BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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RECORD

RECORD 1987/54

NOTES TO ACCOMPANY A 1:5 000 000 SILURIAN STRUCTURAL HISTORY MAP, 1987

BY

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SUMMARY

Summary descriptions are given of the main structural features affecting the continent during the Silurian. Their distribution is shown on a 1:5 000 000 scale map.

A number of structures which lie along the 'Tasman Line' were active during the Silurian. Structural zones to the west of this 'line' are described first, followed by features both along and to the east of the 'line'.

The significance of a number of aspects of Silurian structural history is briefly discussed.

CONTENTS

Figures

Map (in pocket)

INTRODUCTION

A Silurian 'structural history' map was compiled in 1987, as part of a series of maps produced for a joint Bureau of Mineral Resources/Australian Mineral Industries Research Association Limited (Petroleum Division) Palaeogeographic Maps Project. These notes were prepared during the compilation of the map and, as only a short summary will accompany the final publication of the map, they are presented here in full. Following the construction of an Australian correlation chart for each System, time slices were selected upon the basis of correlatable units and hiatuses. In the following notes, S1 to S3 refer to the three selected Silurian time slices. These are:

S1: 434 - 424 Ma
S2: 424 - 414 Ma
S3: 414 - 408 Ma

The 'Tasman Line' (Veevers, 1984) divides Australia into a western region of exposed Precambrian blocks and fold belts overlain by thin Phanerozoic basins and an eastern region of exposed Phanerozoic fold belts overlain by younger Phanerozoic basins.

WEST OF THE TASMAN LINE

West of the Tasman Line are a number of intracratonic basins - The Carnarvon, Canning, Amadeus, Bonaparte Gulf and Arafura Basins. The stratigraphy in the Carnarvon, Canning and Amadeus Basins is well known, but there is poor time control for much of the Silurian record. The presence of Silurian units in the Arafura Basin is known from only one exploratory drillhole and the late Silurian age of the rocks intersected is imprecise. There are no Silurian sequences known at all in the Bonaparte Gulf Basin, but their presence is inferred from diapiric salt intersected in petroleum exploration drillholes. Thus structural correlations between the basins are tentative.

Carnarvon Basin

Deposition in the Carnarvon Basin in S1 to S3 was controlled by movement on the Darling Fault, as a thick fluviatile sediment wedge occurs west of the fault, towards which the sediments markedly coarsen (Hocking, 1979; 1981). Playford and others (1975) suggested that the Darling Fault may have originally developed as a transcurrent fault, but that normal faulting probably occurred during the Silurian. The sediment source for the onshore part of the basin was the Yilgarn Block and adjoining Precambrian rocks to the north. The Northampton Block did not act as a significant source or topographic influence. The palaeoslope was to the northwest and the palaeocoastline trended south-southwest/north-northeast (Hocking, 1979; 1981).

Canning Basin

Four depocentres existed during deposition of the Carribuddy Group, with maximum deposition in the Kidson Sub-Basin. Thick halite accumulations developed behind carbonate sills which formed on basement highs (Lehmann, 1984). The northeast and southwest margins of the basin were shelf edges which generally lapped gently on to cratonic basement, but were locally block-faulted in the north (Yeates and others, 1984). Most of the northwest - southeast fault systems shown on the map in the north of the basin were intermittent growth structures. The Carribuddy Group is inferred to thin, for example, over the Fenton Fault (Smith, 1984). The presence of the Carribuddy Group north of the Fenton Fault has not yet been confirmed.

Amadeus Basin

Broad regional uplift occurred over the Amadeus Basin during the 'Rodingan Movement', which may have extended from the Late Ordovician to the early Silurian (Webby, 1981). There was a tilting of the northeastern margin of the basin and the uplift resulted in a change in basin configuration, reflected in dissimilar isopach patterns (Wells and others, 1970) between the Ordovician Carmichael Sandstone and the overlying Silurian to Devonian Mereenie Sandstone. Up to approximately 1300m of sediments were eroded preceding deposition of the Mereenie Sandstone (Shaw and Wells, 1983), which is a predominantly aeolian sequence (Wells and others, 1970; M. Owen, B.M.R., pers. comm., 1987). No faults in the Amadeus Basin are documented as active during the Silurian.

Silurian uplift probably extended both north and south of the Amadeus Basin. Silurian sediments are absent in the Ngalia, Georgina and Officer Basins, where Early Devonian rocks rest unconformably on Ordovician units.

The timing of the Rodingan Movement in the Amadeus Basin is not well constrained. Present indications are that uplift in the Amadeus Basin occurred at a different time to that in the Canning Basin. In the Canning Basin, the Carribuddy Group appears, from meagre conodont evidence (Brown and Campbell, 1974) to extend into the Ordovician. Thus uplift and erosion prior to its deposition (Forman and Wales, 1981) probably occurred in the Late Ordovician. The disparate uplift timing between the two basins may be due to a broad zone of uplift on the southward continuation of the Halls Creek Mobile Belt, between the Canning and Amadeus Basins (Smith, 1984). This 'zone' is mentioned as a gravity feature in Shaw and others (1984). At present, though, there is no clear evidence that the belt was active in the Silurian. Moreover, the age of the base of the Mereenie Sandstone is not known and any correlation between the two basins during the Silurian is tentative.

Bonaparte Gulf Basin

The Bonaparte Gulf Basin is a conjectural area of Silurian deposition. Salt was intersected as diapirs in petroleum exploration drillholes (Beere and Mory, 1986; Laws and Brown, 1976). The age of the salt is unknown, but, in view of the occurrence of evaporites of probable Silurian age in the Canning Basin to the south, a Silurian age is thought possible. The eastern margin of the basin is well defined for the Devonian (Laws and Brown, 1976) and, given Silurian deposition in the basin, the eastern margin is also inferred to have been an active hinge zone in the Silurian.

Arafura Basin

Money Shoal-1 (Figure 1) in the Palaeozoic Arafura Basin intersected a thin sequence of sediments and intermediate volcanics, containing palynomorphs of probable late Silurian age, on the edge of a post-Silurian pre-Mesozoic graben (Smith and Ross, 1986; Shell Development (Australia), 1971; Brown, 1979; Balke and Burt, 1976). The basin is relatively undisturbed except where deformed by pre-Mesozoic graben structures. The Aru Ridge basement high borders the basin depocentre in the west. As the presence of Silurian rocks throughout this basin is conjectural, further deep drillholes are needed to elucidate the stratigraphy (Smith and Ross, 1986). The significance of the volcanics in Money Shoal-1 is not clear. Silurian volcanics are not recorded elsewhere west of the Tasman Line and the nearest Silurian intermediate volcanics are in the Calliope Island Arc. The geology of this area may be related to that on Irian Jaya to the north, where Silurian shelf sediments occur (Talent and others, 1975; Smith and Ross, 1986). The sediments in Money Shoal-1 were described as non-marine by Balke and others (1973). They may be part of an active area of terrestrial deposition which passed northwards into a continental shelf in the Irian Jaya area.

A Silurian hinge zone is inferred to the south of the Arafura Basin, as Silurian rocks appear to be absent in the northern part of the Northern Territory.

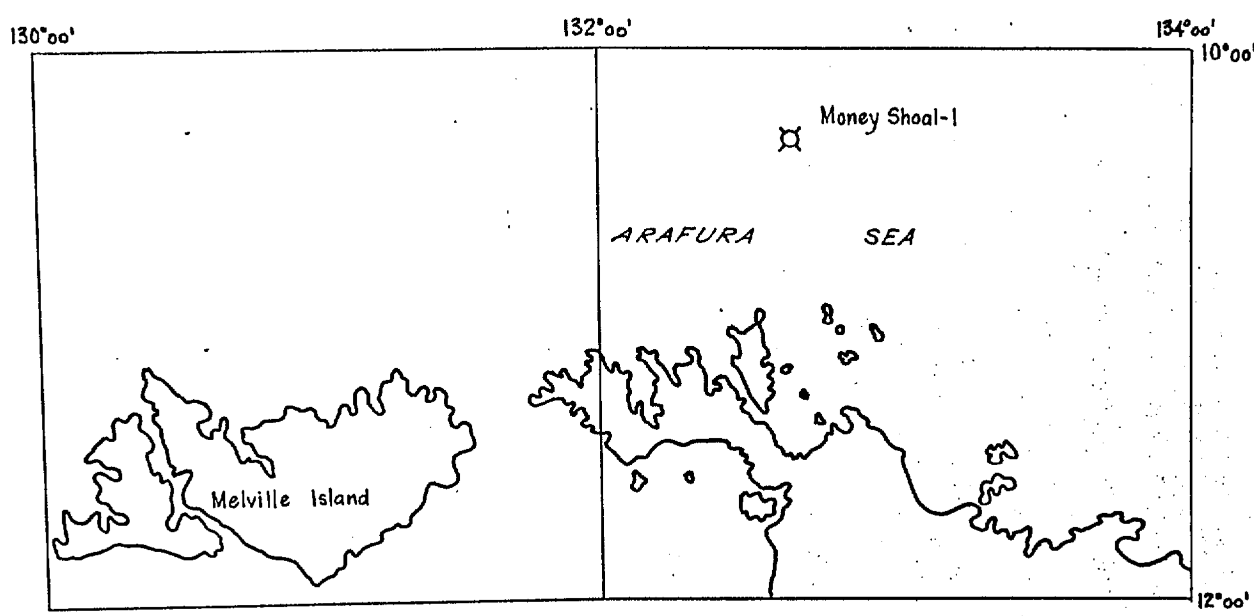

Fig. 1 Location of Money Shoal-1 exploratory oil well

Western Tasmania

S1 sequences in western Tasmania are conformable, or locally disconformable, on Ordovician units. The basin (or basins) of largely shallow marine Ordovician, through S1, to S3 deposition were developed on deformed and eroded Cambrian trough sequences (Cooper and Grindley, 1982; Collins and Williams, 1986). They were described as 'post-trough' sequences by Cooper and Grindley (1982). Subsidence appears to have been greatest in the west, in the Zeehan - Queenstown area (Spry and Banks, 1962). The tectonic setting of the ensialic western Tasmanian basin(s) is not clear. The significance of the contrasting stratigraphic histories of western and eastern Tasmania is discussed later ('eastern Tasmania').

Silurian deposits in Tasmania, in common with those in the Melbourne Trough, were not deformed until the Middle Devonian. However, S1 to S3 K-Ar isotopic dates obtained from Cambrian low-grade metamorphics in western Tasmania and from the Mathinna beds in eastern Tasmania indicate a Silurian tectonothermal event. This event is not reflected in the continuous Silurian stratigraphic record in western Tasmania and thus its significance and the reason for the wide range of isotopic dates are enigmatic (Adams and others, 1985). Perhaps the ages reflect uplift of the basement during deposition of the shallow marine sedimentary cover. Some of the K-Ar data may reflect ages which have been re-set.

ALONG THE TASMAN LINE

A number of features which lie along the Tasman Line were active structures. These include the western margin of the Hodgkinson Province, the Burdekin River Fault Zone and the Diamantina River Lineament in Queensland. Their descriptions are given below in sections discussing the adjacent structural zones.

EAST OF THE TASMAN LINE

The area east of the Tasman Line is the Tasman Fold Belt System, which comprises a number of regions with distinctive geological and structural history. These are described below. Structural features referred to in Queensland are indicated in Figure 2.

Hodgkinson Province

The Hodgkinson Province is considered to have been an ensialic marginal basin, formed on a rifted continental margin. Basalts in the Chillagoe Formation are tholeiitic, but geophysical evidence does not support the presence of an underlying oceanic crust (Fraser and others, 1977). The western margin of this province was probably a tensional zone

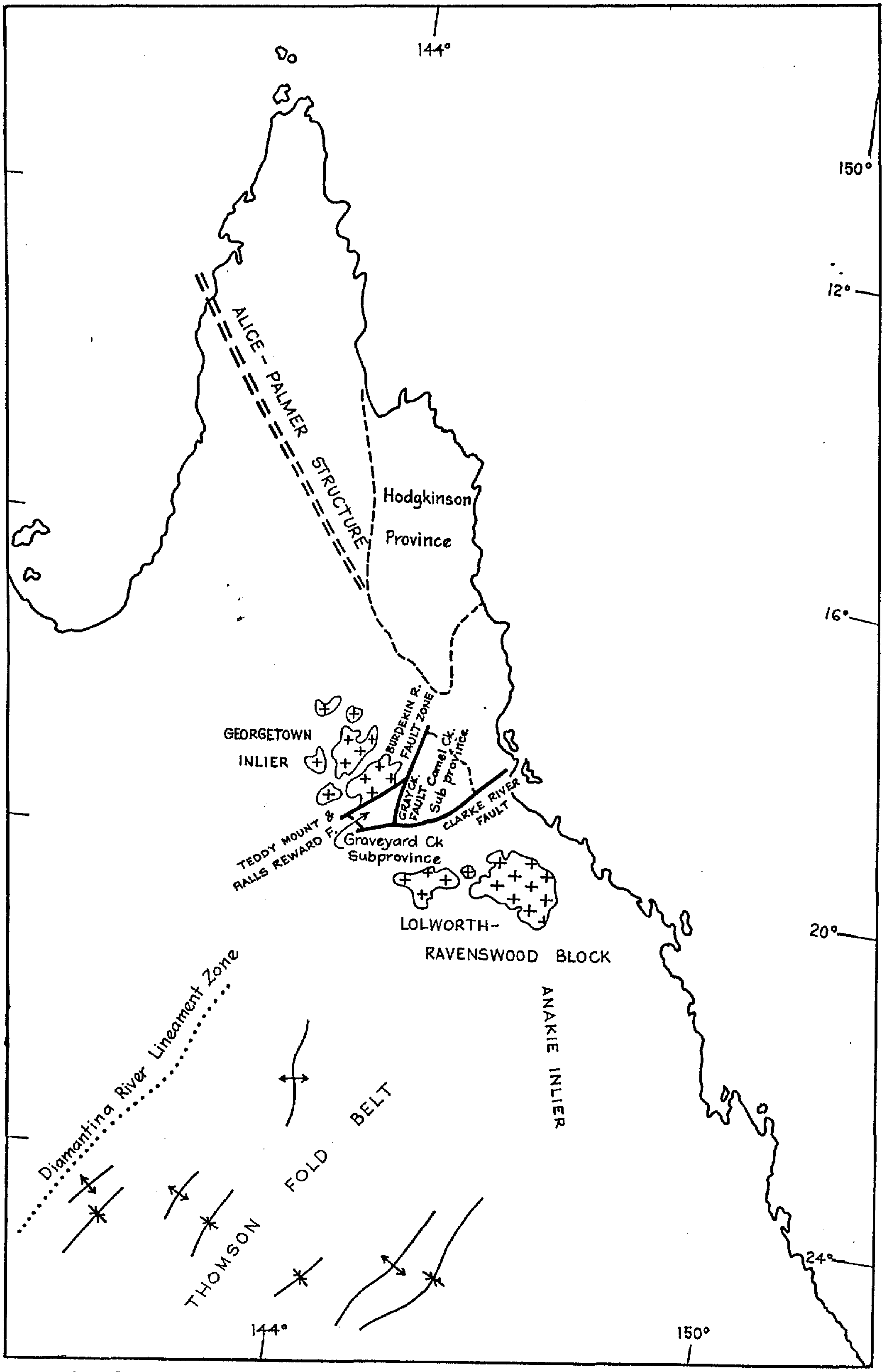

Fig. 2 Location of structural features referred to in Queensland
Position of 'Alice-Palmer Structure' after Shaw et al., (1987)

of block faulting during the Silurian (Shaw and others, 1987).

Broken River Province

The Broken River Province comprises two subprovinces, the Graveyard Creek and Camel Creek Subprovinces, which display different deformation timings both from each other and from the Hodgkinson Province (Withnall, 1985a; Withnall and others, 1985).

Graveyard Creek Subprovince

Within this subprovince there are relicts of a continental margin quartz-rich flysch deposit (the Judea Formation) which is either of Ordovician, or Ordovician to early Silurian, age (Murray, 1986; Withnall, 1985a). This sequence underwent deformation in early S1. Local mesoscopic isoclinal folds, 'broken formation' and bedding-parallel faulting characterized this compressional event (Withnall, 1985a; Arnold and Henderson, 1976). Tonalite intruded the Judea Formation prior to the deposition of the overlying Graveyard Creek Group (Withnall, 1985a).

In the Greenvale Subprovince of the Georgetown Inlier, major eastward-directed thrusting occurred in early S1, within the basement. The Burdekin River Fault Zone marks the easternmost margin of the zone of thrusting and the Judea Formation may have been deformed during the same event (Withnall, 1982, 1985b).

Still during early S1, the Graveyard Creek Subprovince is thought to have become an aulacogen, with the structure of a half-graben, most subsidence occurring adjacent to the active Halls Reward Fault. The beginning of extension in the subprovince was marked by the intrusion of porphyritic dykes (Munson, 1986).

The Georgetown Inlier was an emergent source region for both the Judea Formation and the Graveyard Creek Group during the time interval S1 to S3 (Murray, 1986). Subaerial volcanic activity is inferred to have occurred within the Georgetown Inlier during deposition of the Graveyard Creek Group (Arnold and Henderson, 1976).

Camel Creek Subprovince

This subprovince has been interpreted as an accretionary prism (Withnall and others, 1985; Henderson, 1987) because all pre-Carboniferous formations contain 'broken formation' and the sequences face west, but young to the east. Unlike the basement to the Hodgkinson Province, a gravity high under the Camel Creek Subprovince suggests it may be underlain by oceanic crust (Mathur and Shaw, 1982). More recent work by the Queensland Geological Survey has indicated that this subprovince may be part of a rifted continental margin, similar to the Hodgkinson Province (I.W. Withnall, written comm., June, 1987). If so, an alternative explanation for the underlying gravity high is required. The sense and timing of the movement on the Clarke River Fault Zone to the south of the Broken River Province are still unclear, but the main movement occurred between the early Silurian and the Carboniferous (Withnall and others, 1985).

The Gray Creek Fault separated regions of contrasting deformation in the Graveyard Creek and Camel Creek Subprovinces from at least early S1 onwards. It thus represents a possible 'terrane' boundary (Withnall, 1985a; 1985b).

Thomson Fold Belt

Early S1 folding, S1 to S2 metamorphism of pre-Silurian rocks and granite intrusion affected the subsurface Thomson Fold Belt. The northeast fold trends, imposed during orogenesis which ended the pre-cratonic stage of the Thomson Fold Belt (Murray, 1986), parallel the Diamantina River Lineament Zone, west of which only Precambrian isotopic dates have been obtained. As the Diamantina River Lineament Zone separates areas of different deformation timing, it was probably an active structural boundary during the early Silurian. The tectonic setting of the pre-Silurian sediments of the Thomson Fold Belt is not known, but there appears to be a basement of continental crust in the west, whereas in the east in the Anakie Inlier area (Figure 2), rock types and style of mineralisation indicate deposition in an oceanic basin (Murray, 1986).

In the Georgetown Inlier, granitoids (many of which are poorly dated) were intruded after the S1 thrusting (Murray, 1986; Withnall, 1985b). S3 metamorphism reflects a widespread thermal event in this area (Withnall, 1982).

Post- or late stage- orogenic S2 to S3 silicic plutonism occurred in the Lolworth-Ravenswood Block in the northernmost part of the Thomson Fold Belt (Murray and Kirkegaard, 1978).

Calliope Island Arc and Wandilla Slope and Basin

The Calliope Island Arc and Wandilla Slope and Basin form the northern part of the New England Fold Belt (Murray, 1986). A volcanic island, rather than a continental margin arc setting, is thought likely for the S3 to Devonian Calliope Island Arc (Day and others, 1978; Murray, 1986). Volcanic rock types are felsic to andesitic. The arc was bounded to the east by an ocean basin, in which the basal ?S3 to Devonian unit consisted of pelagic sediments, with minor felsic volcanic detritus (Kirkegaard and others, 1970) derived from coeval volcanism in the island arc. The present structure of the Wandilla Slope and Basin is that of an accretionary prism (Murray, 1975; Fleming and others, 1975), Given a Pridolian age for the commencement of the Calliope Island Arc, subduction may have begun during S3. However, the bulk of the Wandilla Slope and Basin sequence probably accumulated in an Early Carboniferous subduction complex (see Fleming and others, 1975; Murray, 1986).

The island arc may have been separated from the Australian continent by an ensialic marginal basin (Day and others, 1978; Murray, 1986), or a wider ocean basin, as speculated by Veevers and others (1982).

Woolomin Slope and Basin

The Woolomin Slope and Basin forms the southern part of the New England Fold Belt. It comprises a probable S1 to S3 (extending into the Devonian) ocean basin sequence, the present structure of which resembles that of an accretionary prism (Cawood, 1982). However, subduction is likely to have begun in the Devonian and correlate with the development of both the Tamworth forearc basin and a concealed volcanic arc to the west. The Calliope Island Arc and Wandilla Slope and Basin may have originally been contiguous with the Woolomin Slope and Basin (and the associated Early Devonian volcanic arc). Murray and others (1987) suggest that both the Calliope Island Arc and Wandilla Slope and Basin have subsequently been displaced southwards due to Late Carboniferous dextral transform faulting.

Lachlan Fold Belt (LFB)

Numerous workers have attempted to synthesize the structural and tectonic history of the LFB. Recent references to the Silurian structural history of the LFB include Cas (1983); Crawford and others (1984); Crook (1980); Crook and others (1973); Crook and Powell (1976); Degeling and others (1986); Fergusson and others (1986); Pickett (1982); Powell (1983a); Powell in Veevers (1984); Ramsay and VandenBerg (1986); Scheibner (1976) and Wyborn (1977).

Localities referred to below but not shown on the structure map are indicated in Figure 3.

The LFB is a complex orogenic belt affected during S1 by a compressional event, the Benambran Orogeny. From S2 to S3 the belt underwent crustal extension with the development of horsts and grabens, while at the close of S3 and continuing into the Devonian a further compressional phase, the Bowning Orogeny, affected the fold belt.

A number of structural zones within the LFB display different deformation timings, within the broad phases of structural development outlined above.

The earliest S1 structures in the LFB are latitudinal Benambran folds. East-west isoclinal folds are recorded in the Wagga Metamorphic Belt (WMB), east of the Mt. Wellington Fault Zone and at Sofala, on the eastern edge of the Hill End Trough (Cas and others, 1980; Fergusson and others, 1986; Fergusson and others, 1987; Morand and Gray, 1987). There are also early folds in Ordovician rocks at Batemans Bay (Powell, 1983b). At both Batemans Bay and Sofala, the early folds have open profiles and lack an axial-surface cleavage. East of the Wonnangatta Line, the east-west folds are upright and deform an earlier bedding-parallel slaty cleavage in the

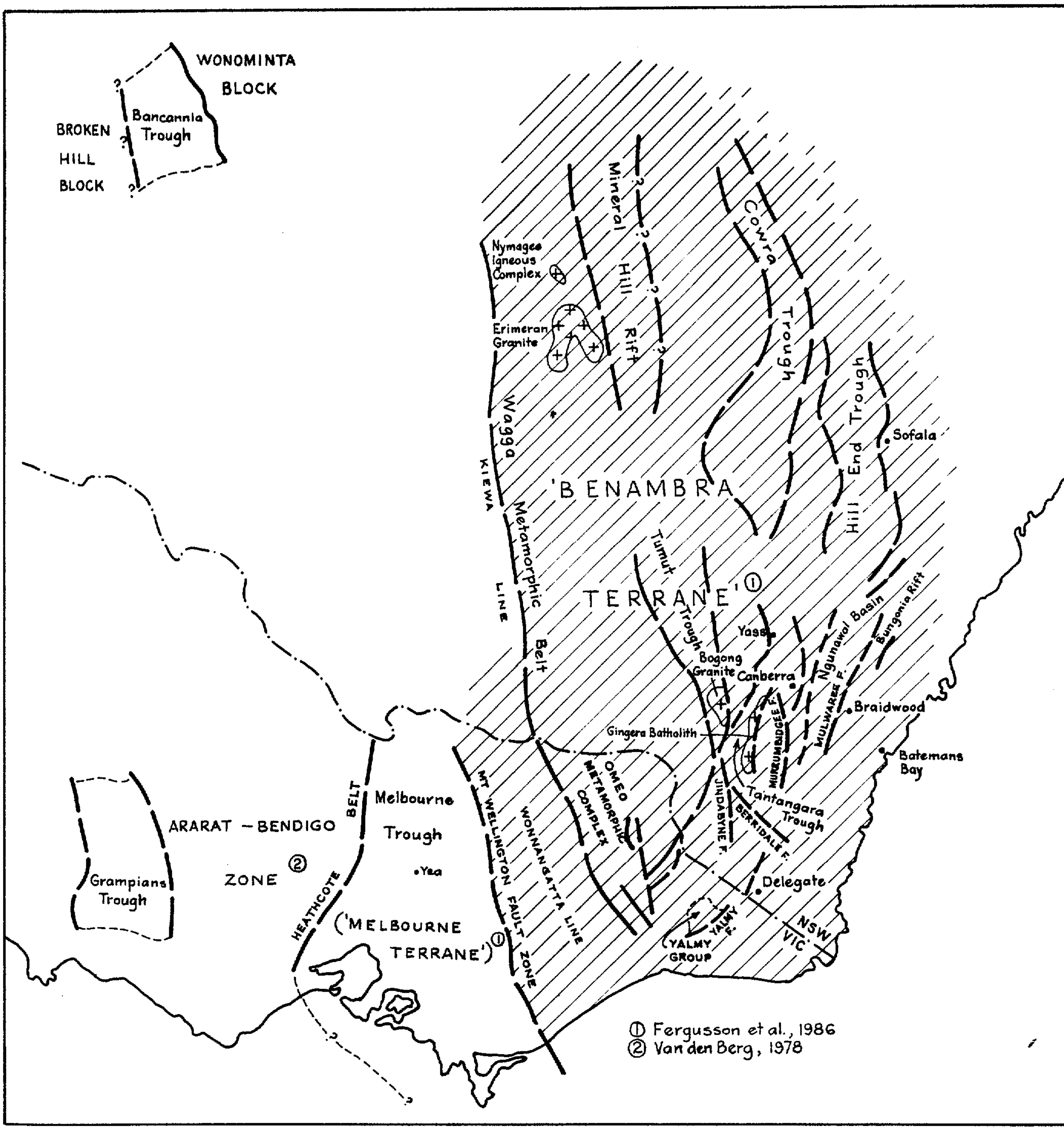

Fig. 3 Localities and structural features referred to in New South Wales and Victoria

Omeo Metamorphic Complex. West of this line, the folds are steeply inclined. They tighten towards the line and indicate a sense of tectonic transport toward the south (Fergusson and others, 1987).

These early latitudinal folds, together with the bedding-parallel cleavage, may be explained by oblique plate convergence involving dextral transcurrent motion in the epi-Ordovician/earliest Silurian, during the early stages of the Benambran Orogeny (Powell, 1983a, 1983b). The closing, uplift and metamorphism of the Ordovician Wagga Marginal Basin produced the WMB. Metamorphic grade in the WMB is low in the north and high in the south (Omeo Metamorphic Complex).

Regional dextral shear along major faults on the western edge of the WMB is considered to have juxtaposed the WMB against the Melbourne Trough (Fergusson and others, 1986). Fergusson and others (1986) refer to the two zones respectively as the 'Benambra Terrane' and the 'Melbourne Terrane'. These 'terranes' do not correspond to the fore-arc 'terrains' in the LFB described by Crook (1980).

The east-west structures in the WMB are over-printed by northwest to north-northwest trending folds (Powell, 1983a; Morand and Gray, 1987). Some of these northwest to north-northwest trending folds in the WMB are also Benambran structures as they pre-date S2 to S3 granitoid intrusions at some localities (for example, Heugh, 1980). The foliated phases of the Nymagee Igneous Complex and the Erimeran Granite in the northern WMB are believed to be coeval with Benambran deformation (Pogson and Felton, 1978; Pogson and Hilyard, 1981).

To the west of the Mt. Wellington Fault Zone, the deformation and metamorphism which occurred in the southwest 'Benambra Terrane' are absent (Fergusson and others, 1986; VandenBerg and others, 1976). The Melbourne Trough may not have developed as a discrete basin until the early Silurian (Garratt, 1983), coincident with uplift of the folded and stabilised Ballarat Trough west of the 'Heathcote Axis' (VandenBerg, 1978). The uplifted area in the west became the main sediment source area for the trough. However, the Benambran Orogeny was reflected only in a facies change from Ordovician black shales to a sandier facies at the base of the trough sequence in S1 (VandenBerg and others, 1976). Active fault margins to the Melbourne Trough have not been clearly identified (A.H.M. VandenBerg, Geological Survey of Victoria, pers. comm., 1987). However, intermittent fault movement both along the trough margins and within the trough is inferred, in view of the occurrence of chaotic mass-flow sediments at intervals within the sequence (see Garratt, 1983). VandenBerg (1978) suggested that the Melbourne Trough, which underwent rapid subsidence in early S1, was an extensional basin produced by crustal stretching during the Benambran Orogeny.

In the Yalmy area, too, Benambran events are signalled only by a facies change from Late Ordovician black shale to sandy turbidites indicative of a very high flow regime (A.H.M. VandenBerg, as above, pers. comm., 1987), while outside the LFB in Tasmania there was merely local uplift in early S1 (Cooper and Grindley, 1982; Adams and others, 1985). There is little information for eastern Tasmania (see separate subheading below), but, again, there appears to be only a conformable facies change, from the argillaceous Ordovician sequence to a sandier Siluro-Devonian sequence, at this time.

In the Cowra Trough, Molong High and Hill End Trough areas, in the northeastern LFB, Benambran effects appear to be weak, producing S1 uplift, but no major folding.

The Benambran Orogeny comprised several phases extending from Late Ordovician to the end of S1. Deformation was characterised by rapid local contrasts in timing. For example, at Delegate, in New South Wales, an early S1 deformation occurred prior to Tombong beds deposition and was followed by a post-Meriangaah Siltstone 'Quidongan' folding (Crook and others, 1973). At Yalmy, in Victoria, however, no break is evident at the Ordovician-Silurian boundary. Activity on the Yalmy Fault, which is situated between the depositional areas at Delegate and Yalmy, appears to have influenced the respective deformation timings (A.H.M. VandenBerg, as above, pers. comm., 1987). In Victoria, the main Benambran effects were apparently later (Late Llandovery, possibly equivalent to the 'Quidongan Orogeny') than in New South Wales (Ramsay and VandenBerg, 1986). The Quidongan event has thus been regarded as the final phase of the Benambran Orogeny.

During uplift and erosion of the WMB, sediment was shed east into a depositional region with continental margin affinities (Powell, 1983a). Relicts are preserved in the Tantangara Trough (Owen and Wyborn, 1979).

In late S1, dextral transcurrent movement along the eastern side of the WMB is believed to have led to the formation of the Tumut Trough, as a pull-apart basin (Powell, 1983a). This event caused uplift of areas of former turbidite deposition in the southern WMB and cut off the sediment supply to the Tantangara Trough, which was deformed into closely spaced meridional folds (Owen and Wyborn, 1979). Uplift and tilting occurred at this time in the Canberra-Brindabella area, as displayed by the unconformity of the Tidbinbilla Quartzite on the Ordovician Adaminaby beds (Owen and Wyborn, 1979).

The Tantangara section of the Canberra-Yass Shelf thus became a positive feature in late S1. By late S1, the north-south zone of deep water ?continental margin deposition had moved further to the east. Gentle folding and uplift (Owen and Wyborn, 1979) produced the Canberra-Yass Shelf by the end of S1, during the Quidongan event.

The dextral shear regime is thought by Powell (1983a) to have led indirectly to the development of the meridional horsts and grabens to the east of the Tumut Trough, between S1 and S2. They formed at approximately 25 degrees in a clockwise sense to the master fault, which was along the eastern side of the WMB (Powell, 1983a).

The Darling River and Murray River lineament zones to the north and southwest of the LFB, respectively, are believed by Degeling and others (1986) to have acted as transform fracture zones following the Benambran Orogeny. Movement on the zones is probably linked to the extensional rift formation within the LFB.

Volcanism in the LFB was confined to S2 and S3, with the exception of the Tumut Trough, in which basaltic volcanics with tholeiitic affinities of possible late S1 age occur (Kennard in Basden, 1982). Volcanism was both subaerial and submarine, occurred mainly on the horsts and was predominantly felsic, although intermediate to mafic volcanics were erupted locally. Bimodal felsic and mafic volcanism characterised, for example, the region formerly named the Captains Flat Trough (Richardson, 1979; Felton and Huleatt, 1977), now incorporated in the 'Ngunawal Basin' (Bain and others, 1987).

The tectonic style of the LFB after the Benambran Orogeny was thus extensional. The direction of crustal extension was east-west (Scheibner, 1974; Wyborn, 1977). The shallow to deep marine troughs were bounded by volcanic highs on which largely shallow marine sediments were deposited. The troughs are considered to be rifts (see Cas, 1983), although the exact nature of the bounding faults is not clear. Furthermore, post-trough faulting has in many cases obscured the original trough boundary. The Ngunawal Basin, for example, is thought by Bain and others (1987) to have been an elongate depression. In some cases, however, there may have been an important component of strike-slip fault movement. Degeling and others (1986) proposed that the Mineral Hill Trough opened along a sinistral strike-slip fault.

The original size of the rifts can be inferred from the amount of later compression. Folding reduced the original width of the Ngunawal Basin by at least fifty per cent (Bain and others, 1987).

Deposition in the Hill End Trough originally spread over what in S3 became the Capertee High. In S1 to S2, the source area and greatest subsidence were in the west and the palaeoslope was to the east. At about the beginning of S3, however, the eastern bounding fault became active and uplift of the Capertee High occurred (Packham, 1968; Pemberton, 1980). The depoaxis moved to the eastern edge of the trough. The Bungonia trough, which was shallow marine throughout, probably developed either as a rift within the Capertee High or as a basin on its eastern edge.

In Victoria, the Cowombat Rift opened in S2 along orthogonal northwest and northeast aligned fractures (Ramsay and VandenBerg, 1986). The beginning of extension was marked here by the eruption of thick subaerial volcanics. In the Grampians Trough, the intrusion of rhyolitic dykes reflected minor crustal extension prior to the commencement of deposition and subsidence. VandenBerg (1978) described the Grampians Trough as a basin of transitional domain, lying on previously stabilised basement.

The Tumut Trough appears to be the only rift to have extended sufficiently to allow the formation of oceanic crust (see Powell, 1983a).

Granitoid intrusion in the WMB was a final phase of the Benambran Orogeny and the earliest (S1) granitoids were intruded in the south of this zone. The oldest granitoids within the 'Benambra Terrane' of the LFB generally young eastwards with time, so that in the WMB they are 430 Ma+ and in the east at Bega/Moruya they are Devonian: approximately 400 Ma. It has been suggested that this was due to an easterly migration of the mantle heat source through time (Powell, 1983a).

The timing of the Bowning Orogeny is poorly constrained except at a few localities. There are indications that compression began toward the end of the Silurian in some parts of the LFB. The Cowombat Rift sequence underwent tight to isoclinal northwest folding, with the development of slaty cleavage, at the end of S3 (Ramsay and VandenBerg, 1986; Fergusson and others, 1987). Further dextral movement along the faults in the southwest 'Benambra Terrane' appears to have occurred at the time of the folding of the Cowombat Rift sequence (Fergusson and others, 1987).

The Tumut Trough was closed and deformed prior to the intrusion of the Bogong Granite (410 +- 16 Ma), toward the end of S3. The eastern edge of the trough became a thrust along which the Coolac ophiolite suite was emplaced (Basden, 1982).

The Canberra-Yass Shelf area from Canberra southwards also underwent end-S3 deformation. The effects of the orogeny appear to have been stronger in the west than in the east of this shelf area, with more intense folding and stronger foliation in granitoids in the Tantangara area in the west than in the Canberra area to the east. Fold trends are variable but are predominantly meridional. Deformation post-dated the Gingera Batholith (412 +- 8 Ma, Owen and Wyborn, 1979) and is considered here to have probably begun in S3, penecontemporaneously with, or a little later than, the closing of the Tumut Trough.

End-S3 north to northeast tight folding affected the Capertee High sequence at Braidwood but not the adjacent Ngunawal Basin, where the main deformation was in the Middle Devonian. The adjacent but different deformation timings are considered to be due to S3 to Devonian activity on the Mulwaree Fault, situated between the two zones.

Faults in the Kosciusko-Berridale area were active both during and after granitoid intrusion. Wyborn (1977) noted that late Silurian batholiths were emplaced into the 'highs' in the LFB during crustal extension. Tensional wrench movement may have occurred on the Berridale Fault during batholith intrusion in S2-3. In support of this are late-stage aplite dykes oriented parallel to and at angles to the fault (White and others, 1977). Sinistral transcurrent movement is thought to have occurred on the Murrumbidgee Fault during emplacement of the Murrumbidgee batholith in S2(?)-3 (Richardson, 1979).

It is possible that fault-controlled batholith emplacement and corresponding local uplift partly account for different deformation timings between adjacent areas within the LFB.

The Jindabyne Fault, to the west of the Berridale Fault, may have acted as a bounding fault to a Silurian trough which has since been obliterated (Wyborn, 1977).

Granitoid emplacement in the Grampians and Ararat-Bendigo zones was largely a Devonian event (Ramsay and VandenBerg, 1986). However, two small intrusions dated at 410 and 411 (+- 4) Ma (late S3) (McKenzie and others, 1984) occur in these areas.

Deposition in the Melbourne Trough continued largely without interruption from S1 to S3. The trough depoaxis, however, moved eastwards during the Silurian and Early Devonian. In S1 deeper water was in the west, while from the early Ludlovian to S3 there was a shallowing of the trough in the west but a deepening to the east, around Yea (Garratt, 1983). The main deformation of the trough was in the Middle Devonian, in striking contrast to deformation timings east of the Mt. Wellington Fault Zone.

The Grampians Trough to the west, however, was deformed prior to the intrusion of Early Devonian granitoids. Although deformation of the Grampians Group was suggested as Silurian by Ramsay and VandenBerg (1986), thelodont remains in the upper part of the sequence which Turner (1986) believes are of Early Devonian, rather than Silurian, age, indicate that the deformation may not have occurred prior to the Early Devonian.

The Darling Basin ('Darling Depression', Scheibner, 1976) is the westernmost structural unit of the LFB. Exploration wells which bottomed in Early Devonian sediments and seismic information for this area support the conjecture that Silurian and older sediments exist beneath the known sediments of this basin (C.M. Brown, B.M.R., pers. comm., 1986). Consequently, speculative S3 deposition is shown in this region. In the Devonian, the sequence suggests a rift-basin setting (Degeling and others, 1986) and this is also inferred for S3.

Eastern Tasmania

Williams (1978) described the Mathinna beds basin of deposition as one 'filled without any interruption'. Both Ordovician and Devonian graptolites have been found within the sequence (see Baillie, 1987) and it is therefore inferred that the entire Silurian is also represented. The northwesterly trending Mathinna beds trough was along strike from the Melbourne Trough (Baillie, 1987) and the two may have been connected. There is no transition between the shallow shelf deposits of western Tasmania and the 'flysch' deposits of eastern Tasmania (Baillie, 1985). The two halves of Tasmania have undergone different stratigraphic and structural histories (Collins and Williams, 1986). They are regarded as 'terranes' which were brought together by lateral movements along the Tamar Fracture System by the Late Devonian (Baillie, 1985).

If, (a) the movement of the eastern Tasmania terrane was sinistral with respect to the western Tasmania terrane, as proposed by Harrington and others (1973),

(b) there was a connection between the Melbourne Trough and eastern Tasmania,

(c) there was sinistral movement of the 'Melbourne Terrane'with respect to the 'Benambra Terrane' in the Benambran Orogeny (Fergusson and others, 1986) and probably again at the end of S3 (see Fergusson and others, 1987),

then it is possible that both the Melbourne Trough and eastern Tasmania were transported together by sinistral strike-slip movement between the Late Ordovician and the Early Devonian. That they may have almost moved to their present positions by the late Silurian is supported by the gradual change in palaeocurrent directions recorded in the Melbourne Trough (see Garratt, 1983). There was no westerly continental source in the earliest Silurian, but by the late Silurian (S2) the predominant source lay in the west, indicating that there was land to the west by S2. The Mathinna beds also display predominantly westerly palaeocurrents (Williams, 1978) and it would be interesting to see whether a detailed palaeocurrent analysis of the Mathinna beds would reveal a similar trend (from southerly to westerly) through this period of time. The amount of the postulated strike-slip movement is not known.

A number of reconstructions for Tasmania, in relation to mainland Australia and Antarctica, have been made (see, for example, Harrington and others, 1973; Baillie, 1985 and Stump and others, 1986). Stump and others (1986) pointed out the difficulty in correlating the Tasmania 'terranes' with the other areas.

Bancannia Trough

The Bancannia Trough is situated between the Broken Hill Block to the west and the Wonominta Block to the east. The Koonenberry Fault was active during deposition of the ?S3 to Early Devonian Mount Daubney Formation, which is thickest adjacent the fault (Rose, 1974; Neef, 1986). Easterly palaeocurrents at Mount Daubney (Neef, 1986) suggest a component of sediment flow and thus a palaeoslope towards the fault, such as found in an active half-graben. The half-graben structure is confirmed in seismic sections (Evans, 1977) and penecontemporaneous bimodal volcanism (Neef, 1986) reflects the crustal extension. The basin was restricted in extent (Rose, 1974). Drillholes south of the southern basin margin shown on the map either bottomed in Middle to Late Devonian sediments or intersected unfossiliferous sediments of presumed Devonian age (Byrnes, 1985). Thus a depositional connection with the Darling Basin is a possibility.

South Australia

There does not appear to have been any Silurian deposition in South Australia, but there is evidence of a mild thermal event, correlative with the Benambran Orogeny, in the southeastern part of the State. K-Ar dates between 420 and 440 Ma were obtained from granites by Webb (1976). There is no evidence that microgranite intrusion accompanied the tectonism, during which the granites were 're-set'. Fission-track dating on apatite supports a mild reheating event at about 430 Ma (Webb, 1976). S2 K-Ar dates obtained from granite on Wright Island (417 and 420 Ma) probably indicate the timing of a shearing event (Webb, 1976).

DISCUSSION

The Canning, Carnarvon and Bonaparte Basins have been regarded as Early Cambrian failed arms, initiated during the break-up of an ancestral northwestern continental margin which bordered the Tethyan ocean. There was mafic volcanism accompanying the break-up during the Early Cambrian and these arms were subsequently filled with sediment during the Ordovician to Devonian (Veevers, 1984).

While there was probably intermittent fault movement along the northern margin of the Canning Basin during Silurian deposition and the eastern margin of the Carnarvon Basin was fault controlled at that time, neither of these basins nor the Bonaparte Basin appears to have been a fault-bounded rift during the Silurian. Fault movement during deposition of the Tumblagooda Sandstone in the Carnarvon Basin was suggested by Veevers (1984) as consistent with the idea of a failed arm, but the Darling Fault is orientated north-south, rather than at right angles to the postulated ancestral continental margin (Veevers, 1984, Fig. 111, p.191). Moreover, the fault movement was related to uplift of the Yilgarn Block to the east.

A distinctive feature of the Tasman Fold Belt System is the disparate style and timing of deformational events between areas which comprise this orogenic zone. Scheibner (1983) discussed the possible existence of 'suspect terranes' in eastern Australia. A number of possible tectonostratigraphic terrane boundaries can be surmised from the structure map. In Queensland, the Burdekin River and Gray Creek Fault Zones and the Alice-Palmer Structure southwest of the Hodgkinson Province (Figure 2) separate areas of different depositional history and deformation timings. The different deformation timings between the Hodgkinson Province and the Camel Creek and Graveyard Creek Subprovinces pose a difficulty in accepting the theory of Harrington (1981) that the three juxtaposing areas can be explained in terms of a Silurian-Devonian triple plate junction.

The Darling River Lineament Zone, either side of which there are different Silurian structural histories, is another possible terrane boundary. The latter zone is shown as a terrane boundary in Scheibner (1983, Figure 2), but its significance was not stated. The 'Kiewa Line' and the fault bounding the eastern edge of the WMB and the western edge of the Tumut Trough have been described as sutures (Kiewa and Gilmore Sutures, respectively; Scheibner, 1983).

Considerable controversy exists over the tectonic setting of the LFB (Cas, 1983) and on whether there are 'suspect terrane' boundaries (as considered by Scheibner, 1983) within the fold belt. Two theories which have been advanced for the tectonic environment of the LFB during the middle to late Silurian are (a) a convergent plate margin, magmatic arc setting, and (b) a rift setting. In the case of (a), an extremely gently dipping subduction zone must be invoked to account for the width of the magmatic arc area. The Philippines are a modern example of a wide (300 km) magmatic arc, situated between two oppositely facing subduction zones. However, there is no evidence for multiple Silurian-Devonian trench-subduction systems within the LFB to compare with the Tertiary subduction history of the Philippines (Cas, 1983).

Crook (1980) proposed a model for the LFB of a dual arc system, with subduction zones both in the Tumut Trough and east of the Capertee High, dipping east and west, respectively. Crook (1979) described syn-sedimentary recumbent folds within the Tumut Trough sequence as having formed during subduction, but the structure of an accretionary prism does not appear to be present. East of the Capertee High, an accretionary prism, if present, is concealed beneath the Permo-Triassic Sydney Basin (Crook, 1980). The presence of accretionary prisms here or elsewhere within the LFB has not yet been confirmed.

Volcanism, predominantly felsic to bimodal, accompanied sedimentation both within the troughs and on the intervening horsts in the LFB. The stratigraphic record, in combination with the lack of evidence for oceanic crustal basement to the LFB (see, for example, Chappell, 1984), supports the theory of a rift setting during S2 to S3. The preservation of oceanic basement material within and along the margins of the Tumut Trough is exceptional and suggests that in this area continental crustal extension and thinning were sufficient to allow the formation of new oceanic crust. During trough closure toward the end of S3, the oceanic basement may have been obducted, rather than subducted. Owen and Wyborn (1979) and Cas (1983) noted that the presently known regional patterns within the LFB best fit an extensional rift setting. Cas (1983) compared the LFB with the late Cainozoic Basin and Range Province of the western United States, which is a complex system of horsts and grabens formed in response to crustal extension (Stewart, 1978). There are a few difficulties with this comparison, however. The Basin and Range Province is up to 800 km across, with much larger structures than those found in the LFB. Moreover, deposition is entirely non-marine (Cas, 1983).

As noted by Cas (1983), an extensional regime is not excluded from a convergent plate margin arc setting. A comparison with the Philippines archipelago remains a possibility, although there is a far greater volume of andesitic volcanism in the Philippines (Rutland and Walter, 1974) than in the LFB.

There is another possible modern analogue to the setting of the LFB. The Tumut Trough is comparable to the mid-Miocene to Recent Los Angeles Basin. This deep narrow trough is in a predominantly strike-slip tectonic environment. Four kilometres of subsidence have occurred in the basin since 11 Ma B.P. The amount of extension in the basin centre is a little larger than estimates of the maximum amount by which continental crust can be stretched before the formation of oceanic crust begins (Sawyer and others, 1987). The Los Angeles Basin is part of the California margin, which since the Miocene has been dominated by wrench tectonics, related to late Cainozoic transform motion between the North American and Pacific lithospheric plates. The wrench-related basins are characteristically rhomboid or lens-shaped and have complex structural and depositional histories (Howell and others, 1980). It is possible that the LFB during the Silurian was part of a continental margin similar to the California margin and that it was dominated by a transtensional regime.

To the east of the LFB, there is a continental slope and ocean basin sequence, the Woolomin Slope and Basin, the western edge of which is believed to have become a convergent plate boundary in the Devonian. However, the relationship between the LFB and the New England Fold Belt during the Silurian is not known, due to the difficulty in correlating the sequences.

The dextral shear regime which is thought to have controlled the development of the LFB during the Silurian (Powell, 1983a; Powell, _in_ Veevers, 1984; Fergusson and others, 1986) has been related to the major plate motion between Gondwanaland and the Palaeo-Pacific plates (Powell, _in_ Veevers, 1984). Australia rotated clockwise relative to the Palaeo-Pacific plate. Austin and Williams (1978) related this rotation to the overall northward progression of the locus of major deformation in the Tasman Fold Belt System during the Cambro-Ordovician to Early Silurian and to the corresponding southward progression of the onset of subsidence in western Australia. However, it is apparent from the present notes and discussion that there is no simple overall northward progression of the locus of major deformation in the Tasman Fold Belt System during the Silurian. The easterly migration of the mantle heat source through time within the LFB (Powell, 1983a), reflected in the corresponding overall younging of the granitoids to the east, may be related to the episodic eastward continental drift of Australia discussed by Austin and Williams (1978).

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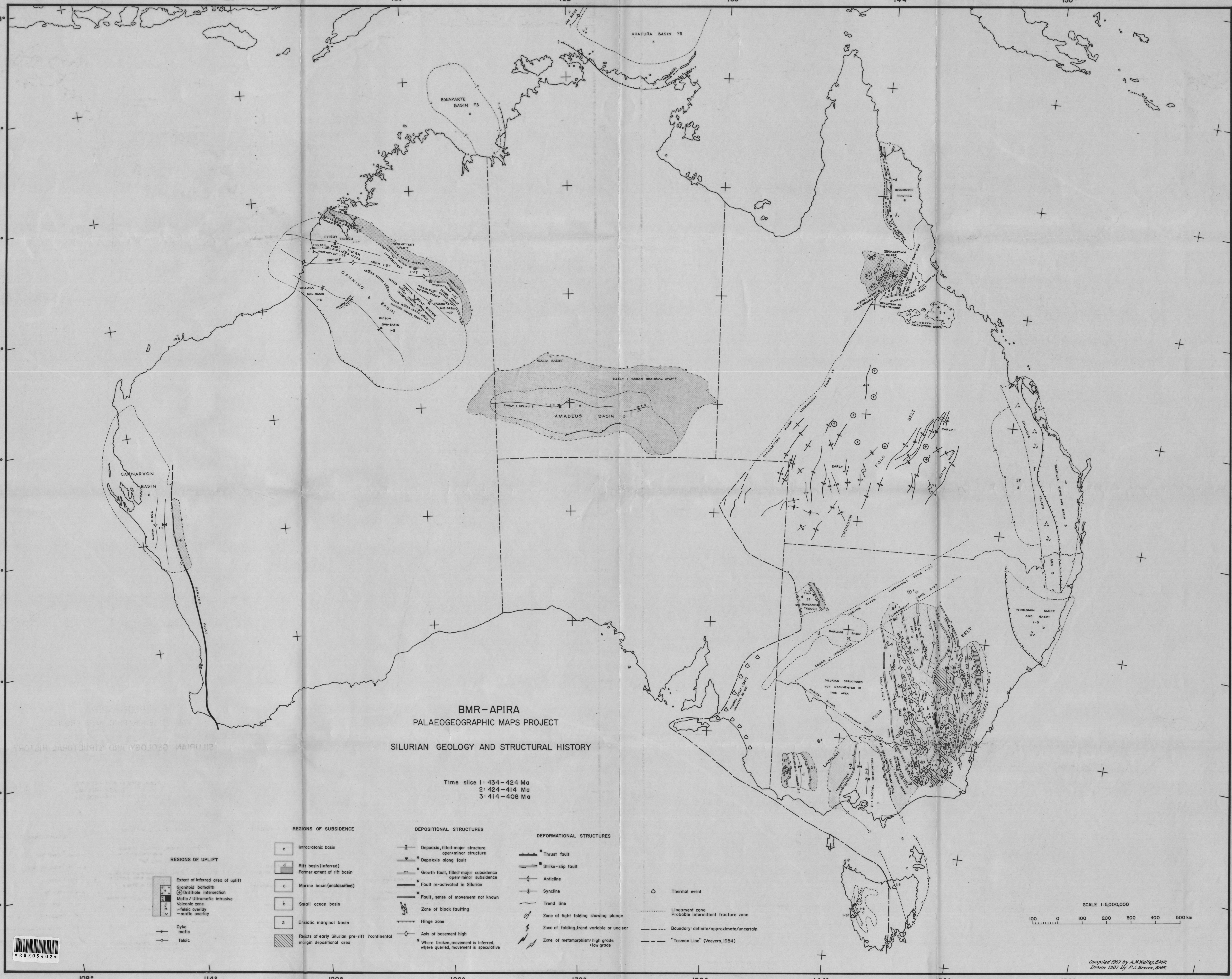
BMR-APIRA
PALAEOGEOGRAPHIC MAPS PROJECT
SILURIAN GEOLOGY AND STRUCTURAL HISTORY
Time slice 1: 434–424 Ma
2: 424–414 Ma
3: 414–408 Ma
REGIONS OF UPLIFT
Extent of inferred area of uplift
Granitoid batholith
Drillhole intersection
Mafic / Ultramafic intrusive
Volcanic zone
-felsic overlay
-mafic overlay
Dyke
mafic
felsic
REGIONS OF SUBSIDENCE
Intracratonic basin
Rift basin (inferred)
Former extent of rift basin
Marine basin (unclassified)
Small ocean basin
Ensialic marginal basin
Relicts of early Silurian pre-rift ?continental margin depositional area
DEPOSITIONAL STRUCTURES
Depoaxis, filled: major structure
open: minor structure
Depoaxis along fault
Growth fault, filled: major subsidence
open: minor subsidence
Fault re-activated in Silurian
Fault, sense of movement not known
Zone of block faulting
Hinge zone
Axis of basement high
Where broken, movement is inferred, where queried, movement is speculative
DEFORMATIONAL STRUCTURES
Thrust fault
Strike-slip fault
Anticline
Syncline
Trend line
Zone of tight folding showing plunge
Zone of folding, trend variable or unclear
Zone of metamorphism: high grade
: low grade
Thermal event
Lineament zone
Probable intermittent fracture zone
Boundary: definite/approximate/uncertain
"Tasman Line" (Veevers, 1984)
SCALE 1:5,000,000
100 0 100 200 300 400 500 km
CANNING BASIN
FITZROY TROUGH
AMADEUS BASIN
NGALIA BASIN
BONAPARTE BASIN
ARAFURA BASIN
CARNARVON BASIN
DARLING FAULT
GEORGETOWN INLIER
HODGKINSON PROVINCE
THOMSON FOLD BELT
LACHLAN FOLD BELT
DARLING BASIN
BANCANNIA TROUGH
WOOLOMIN SLOPE AND BASIN
SILURIAN STRUCTURES NOT DOCUMENTED IN THIS AREA
Compiled 1987 by A.M. Walley, BMR
Drawn 1987 by P.J. Brown, BMR
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