thrust pile, but to the excess mass of the Early Permian Camboon Volcanic Arc to the east. However, a number of workers (Scheibner, 1973; Harrington, 1982; Korsch, 1982; Harrington & Korsch, 1985b; Ziolkowski & Taylor, 1985; Hammond, 1987; Mallett & others, 1988) have argued that the Sydney-Bowen Basin had an extensional or transtensional origin. Korsch and others (1988b) suggested that a normal extensional model is not compatible with seismic evidence of near vertical bounding faults. They proposed that the basin developed in a transtensional environment, with a significant component of strike-slip movement along the controlling Burunga-Goondiwindi-Mooki Fault System.

Sydney Basin

The Sydney Basin is an Early Permian to Middle Triassic basin on the southeastern coast of Australia. The Permian succession consists of Early Permian volcanics and marine sediments overlain by middle Permian coal measures, Early-Late Permian marine sediments, and Late Permian deltaic to fluvial sediments, including coal measures. The northern margin of the basin is now represented by the Hunter-Mooki Fault System. The western margin is an erosional margin which probably approximates the depositional edge of the basin. To the east, the basin continues out to the edge of the continental shelf. The boundary between the Sydney Basin and the Gunnedah Basin to the northwest has in the past been taken along the Mount Coricudgy Anticline. However, the western Sydney Basin succession has been shown to be continuous across this feature, so its validity as a basin boundary is questionable (West & Bradley, 1986).

The Sydney Basin consists of two dominant structural features: a shelf region which extends along the western and southern margins of the basin; and a trough-and-ridge region which occupies the rest of the basin (Brakel, 1984, 1989a). The shelf region is separated from the rest of the basin by a system of faults and/or monoclines (e.g.

Kurrajong Fault, Lapstone Monocline, Nepean Fault and Nepean Monocline) which acted as a depositional hinge-line. The trough-and-ridge region consists of the Macdonald and Lake Macquarie Troughs separated by the meridional Lochinvar-Kulnura Ridge. Another large, meridional ridge has been identified offshore from seismic studies. In the Hunter Valley in the northern part of the basin, several anticlines, the largest of which are the Lochinvar and Muswellbrook Anticlines, were active during deposition of the Late Permian coal measures (Herbert, 1980).

During the Early Permian there were major changes in the tectonic pattern in northeastern New South Wales. Convergent margin tectonism, which had prevailed since the Devonian, was succeeded by an extensional regime, with intraplate rifting and intracratonic basin development, and widespread volcanism (Korsch 1982; Leitch & others, 1988). Bimodal Early Permian volcanics at the base of the section in both the Sydney and Gunnedah Basins suggest an extensional origin for these basins. Scheibner (1973, 1976) suggested that rifting, with attendant volcanism, took place along what became the Sydney-Bowen Basin during the Late Carboniferous-Early Permian; he termed this rift the Ayr Volcanic Rift. Mallett and others (1988), in comparing the structural development of the Bowen and Sydney Basins, concluded that both basins probably shared a similar tectonic history i.e. initial extension, followed by a sag phase, and culminating in foreland basin development. This view is supported by Murray and others (1989b), who based their conclusions on the presence of the Meandarra Gravity Ridge (Lonsdale, 1965), a 1200 km long gravity feature that runs along the axis of the Sydney-Bowen Basin. The southern (Sydney Basin) part of this anomaly has been interpreted as the result of a large, high density mafic source underlying the basin (Qureshi, 1984). The presence of this mafic body implies that crustal rifting preceded the development of the Sydney Basin. Lohe and McLennan (1989), in a lineament analysis of the Hunter Valley in the northern part of the basin and using the model of Mallett and others (1988), interpreted northwest-southeast-trending lineaments as an expression of basin-margin listric normal faults along which extensional basin formation was initiated, and a northeast-southwest-trending lineament set as evidence of transfer faults. Harrington & Korsch (1979) and Harrington (1989) outlined an alternative tectonic model, in which the basin was initiated as a transform basin, by major dextral strike-slip along the Mooki fault system leading to the development of pull-apart basins and ridges.

From the mid-Permian on, the Sydney Basin began to take on the appearance of a foreland basin (Glen & Beckett, 1989). During the mid-Permian (Permian 3-4), a period of folding and thrust faulting (the Hunter Orogeny) affected the New England Orogen and the northern parts of the Sydney Basin. Thrust faulting along the northeastern margin of the basin was taken up along the Hunter-Mooki Fault System. This tectonism resulted in a regression and the subsequent deposition in the northern part of the basin of terrestrial sediments including coal measures (Greta Coal Measures). In the Late Permian, further episodes of thrust faulting along the Hunter-Mooki Fault System resulted in the deposition of thick coal measures and conglomerates along the northeastern margin of the basin. Tuffs are abundant in the Late Permian Newcastle and Wollombi Coal Measures, and include proximal deposits of volcanic centres located to the northeast and east (Brakel, 1984 , 1989a); some possibly represent the distal deposits of the widespread silicic volcanism in the New England Province. Late Permian shoshonitic volcanic rocks (basalts, basaltic andesites and an andesite) in the southern Sydney Basin have been related to partial melting in the mantle wedge following the cessation of subduction in the Late Carboniferous-Early Permian (Carr, 1985).

Gloucester Basin

The Gloucester Basin (or Trough) is a long, meridional trough in the southern part of the New England Orogen in central eastern New South Wales. The Permian succession unconformably overlies Carboniferous sediments and pyroclastics, and consists of Early Permian volcanic rocks and mainly paralic sediments, overlain by alluvial fan to lower delta plain coal measures and coarse clastics. Deposition in the basin was controlled by syndepositional movement along meridional normal faults (Lennox & Wilcock, 1985). The mid-Permian thrust faulting which affected the New England Orogen and northern Sydney Basin is here represented by a hiatus at the top of the Stroud Volcanics. The Gloucester Basin was probably connected with the Sydney Basin to the south during the late Early Permian (Lennox & Wilcock, 1985).

Gunnedah Basin

The Gunnedah Basin is a Permian-Triassic basin which lies along the western margin of the New England Orogen in eastern Australia, and forms the northern extension of the Sydney Basin. The present eastern margin of the basin is defined by the Hunter-Mooki Fault System. To the north, the succession is continuous with the Taroom Trough (southern Bowen Basin); there is no evidence to support the existence of the Narrabri Structural High, a supposed east-west- trending ridge previously considered to be the northern margin of the basin (Hill, 1986). The Gunnedah Basin section consists of basal felsic and minor mafic volcanics (Boggabri and Gunnedah Volcanics) overlain by fluvial, shallow marine and deltaic sediments. The sedimentary succession above the basal volcanics was deposited in a trough-like feature with an axis trending north-northwesterly. Two prominent highs are present within the Gunnedah Basin: the Boggabri Ridge near the eastern margin of the basin, and the Rocky Glen Ridge near Coonabarabran on the western margin. There are three major depositional centres in the basin; the Maules Creek Sub-basin, which lies to the east of the Boggabri Ridge, and two depocentres in the northwestern and southern parts of the basin, between the Boggabri and Rocky Glen Ridges (Russell, 1981; Hamilton & others, 1984). As with the Sydney Basin, the basal bimodal volcanics could indicate an extensional origin for the Gunnedah Basin (e.g. Korsch, 1982); Hill (1986) suggested that the Maules Creek Sub-basin formed as a result of rifting and that the Boggabri Ridge formed the western margin of the rift basin. McPhie (1984) however, proposed that the Boggabri and Gunnedah Volcanics represent the proximal deposits of a silicic volcanic terrain, and therefore reflect a continuation into the Early Permian of the Late Carboniferous ignimbritic volcanism, and hence the Andean-type convergent margin setting (McPhie, 1987).

McPhie (1984) demonstrated that thrusting on the Hunter-Mooki Fault System near Boggabri is no older than latest Early Permian (late Permian 4), since marine rocks dated as Upper Stage 4 are truncated by it. This post-dates the proposed initial thrusting on the Hunter-Mooki Fault System further south in the Hunter Valley (mid-Early Permian). However, R.J. Korsch (BMR, pers. comm., 1990) considers that the Hunter-Mooki Fault System is a major strike-slip fault with a long history of movement and that the thrusts are the surface expression of flower structures produced by reactivation of the fault.

Werrie Basin

The Werrie Basin is a synclinal structure northwest of the Sydney Basin, which contains a Permian section similar to that of the adjacent Gunnedah Basin. Early Permian volcaniclastic sediments reflect nearby contemporaneous ignimbritic volcanism, attributed to the waning stages of convergent margin, Andean-type tectonics by McPhie (1984). The overlying Werrie Basalt could be related to the extensional tectonics which initiated the Sydney-Bowen Basins (Leitch & others, 1988). Brownlow (1978) suggested that prior to the deposition of the Willow Tree Coal Measures, relative uplift on the Hunter-Mooki Fault System led to erosion of Late Carboniferous felsic volcanics and the subsequent westwards transport of sediment into the Gunnedah and Werrie Basins. McPhie (1984), on the other hand, considered that the Early Permian coal measures clastics of the Gunnedah and Werrie Basin were largely derived from the erosion of the Late Carboniferous volcanic pile to the west, and that any easterly component at this time was a distal and early contribution from the New England area, which did not become a major source of detritus shedding westwards until the Late Permian.

Bowen Basin

The Bowen Basin in central-eastern Queensland contains two main depositional areas: the NNW-SSE trending Denison and Taroom Troughs. The troughs are separated by the Comet Platform, and are bounded to the west by the Anakie Inlier and the Collinsville, Springsure and Roma Shelves, and to the east by the Gogango Overfolded Zone and the Eungella-Cracow Mobile Belt. An intensely deformed region in the northern part of the Taroom Trough east of the Comet Platform is termed the Dawson Fold Zone. The western bounding fault of the Denison Trough is the Merivale Fault.

Murray (1985) argued that almost all features of the Bowen Basin are compatible with, and can be explained by, a retroarc foreland basin model and proposed that the initial downwarping was the result of loading of the crust by the volcanic and plutonic rocks of the adjacent Camboon Volcanic Arc. Recently, however, Hammond (1987) proposed the application of a crustal extension model to explain the early development of the Bowen Basin. Using this model, Mallett and others (1988) presented a three-stage history to describe the tectonic development of the Bowen Basin, based on the work of Ziolkowski and Taylor (1985) and Draper (1985) in the Denison Trough. In the Early Permian, the area underwent a rift phase, with thick half-graben sediments deposited in the Denison Trough, and abundant volcanics in the Taroom and Grantleigh Troughs. Bounding faults had a NNW-SSE orientation, following basement grain. The andesitic volcanics in the eastern part of the basin were the product of the Camboon Volcanic Arc, a major feature coincident with the Devonian-Carboniferous

Connors-Auburn Volcanic Arc (Day & others, 1983). This extensional regime was followed by a period of thermal relaxation, with shallow and marginal marine sedimentation over most of the basin and thick deposits in the Taroom Trough. Compression, with some inversion of half-graben successions, was initiated during the late Early - early Late Permian (Permian 4-5). During the Late Permian, the basin underwent a foreland basin phase, with widespread marine transgression, followed by coal measure sedimentation. Deposition was concentrated in the Taroom Trough. Beginning in the latest Permian, the basin underwent a period of shortening, with reactivation of bounding faults, partial inversion of the basin and the development of new high-angle reverse faults, culminating in the Middle Triassic (Ziolkowski & Taylor, 1985). The Gogango Overfolded Zone on the eastern side of the basin contains westwards directed thrusts and tight folds which are consistently overturned to the west; it has a typical foreland fold-thrust belt geometry (Murray, 1985). Deep seismic reflection data, acquired by the BMR across the Bowen Basin in 1989, show that the sedimentary section is dominated by deformation controlled by thin-skinned thrusting on a series of listric faults that dip to the east. These faults root in a major detachment that also dips to the east and appears to flatten in the ductile zone in the middle crust (Korsch & others, 1990b)

As part of their extensional model for the initial development of the basin, Hammond (1987) and Mallett and others (1988) proposed the existence of a set of northeast-southwest trending transfer faults. These inferred faults divide the basin into domains that are internally consistent with respect to NNW-SSE trending features, but which are significantly different from adjacent domains. A BMR deep seismic line (BMR89.B01) positioned to cross two of the postulated transfer faults showed little evidence to suggest their presence.

As noted above, a number of authors (e.g. Harrington & Korsch (1979, 1985b; Korsch & others, 1988b) have suggested that a significant component of strike-slip movement was involved in the initial development of the Bowen Basin. The results of a deep seismic profile across the southern Bowen Basin (BMR Traverse 14 - Wake-Dyster & others, 1987) appear to indicate that the eastern bounding fault of the Taroom Trough is near vertical; Korsch & others (1988b) therefore suggested that the trough did not develop as a result of pure extension in the plane of the section, but rather that the basin-forming mechanism was oblique extension.

Blair Athol, Wolfang and Related Basins

A number of small basins occur to the west of the Bowen Basin within the Clermont Block. They include the Blair Athol, Wolfang, Clermont, Moorlands and Karin Basins. These basins appear to be on the same trend as the Denison Trough and all, except for the Moorlands Basin, probably developed during the Early Permian extensional phase that initiated half-graben development in the Bowen Basin; the Moorlands Basin contains sediments of Late Permian (Permian 6) age.

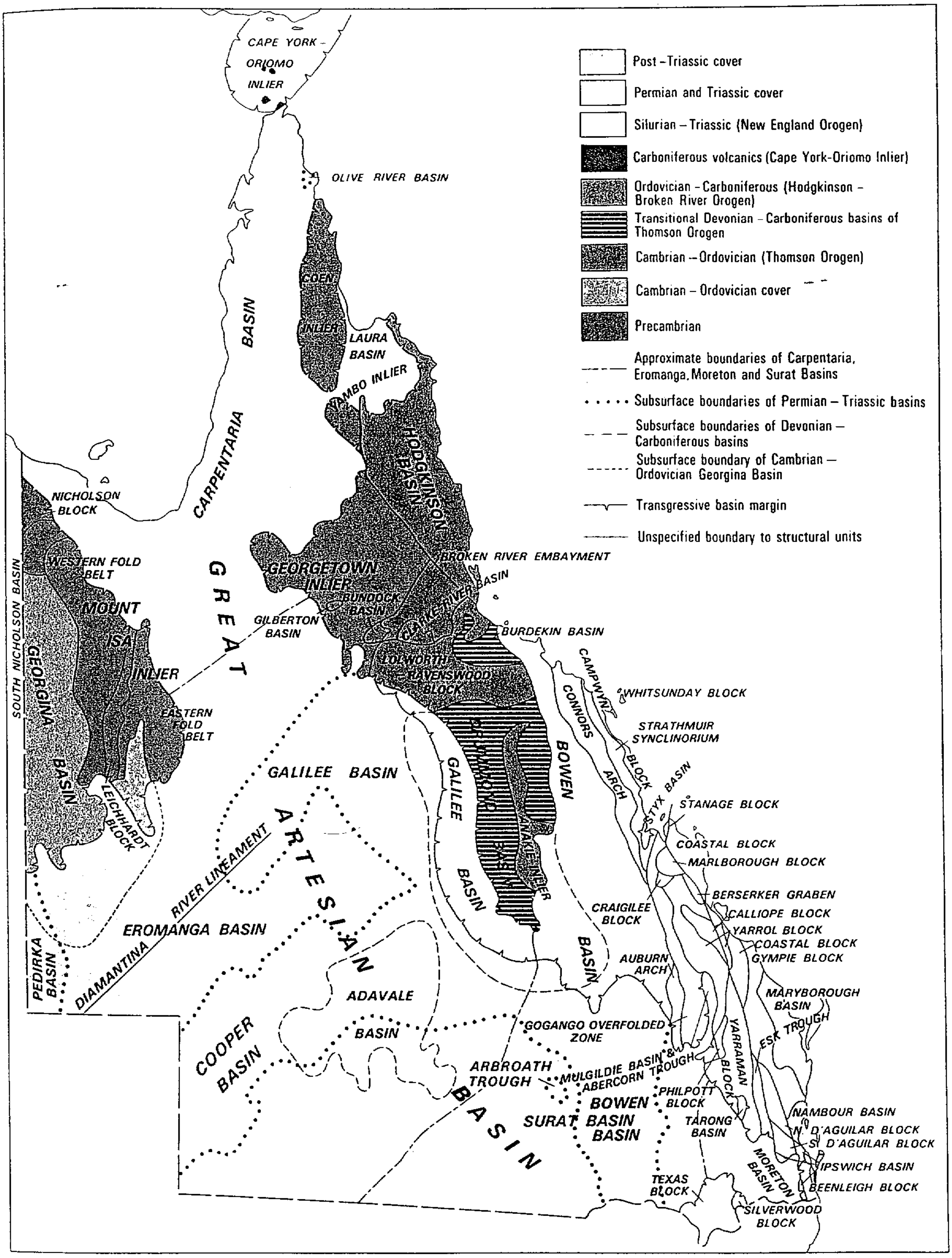

Figure 2. Structural framework of Queensland (from Day & others, 1983).

NEW ENGLAND OROGEN

Yarrol Province

Grantleigh Trough (Gogango Overfolded Zone) and Strathmuir Synclinorium

The Grantleigh Trough developed in the Early Permian along the eastern side of the Camboon Volcanic Arc. It may have formed as a result of rifting and marginal sea development or as a pull-apart basin during major dextral strike-slip faulting (Murray, 1986; Murray & others, 1987); the basin contains deep water turbidites and spilitic pillow lavas similar to ocean floor basalts (Day & others, 1983). The Grantleigh Trough was subjected to deformation from the mid-Permian to the Middle Triassic to form the Gogango Overfolded Zone. The trough underwent compression in the mid-Permian with tight folding along NNW-SSE axes, and regional metamorphism. Deformation was renewed in the Late Permian-Early Triassic with further folding and the development of thrust faults (Kirkegaard & others, 1970; Dear & others, 1971). If the mid-Permian to Middle Triassic evolution of the Bowen Basin is interpreted as the development of a foreland basin, then the Gogango Overfolded Zone represents the associated fold-thrust belt (Murray, 1985).

The Strathmuir Synclinorium contains andesitic volcanic rocks which represent the distal deposits of the Camboon Volcanic Arc. During the mid-Permian, marine sediments were deposited in the southern part of the Strathmuir Synclinorium, which at that time was probably continuous with the Grantleigh Trough. The area was folded in the late Early - early Late Permian into a broad, open synclinal structure, with local, small-scale, tight folding. The southern part of the area underwent further deformation in the Late Permian. The intensity of folding increases towards the Gogango Overfolded Zone (Day & others, 1983).

Yarrol, Marlborough and Coastal Blocks, and Berserker Graben

In the Devonian-Carboniferous, and again in the Early Permian, the Yarrol Block was a fore-arc basin to the Connors-Auburn and Camboon Volcanic Arcs, respectively. Andesitic volcanic rocks which occur in the Early Permian succession in the Yarrol Block (Fig. 2) are related to activity in the nearby arc. The Yarrol Block underwent deformation during the late Early to Late Permian, with open folding along NNW trending axes (e.g. the Yarrol Syncline), and reverse movement on high-angle faults; the intensity of folding increases towards the east. Folding was accompanied by thrusting along the Yarrol Fault System and the emplacement of serpentinites. In the Rockhampton area, folding locally produced dips up to 75°. Deformation was also accompanied by the emplacement of granites. In the Marlborough Block (Fig. 2), a thrust sheet of serpentinite and associated metamorphics was emplaced along part of the Yarrol Fault System during the Late Permian. The Coastal Block (Fig. 2) was regionally metamorphosed and deformed in the late Early Permian. There was high-angle reverse movement on the Boyne River - Tungamull - Broad Sound Fault in the mid-Permian and the Late Permian - Early Triassic (Kirkegaard & others, 1970; Dear & others, 1971; Whitaker & others, 1974; Day & others, 1983). Deformation and serpentinite emplacement during the Permian may have been related to terrane accretion (Brakel & Totterdell, 1988; see also Fergusson & others, 1990).

The Berserker Graben (Fig. 2) contains Early Permian felsic-intermediate volcanics and volcaniclastic sediments. The succession was folded in the Late Permian when there was also major movement on the bounding faults (Kirkegaard & others, 1970; Day & others, 1983).

Granite emplacement in the Yarrol Province probably commenced in the Early Permian (Ridgelands Granodiorite), but the major phase of plutonism was in the Late Permian - Early Triassic (Murray, 1986).

North D'Aguilar Block

The North D'Aguilar Block (Fig. 2) contains metamorphic rocks that are part of a Late Devonian - Early Carboniferous accretionary complex. These rocks were uplifted and cooled in the middle Permian (ca. 260 Ma), at which time the overlying volcanics and coarse clastics were deposited. This uplift is believed to be the result of extensional deformation related to the inception of the Esk Trough immediately to the west (Holcombe & others, 1990; Little & others, 1990).

Gympie Province

The Carboniferous-Permian succession in the Gympie Province shows little evidence of the mid-Late Permian orogenesis which affected the Yarrol Province. Harrington (1983) suggested that the Gympie Province was an exotic terrane, with closer similarities to the Brook Street and Maitai Terranes of New Zealand than with the Yarrol Province; Harrington and Korsch (1985a) suggested that the whole terrane was probably part of a volcanic arc which docked and accreted in the Middle Triassic (235-240 Ma). Murray and others (1989a) and Murray (1990) proposed that the Gympie Province comprises at least three, and possibly up to six, distinct suspect terranes. The basal unit of the Gympie Group, the Highbury Volcanics, contains basaltic-andesitic volcanics. Sivell (1990) described these volcanics as island arc tholeiites that were formed during an early submarine stage of volcanism in an intra-oceanic arc. The volcanics of the Early Permian Amamoor beds and the Cedarton Volcanics, which may represent separate terranes, were generated in continental margin subduction-related settings; they are believed to have been moved to their present position by strike-slip movement along the continental margin (Sivell, 1990).

New England Province

The structural history of the New England Province throughout the Palæozoic has long been the subject of conjecture and debate. The 'consensus' view, as stated by Korsch and others (1988a) and Korsch and others (1990a) is that during the Carboniferous, the New England Province was the site of an east-facing, Andean-type convergent margin, with ignimbritic volcanism in the arc to the west, and fore-arc and accretionary wedge deposits to the east. McPhie (1984) has argued that some waning

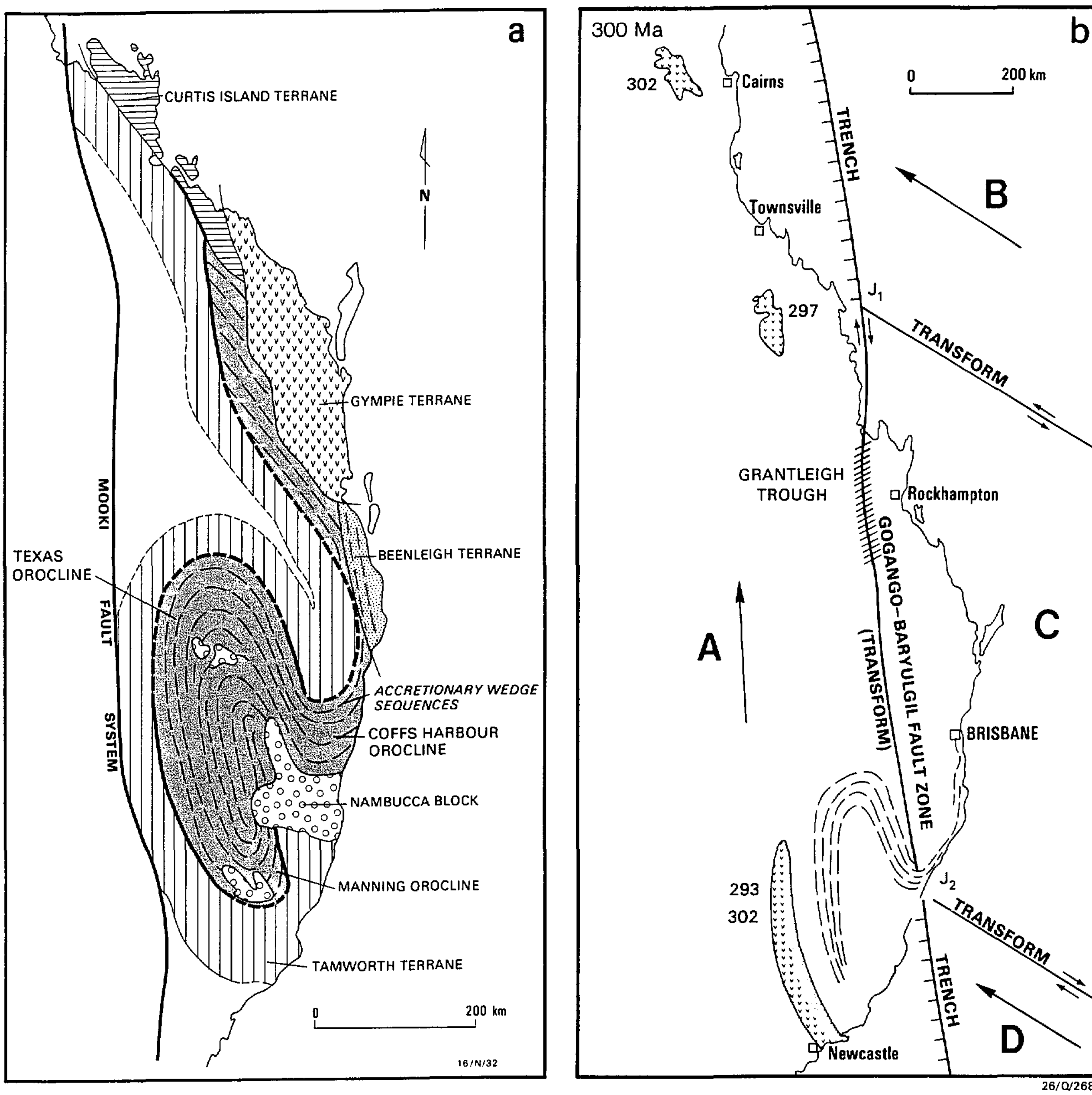

Fig. 3 Orocline models of (a) Korsch & Harrington (1987) and (b) Murray & others (1987). The major difference is in the location of the controlling strike-slip fault zone, which Korsch & Harrington infer to be their Mooki Fault System, whereas Murray & others interpret it to be along their postulated Gogango-Baryulgil transform fault zone (from Korsch & others, 1990).

ignimbritic volcanism continued into the Early Permian. During the Late Carboniferous - Early Permian, there was a change from an oblique convergent margin to a dextral strike-slip margin (Murray & others, 1987; see also Korsch, 1982). Murray and others (1987) proposed that this change was the result of the arrival at the trench of a mid-ocean ridge - transform fault system and subsequent triple junction migration. The Barnard Basin, which includes the Manning Group and sediments of the Nambucca Block, formed in the Early Permian through rifting of the Devonian-Carboniferous convergent margin assemblage (Leitch, 1988). As such, it may represent a marginal or back-arc basin (Scheibner, 1973, 1976), behind a volcanic arc situated outboard of the present continental margin, which is represented by arc volcanics of the Gympie (Queensland) and Brook Street (New Zealand) terranes (Harrington, 1983). Extension in the Barnard Basin may have been sufficient to generate limited oceanic crust, as tholeiitic volcanics of ocean-floor affinity occur (Scheibner & Pearce, 1978; Asthana & Leitch, 1985; Leitch & Asthana, 1985; Leitch, 1988). A consequence of the transcurrent margin was the development of a large orocline in the Early Permian, which increased the overall width of the New England Province. Murray and others (1987) proposed that the change to a dextral transform margin and the subsequent oroclinal bending took place in the Late Carboniferous, approximately 300 Ma; they also suggested that oroclinal bending took place as a result of up to 500 km of dextral movement along their postulated Gogango-Baryulgil Fault Zone (Fig. 3). However, Korsch and Harrington (1985, 1987) argued that deformation and metamorphism of the Nambucca Block, and the deformation of Early Permian sediments in the Texas area in the northern part of the province, are related to the oroclinal bending, which must therefore have taken place in, or later than, the Early Permian. Korsch and Harrington (1987) considered that the controlling strike-slip fault for oroclinal bending was the Mooki Fault System and that movement took place on a crustal detachment on top of the old subduction zone (Fig. 3).

Korsch and Harrington (1981) identified several major deformational episodes in the New England Province, three of which (D2, D3 and D4) occurred during the Permian; D2 and D3 in the Early Permian (c. 290 and 273 Ma) and D4 in the Late Permian (255-250 Ma).

In the Late Carboniferous - Early Permian, the New England Province was intruded by the S-type Hillgrove and Bundarra Plutonic Suites (Fig. 4). Rb-Sr whole rock isochrons of 312±25 Ma (Hensel & others, 1985) and 289±25 Ma (Flood & Shaw, 1977) for the Hillgrove Suite, and 287±10 Ma (Hensel & others, 1985) for the Bundarra Suite probably reflect the age of magma generation (Kleeman, 1988). Kleeman gives the ages of emplacement for the Hillgrove and Bundarra Suites as 293-275 Ma (Cooper & others, 1963; Hensel, 1982; Kleeman, 1975) and 280-270 Ma (Shaw & Flood, 1982) respectively.

Widespread, low-grade, intermediate pressure metamorphism which possibly occurred in the Early Permian (c. 280 Ma), is overprinted by a later (255-250 Ma) metamorphic event (Leitch & McDougall, 1979; Korsch, 1982). Low pressure, high-grade metamorphic complexes at Wongwibinda and Tia are associated with migmatites and plutons of the Hillgrove Suite (Korsch, 1982).

The southern and western margins of the Province, which are defined by the Hunter-

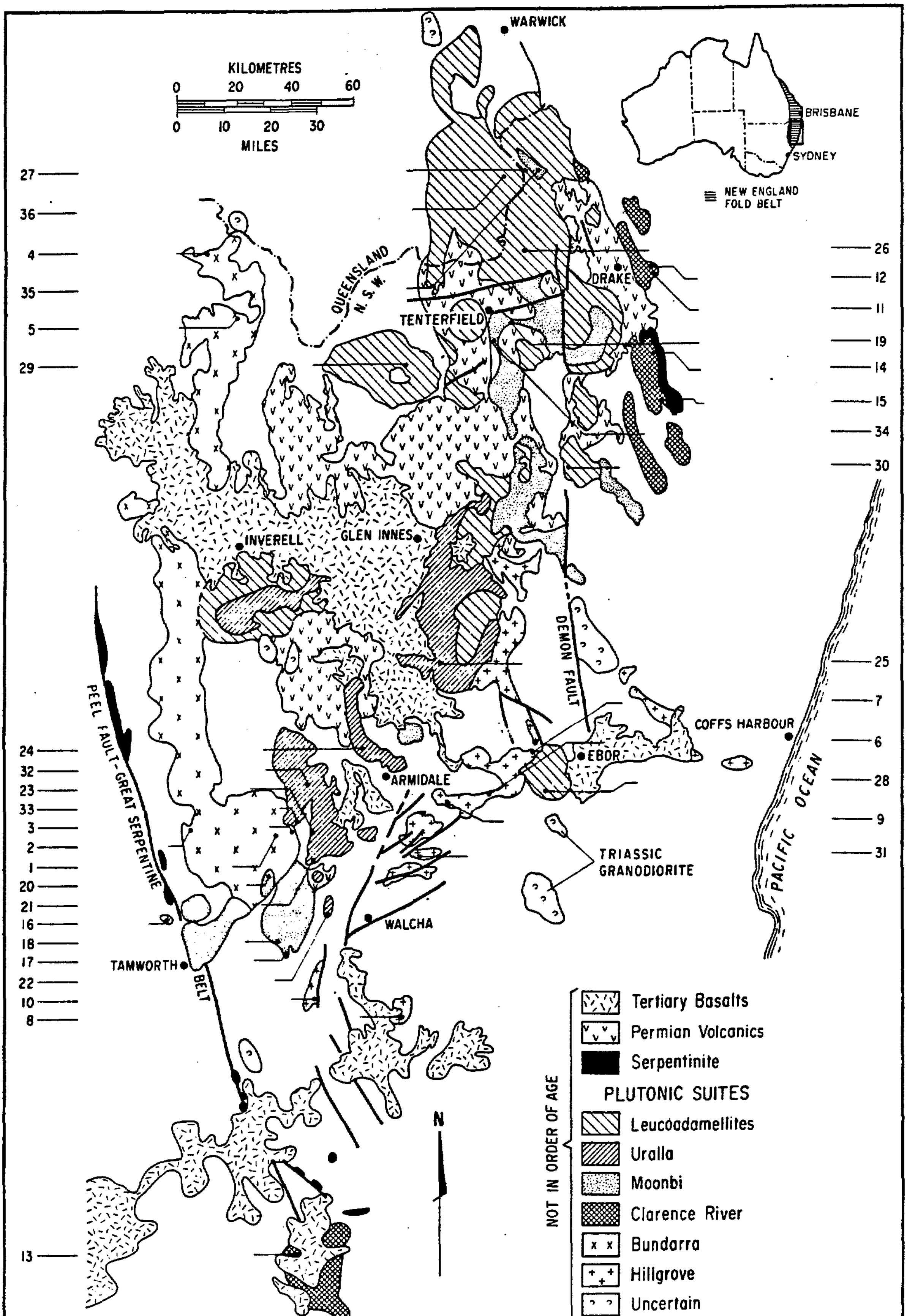

Figure 4. Distribution of plutonic suites and volcanics in New England Province (from Shaw & Flood, 1981).

Mooki Fault System, underwent southerly and westerly directed thrust faulting in the mid-Permian and the Late Permian - Middle Triassic. Extensive emplacement of I-type granitoids throughout the Province began in the late Early Permian and culminated during the Late Permian - Early Triassic (Uralla and Moonbi Plutonic Suites [Fig. 4]). Late Permian silicic volcanics crop out extensively in the New England Province (McPhie, 1986, 1988). The volcanics are cauldron-centred, dominantly rhyodacitic, crystal-rich ignimbrites, and are genetically related to the granitoids. This magmatic activity has been related to a post-orogenic period of crustal extension (Kleeman, 1988). Late Permian subaerial to submarine, intermediate-silicic volcanics at Drake, near the Queensland border (Fig. 4), which contain rich, epithermal Ag-Au deposits (Herbert, 1983; Bottomer, 1986; Perkins, 1988), have been related to pull-apart basin development (Korsch, 1975; Flood & Fergusson, 1984).

The Peel Fault (Fig. 4), and its southeastern extension the Manning Fault, is a major tectonic feature which extends for approximately 400 km. It separates the Devonian-Carboniferous forearc basin (Tamworth Trough) from coeval accretionary wedge rocks to the east. During the Palæozoic, the Peel Fault underwent several phases of movement, both as a thrust fault and a strike-slip fault. Corbett (1976) demonstrated sinistral motion on the northern part of the Peel Fault at about the time of the Carboniferous-Permian boundary. Korsch (1982) proposed that ?Early Permian sediments which occur north of Tamworth were deposited in pull-apart basins associated with strike-slip movement on the Peel Fault. He argued that the geometry of the faults and the locations of the basins suggest that movement on the Peel Fault, in this instance, was dextral. Similar pockets of Permian sediments located along the Peel Fault may also have been deposited in pull-apart basins. Katz (1986) proposed Early Permian dextral-transtensional movement on the Peel Fault at the Woodsreef asbestos mine, and suggested that this movement allowed the syntectonic emplacement of serpentinite. Several serpentinite bodies crop out along the fault, but their age is equivocal. A Permian age (280-275 Ma) has been obtained for a serpentinite block associated with the Peel Fault south of Tamworth (Lanphere & Hockley, 1976), but this may be a post-emplacement tectonic age; also, there were probably several periods of serpentinite emplacement (Korsch, 1982).

Flood and Fergusson (1984) interpreted the Permian successions in the Warwick and Drake areas as pull-apart basin deposits associated with strike-slip movement on a postulated major transcurrent fault, which was later termed the Gogango-Baryulgil Fault Zone by Murray and others (1987).

The Ashford Coal Measures (mid-Permian Greta Coal Measures equivalents) abut the Severn Thrust in the northern part of the Province. It is unclear whether their deposition was fault controlled, or whether they are simply the downfaulted remnant of a more extensive deposit (O'Brien, 1989a).

The Demon Fault is a major north-south trending, dextral strike-slip fault, extending over 200 km in the eastern part of the New England Province. Korsch and others (1978) postulated that the fault was a long-lived feature that may have had a controlling influence on sedimentation in the Early Permian. McPhie and Fergusson (1983) however, suggested that movement on the fault took place after the cessation of Permo-Triassic silicic volcanism, and that there is no evidence to support the prior existence of the fault.

DISCUSSION

The main structural features of the Permian of Australia are: (1) the broad, relatively stable craton and its concomitant basins; (2) the eastern orogenic belt with its history of subduction and arc magmatism, strike-slip movements, arc migration, orogenesis, and crustal extension-related magmatism; and (3) the intervening basins which were initiated by back-arc extension, but later formed part of the foreland basin-fold thrust belt system present along much of the palæo-Pacific margin of Gondwana.

One outstanding feature of the structural development of Australia is the number of basins initiated or reactivated in the Late Carboniferous and Early Permian. These include the Browse, Perth, Pedirka, Arckaringa, Cooper, Galilee, Sydney-Bowen, Oaklands, and Tasmania Basins. The development of the Browse and Perth Basins can be related to a phase of crustal extension and transtension in northwestern and western Australia preceding the rifting off of some Gondwanan fragments (e.g. Sibumasu) in the Early Permian.

The apparently synchronous development of intracratonic basins such as the Arckaringa, Pedirka and Cooper also suggests the involvement of large-scale processes, i.e., those operating on a cratonic or lithospheric plate scale and originating from the plate boundary or sub-lithospheric thermal processes (Quinlan, 1987). Intra-plate stresses, which play a crucial role in basin formation (Cloetingh & others, 1989), can be generated as a result of changes in plate boundary configurations during subduction, collision or rifting, or as a result of convection in the upper mantle, which gives rise to stresses on the base of the continental crust (Houseman & England, 1986). Evans and Roberts (1980) suggested that a dextral force couple was applied to the eastern margin of the craton and the orogen from the Late Carboniferous to the Triassic leading to the development of *en-echelon* basins. Murray and others (1987), using a plate tectonic context, explained this in terms of a change from an oblique convergent to a dextral transform margin. The initiation of the Sydney-Bowen Basin in an extensional (or transtensional) setting, and its subsequent evolution as a foreland basin, is directly related to activity along this plate boundary. The development of the intracratonic basins further west may also have been controlled by the stresses developed by plate interactions along the margin (Leitch, 1988).

Middleton and Hunt (1989) presented a regional tectonic model for Australia during the Permian in which mantle convection was proposed as the principal cause of observed lithospheric processes, such as basin formation. They argued that basin formation in the west was associated with initial passive margin rifting (as mentioned above), and that Early Permian extension on the eastern margin of the continent, specifically in the Denison Trough, was an expression of back-arc spreading. The Galilee, Cooper, Pedirka, Arckaringa and Officer basins were suggested to have formed as strike-slip enhanced structural depressions within a broad intracratonic sag that developed as a result of episodic downwelling of the mantle in central Australia; convective downwelling in the mantle beneath the craton was a necessary consequence of the mantle upwelling associated with rifting on the continental margins.

Klein and Hsui (1987) argued that intracratonic basins generally overlie ancient rifts. Lindsay and others (1987) showed that the Late Proterozoic-Early Palæozoic Officer, Amadeus and Warburton Basins, which underlie the Arckaringa, Pedirka and Cooper Basins respectively, underwent a phase of crustal extension about 600 Ma. However, given that thermal anomalies probably have a life-span of 100-200 m.y. (McKenzie, 1978; Dewey, 1982; Quinlan, 1987), it is difficult to relate the Carboniferous-Permian (ca. 300 Ma) subsidence with the thermal decay of a Precambrian (ca. 600 Ma) rifting event. Nevertheless, pre-existing faults may have had a controlling influence on basin evolution during later Carboniferous-Permian extensional or transtensional events.

PALÆOGEOGRAPHY

The data from most of the Permian basins are generally more than adequate for broad-scale palæogeographic reconstructions of the type undertaken here. In large regions of the continent, however, no record of Permian deposition has been preserved, so that palæogeographic interpretation is necessarily speculative. These regions include the Western Australian Shield, the Lachlan Orogen, much of northern Australia, and for the later time slices, most of central and South Australia. Sometimes an educated guess can be made, by extrapolation from the nearest data. Thus between a fluvial system and the sea there must be a paralic environment of some kind; inland from a delta complex there must be a drainage catchment; inland marine basins must somehow be connected to the world ocean; the presence of an ice sheet can be deduced over wide areas from ice movement and exotic clast dispersal directions; and so on. Erosional areas shed debris into adjoining basins, but even long distances from a depocentre, uplifts (and therefore subsequent erosion) may be revealed by fission track or isotopic studies, or inferred from tectonism or the intrusions of large plutons. Where there is no data, and no reasonable inferences can be made, the maps show unclassified marine or land environments, or are left blank.

Age control on depositional sequences is variable. It is particularly sparse on the Early Permian glaciogenic and volcanic units, and on the Late Permian terrestrial formations (such as in the northern Bowen Basin) which have been subjected to sufficient heating to carbonise the enclosed palynomorphs. Deformed sequences in the New England Orogen are likewise poorly controlled where their marine fossils have been damaged beyond definite identification. Most marine successions, however, have yielded good biozonations, although as mentioned previously, correlations in some areas are still controversial. Terrestrial sediments have usually provided good palynomorph assemblages; a notable exception is Tasmania, which had an impoverished microflora because of its proximity to the palæopole. Isotopic dating, chiefly using the K-Ar and Rb-Sr methods, has been extensive on the granitic intrusives of New South Wales and Queensland, but as discussed before, there is some uncertainty as to what the ages actually represent. The isotopic dating of biostratigraphic zones is very sparse, and still in its infancy.

Most detailed sedimentological studies have been carried out in the main coal basins. Outside these basins, palæocurrent measurements are usually very limited and unsystematically collected, and detailed palæo-environmental interpretations are

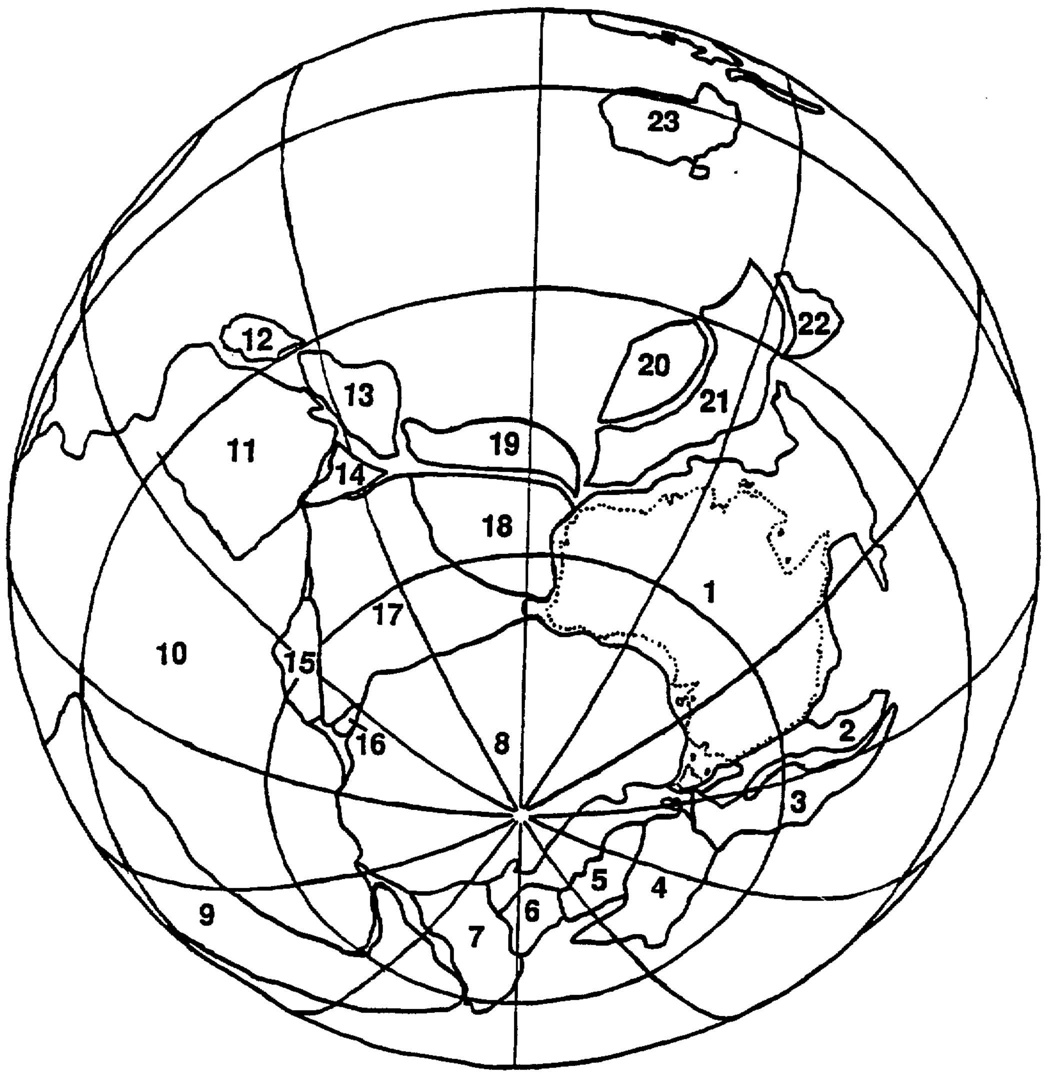

Figure 5. Australia's position in Gondwanaland at about 280 Ma. 1. Australia; 2. Lord Howe Rise; 3. Northern New Zealand - Norfolk Rise; 4. Southern New Zealand - Campbell Plateau - Chatham Rise; 5. Marie Byrd Land; 6. Thurston Island Block; 7. Antarctic Peninsula - Ellsworth Mountains; 8. East Antarctica; 9. South America; 10. Africa; 11. Arabia; 12. Turkey; 13. Iran; 14. Afghanistan; 15. Madagascar; 16. Sri Lanka; 17. Peninsula India; 18. Northern extension of "Greater India"; 19. Tibet; 20. Indo-China; 21. Sibumasu (Burma-Thailand-Malaya-Sumatra); 22. West Borneo; 23. South China. The assemblage of blocks shown along the northern margin of Gondwana is one of several possible.

relatively few.

As noted earlier, it was impractical at the time of compilation to present the maps on a palinspastic base. For the New England Orogen, it is known that the Gympie Terrane lay at an unspecified distance to the east of its present position, and docked with eastern Australia during the mid-Triassic (Harrington, 1983). The Curtis Terrane may have docked during the mid-Permian (Brakel & Totterdell, 1988). Strike-slip movements of about 500 km have been postulated along the Mooki Fault system (Harrington & Korsch, 1985b), and the Texas - Coffs Harbour Megafold may have formed as late as the Early Permian (Murray & others, 1987). As a result, *the palæogeography mapped for the orogen may bear little relationship to the distribution of the rock units at the time of their formation*. This tectonically naïve presentation is preferable to leaving the orogen blank, because at least the palæo-environments of the present outcrop areas are depicted. The exotic derivation of the Gympie and Curtis Terranes is indicated on the maps by white line boundaries, but there may be others not yet recognised. Flood & Aitchison (1988) defined 11 terranes in New England, and some of these may not have been in their present positions in the Permian. Research on the tectonic evolution of the New England Orogen is currently being pursued vigorously on several fronts, and a reasonable palinspastic reconstruction of this region will have to await the outcome of this work.

During the Permian, Australia was a part of eastern Gondwanaland (Fig. 5). The present Lord Howe Rise and New Zealand lay to the east and southeast of Australia, while Antarctica adjoined its southern margin (Lawver & Scotese, 1987). To the west, a land mass often referred to as "Greater India" was present, the part abutting southwestern Australia probably being modern Assam. Palinspastic reconstruction of the Himalayan fold belt (Klootwijk & others, 1985) suggests that this land mass extended north along the Western Australian coast as far as North West Cape (Powell & others, 1988). Farther along the northwestern and northern margins of the Australian plate, reconstructions of former neighbouring continental blocks are more nebulous. Most workers believe that blocks now incorporated into Asia were part of this region of Gondwana. Palæomagnetic work on the Chinese blocks shows that these were already moving across central Tethys by the Late Carboniferous (Lin, 1987), and were far from Australia during the Permian (McElhinny & others, 1981; McFadden & others, 1988). A recent reconstruction by Audley-Charles (1988) proposes that South Tibet lay opposite North West Cape, and Burma along the Northwest Shelf, with a line of other blocks such as North Tibet and Indochina still farther to the northwest; Thailand, Malaya, and various Indonesian fragments were arrayed along the margin west and north of New Guinea. North Tibet - Indochina was rifted off in the Late Permian, but the other blocks remained attached to Australia until the Late Jurassic. Metcalfe (1988), however, argues that the latter blocks (Sibumasu) had already been rifted from Gondwana by latest Early Permian times.

In the remainder of this section, each of the seven time slices will be dealt with in turn, starting with the oldest. As the tectonics has already been treated under a separate heading, the sedimentological aspects of the palæogeography will be emphasised here, although the two topics are of course inextricably associated. No attempt is made to detail the entire Permian geology of Australia, or to cite every source of data, because just listing every reference that has ever been published on the Permian would alone occupy an entire volume.

PERMIAN 1: ASSELIAN (286-277 Ma)

As indicated previously, this time slice is considered to be latest Carboniferous by some workers, and its designation as Asselian is somewhat arbitrary, for neither the top nor base of the Asselian can be recognised with confidence in Australia. In New South Wales, and possibly elsewhere, the base of this time slice co-incides with a hiatus (Brakel, 1984 ; Briggs, 1985).

Glaciation

The most striking feature of the map, which represents the climax of the late Palæozoic glaciation, is the domination of the southern and western parts of the continent by extensive ice sheets. The largest of these sheets occupied Western Australia south from the Great Sandy Desert, and extended into central Australia east of Alice Springs. Although much of the Yilgarn Block now bears little evidence of this glaciation, its role as a major ice centre is shown by the basal tillites and glacigenic sediments in the Collie and Perth Basins, and the outwardly-radiating ice movement directions ranging from easterly on the margins of the Officer Basin (Jackson & van de Graaff, 1981a), to northerly west of Lake Carnegie (Bunting, 1980), to north-northwesterly near Geraldton (Playford & others, 1976). The interpretation of surviving Permian glacial landforms on the Yilgarn (Finkl & Fairbridge, 1979) has been discounted by van de Graaff (1981d). The ice cap is inferred to have extended onto adjacent Antarctica to the south, and onto "Greater India" to the west. Its extent eastwards near Eucla is uncertain.

Another major ice centre occupied the Pilbara region. West-southwesterly to southerly (and local southeasterly) ice movement directions are preserved as striae on glacial pavements in the Carnarvon Basin. Proterozoic erratics in the Lyons Formation in this region have been transported about 250 km (Grey & others, 1977), a distance which would require an ice cap thickness of about 1.5-3 km according to Nye's (1952) formula. Although this assumes that the ice moved over a horizontal surface, the estimate at least confirms that the ice was thick enough to be an ice cap. The Lyons Formation contains a thick sequence of terrestial and marine sediments, with glacially cut clasts, implying that at times a floating ice shelf extended off the coast. This is depicted on the map, but the maximum extent of the shelf westwards is conjectural. Lavering (1985) interpreted the unit as part of a glacially-derived alluvial fan-delta to gravelly fluvial system which was periodically inundated by the sea. Along the southern margin of the Canning Basin, striated pavements display ice movement towards the north and northwest, a pattern which, when taken in conjunction with northerly directions along the eastern Pilbara, suggests that stronger ice flow from the Yilgarn centre was by-passing the more lethargic Pilbara sheet. Lodgment tillite, recently discovered in boreholes on the Broome Arch in the Canning Basin (Redfern, 1991) demonstrates the presence of grounded ice there. Clasts of Precambrian lithologies in this till indicate that the ice was not a small local accumulation, but had come across the basin from the Precambrian hinterland to the south. There is no evidence to show whether or not the ice in the southern Canning Basin was grounded all the way, or formed a floating shelf on marine water. The glacigene deposits along the southern Canning margin are ice retreat sequences, post-dating the maximum advance. It is even possible that during the coldest stadia the ice may have extended across to the Kimberley and Stuart Blocks, but it is more likely that at such times a small transient ice cap and valley glaciers existed in these areas. Ice-rafted debris was also dropped into the Bonaparte Basin, either from icebergs or seasonal ice.

Also part of the great western ice sheet, the central Australian ice centre radiated ice southwesterly into the Officer Basin, northerly near Lake Mackay, and southeasterly into the Pedirka Basin, the last direction being inferred from the source of transported clast lithologies. The northerly and easterly extent of the ice is unknown, but the minimum area glaciated would have included the Musgrave Block, and the region uplifted during the Carboniferous Alice Springs Orogeny and still forming highlands in the Early Permian. In the Officer Basin, opposing ice flows from the Yilgarn and central Australian centres converged, and presumably were deflected to the north and south. An erosional high along the eastern side of the Pedirka Basin shed detritus westward, and may have supported a transient ice cover during the coldest stadia, to connect the great western and southern ice sheets.

The South Australian portion of the southern ice sheet formed an irregular lobe with apparently no radial flow directions. Tillite on the western side of the Peake and Denison Ranges, along the margin of the Boorthanna Trough of the Arckaringa Basin, suggests that ice debouched off the ranges directly into the sea. There it dumped its load of till into the water of the fault-bounded trough, to be deposited as turbidites (Townsend, 1976). A narrow ice shelf along the shore was likely. Diamictite in the Wallira and Phillipson Troughs of the basin imply an ice shelf there also, fed from the Gawler Craton to the south. The glaciofluvial sediments of the southern Cooper Basin (Williams & Wild, 1984a) must have been supplied by glaciers on the basin edge, but the only tillite known occurs in bores near the western margin. This western area also contains lacustrine facies, and paraglacial eolianites deposited as dunes by catabatic winds coming off the ice (Williams & others, 1985). Early Permian (280 Ma) fission track ages from the Broken Hill Block indicate uplift of the crust, possibly as a result of isostatic adjustment after extensive glacial erosion (Stevens, 1986). Alternatively, uplift may have come first, and aided glacial development on the higher topography. Drilling in the Murray infra-basinal area (O'Brien, 1986a) indicates that floating ice did not extend far into this basin, and that the volume of debris shaved off the Broken Hill Block was not unusually great. Southwest of Adelaide, striations on glacial pavements mostly display northerly and northwesterly ice movement, but in the Inman Valley, basement topography deflected ice flow towards the west. There are no glacials on the Yorke Peninsula, and the marine sediments there probably record post-glacial deposition near the end of the time slice. The Polda Basin sediments contain erratics or dropstones, and are of uncertain but possibly glaciolacustrine facies.

The ice lobe over Victoria again shows no evidence of having been an independant ice centre, as all ice directions are northerly. Subsurface data from the Murray infra-basinal area (O'Brien, 1986a) indicates that floating ice did not extend far north. The limit of ice cover to the northeast is unknown; it may have flowed against the southern part of the highlands uplifted by the Carboniferous Kanimblan Orogeny (as shown on the map), perhaps being joined by coalescing ice streams descending from the higher topography, but if precipitation was inadequate, only scattered valley glaciers may have been possible here, as in New South Wales. In SE South Australia, a marine connection existed between the Murray infrabasinal area and the sea beyond. During the coldest periods, a floating ice shelf was probably established over this water, to connect the glacial lobes of Victoria and South Australia, but in warmer times an open seaway may have been present, except for a cover of seasonal winter ice.

Meanwhile, western Tasmania experienced an invasion of ice from the west, but the flow was deflected to the northeast and southeast by a number of monadnocks. The glacial sheet met the sea in central Tasmania, giving rise to another floating ice shelf. Islands to the east bore only small ice caps.

Clearly, the ice encroaching onto Tasmania, Victoria, and South Australia radiated out from a centre in northern Victoria Land, in adjacent Antarctica. To do so, it had to pass over marine passages lying across its path. Its access to South Australia was via a rather narrow neck, which may have been wider than shown if it is assumed that any glaciation on the Yorke and Eyre Peninsulas left no trace of its presence. Nevertheless, the broad expanse of this lobe compared to its constricted southern connection strongly implies additional nourishment of this sheet by precipitation.

The eastern seabord region of the continent developed only minor valley glaciers. Carboniferous palæochannels cut to over 200 m deep in the southern Sydney Basin have been interpreted as glacially carved by Herbert (1972), and glaciers may still have occupied the heads of these valleys at the start of the Permian, supplying coarse glaciofluvial debris downstream. The "late upper marine" (Kungurian) glacial valleys described by Dulhunty (1964) may have been first cut by ice at this time (to be re-occupied by glaciers in the Kungurian), and a glacial moraine on the northern rim of the basin has been claimed by Dickins & Sutherland (1979). However, there is no evidence of glaciation in the nearby Gloucester Basin.

Contemporaneous sediments in Queensland's Galilee Basin have been interpreted as glacigene in part, and derived from alpine glaciers in highlands to the east and north (Crowell & Frakes, 1971; Hawkins, 1978). Local ice developments may have existed as far north as the Gulf of Carpentaria, where subsurface diamictite has been intersected in the Burketown Depression (Meyers, 1969). Dating of this rock has been frustrated by the complete absence of fossils, and because it overlies a Cambrian carbonate, it has been considered by some to be part of the Cambrian sequence. However, there is no evidence of glaciation in Australia during the Cambrian, and we agree with Burgess (1984) that the lithology is more likely to represent a Permian tillite. Both the glacier shown in the southeastern lobe of the Burketown Depression, and the fluvial environment in the rest of the depression, are speculative. The presence of glacial ice elsewhere in northern Australia is conjectural.

By the end of the time interval, most of the ice had withdrawn from Australia, leaving retreat sequences behind in places. An extensive example of such a sequence is found in the Officer Basin, where glaciofluvial deposits overlie the basal tillite; the palæocurrents shown on the map (from Jackson & van de Graaff, 1981a) refer to this post-glacial condition. Notable following the departure of the ice from the marine portion of Tasmania was the sporadic development across the north of the state of a 2 metre-thick nearshore *Tasmanites* oil shale.

Non-glaciated Regions

Apart from the great ice sheets, the most conspicuous feature of the continent during Permian 1 was a 1800 km-long volcanic belt parallel to the east coast and stretching from the Sydney Basin to Townsville. It consists of bimodal volcanics which, under the Sydney Basin, form a pile at least 8.6 km thick (Qureshi, 1984). Between the outcrops of the Boggabri Volcanics in the Gunnedah Basin and the Camboon Andesite in the Bowen Basin, the eruptives are known from numerous petroleum and coal exploration drill holes, and from their geophysical expression as the Meandarra Gravity Ridge. With contemporaneous activity taking place northeast of Newcastle, north of Mackay, and west of Cairns, the volcanism spanned a total length of about 2200 km. Termed the Ayr Volcanic Rift by Scheibner (1976), it was attributed to rifting in front of a subduction zone lying off the east coast. However, the Camboon Andesite and equivalents appear to represent a short-lived volcanic arc coincident with the earlier Devonian - Carboniferous Connors - Auburn Arc (Day & others, 1983), while the suite of volcanics to its west and south can be accounted for by back-arc extension.

A subduction complex existed in eastern New England in the Late Carboniferous, but was terminated in the Early Permian, when tectonic movement changed from essentially convergent to dominantly strike-slip (Cawood, 1982b). Deep-water sediments collected in the region; they contain basalt occurrences of mid-ocean ridge character, although this does not necessarily mean that a spreading centre formed locally. The basic volcanics may have been associated with the earliest stages of rifting which never proceeded to the sea-floor spreading stage (Leitch & Asthana, 1985; Scheibner & Pearce, 1978). Korsch (1982) suggested that one of the basalts possibly represents a seamount.

In the Gympie Terrane, the sediment types at the start of the Permian are also indicative of a deep oceanic setting (Day & others, 1983), but the subsequent dominantly andesitic Highbury Volcanics are amygdaloidal (Runnegar & Ferguson, 1969), signifying lower water pressures and shallower depths, with chemical evidence pointing to eruption in an intra-oceanic arc (Cranfield & Murray, 1989). The terrane itself is allochthonous, being located at the time an unspecified distance to the east in the Eopacific and attached to similar terrane, part of which now occurs in New Zealand (Harrington, 1983; Waterhouse & Sivell, 1987).

Shallow marine environments in Queensland are represented by the clastic Burnett Formation of the Yarrol Basin, and parts of the Rannes and Carmila beds of the Gogango Folded Zone. The latter domain received appreciable ashfalls from nearby volcanism. A continental shelf presumably existed northwards from these areas to east of Cape York Peninsula. The Silver Spur beds near the New South Wales border were also shallow marine. In the Sydney Basin, deposition was beginning with the marine transgression which laid down the Lochinvar Formation in a cold climate, accompanied by basaltic volcanism. Eastern Tasmania also experienced cold shallow marine conditions, except for large island areas which were presumably erosional.

Extensive bodies of marine water occupied the sub-Murray and Arckaringa basins of the southern interior. Very impoverished faunas of foraminifera (O'Brien, 1986a) and gastropods and foraminifera (Townsend & Ludbrook, 1975) respectively, point to conditions too stressful for most marine organisms, probably because of regular large influxes of meltwater into these semi-enclosed embayments from the adjacent ice caps. The question arises as to how these isolated marine basins were connected to the world ocean. No connection was possible across the Kanimblan highlands to the east, nor is there any evidence of contemporary marine sediments to the north or in the Officer Basin. The most reasonable route seems to lie to the southeast, to the north and/or west of Tasmania, via a Red Sea-type passage filling a rift valley along the site of the later break between Antarctica and southern Australia. Much of this narrow connecting sea would have been covered by an ice shelf, as the Antarctic ice cap advanced across into Tasmania, Victoria and South Australia. The location of a southern entrance to the Arckaringa Basin is unclear; the only known evidence for one is the 90 m-thick sequence of fine-grained sediments of uncertain age and affinity in the Mallabie Depression.

The Canning Basin, apart from the partial ice cover already alluded to, contained cold marine water, which became deeper, or at least quieter, in the latter part of the interval (Forman & Wales, 1981; Towner & Gibson, 1983a). Ice-rafted dropstones are a feature of the sequence. In the Bonaparte Basin, the sea regressed during the interval, with nearshore and high-energy barrier and beach facies grading up to fluvial and lacustrine deposits (Laws & Brown, 1976; Mory & Beere, 1988). Again there is evidence of ice-rafting, by seasonal or glacial ice. The presence of some deltas is inferred on the map, as is the extent of the fluvial area beyond the coastal zone. Alluvial fans formed in response to basin and hinterland uplift, and some fed directly into the sea (Mory & Beere, 1988). Regression is also indicated in the Rob Roy 1 well (Browse Basin), where the sequence begins as marine, but grades up to non-marine (Crostella, 1976). The Scott Plateau area off northwestern Australia may have been above sea level and eroding at this time (Stagg, 1978; Allen & others, 1978).

Sediments of tentative Stage 2 age have been intersected in the Tasman 1 and Kulka 1 wells in the Arafura Basin (Petroconsultants Australasia, 1989). The sequence at Tasman 1 is fine-grained, with minor coal implying non-marine facies. That at Kulka 1 comprises fine-grained clastics of uncertain, probably marine, origin.

Fluvial deposition probably took place over much of the land area of the continent, especially in outwash aprons along the margins of ice sheets, but most of these deposits have not survived later erosion. However, in the Officer, southern Canning, Pedirka and Cooper Basins, as mentioned previously, glaciofluvial units have been preserved by basin subsidence. The eastern Galilee Basin received fluvial and fluviolacustrine sediments from surrounding erosional highlands (Hawkins, 1978). The Denison Trough of the Bowen Basin holds a great thickness of terrestrial Reids Dome beds, but the base of the pile in the main graben complex has not yet been reached by drilling and its age is unknown. On the map it is assumed that filling of the trough began during this time slice. Certainly in the Strathmuir Synclinorium to the northeast, the fluvial basal portions of the Carmila beds (with interbedded volcanics) were being laid down at this time. Another fluvial facies of note is the lower Temi Group, within the Werrie and Temi Basins in eastern New South Wales.

Of the erosional areas not already mentioned, those shown for the Cape York Peninsula region and western New England are postulated on the basis of intruding plutons probably being accompanied by uplift. The New England high was the likely source of the conglomerates in the Temi Group.

PERMIAN 2: EARLY - MIDDLE SAKMARIAN (277-271 Ma)

This time slice is essentially a deglaciated version of Permian 1. The only ice remaining was in the form of localised valley glaciers in northern Victoria, and in the Oakover Valley area on the southern Canning Basin margin; the glacigene deposits in both places have been dated by palynology.

As sea level rose because of the melting of the ice caps, marine transgressions occurred in southern Victoria, Tasmania, the eastern Murray infrabasinal area (to the Oaklands Basin), and the Bonaparte, Carnarvon, northern Perth, and Temi Basins, and to a lesser extent in the Sydney Basin. But in the Canning and Arckaringa Basins the influx of sediment on their northeastern sides more than kept pace with the rising sea level, and actually caused the shorelines to prograde. An apron of fluvial and some lacustrine deposits along the northeastern Canning Basin was fed by an erosional region to the north, and similarly, a fluvial and deltaic apron along the northeastern Arckaringa Basin was supplied from highlands to the east. In the Pedirka Basin, initially low energy, fine-grained fluvials gave way to higher energy sand-dominated fluvial aggradation by the end of the time interval. This sedimentary influx into the central Australian basins was probably caused by recycling of glacial detritus left behind on the land surface, and by increased erosion in highlands rising on the removal of the ice load. Fission track dating indicates uplift around the northern Amadeus Basin at 280-260 Ma (Tingate & others, 1986).

The southern Perth Basin was a graben between the Yilgarn Block and "Greater India", and the site of fluvial peatlands. A significant amount of the sedimentary fill may have been derived from the adjoining part of Antarctica to the south. A sedimentary basin occupied a substantial portion of the southwestern Yilgarn Block, but now only remnants such as the Collie Basin remain (Wilson, 1989). Apart from the Naturaliste Plateau and the Leeuwin Block, the land shown west of the Perth Basin was rifted away when India and Australia separated in the Early Cretaceous. The northern Perth Basin and the Carnarvon Basin comprised a cold-water marine gulf, which only supported a fauna of low diversity. Most of the Canning Basin, as well as the Bonaparte Basin, experienced shallow marine conditions. The environment prevailing over the Scott Plateau area at this time is conjectural.

Seismic sections in the Arafura Basin show a substantial thickness of sediments between the sub-Jurassic unconformity and the youngest Palæozoic (palynological Stage 2) found by drilling. This undrilled succession, which itself contains a sequence boundary, probably spans the entire Permian period, and possibly much of the Triassic as well. The seismic character of the beds is similar to shallow marine equivalents in the Bonaparte Basin (J. Bradshaw, BMR, pers. comm.).

The marine sediments at the top of the sequence in the Bacchus Marsh area could be attributed to the higher sea level resulting from the melting of the ice caps, before the crust had time to adjust fully by isostacy to the removal of the ice load. If so, they would record a very short span of time, of some 10 000 -20 000 years, before continuing isostatic rebound caused the flooded land to re-emerge. Early Permian marine sediments in the Duck Bay 1 well in Gippsland (Bowen & Thomas, 1976) may also have originated in such an event. Tasmania, where an archipelago of sizable islands had appeared, must have been similarly affected, but the larger marine areas remained as such even after rebound.

Marine transgression in the southern Sydney Basin took place across an uneven land surface, and turbulent littoral conditions denote a coast facing the open ocean. Large erratics were dropped from seasonal ice, and sedimentary breccias at the base of the sequence may have been emplaced as rock glaciers or solifluction lobes (Gostin & Herbert, 1973). In the north of the basin, the Allandale Formation records a sublittoral facies, locally developed around basaltic islands. Basaltic volcanism continued, though in the western part of the basin, rift eruptions appear to have ended. No rocks of this age are preserved in the west, and the land here may have been a sediment by-pass area. The rest of the volcanic belt in eastern Australia remained active.

Near Taree, the formerly deep marine area was filled in to become shallow marine, but further north deep water turbidite sedimentation continued. In the Gympie Terrane, the Highbury Volcanics are amygdaloidal in places, suggesting shallowing, but the actual water depths are uncertain.

Carbonates were deposited within the generally clastic sequences on the shallow marine Yarrol Basin. Parts of the Gogango zone also continued as shallow marine, flanked to the east by fan deltas (Youlambie Conglomerate) derived from the adjacent eroding uplifted highland. Conditions in the Strathmuir Synclinorium and Grantleigh Trough were still fluvial.

A coal-forming fluvial setting, including alluvial fan and lacustrine facies, prevailed in the Reids Dome beds of the Denison Trough (Draper & Beeston, 1985a). The eastern Galilee Basin was partly occupied by rivers and some lakes, but without peat development (Hawkins, 1978), and a shallow repository also began forming in the Lovelle Depression to the west (Hawkins & Harrison, 1978). In the Cooper Basin, a fluvial sequence ranged vertically and laterally from braided (Tirrawarra Sandstone) to meandering streams (Patchawarra Formation), with the latter facies containing the most coal. The lithofacies and palæogeographic maps by Thornton (1979) imply an outlet to the north, but this is uncertain; outflow may have gone either into the southern Galilee Basin, or into the Murray marine embayment. Outflow into the Arckaringa Basin is less likely in view of the highland area between the two basins.

The major erosional areas were broadly similar to those of Permian 1. The deglaciated central Australian highlands, after rising by isostatic rebound, were now subject to water erosion, and probably remained so for the rest of the Permian. West of the Sydney Basin, probable early Permian palæokarst, pre-dating the Snapper Point Formation, has been recognized (Osborne & Branagan, 1985).

PERMIAN 3: LATE SAKMARIAN - EARLY ARTINSKIAN (271-266Ma)

By the late Sakmarian, the continent was no longer affected by glaciation or associated isostatic effects. The base of the time slice corresponds to a hiatus in the Canning Basin, the temporary end of Permian deposition in Victoria, the beginning of deposition in parts of the New England Orogen, and the change from marine to non-marine conditions in Tasmania.

The retreat of the sea was particularly marked in southeastern Australia. Deposition ended in the Murray Basin and Victoria generally, while in Tasmania fluvial sediments, including coal measures, extended across the state towards the southeast, except for some erosional areas, a probable lagoonal complex extending northwards to Interlaken (Forsyth, 1989), and some east coast marine embayments. The sea was expelled from the Arckaringa Basin by the continued infilling by clastics derived from the east and from the large central Australian erosional area via the Pedira Basin. Both basins developed coal measures in the later half of the time interval, as clastic input declined and peatlands were able to form.

Coal measures, mostly fluvial, are a feature of the time slice, as they were also deposited in the Denison Trough (Bowen Basin) and the Galilee, southern Cooper, Collie, and southern Perth Basins. The Denison Trough and Cooper Basins also contained lakes. The Nappamerri Trough of the Cooper Basin has a concentration of channel belt sandstones, because it subsided slightly faster than adjacent areas and attracted the drainage, whereas slower subsidence is indicated for the Patchawarra Trough (Wells & O'Brien, 1989). Aramac Coal Measures collected in both depocentres of the Galilee Basin, with clastic components being fed in from neighbouring highs (Hawkins, 1978). The Sydney Basin was not coal-forming at this time, except for small, sporadic, uneconomic lenses in its southern portion, representing marshes behind the fringing barrier bars of a fan delta complex (Evans & others, 1983). Seasonal ice rafting shows that the climate was still moderately cold. In the rest of the basin, shallow marine conditions continued; a narrow paralic zone presumably existed along the shore line. Minor uneconomic coal also occurs in the meandering stream facies of the upper Carmila beds in the Strathmuir Synclinorium of central eastern Queensland.

Eruptions continued along of the vast eastern Australian volcanic zone, and the Werrie Basin (NSW) was filled by basalts as the belt widened eastwards. Volcanism in the New South Wales portion of the belt ended sometime during the interval, however, and a period of intense subaerial weathering ensued. Activity persisted longer in the Queensland section of the belt, but did not last into the next time slice. Some dominantly felsic activity (Nychum Volcanics) occurred in north Queensland.

In the shallow marine Yarrol Basin, limestone now dominated over clastic deposition, and a wide range of marine fauna flourished. In the Candlelight Embayment northwest of Rockhampton, however, submarine eruptives of spilitic pillow lavas, and pyroclastics, came to interfinger with mudstones. The Berserker Graben may have been initiated as an actively subsiding fault trough at the eastern edge of the shelf (Day & others, 1983), although this is by no means certain; its early fill was dominated by felsic and intermediate volcanics, with accompanying marine clastics.

The marine region of eastern New England shallowed to become a carbonate-clastic province, as indicated by units such as the Yessabah Limestone and Warbro Formations (Hastings Block), and the Kimbriki Formation and Cedar Party Limestone (Manning district). The Nambucca beds and western equivalents still suggest deep water, but age control for them is poor, and they may be older than this time slice. Water depths over the Gympie Terrane are uncertain; the Highbury Volcanics were still erupting.

The northern Perth Basin early in the interval received a richly fossiliferous, shallow marine carbonate-lutite sequence (the Fossil Cliff Member), followed by a shallow marine sandstone which may have been partly littoral in origin (Playford & others, 1976). The siliciclastics coarsen towards the Darling and Urella Faults, perhaps being a tectonic signature of activity on these structures during or before the emplacement of these sediments. At the close of the interval, the fluvial facies of the Irwin River Coal Measures extended across the region following a marine regression.

The eastern Carnarvon Basin experienced a series of diverse events during Permian 3, recording an interplay of marine and paralic lithotopes due to fluctuating shorelines. At first, low clastic influx on a wide shelf gave rise to the highly fossiliferous carbonate-lutite associations of the Carrandibby and Callytharra Formations (Lavering, 1985). After a withdrawal of the sea exposed the southeastern basin to a period of karst-forming subaerial weathering, renewed sea level rise and transgression set the stage for the outbuilding of a large delta complex (the Wooramel Group). This delta was initially sand-rich, but after inundation by further sea level rise, a mud-prone deltaic progradation was established, only to be drowned in turn as marine shelf sedimentation was finally restored. The Wooramel delta complex had more than twice the area of the Mississippi delta according to Lavering's map reconstruction, and must have been fed by a comparably large drainage system. The catchment area probably extended to the central Australian highlands, and may have drained part of Antarctica as well. Offshore from the delta, shelf conditions prevailed.

The Canning Basin began the interval with an erosional hiatus, caused either by uplift (Crowe & others, 1983), or by a eustatic sea level low stand. Most of the basin was then transgressed, resulting in a widespread nearshore to very shallow marine, dominantly sandy sequence (the Poole Sandstone). Its basal Nura Nura Member in the northwest tends to be calcareous and coquinitic, however, and preserves a faunal assemblage which lived in warm to temperate open seas (Foreman & Wales, 1981). A contemporaneous fauna in the south of the basin (Towner & others, 1983) implies similar conditions there. The northern margin differed again, in that a migrating barrier bar and lagoonal zone was constructed between the sea and an apron of coalescing fan deltas at the distal end of braided fluvial systems draining the Kimberley highlands to the north.

A prograding shoreline of sandy deltas with minor coal (lower Sugarloaf Formation) was constructed along the eastern Bonaparte Basin (Dickins & others, 1972). Most of the basin continued to be shallow marine, receiving fine, carbonaceous, prodeltaic clastics, and some limestone (Laws & Brown, 1976). Hughes (1978) shows a basement high near Newby 1 on which no Permian was detected by seimic work; this may have formed a small erosional area throughout most of the Permian. Undrilled

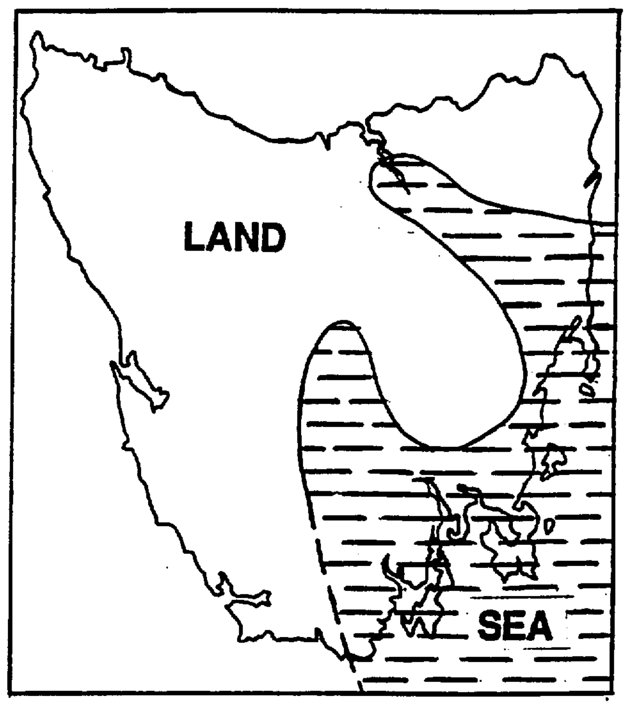

Figure 6. Tasmania during Cascades Group time, after Banks & Clarke (1987).

equivalents of the Bonaparte succession in the Arafura Basin, for reasons given earlier, were probably also shallow marine.

As this was a time of lowered sea levels in Australia, the Scott Plateau area was probably emergent.

PERMIAN 4: LATE ARTINSKIAN - KUNGURIAN (266-258 Ma)

The start of the interval was placed at an important sedimentation and environment change in eastern Australia, when dominantly terrestrial sedimentation was replaced by dominantly marine. It also corresponds to hiatuses in the Galilee Basin, Strathmuir Synclinorium, northern Tasmania, and many parts of the Sydney - Bowen line of foreland basins, as well as marking the end of deposition at several sites.

A chilling of the climate brought the local return of glaciation to western Victoria and the uplands along the western margin of the Sydney Basin. Evidence for this in Victoria comprises tillite and varved claystone (Bowen & Thomas, 1976), in a sequence which contains a palynological Stage 4 assemblage (Kemp & others, 1977). Alpine glaciers waxed amid spectacular 6000 m topography along the western Sydney Basin (Dulhunty, 1964), and these glaciers were the probable source of icebergs which rafted 4-5-tonne erratics into the marine Branxton Formation to the east, where dropstones were toppled onto a quiet sea floor, in places covered with the delicate fronds of the bryozoan *Fenestella* (David, 1907).

Conspicuous by its absence is the great Ayr Volcanic Rift, where volcanism had by now ended. Extant eruptive activity was confined to the basic-andesitic submarine outpourings in the Yarrol Basin, minor submarine andesite in the Gympie Terrane, felsic to mafic volcanism in northeastern New England, and at least partly subaerial rhyolitic eruptions in the Yarraman block west of Brisbane.

The time slice was a period of renewed marine transgression in many basins. In Tasmania, the sea at first advanced towards the north and west as two lobes (Fig. 6), during Cascades Group time (Banks & Clarke, 1987; Clarke, 1989). Later in the interval, after a hiatus had interrupted deposition in all but the easternmost parts of the basin, inundation overwhelmed the eastern half of the state, and eventually reached as far west as the present west coast in the vicinity of Strahan. The greatest subsidence and sedimentation was in a trough along the Tamar Fracture System, with sediment feeding in from source areas lying to the southwest, northwest, and northeast, at different times (Banks & Clarke, 1987). The sequences contain cold-water faunas, dropstones presumably carried in by seasonal ice, and limestones. The average sea water temperature of -1.8°C was comparable to that for the present day Antarctic shelf (Rao & Green, 1982).

An apron of coalescing fan deltas, constructed south of a rising hinterland, formed a prograding coastline in the northern Sydney Basin early in the period, while a similar line of alluvial fans and distal alluvial plains extended northwesterly, into the Gunnedah Basin. The latter was divided into two sub-basins by the Boggabri Ridge. Peat, aggrading in raised bogs on the fan surfaces, gave rise to the important seams of the

Greta Coal Measures and their equivalents. This stage of development is portrayed on the map. Subaerial deposition was ended by a relative sea level rise in Branxton Formation times, which also submerged the western margin of the Sydney Basin. Flooding was diachronous, and took some time to penetrate northwards deep into the Gunnedah Basin. The small Gloucester Basin north of Newcastle also felt the effects of this marine encroachment, and preserves a complex of nearshore marine, barrier and lagoonal facies of a wave-dominated (and coal-bearing) fan delta system which was sourced from the east and north (Lennox & Wilcock, 1985).

The only rocks of this age in the marine region of eastern New England contain Fauna II assemblages (Runnegar, 1970), diagnostic of the earliest part of the interval. These register a continuation of the shallow marine environment of the previous time slice. The later transgression is not recorded, either because the orogen was already experiencing uplift, or because tectonic movements at the end of the time slice caused any ensuing marine deposits to be lost to erosion. The Gympie Terrane, however, chronicled continuous deposition. Fauna II times were marked by the shallowing-upward shelf succession of the Rammutt Formation, which culminated in high-energy sublittoral sands at the base of the South Curra Limestone. A rapid deepening, probably coinciding with the transgression noted in other basins, led to the deposition of calcareous siltstone, before shallowing again took over, with calcarenite aggradation.

Shallow marine conditions continued to pertain in the Berserker Graben and in the Yarrol Basin. In the latter however, most of the rocks constitute a thick submarine volcanic pile. Early on, the sea spread westwards from the Yarrol Basin across the Bowen Basin in Fauna II time, and remained there for the duration of Fauna III. The Buffel Formation limestones in the southeast Bowen contain robust shelly fossils indicative of high-energy, and therefore very shallow, nearshore waters. Fauna III rocks are missing from this eastern region because of removal during later tectonism, but there is no reason to believe that the sea did not persist here, as in the rest of the basin. On the western flank of the basin, the large Aldebaran Sandstone delta, supplied by detritus eroded off the Anakie High and probably the Galilee Basin area, at first filled the Denison Trough, and then spilled over the confining Comet Platform (Brakel, 1989b). The northern tip of the basin was occupied by the Fauna III alluvial fan of the Collinsville Coal Measures, advancing mainly from the west before the marine transgression had reached the site, and eventually meeting the sea as a fan delta. The Calen Basin in the Strathmuir Synclinorium, meanwhile, collected coal measure sediments in a predominantly lower delta plain setting (Brakel, 1989c).

Marine advances also feature on the western side of the continent, in the Bonaparte Basin and along the northern side of the Canning Basin. But the Broome Arch in the central Canning was uplifted, and part of it became emergent. Most of the Canning Basin remained an extensive shallow sea, with clastic and some carbonate deposition (Noonkanbah Formation); the paleotemperature of the water was 24°-26°C (Forman & Wales, 1981). An erosional break between the Noonkanbah and Lightjack Formations in the Balgo Hills in the northwest (Yeates & others, 1975) may be the local expression of a basin-wide sequence boundary. Above this boundary, a shallowing of the sea to less than 60 m is apparent (Forman & Wales, 1981). Shallow marine conditions in the Carnarvon Basin vacillated from those of quiet lower offshore

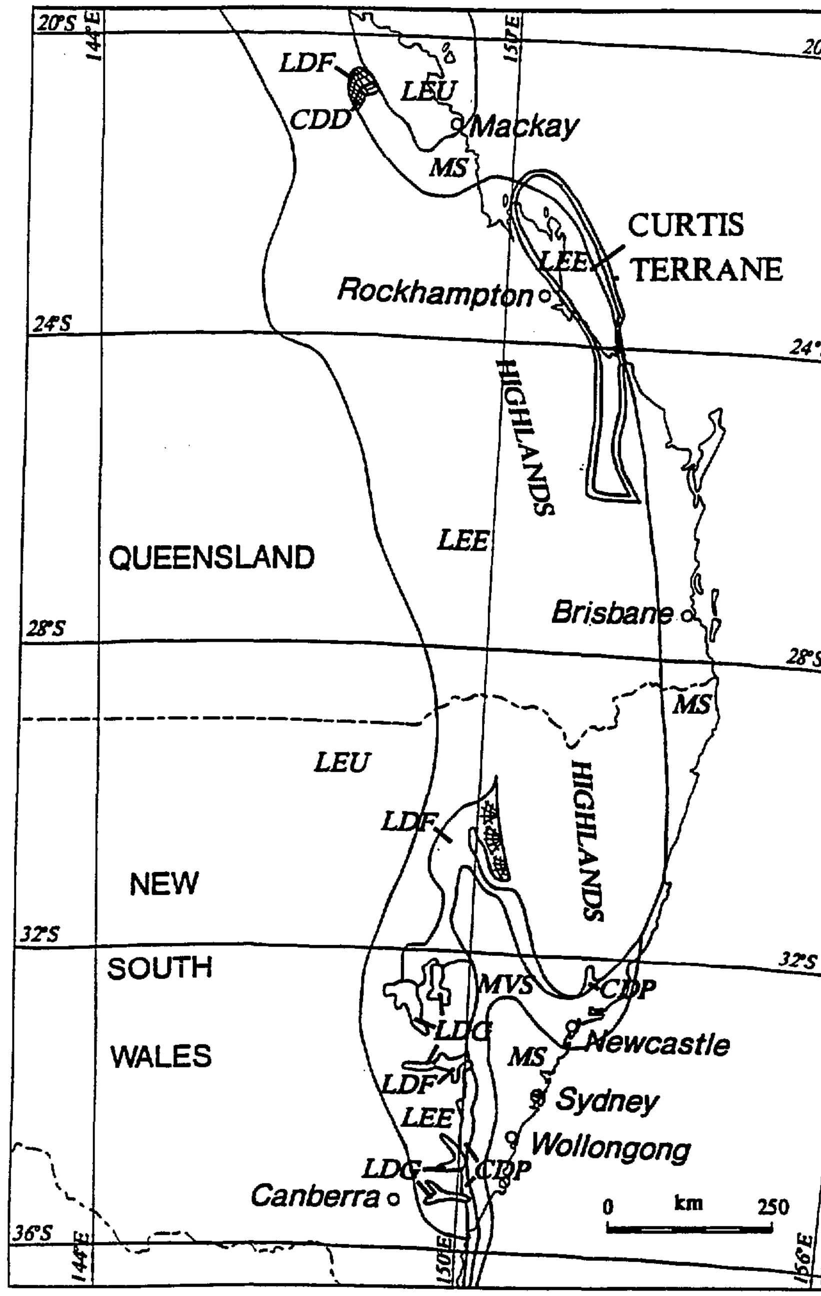

Figure 7. Eastern Australian palæogeography at the end of Permian 4, during the tectonic episode associated with the docking of the Curtis terrane. While most of the Bowen Basin appears to have become temporarily emergent, the regression in the Sydney Basin produced a sheet of near-shore sands. Any fluvial or paralic sediments that may have formed at this time were completely re-worked by the subsequent transgression (Herbert, 1980). MS = shallow marine; MVS = very shallow marine; CDD = deltaic; CDP = unclassified paralic; LDF = fluvial; LDG = glacial; LEE = erosional; and LEU = unclassified land environment.

to wave-dominated upper shoreface zones (Moore, Denman & Hocking, 1980), with storm activity prominent at various times (Hocking & others, 1983; Moore & Hocking, 1983). Scattered erratics near the base of the interval suggest the presence of floating ice, as the climate became cool to cold for the first third of the interval (lower Byro Group) before an amelioration (Crespin, 1958; Moore & others, 1980a). The cooling is consistent with the reappearance of glaciers in southeastern Australia, but intriguingly, it is in marked contrast to the warm conditions in the nearby Canning Basin, implying that the latter was influenced by a subtropical ocean current that did not reach farther south. Only the restricted shallow marine Carynginia Formation, at the base of the time slice, is preserved in the northern Perth Basin, and no significant areal change in the marine facies is indicated there. However, the long post-Carynginia hiatus implies a subsequent erosional event, possibly coincident with the tectonic hiatus at the end of the time slice in eastern Australia (see below). Fluvial coal measures continued to collect in the Collie and southern Perth Basins. Border faults, affecting sedimentation, were active in the Collie Basin, and may have restricted the area of deposition to within the presently preserved basin (Park, 1982), but Wilson (1989) believes that the wider area of deposition of earlier times may have persisted.

No record of deposition is preserved in the Arckaringa and Pedirka Basins, but regardless of whether sedimentation continued into this time slice, or the basins had filled to become sedimentary by-pass areas, the earlier drainage patterns almost certainly lingered on.

The southern Cooper Basin twice saw the development of large lakes, of about 250 by 150 km in size, in both cases extending diachronously westwards. This suggests blocking of the drainage at the northeastern end of the basin and backfilling of the lakes towards the southwest (Stuart, 1976), perhaps because of ponding as a result of global eustatic highstands, or tectonic movement along the Karmona trend. Although some workers have postulated restricted sea conditions instead, there is no evidence for marine environments, or for any marine connection to the open ocean. The first lake was infilled by deltas and the reclaimed territory converted to peatlands, which were in turn inundated when the second lake formed and encroached westwards (Thornton, 1979).

Highlands still existed in central Australia, and in the western New England - Yarrol region between the Sydney - Bowen trough and the eastern sea. A small intermontane basin near Ashford was able to accrue coal measures, which were preserved by later down-faulting. Highlands also persisted from west of the Bowen Basin to beyond Cairns in north Queensland, as a remnant effect of earlier igneous and tectonic activity.

In a disruptive end to the time slice, a major episode of uplift and folding affected a large portion of eastern Australia, generating hiatuses from the Sydney to the Bowen Basin. The likely palæogeography of the region affected is shown in Fig. 7. The formerly marine area in most of the Bowen Basin appears to have undergone a short-lived subaerial exposure and erosion, the thickness of sequence removed being greatest in the eastern Mimosa Syncline and on the Roma and Springsure Shelves, where the whole of the Fauna III biozone is missing. The Sydney Basin embayment shallowed due to regression. The long hiatus in the Galilee Basin, which contains no rocks at all of Permian 4 age, could be a reflection of the same event. All this coincided with folding and serpentinite emplacement east of the Bowen Basin (Malone & others, 1969), both of which may have been caused by the docking of the Curtis terrane.

PERMIAN 5: EARLY KAZANIAN (UFIMIAN) (~256-258 Ma)

The incoming of Fauna IV, after the hiatus in eastern Australia, marks the beginning of the Late Permian and the base of the next time slice. This interval, though of less than 2 m.y. duration, is distinguished by an important marine transgression in many basins.

Most notable is the establishment of a seaway along the full length of the Sydney - Bowen trough, isolating the New England - Yarrol highlands from the mainland. The continuity of this seaway across the New South Wales - Queensland border has been verified by recent drilling in the northern Gunnedah Basin (M. Hill, GSNSW, pers. comm. 1986). The northwestern margin area of the Bowen Basin was claimed by a Permian sea for the first time, but on the Springsure Shelf to the south, a fluvial facies prevailed. The dying stages of the submarine Rookwood volcanism were evident west of Rockhampton. Ice-borne erratics are common in the Sydney and Gunnedah Basins, but the souce of the ice is speculative; much of the ice was probably seasonal, though remnant glaciers debouching from the adjacent mountains cannot be discounted. The small Gloucester Basin at the southern tip of the New England land mass experienced paralic conditions.

Felsic volcanism began afresh in the Drake district of New England, but apparently nowhere else in the province, even though there may have been other magmatic activity, such as near Armidale, where the Dummy Creek Conglomerate has been interpreted as infilling rim synclines formed as a result of intruding igneous diapirs (Korsch, 1977). The eastern sea, which had an embayment southwest of Warwick, was inhabited by a shelfal fauna including corals, and uninterrupted deposition was maintained for the South Curra Limestone in the Gympie Terrane.

In Tasmania, the transgression reached its maximum extent, with only the northeast and northwest corners of the state, and some islands in the east, remaining above sea level. A sea level drop at the close of the time span led to the formation of the Risdon Sandstone offshore barrier bar facies in the Hobart region (Banks & Clarke, 1987).

Transgression also continued in the Bonaparte and Carnarvon Basins. The product of sedimentation in the Bonaparte was the bryozoal biomicrite at the top of the Fossil Head Formation. Most of the Carnarvon Basin was characterized by a broad sandy shelf with a very low palæoslope (Moore & others, 1980b), but paralic facies formed along the shoreline, especially along the northern margin of the basin where debris was shed into the sea from the scarp of the active Sholl Island Fault (Kopsen & McGann, 1985; Bentley, 1988).

The Canning Basin by contrast was dominated by tectonic emergence of the southern and central portions, which were to last as dry land until the Late Jurassic. But the

Fitzroy Tough underwent subsidence instead, to become the locus of a barrier - lagoonal complex, mostly with fringing deltas in the southeast, and very shallow marine water to the northwest.

The Wagina Sandstone of the northern Perth Basin denotes marine regression in this area, as it records continental to paralic environments, including coal swamps (Playford & others, 1976). Coal-prone fluvial aggradation remained the feature of the Collie and southern Perth Basins, and appeared for the first time in the Oaklands Basin of southern New South Wales.

The main erosional terrains of the continent were little changed in broad aspect from Permian 4 times.

PERMIAN 6: MIDDLE KAZANIAN - MIDDLE TATARIAN (250-256 Ma)

Although many marine areas continued as such, the Permian 6 interval witnessed the start of the general progradation that characterized the rest of the Permian and the Triassic, when non-marine and paralic depositional sites increased at the expense of marine ones. The development of large progradational complexes on both sides of the continent, except where local tectonics determined otherwise, points to a eustatic drop in sea level as the common cause. The base of the time slice is set at the beginning of the regression in the Sydney and Gunnedah Basins (which allowed the deposition of the important upper coal measures succession in eastern Australia); it also corresponds to the beginning of regression in the Bonaparte Basin, and approximately to the change from marine to non-marine/paralic in the Cressbrook-Buaraba Block of southeastern Queensland. The 250 to ~256 Ma date of the interval is based on K-Ar dating of latites at the base of the Illawarra Coal Measures and the Harland & others (1982) time scale, but as noted previously, if a U-Pb zircon date of 266±0.4 Ma from the middle of the Tomago Coal Measures by Gulson & others (1990) is confirmed, this time slice would be considerably older.

The Sydney and Gunnedah Basins filled with deltaic and fluvial coal measures, as clastics poured in from adjacent uplifted areas in New England, and to a lesser extent from the western Lachlan highlands. The major anticlines in the northern Sydney Basin were also active. The main progradation direction was southerly along the basin axes, but most detritus was introduced into the depositional system from the sides via alluvial fans. Early in the interval, subsidence of the eastern parts of the basins briefly admitted the sea (the Kulnura Marine Tongue and equivalents), and promoted the growth of an extensive alluvial fan apron along the western margins (Marangaroo Conglomerate) (Brakel, 1984 ; Havord & others, 1984; Hunt & others, 1986). Another marine incursion (Dempsey Formation and equivalents), this time eustatic in nature (Brakel, 1986), marked the end of the time slice.

Volcanoes were active in the southeastern Sydney Basin at the start of the interval (the Gerringong latitic eruptions). Later, felsic volcanism began further north on the eastern side of the basin off Newcastle, contributing tuffs to the Tomago Coal Measures, and one of these tuffs, the Thornton Claystone, originated in a lateral blast eruption which devastated a forest and laid out the tree truncks in a NE-SW orientation (Diessel &

others, 1985). Granitic intrusion accompanied the uplift and consequent erosion in New England, and where magma broke through to the surface between Drake and Armidale, a major eruptive region developed, generating terrestrial felsic volcanics (including the Annalee Pyroclastics), and some marine volcanics on the northeastern fringe. Actual vents have been identified and described (e.g. by McPhie, 1986). There was also some andesitic activity in southeastern Queensland. The Gympie Terrane, initially continuing with carbonate deposition, changed over to sandstone and shale shelf clastic sedimentation.

The Bowen Basin remained marine at first, with continuing transgression in the west and onto the Springsure Shelf leading into the southern Galilee Basin. Dropstones, rafted in by seasonal ice (Draper, 1983), are abundant at some levels. Late in the interval a coal-prone deltaic facies prograded from the north (Moranbah and German Creek formations), to be interrupted by the same eustatic highstand responsible for the Dempsey Formation in the Sydney Basin. The small Moorlands Basin, between the Galilee and Bowen Basins north of Clermont, experienced three marine episodes interspersed with paralic and fluvial interludes, including peatland development (Sorby & Scott, 1988).

Extensive fluvial coal measures deposition resumed in the Galilee Basin, and later in the Cooper Basin, to enlarge these basins to their greatest ever areal extent. Outflow from both basins was into the Bowen Basin sea via the Springsure Shelf embayment. The Galilee Basin was bordered by highlands of moderate relief, with some uplift in the east (Hawkins, 1978). In the Cooper Basin, subsidence was greatest at the southeastern end, and especially in the troughs, while the adjacent anticlinal ridges, such as the Gidgealpa-Merrimelia-Innamincka culminations, stood above the depositional plain. Some lakes were present within the peatlands.

Rifting in two places on the site of the later Laura Basin on Cape York Peninsula, attended by some rhyolitic volcanism, allowed entry of the sea in places and the initiation of paralic and fluvial facies, some with impure coal seams (de Keyser & Lucas, 1968). The small Mount Mulligan and Olive River Basins preserved wholly terrestrial coal measures sequences, in the former because of contemporaneous faulting. North from Olive River there is no indication whether land or sea was present.

In the Bonaparte Basin, an early marine shelf setting was succeeded by the construction of the delta and lagoon complex of the Cape Hay Member of the Hyland Bay Formation (Bhatia & others, 1984; Mory, 1988). This enormous delta was more than twice the size of that of the Mississippi. Similarly, the eastern Fitzroy Trough received large volumes of deltaic and fluvial fill (Condren Sandstone), while the western portion stayed marine. Late in the interval (lower Hardman Formation), the sea briefly re-invaded the site, until displaced by barrier bar and accompanying lagoonal facies encroaching over the area.

The remainder of the continent saw little change from its condition in Permian 5 time. Some marine advancement continued in the Carnarvon Basin, to be reversed in the later half of the time span causing the region to become emergent. Three regression-transgression cycles have been recognized in Tasmania, each transgression exposing successively smaller areas in the southeast of the state to open marine levels of salinity, the rest of the marine area being brackish (Banks & Clarke, 1987). Tasmania then lay in an embayment with the western side formed by the northern Victoria Land sector of Antarctica, which, because no contemporaneous sediments occur there (Barrett & others, 1986), was probably erosional land. Brackish conditions would have come about by the influx of fresh water into the restricted bay. Ice-rafted debris, some up to 2 m across, were still being dropped in, perhaps by pack ice. Littoral deposits formed in places around the shores of the gulf. A high proportion of silicic tuff in the upper part of the sequence 30 km south of Hobart testifies to some local volcanism.

The large deltaic complexes in the Bonaparte Basin and Fitzroy Trough point to considerable erosion in the central Australian hinterland, but this is not shown on the map because the exact location of eroding areas is uncertain, and at least one intermontane basin is known from the region. The eustatic fall in sea level intimates that the Scott Plateau area may have been subaerial once more, and probably remained so for the rest of the Permian.

PERMIAN 7: LATE TATARIAN (248-250 Ma)

The last Permian time slice, of but short duration, represents the culmination of the Late Permian progradation, when very few marine domains were left within the present day coastlines. It was characterized by the most widespread coal deposition the continent has ever known, for every non-marine basin from Cape York to Tasmania and across to Perth was storing up coal (Harrington & Brakel, 1989; Brakel & Totterdell, 1988). The base of the interval is defined as the base of the economically important Newcastle Coal Measures, which corresponds to the recession of the aforementioned short-term eustatic marine incursion. The top of the Permian is taken as the top of the *Protohaploxypinus reticulatus* palynozone and its equivalents. A U-Pb zircon date of 256 ± 4 Ma from near the top of the Newcastle Coal Measures (Gulson & others, 1990) would make the time slice somewhat older than the dates intimated by the Harland & others (1982) scale.

After the eustatic interruption, the subsiding Sydney-Bowen foredeep was again overwhelmed by detritus shed from actively rising highs in the orogen to the east, and to a lesser extent from westerly sources. The Sydney Basin was at first occupied by deltaic peatlands, but with continuing southerly progradation alluvial fans advanced into the depositional site from the north and northeast (Brakel, 1989a). In the northern proximal areas, raised peat bogs formed on the fan surfaces during quiescent periods, leading to coal seams becoming sandwiched between thick conglomerates. Large volumes of tuff were contributed to the Newcastle and Wollombi Coal Measures, mostly from volcanic centres along the Northumberland Ridge to the east. One eruption took the form of a Mt. St. Helens - type laterally directed blast, which devastated a forest and laid out the tree trunks in an ENE-WSW orientation, with a thick blanket of volcanic ash completely overwhelming the peat swamp in which the trees were growing (Diessel, 1985). The climate was still cold temperate (Riek, 1972). The coal measures were succeeded by braided fluvials of the basal Narrabeen Group, but some reports of glauconite and foraminifera near their mutual boundary suggest a short-lived interlude of marine influence between the two units, at least locally. The Gunnedah Basin, upstream from the Sydney Basin, exhibits a similar depositional history of upper delta plain facies being covered by fluvial plain and alluvial fan coal measures (Hamilton & Beckett, 1984). Again a southerly drainage system prevailed. As with the Sydney Basin, volcanic ash was repeatedly showered over the region, in this case mainly originating from the eruptive complexes in New England.

The Bowen Basin history at this time was also one of infilling, with marine and deltaic facies being succeeded by fluvial systems. A cool temperate climate prevailed over the region (Rigby, 1972), and peatlands were widespread until Rewan Group times. Progradation initially followed a radial pattern from the basin sides, before proceeding along the basin axis. Palæocurrent measurements by Jensen (1975) show southerly- and northerly-directed currents in the north and south of the exposed portion of the basin respectively, converging on the central area, and consistent with tributaries supplying a trunk drainage flowing easterly out of the basin. The higher sulphur levels in the coals of the central eastern margin area (Hunt and Brakel, 1989) confirm that the last remnant of the sea occupied this area before its final expulsion. A few spinose acritarchs reported from near the base of the Rewan Group in the southeastern Bowen Basin (Foster, 1979) hint that the sea was still not far away when coal deposition ended there. Much addition of tuff is again evident in the coal measures, and although the locations of the source vents are not established, they probably lay along the eastern side of the basin (Connors Arch and Auburn High). The volcanic arc would have had at least one gap, similar to the gaps in the modern Sunda Arc, to allow out the drainage from the Bowen Basin.

Intensified tectonism generated a number of local unconformities in the Sydney - Bowen trough in latest Permian - Early Triassic time. Even where there was no structural tilting, regional scour surfaces were developed at the bases of the Narrabeen Group, Digby Formation and Rewan Group, in response to a widespread change in the eastern Australian crustal stress regime.

Along the eastern side of the New England - Yarrol highlands, the sea was forced back by the continuing uplift in the orogen. Conditions in the Gympie Terrane remained shallow marine, but with mainly mud being deposited.

The Galilee and Cooper Basins continued as large expanses of coal-prone fluvial deposition, draining easterly into the Bowen Basin. Differential subsidence in the Cooper Basin troughs attracted meandering streams to the lower areas (Wells & O'Brien, 1989); lake-dominated areas also existed, some bordered by erosional highs (Thornton, 1979).

The state of the small basins at Oaklands and far north Queensland was little changed. Tasmania shared the progradational, coal-forming experience of the main eastern Australian basins, as the former marine embayment was filled in by the Cygnet Coal Measures and equivalent fluvial formations. Much of the sediment appears to have been sourced in northern Victoria Land, and may have reached its final resting place after up to 2000 km of transport via an arcuate river system (Barrett & Fitzgerald, 1985). Postulated uplift and erosive areas in NE, NW,and SW Tasmania (Banks & Clarke, 1987) imply some contribution of detritus from these regions as well.

The coal measure theme was reiterated in the southwestern corner of the continent, by the upper Sue Coal Measures and minor coal in the Sabina and Wagina Sandstones of the Perth Basin. The latter two formations, though predominantly fluvial, seem to become increasingly paralic towards the north (for example, acritarchs at the base of the Sabina Sandstone indicate brackish - ?marine water), hinting at a marine incursion in the north of the basin. A coal-forming environment may also have lingered on in the Collie Basin, but if so, the sedimentary record has not been preserved.

Most of the Carnarvon Basin remained subject to subaerial erosion. The northern end of the basin, however, was reclaimed by the sea, and a sandy marine shelf formed with localized concentrations of skeletal carbonate debris in banks and shoals (the Chinty Formation of Hocking & others, 1987). The Sholl Island Fault scarp was probably still shedding an apron of rubble into the adjoining paralic and maritime zones.

A similar limited marine incursion in the southwestern Canning Basin led to the inception of the Chirup Formation in the coastal marshes at the head of the embayment (Forman & Wales, 1981). In the Fitzroy Trough, where a lagoonal setting had come into being late in the previous time slice, a large fluvial lobe, this time supplied from the Kimberley uplands, built out into the central part of the repository. Meanwhile, at the southeastern extremity of the trough, lagoonal tidal flat sediments of the Godfrey beds were being laid down. The sedimentation style was transformed by the sudden marine intrusion represented by the upper Hardman Formation, when the site received first shallow marine muds and minor carbonate, then nearshore and coastal sands, and eventually even minor coal as progradation began to be re-asserted. The interval ended with most of the trough being temporarily non-depositional, revealed in the stratigraphic record by a hiatus.

The large delta in the Bonaparte Basin was drowned beneath the advancing waters of a marine transgression, after which a smaller delta was re-established in a lagoonal tract behind a prograding barrier bar. Presumably the new delta was also furnished with clastics eroded at least in part from the central Australian highlands. The northern sector of the basin was maintained as a marine shelf throughout the Late Permian. As in previous time slices, there may have been equivalents of the Bonaparte shallow marine sequence in the Arafura Basin. This portion of the continent had a warmer climate than any other region at any time during the Permian, becoming warm temperate to tropical (Dickins, 1978).

PERMIAN ENERGY & MINERAL RESOURCES

OIL AND GAS

The Permian system is a critical one with regard to the distribution of energy resources in Australia. Economic and sub-economic oil and gas accumulations occur in the Bonaparte, Cooper, and Bowen Basins, but even more importantly, many of the larger accumulations reservoired in the Mesozoic sequences of the Eromanga and Surat

Basins were sourced from the underlying Permian. The extensive coal deposits present in many of the Permian basins appear to have been particularly significant in the generation of oil and gas. The data maps show the location of representative oil and gas occurrences by age of reservoir.

Bonaparte Basin

The Bonaparte Basin is notable for the Tern and Petrel gas fields, both currently (1989) sub-economic. The Tern reservoirs lie at the top of the Late Permian Hyland Bay Formation, and consist of lower shoreface zone sands (Bhatia and others, 1984). The Petrel reservoirs occur lower down in the same formation, and were deposited as sands in estuarine channels, tidal bars and mouth bars, within lower delta plain and adjoining delta front platform settings. A minor gas accumulation in Penguin 1 is present in shallow marine calcareous sandstone, at the base of the Hyland Bay Formation (Lavering & Ozimic, 1989) (top of Fossil Head Formation according to Bhatia & others, 1984). Oil shows have been encountered in Barnett 1 in both shallow marine limestone of the Hyland Bay Formation, and in marginal marine sandstone of the Late Carboniferous - Early Permian Kulshill Group. Other oil shows in the Kulshill are known from Lacrosse 1, Turtle 1, and Kulshill 1 (Lavering & Ozimic, 1989), in fluvial, deltaic, and shallow marine facies respectively. The best Kulshill reservoirs are generally restricted to the upper part of the formation and the south of the basin (Gunn & Ly, 1989).

Canning Basin

The majority of hydrocarbon shows in the onshore portion of the Canning Basin are bitumen and asphalt in the Grant Group (Foreman & Wales, 1981), particularly in the shallow water glaciomarine sands of the Betty Formation, where porosities (commonly >20%) and permeabilities are usually highest. Exploration at this stratigraphic level was stimulated by the oil discoveries in the West Terrace and the Sundown oil fields, the latter producing from two quartz sandstones. Large palæochannel systems exist within the Grant Group, with interfluvial highs, and to a lesser extent, channel-form pinch-outs, providing attractive but high-risk drilling targets (Goldstein, 1989). Potential reservoir sands, with porosities up to 30+%, also occur at the top of the Grant Group, but shows at this level are rare, casting doubt on the seal quality of the overlying Nura Nura Member, even where it contains tight carbonates, shales, and siltstones, as in the northwest (Goldstein, 1989). The Artinskian fluvial, lagoonal, and barrier bar Poole Sandstone , with porosities ranging to over 30%, ought to contain good reservoirs, but the seal quality of the overlying Noonkanbah Formation is suspect, and the unit is also stratigraphically remote from mature source rocks. Shales within the Grant Group, Nura Nura Member, and particularly the shallow marine Noonkanbah Formation may be source rocks (Forman & Wales, 1981); the last named consistently shows high total organic carbon (TOC) up to 6% in the wells sampled (Burne & others, 1979). Though some sandstones within the Noonkanbah have the potential to act as reservoirs, organic maturity of the formation is often insuffient. However, the interval may be mature in the eastern Fitzroy Trough and in parts of the Kidson Sub-basin (Forman & Wales, 1981). The thermal maturation study of Nicoll & Gorter (1984) suggests that the oil generation window may be restricted to a zone 1100 m thick, between 1600 to 3000 m depth, except where younger intrusives have increased the heat flow and raised the top of the zone to as shallow as 800 m. There is very little information on the offshore Canning Basin.

Onshore Carnarvon Basin

Both the glacio-fluvial to glacio-marine Lyons Group and the shallow marine Byro Group contain few known sandstone units of sufficient quality to be potential reservoirs, because of a high proportion of clay matrix and widespread diagenesis (Lavering, 1985). Although Kennedy Range 1 produced gas shows from thin sandstones in the Bulgadoo Shale of the Byro Group, the sands are very tight. Lavering nominated the deltaic Moogooloo Sandstone of the Wooramel Group as the best reservoir unit with a top seal and an underlying source rock; the shallow marine Kennedy Group has very good reservoirs, but lacks seals, and the associated source rocks are immature. He also noted that the source material in the onshore Carnarvon sequence is possibly gas prone, and potential reservoirs have moderate porosity but little permeability, downgrading the potential for the commercial recovery of liquid hydrocarbons. Likely hydrocarbon sources in the Merlinleigh Sub-basin are siltstones in the Byro Group, and calcilutites in the shallow marine Callytharra Formation and Wooramel Group (Percival & Cooney, 1985).

Offshore Carnarvon Basin

The Permian of the offshore (northern) Carnarvon Basin lies just within the oil-generative window (Forrest & Horstman, 1986), but despite about 200 wells drilled in the region, very few have reached the Permian, because most set out to test only Mesozoic targets. The Palæozoic has usually been regarded as economic basement, probably influenced in part by a study of kerogen in Onslow 1 and Flinders Shoal 1 which indicated that the oil source potential of the Permian is poor in these wells (Demaison & Shibaoka, 1975). However this is not true everywhere in the region, nor does it exclude the possibility of gas generation.

Thin coaly claystones in the Kennedy Group with 3-8% TOC, which formed as lagoonal swamp facies interfingering with barrier bar sands, have good source potential (Bentley, 1988). A stack of thick massive sandstones, interpreted as either offshore barrier bars (Bentley, 1988) or wave-dominated delta cycles (Delfos & Dedman, 1988), usually occurs in the middle of the Kennedy Group and have good porosities averaging up to 30%, making it an exploration target where a sealing formation can be found. An intraformational seal is unfortunately lacking, but where the unit has been juxtaposed against the Triassic Locker Shale, itself a source rock, a lateral seal might be formed. Syndepositional activity on the Sholl Island Fault has had important conflicting palæogeographic effects on both source rock and reservoir potential to its west: the coarse clastics shed from the fault and beyond may have led to the localised development of reservoirs along the fault, while diluting potential finer-grained organic-rich source beds (Delfos & Dedman, 1988; Bentley, 1988). This almost mutually exclusive development of key facies is probably the reason why a rollover structure in this area, ideally suited to trap hydrocarbons, seems to be unprospective.

The latest Permian Chinty Formation, a basal transgressive sand, has good quality reservoir sandstones, and may host hydrocarbons from the adjacent Locker Shale, or perhaps from lower in the Permian section (Parry & Smith, 1988).

Shales in the Byro Group (Permian 4) were deposited in shallow marine reducing conditions, and may have generated hydrocarbons. Shallow water sandstones are common at the top of the unit, and have porosities of 15-22%, but the seal formed by the Kennedy Group is poor (Bentley, 1988).

The basal Permian Lyons Group, though argillaceous, is generally believed to lack source potential because the prevailing glacigene depositional setting is assumed to have been inimicable to the development of organic-rich sediments (Delfos & Dedman, 1988). However, Domak (1988) has shown that a time of sediment starvation follows the retreat of a polar marine ice shelf, so that organic-high sediments can accumulate. Glacioeustatic falls in sea level might restrict circulation in some areas, resulting in kerogen-rich deposits. Also, coals and organic-rich mudstone can accumulate on the distil parts of glaciofluvial outwash plains (Boothroyd & Ashley, 1975; Thornton, 1979). Subglacial tunnel valley infills could in theory form reservoirs large enough to be possible targets, and any sand or gravel facies in the outer glacial or periglacial zones may have good reservoir characteristics (Brakel & others, 1988). Thus although glacigene facies represent high risk for petroleum exploration, their potential should not be overlooked. The Lyons Group may also act as a seal for the underlying Carboniferous Quail Formation.

Permian igneous activity, interpreted as volcanism, occurred around Enderby 1 and Edel 1 in the northern and southern offshore Carnarvon Basin respectively, and may have locally raised the geothermal gradient and affected organic maturity.

Seismic work suggests the existence of Palæozoic rocks in the Exmouth Plateau, which are inferred to include equivalents of the marine Permian in the Carnarvon Basin (Exon & Willcox, 1978, 1980). Such rocks would have been buried deeply enough to have sourced hydrocarbons, in contrast to the younger immature sequence deposited since the Mesozoic continental break-up.

Perth Basin

In the northern Perth Basin, gas has been produced from Permian levels in three fields. The reservoirs in the Dongara district include the Early Permian fluvial Irwin River Coal Measures and the Late Permian fluvial Wagina Sandstone, the source of the gas in both cases being the associated coal and carbonaceous shales. These units are productive despite low permeabilities, and, in the case of the Wagina, low porosities of only 5-15% (Hall, 1989). Thin, discontinous sandstones with 11-20% porosity in the nearshore Early Permian Carynginia Formation also produce gas. The main reservoir of the Woodada Gas Field is coquinitic limestone of the same formation, but because of extensive diagenesis, production has to rely on secondary fracture porosity. Of the other possible reservoirs in the sequence, sands in the glacigene

Nangetty Formation are usually tight, except locally (Wicherina 1), but those within the overlying Holmwood Shale in Abbarwardoo 1 and Wicherina 1 have good characteristics (Hall, 1989). The cold water marine Holmwood Shale itself is a gas-prone source rock, with TOC up to 3.3% in those muds laid down in reducing conditions, and also forms a seal for the enclosed sand members and the Nangetty Formation. The Irwin River and Carynginia reservoirs are sealed intraformationally. The Permian in the Dandaragan Trough has been buried to such great depths that any reservoirs are assumed to be too tight to be prospective. Organic maturity data indicate that only the Dongara - Woodada and part of the adjacent offshore region lies in the oil window, with a gas-only zone to the south (Hall, 1989). Farther offshore, in the Yalthoo Trough, the Permian sequence contains few potential reservoirs, lacks good seals (except within the Irwin River Coal Measures), does not contain good source rocks, and appears to lie within the gas-generating zone (Smith & Cowley, 1987).

No commercial fields have been found in the southern Perth Basin, but shows of gas have been obtained from the fluvial Sue Coal Measures in Whicher Range 1 and Wonnerup 1 (Jones, 1976). The coal measures are a gas-prone source, and have intraformational seals, but the permeabilities of reservoir lithologies are very low because of diagenesis on deep burial. The predominantly fluvial latest Permian Sabina Sandstone has the porosity to store gas coming up from the coal measures, but lacks a seal (Hall, 1989).

Officer, Arckaringa, and Pedirka Basins

The Paterson Formation of the Officer Basin appears never to have been buried deeply enough to reach organic maturity, and so must be written off as a hydrocarbon generator even if rare occurrences of source lithologies could be located in this glacigene and glaciofluvial environment. The upper fluvially-dominated portion could be expected to contain potential reservoirs, but their hosting of hydrocarbons is dependant on the possibility of migration from deeper sources, such as the playa facies in the Cambrian (Cook, 1982), through the mud-rich diamictites at the base of the Paterson. Downgrading the petroleum potential of the Permian section still further, flushing of the formation (Jackson & van de Graaff, 1981a) may be a problem.

The Arckaringa Basin is very much a frontier region for exploration. Moore (1982) has upgraded the previous very pessimistic assessments of the basin, and noted that sediments in the deeper parts of the Boorthanna Trough lie within the oil window, with the basal shaly member of the glaciomarine Boorthanna Formation having some source potential. The quality of source rock in the marine Stuart Range Formation is generally good, and an excellent potential source rock exists in the paralic lower Mt Toondina Formation, but they are usually immature. The upper Mt Toondina coal-bearing sequence should be gas-prone, if it has reached the requisite maturity anywhere. Several thick sandy and conglomeratic units dominating the Boorthanna Formation have very good porosities and permeabilities, with the Stuart Range Formation providing an excellent seal. The reservoir qualities of Mt Toondina Formation sandstones are generally poor (Moore, 1982).

The Pedirka Basin's petroleum prospects are also poorly known. The coals and carbonaceous shales of the Purni Formation constitute source rocks which are probably gas-prone, and in the deeper eastern part of the basin they may have reached organic maturity (Youngs, 1976). In Mokari 1, for example, the main coal-bearing section lies between 1800 to 2000 m depth, with the rest of the Permian extending down to about 2250 m. At least some of the fluvial sandstones in the Purni Formation would qualify as reservoirs, because they form good aquifers, but this in turns means that most of the hydrocarbons may have been flushed from them. Many potential reservoir units may not have been flushed, however. Shales in the fluvial sequence could act as seals, as could any overlying Triassic shales. The Purni Formation warrants greater attention, especially as it is situated between the gas fields of the Amadeus and Cooper Basins, and could be connected to the distribution pipelines of either fairly easily (Youngs, 1976). The glaciofluvial Crown Point Formation, like the Grant Group in the Canning Basin, may provide high-risk targets.

Cooper Basin

The Cooper Basin is the most prolific hydrocarbon-bearing Permian basin in Australia, and is the sole source of natural gas for New South Wales and South Australia. To date (1989), 18 oil fields and 121 gas fields have been discovered (L. Pain, BMR, pers. comm.). As well as reservoiring hydrocarbons, the Permian sequence is the source of the bulk of the oil in the overlying Mesozoic Eromanga Basin (Gilby & Mortimore, 1989; Jenkins, 1989; Heath & others, 1989). Gas accumulations occur in every formation, except the glacigene Merrimelia Formation and the lacustrine Murteree and Roseneath Shales. Oil has been recovered mainly from the braided-fluvial Tirrawarra Sandstone, and in lesser amounts from the meandering-fluviodeltaic Patchawarra and Toolachee Formations.

The Merrimelia Formation contains a variety of sub-facies, including glaciofluvial outwash, tillite, glaciolacustrine muds and rippled sands, and paraglacial eolianites. Some of the lacustrine muds might be rich enough in algal remains to be source rocks (Battersby, 1976), and some of the better-sorted sands may form locally developed reservoirs (including the tops of porous eolianites as suggested by Williams & others (1985)), but detailed palæogeographic studies will be required to delineate such plays. The formation interfingers with the Tirrawarra Sandstone, leading to the possibility that tongues of hydrocarbon-bearing Tirrawarra facies may be stratigraphically trapped in seal lithologies of Merrimelia Formation in such zones (Williams & Wild, 1984a). The Tirrawarra Sandstone holds over 95% of Cooper Basin oil, and 12% of the gas (Heath, 1989); it is dominated by thick, multistorey sandstones typical of low-sinuosity, braided, bedload fluvial channels, but also contains source beds such as minor coals.

The Patchawarra, Epsilon, Daralingie, and Toolachee Formations are coal measures units which were deposited as lacustrine deltas or fluvial systems. As such, they contain an abundance of organic source material, as well as channel and delta front sandstone reservoirs, and intraformational seals. The lacustrine Murteree and Roseneath Shales provide regional seals to the Patchawarra and Epsilon Formations respectively. Palæogeographic controls operated to determine the locations of channel belts, and thus of potential reservoirs: for example, the Nappermerri Trough subsided faster than elsewhere, resulting in most stream channels being concentrated there. Porosity, being dependant on the depth of burial, is almost twice as high over the main palæo-highs as in the major troughs, and is higher still towards the basin margins (Heath, 1989). Continued uplift along the palæo-highs after the mid-Permian ensured the further structural growth of most Patchawarra closures before hydrocarbon generation and migration (Heath, 1989). Thirty per cent of the gas-in-place in the Cooper Basin is in the Patchawarra Formation, while about 40% is located in the Toolachee - Daralingie formations.

Galilee Basin

No hydrocarbon accumulations of consequence have been found in the Galilee Basin to date (1989). Apart from a Late Permian marine incursion across the Springsure Shelf in the SE, the entire sequence is non-marine. The best source rock potential occurs in the Aramac Coal Measures, and the Colinlea Sandstone and Bandanna Formation correlatives (Hawkins, 1978; Hawkins & Harrison, 1978; Scholefield, 1989). Sapropelic debris which collected on lake bottoms (such as the torbanite oil shale near Alpha) is especially likely to have yielded light to intermediate hydrocarbons. Vitrinite reflectances and temperature gradients indicate that the sequence is in the lower half of the oil window. Good reservoir lithologies are present in the Aramac Coal Measures and Colinlea Sandstone, with porosities up to 23% and 16% respectively; stratigraphic traps containing these sands may have been formed where distributary channels became enclosed by fine-grained floodbasin deposits, or, in the Lovelle Depression, in the form of sand wedges against syn-depositional fault scarps (Hawkins, 1978). Intraformational shales, or the overlying Triassic beds, could provide suitable seals. The mid-Permian period of erosion may be partly implicated in the apparent absence of oil and gas in the pre-Colinlea section – as Hawkins & Harrison (1978) have pointed out, during this hiatus in the Galilee Basin, sediments were being deposited in the adjacent Cooper and Bowen Basins which now contain hydrocarbon reserves.

Torres Shelf, Olive River and Sub-Laura Basins

The Permian sequences in these small repositories contain coal in places, and carbonaceous shales relatively rich in humic kerogen. The potential source rocks of the Torres Shelf (and, presumably, the Olive River Basin) have reached oil generation maturity, but the sub-Laura sequence is overmature, even though there is no evidence for deep burial, suggesting a high geothermal gradient. No potential reservoirs are known, and sandstones in the Jurassic-Cretaceous succession appear to be flushed (Smart & Rasidi, 1979). In any case, as the Mesozoic is only marginally mature, it is probable that most hydrocarbons were expelled from the sub-Laura Permian before the later deposits were emplaced.

Bowen Basin

The Permian succession of the Bowen Basin is largely gas-prone: Allen's (1980) listing indicates a ratio of gas to oil fields of 19:7. The organic maturity of the eastern side of the outcropping portion of the Bowen Basin is even beyond the peak of gas generation (based on the vitrinite isoreflectance maps of Beeston (1981) and Middleton (1989)), but nevertheless this region still has noteworthy potential for methane drainage from the Late Permian coal seams (Bell, 1987). The organic maturity decreases to the south, until south of Meandarra, and northwards from there along the basin edges, the sequence lies within the oil window (Thomas & others, 1982). The known hydrocarbon accumulations are small, and occur in three areas - the Moonie district, the Roma Shelf, and the Denison Trough. However, most, if not all, of the discoveries in the overlying Surat Basin were also sourced from the Permian (Thomas & others, 1982).

Source rocks are generally within coal-bearing intervals of the Reids Dome beds and the Back Creek and Blackwater Groups. The Bandanna Formation contains a 0.7 m - thick oil shale (torbanite). The shallow marine muds of the Denison Trough sequence (Black Alley Shale, Peawaddy Formation, Ingelara Formation, and particularly the Cattle Creek Formation), also have fair to good source potential (Jackson & others, 1980). But although lying within the oil-generative zone, the Denison Trough has a preponderance of humic kerogen, and is therefore gas-prone (Paten & others, 1979). Below the Surat Basin, Permian sandstones generally lack good porosities and permeabilities, due to their lithic and argillaceous natures; in places where better reservoir properties do occur, hydrocarbons have been produced (Butcher, 1984). Locally, palæochannels have been concentrated between isolated highs, and Cosgrove & Mogg (1985) have interpreted potential alluvial fan reservoirs in the upper Tinowon Formation. Gas has flowed from the Camboon Andesite in Burunga 1 and Scotia 1 (Elliott, 1989). In the Denison Trough, gas has been discovered in all the sandstone-dominated formations between the upper Reids Dome beds (a coal measures unit) and the high-energy nearshore Mantuan *Productus* bed at the top of the Peawaddy Formation, with the thick, fluviodeltaic Aldebaran Sandstone being an important reservoir formation in the succession. The Late Permian Bandanna Formation, also gas-bearing, should contain a variety of reservoir sand types in its meandering-fluvial, deltaic, and shoreline facies. In general, these units are not as permeable as those of the Roma Shelf. Zones with good reservoir characteristics in the upper Reids Dome beds are associated with marginal marine settings (Draper & Beeston, 1985b). Sealing lithologies are provided regionally by the marine shelf mud formations and, in some areas, by the Early Triassic Arcadia Formation of the lower Rewan Group. Intraformationally, shallow marine sandstones can be entirely encased in shales, and flood plain silts can enclose the coarser sediments of channel belts and alluvial fans.

Gunnedah Basin

No commercial hydrocarbons have been located in the basin so far, but a sub-commercial gas field has been discovered at Wilga Park 1. Other gas shows have been encountered in the Porcupine, Watermark, and Black Jack Formations, and an oil show has been observed in the Early Permian Boggabri Volcanics. The Permian sequence is usually in the early part of the oil generation zone, and has reached greater maturity near some igneous intrusions, so that the hydrocarbon potential is considered high (Hamilton & others, 1988). The best source rocks are in the shallow marine Watermark Formation, and in the Arkarula Sandstone Member, a marine intercalation within the Black Jack Formation; the Maules Creek Formation (a coal measures unit), and the rest of the coal-bearing Black Jack Formation have only fair, but still significant, oil source potential. Good highly-permeable reservoirs may be found in the quartzose sandstones of the lower Black Jack, and the Clare Sandstone Member, derived from westerly sources. Easterly derived sands, being of volcanolithic composition, have very poor reservoir characteristics, unless they were cleaned up and their porosity improved somewhat by being re-worked in littoral or tidal shallow marine situations, such as occurred at some levels in the upper Watermark and lower Black Jack Formations. The Permian could also have supplied hydrocarbons to suitable reservoir lithologies in the Triassic and Jurassic. Regionally extensive shales, laid down either by marine incursions or lacustrine episodes, cap most potential reservoir units, and more local seals are provided by other intraformational shales, particularly within the coal measures (Hamilton & others, 1988).

Sydney Basin

The search for oil and gas in the Sydney Basin has been unsuccessful, due mainly to the tightness of putative reservoir lithologies. The cause has a palæogeographic background, in that the sandstones are lithic and clay-rich because of their derivation from the uplifted New England Orogen. The largest permeabilities occur in the Illawarra Coal Measures, in the Marrangaroo Conglomerate alluvial fan / fan delta, and in a quartzose sandstone below the Tongarra Coal, but range up to only 10 md (Herbert, 1987). However, better reservoir units have been identified in the Triassic Narrabeen Group (Herbert, 1987; Hamilton & Galloway, 1989), signifying that examination of the Permian section for hydrocarbon generation is not academic. The coals and carbonaceous shales of the coal measures units are obvious source rocks, as are the lenses of oil shale they contain in places. Shows of free gas and oil have been encountered in the Illawarra Coal Measures, and to a lesser extent in the shallow marine Shoalhaven and Dalwood Groups. Coal rank studies of the top of the Permian (Middleton, 1989) show that the centre of the basin is overmature for oil, but may be a gas generator. Also not to be overlooked is the methane drainage potential of the coal seams; two collieries south of Sydney are currently using their drained methane for small-scale electricity generation to power mine plant, with any surplus being fed into the domestic electricity grid (Bishop & Callinan, 1987).

Torbanite oil shales are known from 34 localities around the margins of the Sydney Basin, and several of these deposits were worked in the period 1865-1952 (Mayne, 1970). All are associated with the coal-bearing sequences: 30 occur within the Late Permian coal measures, 3 in the Early Permian Greta Coal Measures, and 1 in the Early Permian Clyde Coal Measures. The deposits are developed as lenses in coal or carbonaceous shale, and originated as algal muds at the bottoms of open bodies of water within peat swamps. The largest, in the Glen Davis - Newnes district, is continuous over an area of 35 km^2 and has a maximum thickness approaching 2 m (Morris, 1975); it lies within the Glen Davis Formation of the Illawarra Coal Measures (Permian 6).

Murray Infra-basins and Oaklands Basin

No hydrocarbon assessments appear to have been published on the largely glacio-marine Early Permian Urana Formation. Like its correlates in other basins, it may have appropriate localised source rocks and reservoirs, but finding these would be difficult and would entail high risk. The best reservoir candidates are the conglomerate and coarser sandstone facies, formed in beaches, deltas, subaqueous outwash fans, or current-swept shallow sea beds. The abundant shales and diamictites could furnish any intraformational seals required. The Late Permian fluvial coal measures of the Oaklands Basin should contain source, reservoir, and seal lithologies, but with a vitrinite reflectance of only 0.36% (Middleton, 1989), the rocks are organically immature.

Tasmania Basin

The only oil production in Tasmania has been on a small scale by distillation from the *Tasmanites* oil shales in the northern region of the state (Clarke & others, 1976b). These developed in nearshore areas following the withdrawal of the ice late in the Permian 1 interval. Freshwater torbanite is associated with the Mersey Coal Measures and equivalents, but the occurrences are too limited to be of economic interest (Banks & others, 1989). The oil shales would be excellent source rocks, were it not for their general organic immaturity; similarly, the coals and carbonaceous shales in the two coal measures are only immature to marginally mature, with a peak vitrinite reflectance of 0.6% away from dolerite intrusions (Banks & others, 1989). It is possible, however, that in the deep axial portion of the basin organic maturity may have been attained, and it is pertinent that a show of mature oil in the basal Permian, similar to *Tasmanites* oil, has been recorded (Bendall & others, 1991). Reservoir lithologies would be expected in the fluvial channel fills of the coal measures, in high-energy littoral gravel or sand bodies such as the Risdon Sandstone (barrier bar, Permian 5) and the Blackwood Conglomerate (beach gravel, Permian 6), and even perhaps in the basal glacigene facies in places where sands and gravels have had the opportunity to become well-washed. However, the presence of hydrocarbons in the glacigene reservoirs is dependant on the supply from pre-Permian sources, some of which are noted by Bendall & others (1991) to be within the oil window.

COAL

The Permian is Australia's main source of black coal, which not only supplies the bulk of the national energy needs, but is currently (1989/90) Australia's largest export earner. It occurs in all states except Victoria, while in the Northern Territory it is known only in minor amounts from the Tasman 1 well in the offshore Arafura Basin. The greatest production by far comes from the Sydney and Bowen Basins: the Sydney Basin is the largest overall producer (domestic use plus export), whereas the Bowen Basin has the largest export market. The combined size of the five main eastern coal basins is comparable to that of the European Carbonifeous coal basins, which extend from Wales to the Ukraine.

It is striking that most of the coal was formed in two intervals of time, Permian 3 and Permian 6-7, the latter having the volumetrically greatest and areally most widespread coal development. The other intervals generated less coal, and glacially-dominated Permian 1 remained barren except for very minor occurrences in the Cooper and Arafura Basins. All humid depositional environments on land were potentially capable of preserving coal, given appropriate tectonic conditions. Deltaic and meandering-fluvial systems were the most productive, but also significant were braided fluvial (including alluvial fan), fluvio-lacustrine (including raised bog), and back-barrier settings. Climate played a key role in peat preservation. Low palæotemperatures greatly retarded organic decomposition, allowing vegetable matter to accumulate in situations and to thicknesses otherwise not possible, analogous to much of modern Canada and Siberia. In this context, it may be significant that the huge Late Permian delta complexes in the Bonaparte Basin and Fitzroy Trough, by forming in a time and place experiencing the warmest climate of the Australian Permian (Dickins, 1978), preserved no economic coal.

The coal basins to which the sea had access in the Early Permian (Sydney, Tasmania, Arckaringa and northern Perth Basins) followed a common sedimentary evolution during Permian 1-4 of initial marine conditions regressing to coal measures deposition. Basins dominated by rift volcanism (Gunnedah, Werrie, Gloucester, and Bowen Basins) have a thick volcanic pile substituting for all or most of the basal marine sequence, while basins beyond the reach of the sea (Pedirka, Cooper, and Galilee Basins, and Strathmuir Synclinorium) have fluvial sequences instead. The widespread accumulation of coal in Permian 3 can be attributed in part to a eustatic sea level lowstand, but other factors also played a role, because these coal measures were not all synchronous (and the Early Permian Gunnedah and northern Sydney Basin coals did not form until Permian 4), and economic coal did not form in contemporaneous deltaic or fluvial settings in the Carnarvon Basin Wooramel delta, in the Fitzroy Trough, or in the Bonaparte Basin.

The Collie and southern Perth Basins followed a different path, of coal measures being either the initial deposition, or taking over from a thin basal glacigene layer. This probably arose because these areas were at first occupied by the Yilgarn ice cap, with peatlands developing later, on a poorly drained landscape patchily covered by ice retreat sediments. The Denison Trough succession also appears to have begun directly with coal measures, at least on the trough margins, but the base of the unit in deepest part of the trough has not been intersected by drilling, and may well lie on a fluvial or volcanic substrate.

Subsequent to the Permian 3 - early Permian 4 coal-forming episodes, the general pattern for the rest of the Permian was that of a major marine inundation followed by another long period of regression, again culminating in coal measures deposition, but there were many variations on the general trend. Brief marine incursions at times interrupted non-marine sedimentation. The western and northern parts of the Bowen Basin went through two regressive cycles, the first (Permian 4) fluviodeltaic outbuilding in the west (Aldebaran Sandstone) yielding very little coal, at a time when in the north of the basin a coal-bearing alluvial fan prism (Collinsville Coal Measures) was heaped on basal Permian volcanics and older rocks. In the Cooper Basin, the large lakes which appeared twice in Permian 4 were each replaced by coal-productive peatlands as they were infilled; a hiatus occurred before coal deposition resumed towards the end of the Permian. Mid-Permian hiatuses occurred in the Galilee, Gloucester, and northern Perth Basins, and the Roma Shelf, before the onset of paralic and/or non-marine deposition. In the case of the northern Perth Basin, only token amounts of coal were formed. The southern Perth and Collie Basins were unusual in that coal accumulation continued uninterrupted there throughout most of the Permian. The small Mount Mulligan, sub-Laura, Blair Athol, and Oaklands Basins began collecting their coaly sequences with no related precursor sediments. Harrington & others (1989) describe the eastern Australian basins in greater detail. Both eustatic and tectonic controls interacted to produce the features of many basin sequences. Arditto (1987) has interpreted the Illawarra Coal Measures in terms of the response of an essentially non-marine system to changes in base level.

MINERALS

Metalliferous deposits in the Australian Permian are virtually confined to the Tasman Fold Belt System of eastern Australia, especially the New England Orogen and northern Queensland igneous province. Gold, wolfram, molybdenum, bismuth, copper, lead, zinc, silver, tin, antimony, and arsenic were emplaced by plutonism either in the intrusives themselves, or in the adjacent skarn and hydrothermal zones. Volcanism has led to gold, silver, molybdenum, and some uranium mineralization. Many of the Permian reef ores were the source of gold and tin in Cainozoic alluvial placers. Some Permian placer gold and tin deposits, and syngenetic manganese and uranium in marine sediments, also occur. The following resumé is largely derived from the reviews by Murray (1986) and Degeling & others (1986), except where otherwise indicated.

The earliest Permian mineralisation is often difficult to distinguish from that of the Late Carboniferous, because of poor age constraints on much of the metallogenesis, and apparently continuous magmatic activity in the orogenic zones during that time. Undoubtedly the most important region for ores of this age is northern Queensland, inland from Cairns, where numerous small, but high-grade, occurrences have been worked. These were formed in connection with the large volumes of felsic magma related to kinematic extension (Oversby, 1987; Mackenzie, 1987b). Granitoid intrusives carried with them Au, Ag, Cu, Pb, Sn, W, Mo, and Bi, which were deposited in veins; Cu, Mo, and Ag, emplaced as porphyry-style deposits; and Pb, Cu, Ag, and W, lodged in contact skarns where lime-rich sediments were intruded. Volcanics and their associated sediments came to host volcanigenic, bulk-tonnage, low-grade Au, Ag, Cu, Zn, U and Mo in breccia pipe, vein stockwork, and skarn bodies. Relatively little contemporaneous mineralisation was taking place in the New England Orogen, possibly in Queensland because of a plate transform margin setting interpreted by Murray & others (1987). Minor tin in sheeted veins is associated with the Bundarra Plutonic Suite in western New England, and the Hillgrove Plutonic Suite bears locally substantial Au, Ag, As, and Sb. The serpentinites along the Peel Fault hold cumulate chromite deposits, but although an age on nephrite has established Early Permian tectonism, there is evidence that the serpentinite itself (and hence the chromite) represents the remains of a pre-Early Devonian ocean floor (Blake & Murchey, 1988). The Gympie Terrane contains numerous Mn occurrences in quartzite, chert, jasper, and slate, originally deposited on the eo-Permian ocean floor, and later weathered to form residual replacement concentrations. In Tasmania, small amounts of Au and Sn were concentrated by water action in basal conglomerate (Banks & others, 1989). Recent palæomagnetic studies in the Flinders Ranges of South Australia have suggested that uraniferous quartz-hematite breccias at Mount Painter may be Permo-Carboniferous in age, although a latest Cretaceous age is also possible (Idnurm & Heinrich, 1989).

The Early to middle Permian saw the beginning of a shift in the locus of the main metallogenesis to the New England Orogen. In New South Wales, stratiform Cu, Pb, Zn, and Ag was developed in felsic volcanics at Halls Peak. In Queensland, the important Cracow gold and silver deposit was formed in an epithermal vein system in penecontemporaneous andesites. North of Cracow, the andesites contain some disseminated copper mineralisation. Volcanogenic massive sulphide orebodies occur at Mt Chalmers (Au and Cu) and Silver Spur (Ag, Pb and Cu), in silicic volcanics and graphitic slate respectively. Podiform chromite was emplaced with its host serpentinite along the suture zone bounding the western Curtis Terrane when the latter was welded to the central Queensland mainland towards the end of the Early Permian. The serpentinite also accommodates gold-bearing quartz reefs in two localities. The major Gympie gold field, in the Gympie Terrane, has no obvious source for its gold; the metal was precipitated preferentially in a favorable redox environment where quartz reefs cut across marine carbonaceous shales in volcaniclastics. Uranium was scavanged by the reducing environment of black pyritic marine shale in the lower Aberfoyle Formation near Rossarden, Tasmania, to form a low grade sedimentary uranium occurrence (Banks & others, 1989). In the Blair Athol and western Bowen Basin region, gold was eroded and concentrated in placer lodes at the base of the Permian fluvial sequence.

The Late Permian metallization is, once again, not always easy to differentiate from that of the adjoining Period. In the New England Orogen during this interval it is somewhat similar in style to that of northern Queensland at the start of the Permian, in that a wide variety of metals and types of metallogenesis are represented, as numerous deposits in granitic and volcanic rocks. Au, Sn, As, Sb, and minor W collected in veins and greisen zones in granitoids and nearby country rock; some intrusives, such as the Barrington Tops Granodiorite at the southern end of New England, acted as a heat source for mobilising the metals in surrounding sediments into hydrothermal fluids. The Au and Sb lodes in the region east of Armidale (e.g. the notable Hillgrove deposit) had such a metamorphic-hydrothermal origin, with the fluid flow being focussed into major shear zones. Although most individual ore bodies are small, the collective production from vein and fracture occurrences has been substantial. Many porphyry-style Cu- and Mo-bearing granitoids were also emplaced, but all are sub-economic at present. Subvolcanic plutonism provided Ag, Au, and lesser Cu, Pb, Zn and Sn in veins and disseminated mineralization in subaerial to shallow marine intermediate-silicic volcanics in the Drake region (Markham, 1974; Herbert, 1983; Perkins, 1988). Small intrusions of gabbro in southeastern Queensland differentiated in place to yield cumulate magnetite in layers, but the Ti content is high.

Non-metallic economic minerals are few in the Australian Permian. Related to igneous activity is hydrothermal alunite in fractures and small disseminations in the earliest

Permian Alum Mountain Volcanics, in the Myall Syncline near Bulahdelah (McIlveen, 1974). Analcite and bentonite, in altered tuffs in the Newcastle and Wollombi Coal Measures respectively, may be of economic interest (Menzies, 1974). The fine-grained sediments and tuffs in coal measures are often suitable for making bricks, tiles, and earthenware pipes, an example being the exploitation of shales in the Tomago Coal Measures near Newcastle. Refractory clays used in the manufacture of furnace-lining bricks may also be found in such facies; particularly noteworthy are the flint clays in the Skeletar Formation (Greta Coal Measures) and equivalents, derived from regolith developed at the top of the underlying volcanics by deep weathering during a hiatus in Permian 3 time. Permian limestone has been used on occasion, e.g. in Tasmania, for agricultural purposes and making Portland cement.

Permian rocks have, of course, also been used for their physical properties, for construction purposes such as building stone, concrete aggregate, road sub-base course, fill for groynes and retaining walls, etc., wherever suitable outcrops occur close to a need for these materials.

Throughout geological time there seems to have been a relation between glaciation and subsequent phosphorite deposition (Cook & Shergold, 1986), and indeed globally the Permian Period was a peak time of phosphogenesis (Cook & McElhinny, 1979). Despite these favorable factors, the Australian Permian is not endowed with significant phosphate deposits, the only reported occurrences being in the Liveringa and Noonkanbah Formations of the Canning Basin (Ingram, 1973b), and concretions in the Byro Group of the Carnarvon Basin (Cope, 1976). This deficiency is probably attributable to the continent's high palæolatitude. Phosphorites are known to form preferentially in low latitudes, and the richest Permian deposit, in the western USA, as well as occurrences in the northern Caucasus, and probably Vietnam, were formed within 30° of the palæo-equator. If, nevertheless, sizable deposits did accumulate in the Australian Permian, the most favorable locations would have been in shallow embayments extending inland from upwellings along the northwestern palæo-coast, i.e. the Carnarvon, Canning, Bonaparte, and Arafura Basins. It is pertinent that the Indian deposits of the Mussoorie region, and in the Himalayas north of Delhi, formed at a similar palæolatitude.

DISCUSSION

From the stratigraphic columns three broad subdivisions of the Permian are apparent, namely, Permian 1-3, in which non-marine facies dominate over marine ones, especially in much of eastern Australia; Permian 4-5, with marine environments more common, and in many basins separated from the first subdivision by a pronounced hiatus; and Permian 6-7, when non-marine and paralic regimes were re-imposed in most regions. The impression of non-marine dominance during Permian 1-3 is deceptive, however, because the stratigraphic columns are biassed towards the eastern half of the continent, where such conditions were more common. In terms of the *areas* of marine lithotopes, the maps show a greater marine coverage in the Asselian and Sakmarian than in the mid-Permian. Hence the broad, first-order marine inundation curve starts from a maximum in the earliest Permian and declines through

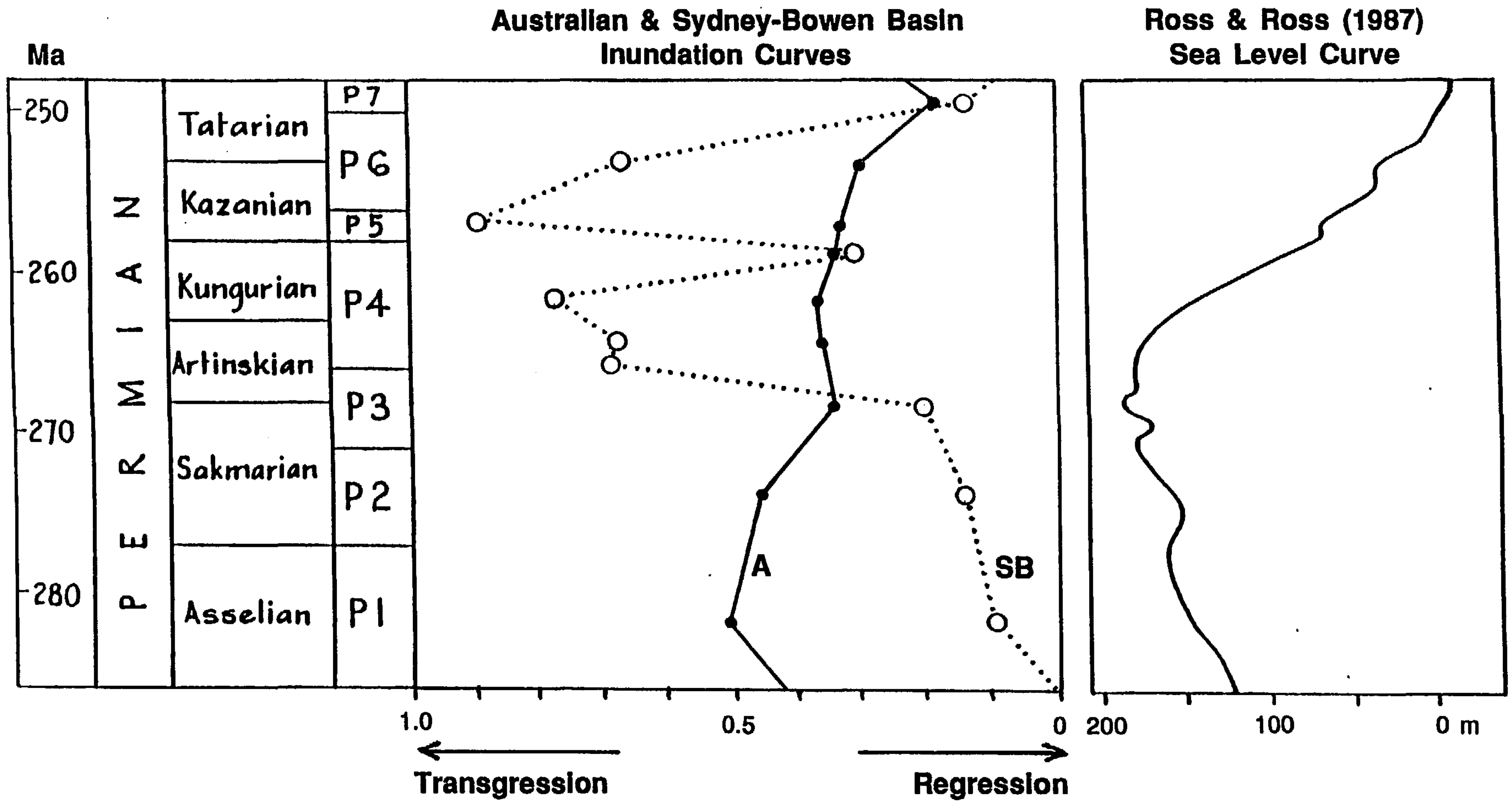

Figure 8. Australian (A) and Sydney - Bowen Basin (SB) inundation curves for the Permian compared to the global sea level curve of Ross & Ross (1987). Australian data were obtained from the palæogeographic maps herein. Based on Struckmeyer & Brown (1990), except for additonal data points included in Permian 4, and the adjustment of Permian 1 to include marine areas covered by ice shelves.

to the end of the period (Fig. 8). This disagrees with the global curve obtained from stable cratonic shelves by Ross & Ross (1987), which has a peak inundation in Permian 3 time instead of Permian 1. The difference between the curves in the earliest Permian is due to isostatic depression of the crust by the large ice caps, which caused marine inundation in the affected region. The striking departure of eastern Australia from the pan-Australian curve, as exemplified by the Sydney-Bowen Basin (Fig. 8), can be attributed partly to indigenous tectonism, but also partly to its distance from the main centres of glaciation in the earliest Permian, when it recorded a sea level history more similar to the global curve. Superimposed on the first-order curves were shorter-term fluctuations.

Volcanism peaked during Permian 1-3, owing to the intense activity of the Ayr Volcanic Rift, declined during Permian 4-5, then rose again to a subordinate peak during the remainder of the period. These eruptions, and accompanying plutonic intrusions, were of such a scale that plate movements significant in a world context must be invoked to explain them. Despite this, the continent appears not to have undergone any dramatic latitudinal changes, as far as can be judged from the poorly constrained palæomagnetic data and the evidence of prevailing climate. Glaciation, at a climax in Permian 1, ended rapidly, but re-appeared briefly in a minor way in two local areas in Permian 4. There was some temperature rise with time, becoming highest in the Bonaparte Basin by the end of the Permian, but the trend is likely to be symptomatic of a global warming rather than a northerly drift of the Australian Plate.

The Permian palæogeography portrayed on the maps shows the controlling influence of eustatic sea level cycles and the largely frigid to cold temperate climates, interacting with a tectonic scenario which was predominantly extensional for most of the continent, except for the east coast region, which was marked in the Late Carboniferous - Early Permian by a change from a convergent margin to strike-slip margin, accompanied by the development of an orocline, followed by extension and rift volcanism, and from the mid-Permian onwards by compressional events, including terrane docking. The mosaic of environments that resulted has determined the location of coal resources and organic-rich sediments, and in turn the location of oil and gas in both Permian and Mesozoic sequences. The orogenic movements and associated igneous activity in the east promoted the emplacement of metalliferous ores in that zone.

As the more obvious deposits of mineral and energy resources are found, exploited, and depleted, there will be an increasing need to delineate the pattern of past environments. This is already happening in the Cooper Basin, where petroleum exploration has entered a mature phase and stratigraphic traps are being targetted with the aid of detailed palæochannel mapping (Fairburn, 1989; Taylor & Thomas, 1989). Knowledge of the geometry of sand bodies, of whatever origin, is essential also for the accurate volumetric estimation of hydrocarbons in complex reservoirs. Innovative geological thinking will therefore be required from the exploration to the production phase. Coal seam development is equally sensitive to palæogeographic parameters. For example, river channels are preferentially stacked in the lower topography areas along the growth faults of half-grabens, so that more and better quality coal is found towards the hinge lines of such structures. On a local, mining-lease scale, a detailed knowledge of the palæogeography is important for predicting the ash and sulphur contents of coal, the composition and types of coal, thickness variation and splitting of seams, "wants" and stone rolls in seams, the safest and least costly directions of underground mining, the stability of roof and floor strata in underground workings, and the stability of high walls in open cuts. Even thick volcanic ashfalls can affect coal seam development by smothering pre-existing topography and filling in depressions. Innumerable case histories have been published illustrating all of the above.

The maps presented here are a starting point for further study of the Permian in Australia. Details on the maps can be expected to change with time as more data become available. This is particularly true for the New England Orogen, currently the focus of much intellectual ferment, where theories of major strike-slip movements, oroclinal bending, and terrane docking are being proposed and tested, even as far-reaching changes to the ages of some successions are being announced. By the end of this century, the face of the orogen as we currently understand it may be radically altered. In the meantime, the present maps are still useful here in at least showing the environments recorded by the outcrops, even if the rocks may have been in different relative positions in the Permian.

The palæogeography of the Australian Permian in this Record is the most detailed and has the finest time resolution so far published. Not only will these maps be used extensively in resources exploration, but they will also be incorporated into world palæogeographic studies, and thereby help to develop a better understanding of global changes in climate, ocean circulation, and plate tectonic movements during the late Palæozoic.

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ENVIRONMENT SYMBOLS ON PERMIAN INTERPRETATION MAPS

LAND

LEU	Land, unclassified
LEE	Erosional
LDF	Fluvial
LDFL	Fluviolacustrine
LDL	Lacustrine
LDA	Aeolian
LDG	Glacial
LDU	Volcanic terrain

COASTAL

CDP	Paralic	CDIS	Intertidal
CDD	Deltaic		

SEA

MU	Marine, unclassified
MVS	Very shallow (0 - 20 m)
MS	Shallow (0 - 200 m)
MBA	Bathyal - abyssal (>200 m)

Palaeocurrent direction

Alluvial fan

Diagrammatic drainage

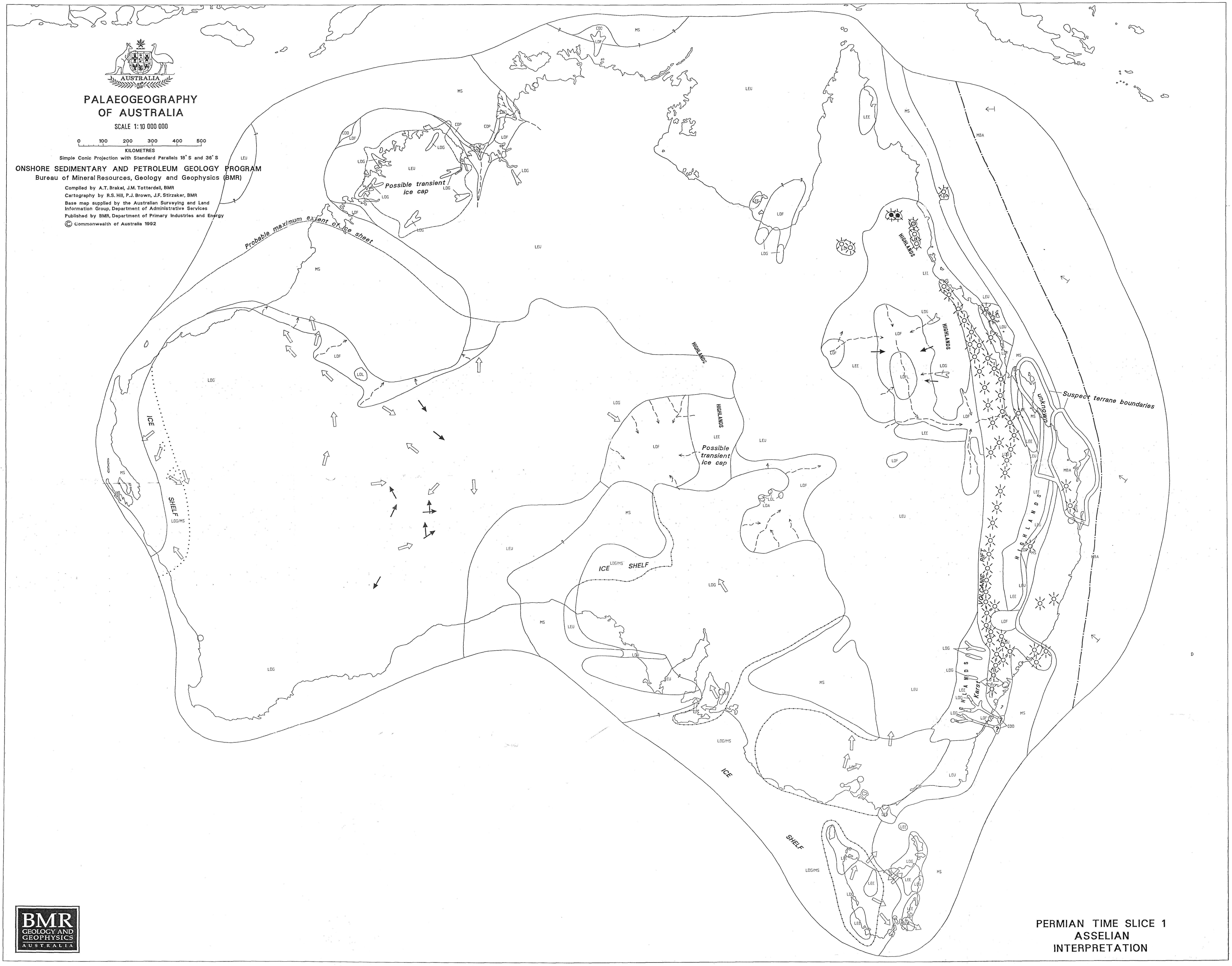
Igneous centre

Fore-arc trench

Environment boundary

? Environment boundary approximate or guessed

Direction of plate movement



AUSTRALIA
PALAEOGEOGRAPHY
OF AUSTRALIA
SCALE 1: 10 000 000
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KILOMETRES
Simple Conic Projection with Standard Parallels 18° S and 36° S
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Probable maximum extent of ice sheet
Possible transient ice cap
Possible transient ice cap
HIGHLANDS
HIGHLANDS
HIGHLANDS
HIGHLANDS
HIGHLANDS
VOLCANIC RIFT
Karst
Suspect terrane boundaries
unknown
ICE SHELF
ICE SHELF
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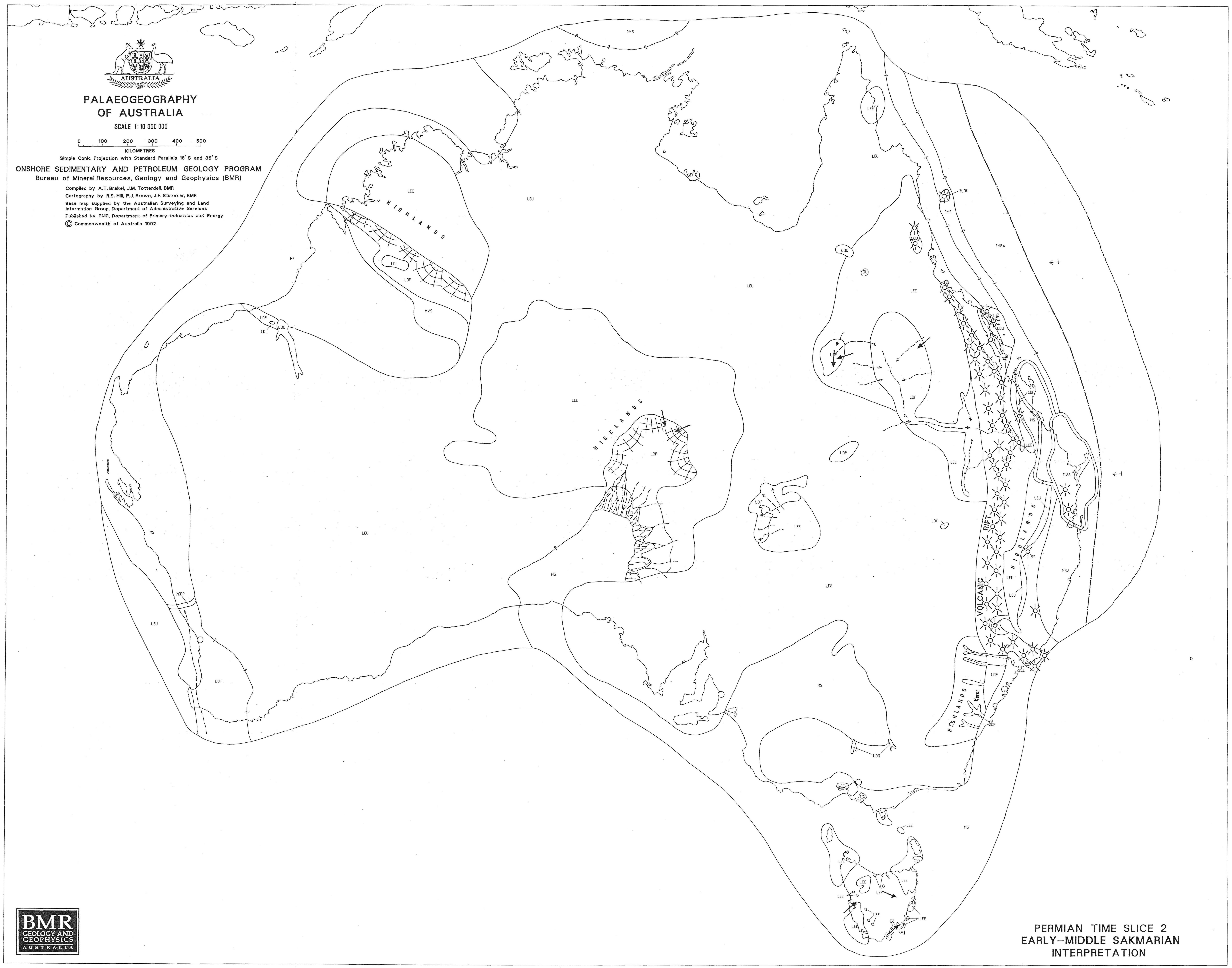
BMR GEOLOGY AND GEOPHYSICS AUSTRALIA
PERMIAN TIME SLICE 1
ASSELIAN
INTERPRETATION



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HIGHLANDS
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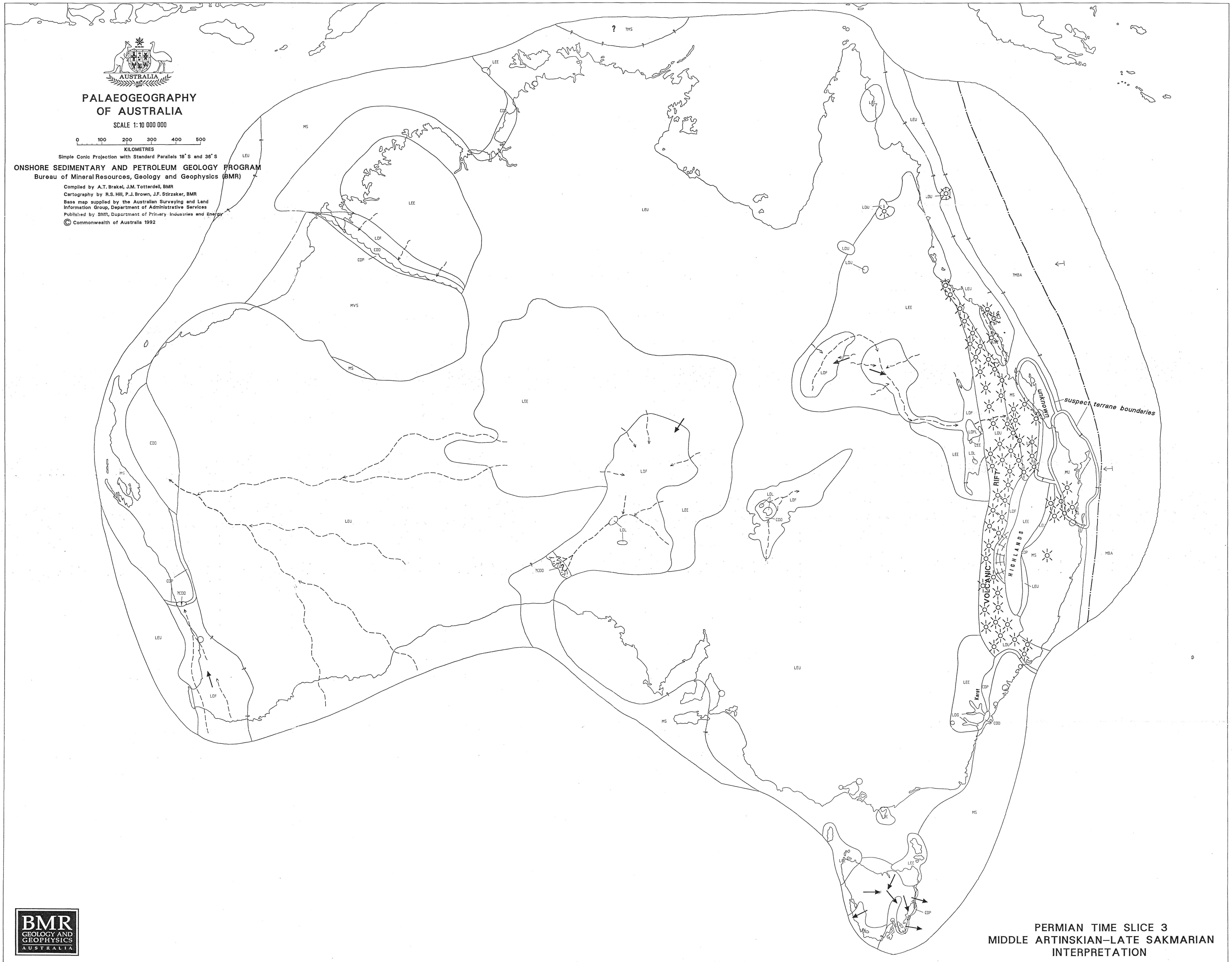
BMR GEOLOGY AND GEOPHYSICS AUSTRALIA
PERMIAN TIME SLICE 2
EARLY–MIDDLE SAKMARIAN
INTERPRETATION



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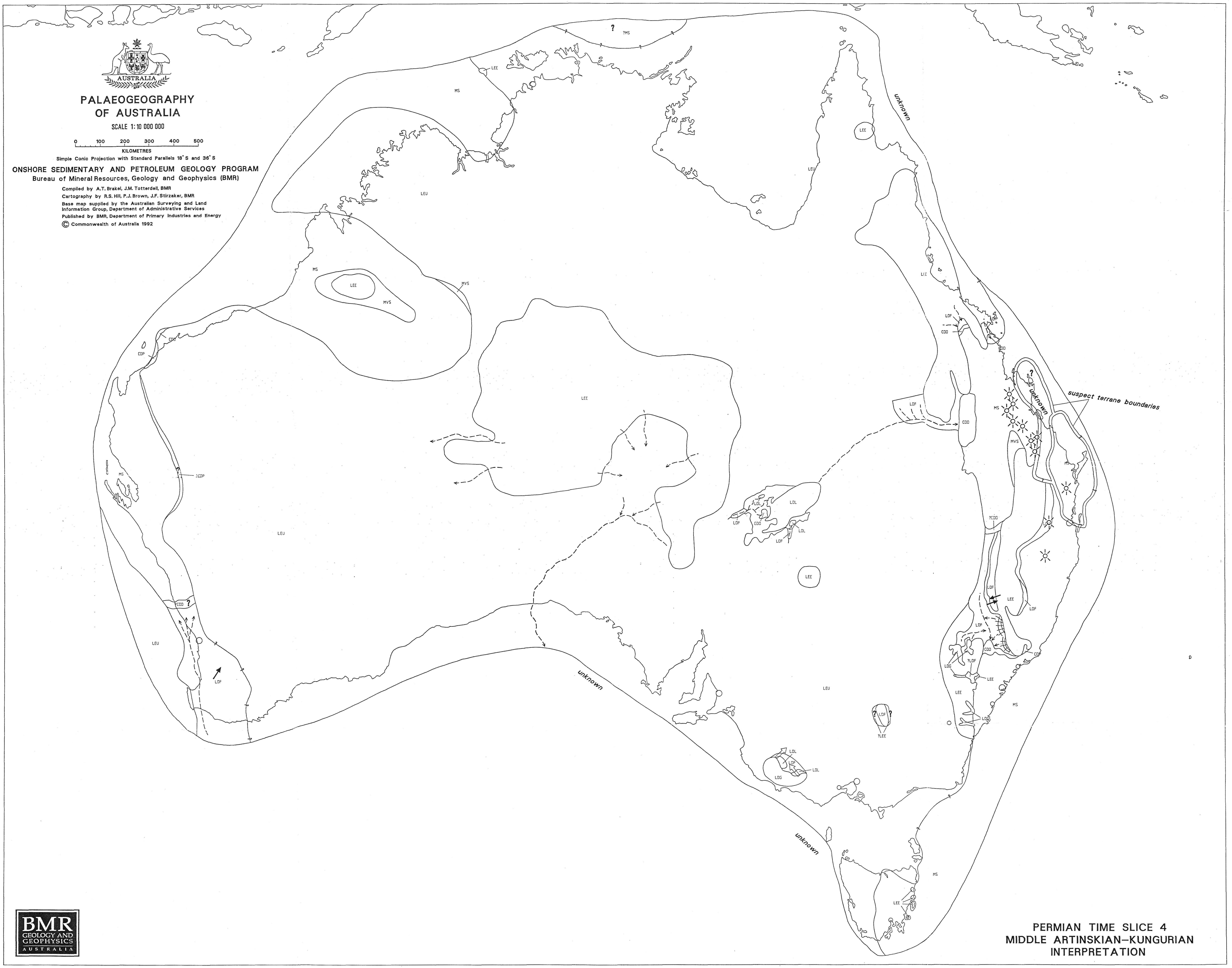
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AUSTRALIA
PALAEOGEOGRAPHY
OF AUSTRALIA
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KILOMETRES
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unknown
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BMR GEOLOGY AND GEOPHYSICS AUSTRALIA
PERMIAN TIME SLICE 5
EARLY KAZANIAN
INTERPRETATION

AUSTRALIA
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suspect terrane boundary
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GEOLOGY AND GEOPHYSICS
AUSTRALIA
PERMIAN TIME SLICE 6
MIDDLE KAZANIAN – MIDDLE TATARIAN
INTERPRETATION

PALAEOGEOGRAPHY OF AUSTRALIA

SCALE 1: 10 000 000

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KILOMETRES

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PERMIAN TIME SLICE 7
LATE TATARIAN
INTERPRETATION


BMR-APIRA
PALAEOGEOGRAPHIC MAPS PROJECT
PERMIAN STRUCTURE MAP
DEPOSITIONAL AREAS
A Intracratonic basin
B Extensional basin - Foreland basin
C Marginal (back-arc) basin
Encompasses small depositional areas and basin remnants within orogenic province
Present day extent of Permian deposition; inferred where queried
IGNEOUS ACTIVITY
Intrusives, indicating uplift
Volcanics
+ Felsic
× Mafic & Intermediate
Λ Felsic
V Mafic & Intermediate
Drillhole intersecting volcanics / intrusives
Ultramafic rocks
Subsurface volcanics of possible Early Permian age
Kimberlitic intrusive
STRUCTURES
Depoaxis: Major structure Minor structure
Depoaxis along fault
Growth fault
Fault; tick indicates downthrown side
Fault; sense of movement not known
Basin floor arch / Axis of basement high
Thrust fault
Transcurrent fault
Hinge zone
Anticline
Syncline
Monocline
Trend lines of oroclinal bending
Zone of tight folding (indicating strike)
Metamorphism: high grade; low grade
1-4, 6 Timing of events by Permian time slice
C Continues from Carboniferous
R Continues into Triassic
SCALE 1:5,000,000
100 0 100 200 300 400 500 km
Compiled 1987 & Revised 1990 by J.M. Totterdell, BMR
Drawn by P.J. Brown, BMR
BONAPARTE
Petrel Sub-basin C-R
BASIN
BROWSE BASIN C-?1
Block faulting
Extensional Tectonism C-?1, 6-7
Fitzroy Sub-basin C-R
Pinnacle Fault 2-3
Fenton Fault
Broome Arch
CANNING
Willara Sub-basin C-2
Wallal Embayment
Gregory Sub-basin C-7
Anketell Shelf C-2
BASIN C-R
Kidson Sub-basin C-4
Gentle folding and block faulting 6-7
Barrow Sub-basin
Gascoyne Sub-basin
CARNARVON BASIN
Byro Sub-basin
Abrolhos Sub-basin
PERTH BASIN
Irwin Sub-basin 1-6
Darling Fault
Dandaragan Trough
Beagle Ridge
COLLIE BASIN 1-6
WILGA BASIN
OFFICER BASIN
MALLABIE DEPRESSION 1-3
PEDIRKA BASIN 1-3
ARCKARINGA BASIN 1-3
Tallaringa Trough
Wallira Trough
Mulgathing Trough 1-2
POLDA BASIN
TROUBRIDGE BASIN 1
COOPER BASIN
Nappamerri Trough
Tenappera Trough
GALILEE BASIN
Lovelle Depression
Koburra Trough
Barcaldine Ridge
BLAIR ATHOL BASIN
Comet Platform
BOWEN BASIN
Taroom Trough
Arbroath Trough 2-3
Strathmuir Synclinorium 1-4
Berserker Graben 3-4
Yarrol Shelf 1-7
Yarrol Fault System
YARROL PROVINCE C-7
GYMPIE PROVINCE C-7 (8?)
Probable Permian rocks concealed under younger basins
NEW ENGLAND PROVINCE C-7
NEW ENGLAND OROGEN
Oroclinal bending 1-3
Deformation with NNE foliation C-7
Nambucca Block 1-2
Deformation 1-3
Manning Fault System 2-3
GLOUCESTER BASIN 2-7 (8)
MYALL SYNCLINE 2-7 (8)
Northumberland Ridge
GUNNEDAH BASIN
SYDNEY BASIN
Illawarra Shelf
OAKLANDS BASIN 2-7
Numurkah Trough 1-2
Bacchus Marsh
Netherby Trough
Blantyre Trough 1
Ivanhoe Trough 1
Wentworth Trough 1
TASMANIA BASIN C-R
OLIVE RIVER BASIN 6-7
Palmerville Fault
Coastal Ranges Igneous Province
Goulburn Graben C-1

SUMMARY STRATIGRAPHIC COLUMNS

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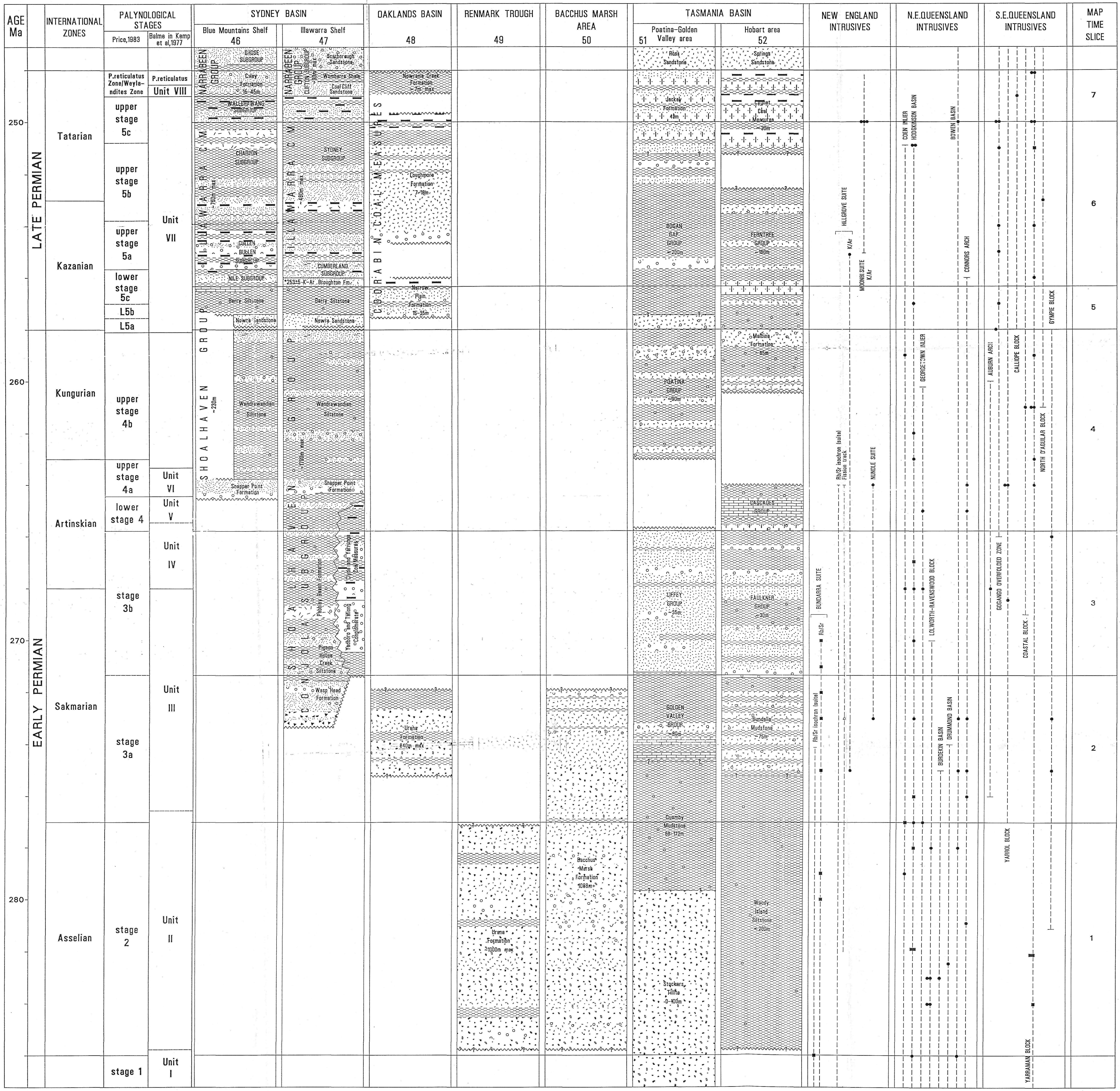
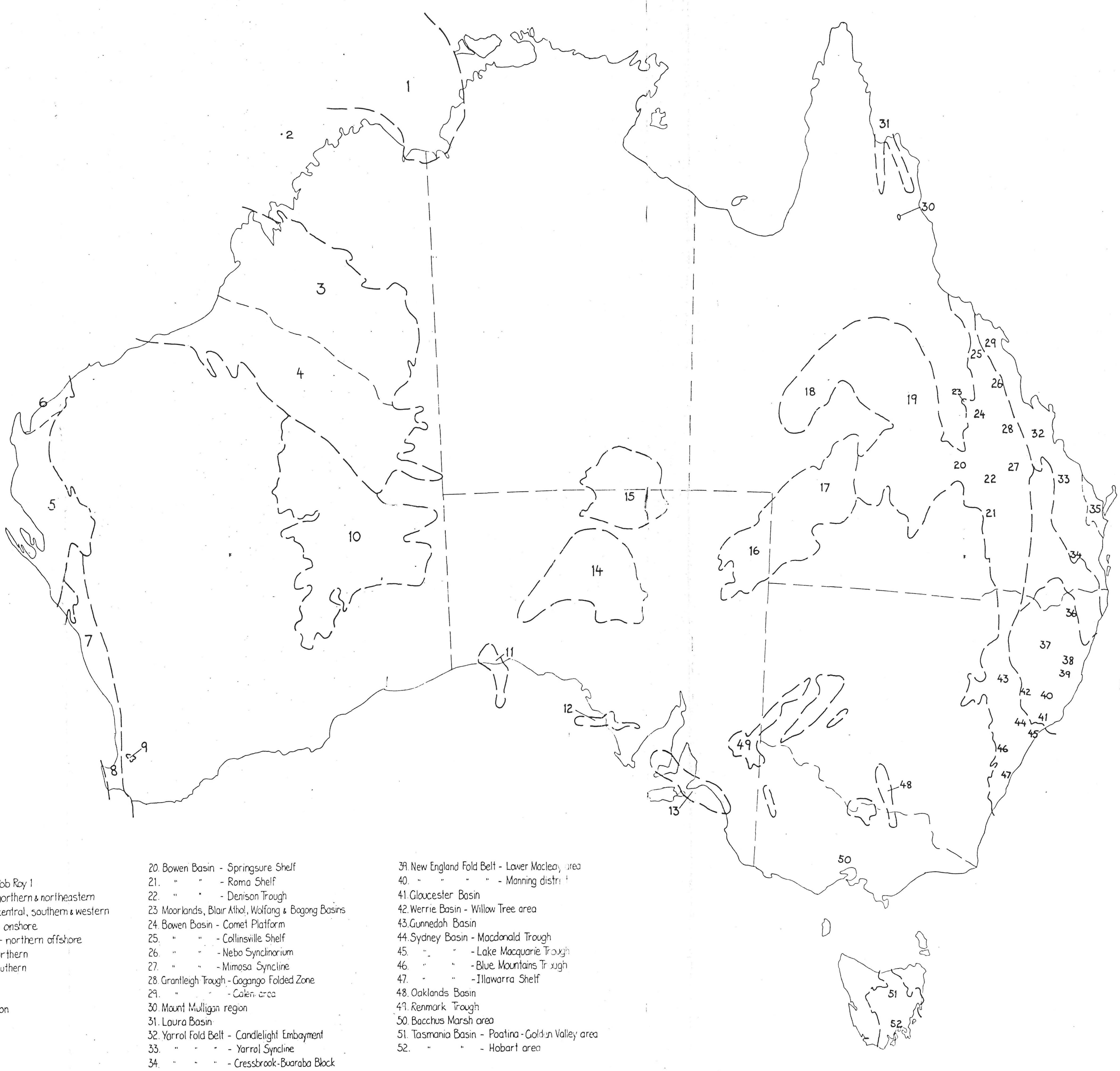


SUMMARY STRATIGRAPHIC COLUMNS

Permian summary columns: location diagram



1. Bonaparte Basin
2. Browse Basin - Rob Roy 1
3. Canning Basin - northern & northeastern
4. " " - central, southern & western
5. Carnarvon Basin - onshore
6. " " - northern offshore
7. Perth Basin - northern
8. " " - southern
9. Collie Basin
10. Officer Basin
11. Mallabie Depression
12. Polda Basin
13. Troubridge Basin
14. Arckaringa Basin
15. Pedirka Basin
16. Cooper Basin - southern
17. " " - northern
18. Galilee Basin - Lovelle Depression
19. " " - northeastern
20. Bowen Basin - Springsure Shelf
21. " " - Roma Shelf
22. " " - Denison Trough
23. Moorlands, Blair Athol, Wolfang & Bogong Basins
24. Bowen Basin - Comet Platform
25. " " - Collinsville Shelf
26. " " - Nebo Synclinorium
27. " " - Mimosa Syncline
28. Grantleigh Trough - Gogango Folded Zone
29. " " - Calen area
30. Mount Mulligan region
31. Laura Basin
32. Yarrol Fold Belt - Candlelight Embayment
33. " " - Yarrol Syncline
34. " " - Cressbrook-Buaraba Block
35. Gympie Block
36. New England Fold Belt - Drake area
37. " " " - Tilbuster-Exmouth area
38. " " " - Nambucca Block
39. New England Fold Belt - Lower Macleay area
40. " " " - Manning district
41. Gloucester Basin
42. Werrie Basin - Willow Tree area
43. Gunnedah Basin
44. Sydney Basin - Macdonald Trough
45. " " - Lake Macquarie Trough
46. " " - Blue Mountains Trough
47. " " - Illawarra Shelf
48. Oaklands Basin
49. Renmark Trough
50. Bacchus Marsh area
51. Tasmania Basin - Poatina - Golden Valley area
52. " " - Hobart area

Permian summary columns: location diagram

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