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NOTES TO ACCOMPANY A 1:5 000 000 SCALE PERMIAN STRUCTURE MAP OF AUSTRALIA

by

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Phanerozoic Palaeogeographic Maps of Australia Project

CONTENTS

FIGURES

TABLE

ACCOMPANYING MAP

SUMMARY

Permian sediments are preserved in a number of Australian basins. The Permian evolution of the basins on the western and northern margins of Australia was controlled by extensional processes that have been related to the rifting of some continental fragments from the margin of Gondwana. The development of many of the Permian basins in central and eastern Australia can also be related to stresses generated along the margins of the continent. The Sydney-Gunnedah-Bowen Basin was initiated in the Early Permian as a result of back-arc extension or transtension. The basin was later affected by periods of compressional or transpressional tectonism which culminated in the Middle Triassic. A change in relative plate motions on the eastern margin of Australia in the latest Carboniferous or Early Permian resulted in the formation of a large double orocline in the New England Orogen and the migration eastwards of the southern portion of the magmatic arc. The New England Province was therefore in a back-arc extensional setting throughout most of the Permian, whereas the Yarrol Province to the north remained in an arc and fore-arc setting. Convergent margin volcanism ceased in eastern Australia by the mid-Permian.

INTRODUCTION

The Permian structure map was compiled in 1987-88 as part of the Bureau of Mineral Resources/Australian Petroleum Industries Research Association Palaeogeographic Maps Project. For the purposes of compiling the palaeogeographic maps, an Australia-wide correlation chart for the Permian was constructed and time-slices were chosen (Brakel & Totterdell, in press). Time-slice selection was determined by the presence of regionally extensive breaks in sedimentation, or by significant changes in depositional environments. The seven time-slices chosen for the Permian are listed in Table 1. The Permian structure map shows the depositional areas and structural elements that were active during the Permian. The timing of both deposition and deformation is indicated in terms of the time slices used for the Permian palaeogeographic maps. The depositional areas are classified as intracratonic, marginal (or back-arc), or polyhistory extensional-foreland basins. The latter category refers specifically to the Sydney-Gunnedah-Bowen Basin and will be explained in the text. 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 shown 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. These notes, which were written to accompany the map, provide a summary of the structural development of Australia during the Permian.

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

Table 1: Permian time slices (absolute ages based on the time scale of Harland & others, 1982)

BASIN CLASSIFICATION

A number of different basin classifications are used on the map and referred to in the notes. A brief description of these basin types has therefore been included.

Intracratonic basin

Intracratonic basin is a descriptive term applied to a basin that developed on top of, or within, a craton; it is not a genetic term. Klein and Hsui (1987) suggested that most intracratonic basins form by thermal subsidence over earlier rifts. Quinlan (1987) cited the following processes as possible influences on the development of intracratonic basins: "decay of thermal anomalies with or without some specified mechanical modification to the lithosphere such as might be produced by subaerial erosion or phase transformations; isostatic equilibration of ancient rift structures underlying intracratonic basins by the application of in-plane lithospheric stress; uplift of adjacent arches through either thermal or mechanical processes; and mechanical coupling of intracratonic basins with adjacent foreland basins".

Extensional basin

Unlike a descriptive geographic term such as "intracratonic", the term "extensional basin" describes the mechanism of basin formation. An extensional basin is one developed by horizontal extension of continental lithosphere. It is "characterised by faulted margins with tilted horst and terrace systems developed on both listric and planar normal faults. Structural elements of the margins are offset by lateral transfer ramps and folds which allow complex integrated subsidence to occur along the basin margin. Following the fault-dominated extensional phase of the basin development, thermal subsidence can result in large scale rotation and reactivation of some of the earlier geometries" (Gibbs, 1984). In many cases, the direction of extension is not purely orthogonal to the bounding faults and has a component of strike-slip movement. Basins formed in such settings are called transtensional basins.

Foreland basin

A foreland basin can be defined simply as a sedimentary basin lying between the front of an orogen (the fold-thrust belt) and the adjacent craton. Foreland basins are asymmetrical and deepest near the fold-thrust belt (Mitchell & Reading, 1986). Although it can be used in a purely descriptive sense, the term "foreland basin" now carries the geophysical connotation that such basins result from downward flexuring of the lithosphere by a migrating fold-thrust belt. Therefore, the evolution of a foreland basin is coupled to that of its adjacent orogenic belt (Price, 1973; Beaumont, 1981). The term "foreland basin", as used here, is descriptively synonymous with "marginal basin" (Krumbein & Sloss, 1963), "foredeep" (Aubouin, 1965; Price, 1973), and "peripheral and retroarc foreland basin" (Dickinson, 1974). In the nomenclature of Bally and Snelson (1980), foreland basins are included in the class of perisutural basins on continental lithosphere associated with major compressional zones of deformation or megasutures (Allen & others, 1986).

Marginal (back-arc) basin

Karig (1971) defined marginal basins as "the semi-isolated basins and series of basins lying behind the volcanic chains of island arc systems". Karig proposed that these basins were of extensional origin and were all underlain by oceanic crust. Marginal basins are believed to form through a sea-floor spreading process similar to that in the major ocean basins (Karig & Moore, 1975; Taylor & Karner, 1983). Hsui and Toksöz (1981), in a review of the mechanisms of back-arc spreading, favoured an induced convective current in the mantle wedge immediately above the slab as the likely mechanism for initiation of the back-arc spreading. Alternatively, Crawford and others

(1981) proposed that back-arc basins develop as a consequence of the diapiric upwelling of mantle material beneath the arc axis.

Despite Karig's (1971) original definition, which was based largely on tectonic position, the terms "marginal basin" and "back-arc basin" are not strictly synonymous. Rifting in the vicinity of a volcanic arc to produce a marginal basin can occur in a fore-arc, intra-arc or back-arc position (Taylor & Karner, 1983). In addition, some authors (see Kokelaar & Howells, 1984a) believe that marginal basins are not restricted to intra-oceanic settings, and may develop within continental crust at convergent plate margins. In this setting, thinning of continental crust may or may not be accompanied by the emplacement of oceanic lithosphere.

NORTHERN AND WESTERN AUSTRALIA

ARAFURA BASIN

Lower Permian (Stage 2) sediments have been intersected in two wells in the Goulburn Graben of the Palaeozoic-Lower 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 represented an intracratonic sag phase of basin development following a Late Devonian-Early Carboniferous rifting event.

BONAPARTE BASIN

The Cambrian-Mesozoic Bonaparte Basin in northwestern Western 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 represented 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 Hay Member of the Upper 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 is considered 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 is constrained by the presence in parts of Sibumasu of Lower 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 (1976) 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 uplifted at this time. The Ashmore-Sahul Block and Scott Reef areas however, have a thick Permo-Triassic section suggestive of graben fill (Powell, 1976).

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, 1983). 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 Upper Permian and Lower 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 Upper 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 & others, 1980a). After the deposition of the Callytharra Formation (P3), 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-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 north 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 (P5-6), 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 north Perth Basin exhibits similarities to regions such as the San Andreas Fault System at the present time, where 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 north 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 south 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, in press).

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 south 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 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 southern 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, 1981). 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 subsequently preserved.

TROUBRIDGE BASIN

The Troubridge Basin in southeastern South Australia contains a thin but extensive succession of Lower 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 a Permian intracratonic basin in central Australia. The basin can be divided into western and eastern sub-basins along the McDills Trend, a roughly northeast-southwest trending pattern of gravity anomalies. In South Australia the McDills Trend runs northwest-southeast, and appears to be associated with the Peake and Denison Ranges trend. The eastern sub-basin contains a much thicker Permian and Triassic section (Youngs, 1976a).

Throughout the latest Carboniferous and Early Permian the eastern Pedirka Basin accumulated a thick sedimentary section. 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, 1976a). Deposition ceased in the late Artinskian and most of the region underwent a period of non-deposition and/or erosion until the Jurassic.

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, 1989). 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 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 Upper 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 northeast trending faults and lineaments in Lower Palaeozoic 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 Palaeozoic 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 (P2-3), 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-northwest 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 (P3). 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-northeast 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, 1984a).

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, 1984c).

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, 1984b).

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. 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 northwest-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 Palaeozoic-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 Lower Permian glacial sediments (Urana Formation), unconformably overlain by the Upper Permian Coorabin Coal Measures (O'Brien, 1986; SCCGNSW, 1978). The southern part of the trough (Ovens Graben) contains a slightly older succession of Lower Carboniferous red beds, Upper Carboniferous conglomerates, and Upper Carboniferous-Lower 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, 1984b).

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 Lower Permian glacial deposits occur in northeast, 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 an Upper Carboniferous-Upper 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 (P4-5) 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 palaeo-Pacific margin of the Antarctic-Tasmanian sector of Gondwana (Collinson, in press).

SYDNEY-GUNNEDAH-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, in press). 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 Lower Permian Camboon Volcanic Arc to the east. However, a number of workers (Scheibner, 1973; Harrington, 1982; Korsch, 1982; Harrington & Korsch, 1985; Ziolkowski & Taylor, 1985; Hammond, 1987; Mallett & others, 1988) have argued that the Sydney-Gunnedah-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 a Lower Permian to Middle Triassic basin on the southeastern coast of Australia. The Permian succession consists of Lower Permian volcanics and marine sediments overlain by middle Permian coal measures, Lower-Upper Permian marine sediments, and Upper 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). 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 Lower 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-Gunnedah-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-Gunnedah-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.

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 (P3-4), 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 Upper Permian Newcastle and Wollombi Coal Measures, and include proximal deposits of volcanic centres located to the northeast and east (Brakel, 1984); some possibly represent the distal deposits of the widespread silicic volcanism in the New England Province. Upper 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 Lower 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); Hill (1986), has shown that 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 (Exon, 1974; Russell, 1981). 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 the long 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 the Hunter-Mooki Fault System near Boggabri is no older than latest Early Permian (late TS 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 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. Lower Permian volcaniclastic sediments reflect nearby contemporaneous ignimbritic volcanism, related to the waning stages of convergent margin, Andean-type tectonics (McPhie, 1984). The overlying Werrie Basalt could be related to the extensional tectonics which initiated the Sydney-Gunnedah-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 Upper Carboniferous felsic volcanics and the subsequent westwards transport of sediment into the Gunnedah and Werrie Basins. However, McPhie (1984) found no evidence for an easterly provenance for the Lower Permian coal measures, nor for movement on the Hunter-Mooki Fault System at this time, and suggested that the Gunnedah and Werrie Basin coal measures were derived from the erosion of the Upper Carboniferous volcanic pile to the west.

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 graben and 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 short-lived but 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 grabens, was initiated during the late Early-early Late Permian (P4-5). 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 intense compression and inversion of half grabens, culminating in a major thrusting event in the Middle Triassic. 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 is a typical foreland fold-thrust belt (Murray, 1985).

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.

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. They probably developed during the Early Permian extensional phase which initiated graben and half-graben development in the Bowen Basin.

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 Lower Permian succession in the Yarrol Block (Fig. 1) 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. 1), 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. 1) 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. 1) contains Lower 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).

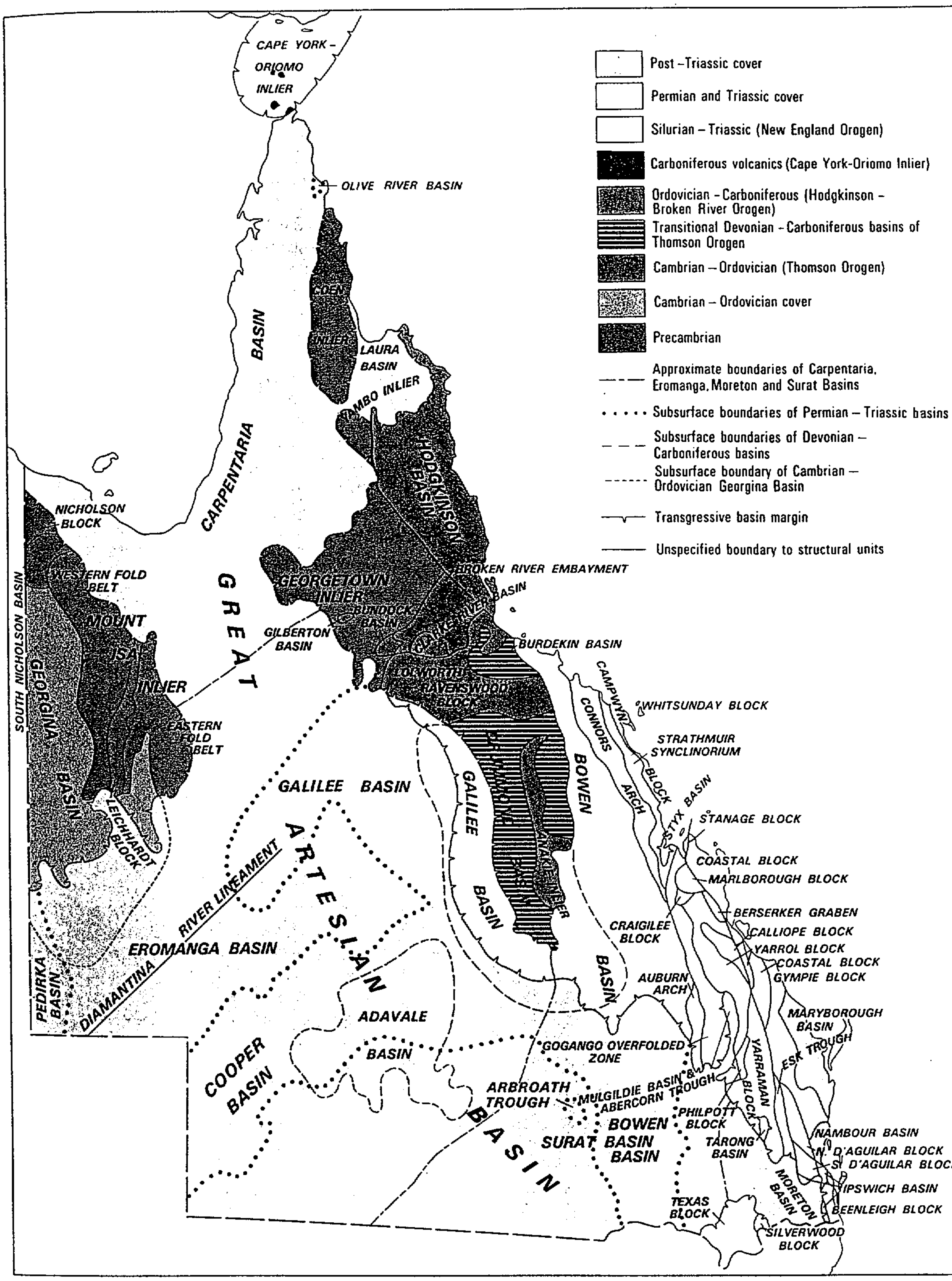

Figure 1. Structural framework of Queensland (from Day & others, 1983).

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. 1) contains metamorphic rocks that are part of an Upper Devonian-Lower 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) demonstrated 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 Lower Permian Amamoor beds and the Cedarton Volcanics, which are thought to 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 Palaeozoic has long been the subject of conjecture and debate. The 'consensus' view, as stated by Korsch and others (1988a) and Korsch and others (in press), 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 shown that some waning 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 appears to 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. 2). However, Korsch and Harrington (1985, 1987) argued that deformation and metamorphism of the Nambucca Block, and the deformation of Lower Permian sediments in the Texas area in the northern part of the province, are related to the oroclinal

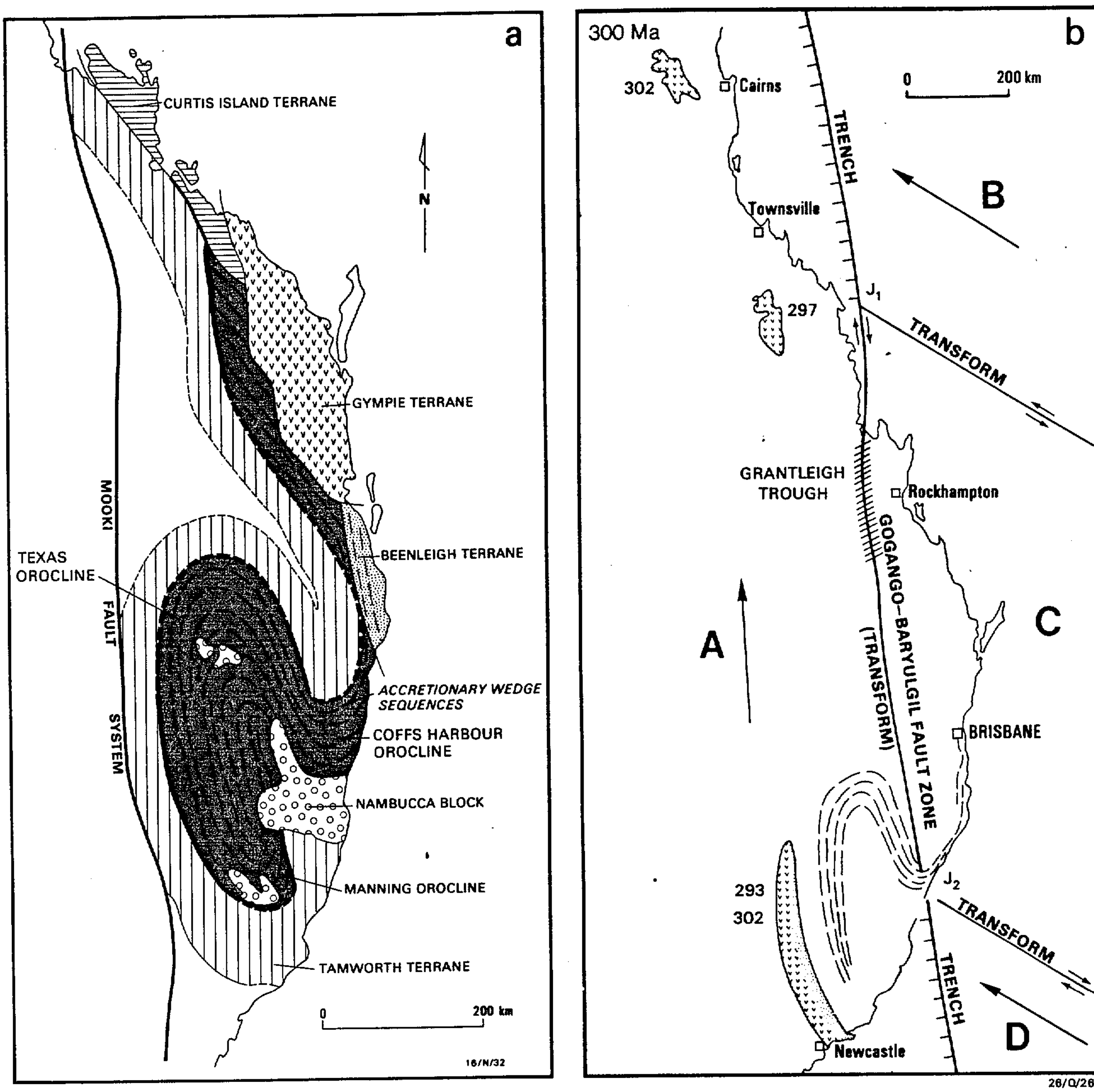

Fig. 2 Orocline models of (a) Korsch & Harrington (1987) and (b) Murray & others (1987). The major difference is in the location of the controlling strike-slip fault zone, which Korsch & Harrington infer to be their Mooki Fault System, whereas Murray & others interpret it to be along their postulated Gogango-Baryulgil transform fault zone.

(from Korsch & others, in press).

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. 2).

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. 3). 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-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. 3]). Late Permian silicic volcanics outcrop 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

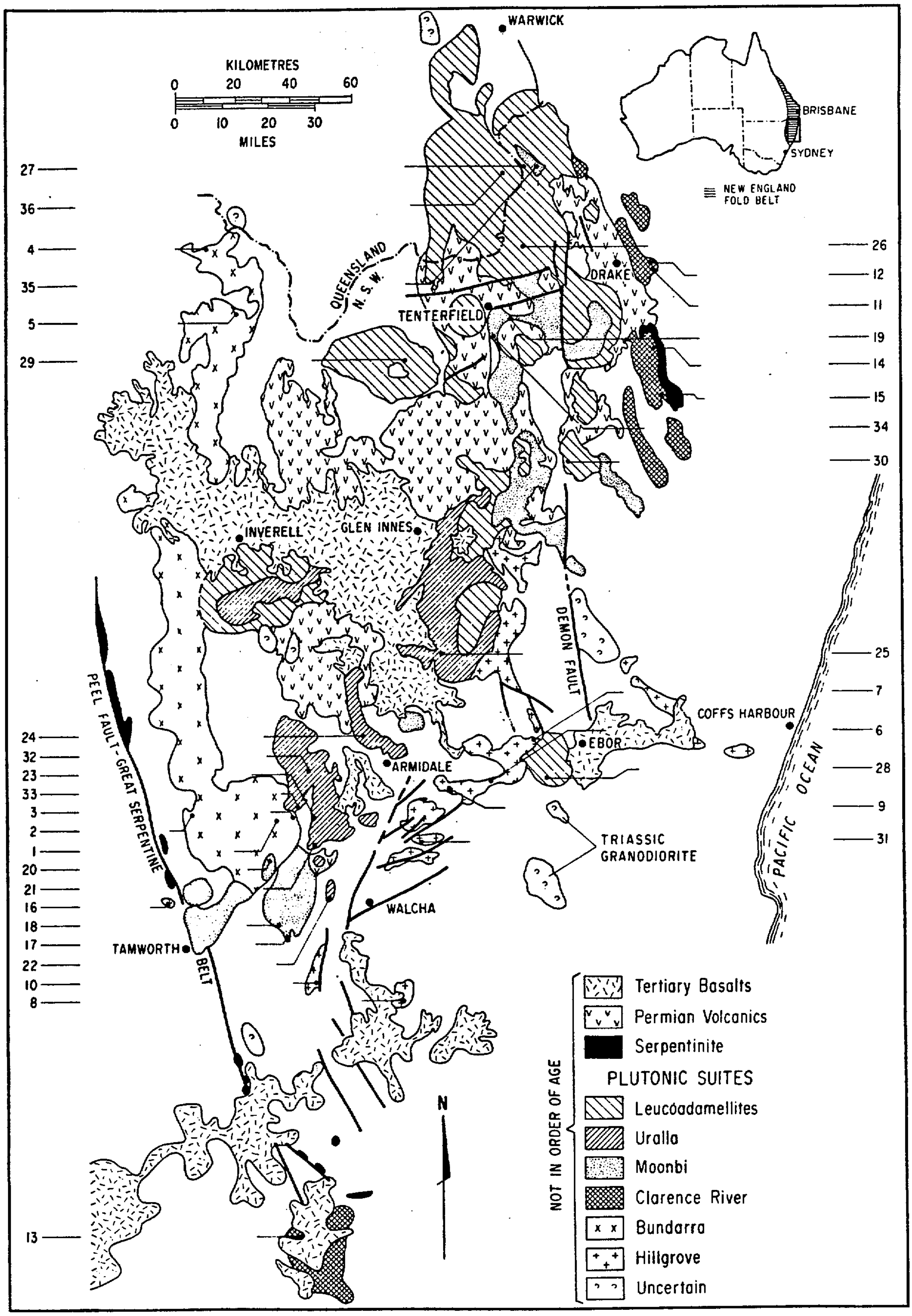

Figure 3. Distribution of plutonic suites and volcanics in New England Province (from Shaw & Flood, 1981).

related to a post-orogenic period of crustal extension (Kleeman, 1988). Upper Permian submarine, intermediate-silicic volcanics at Drake, near the Queensland border (Fig. 3), 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. 3), 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 Palaeozoic, the Peel Fault has undergone 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 about the time of the Carboniferous-Permian boundary. Korsch (1982) proposed that ?Lower 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 outcrop along the fault, but their age is equivocal. A Permian age (280-275 Ma) has been determined for a serpentinite block associated with the Peel Fault south of Tamworth (Lanphere & Hockley, 1976), but 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, 1984a).

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 palaeo-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-Gunnedah-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-Gunnedah-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 previously), 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 Upper Proterozoic-Lower Palaeozoic 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.

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