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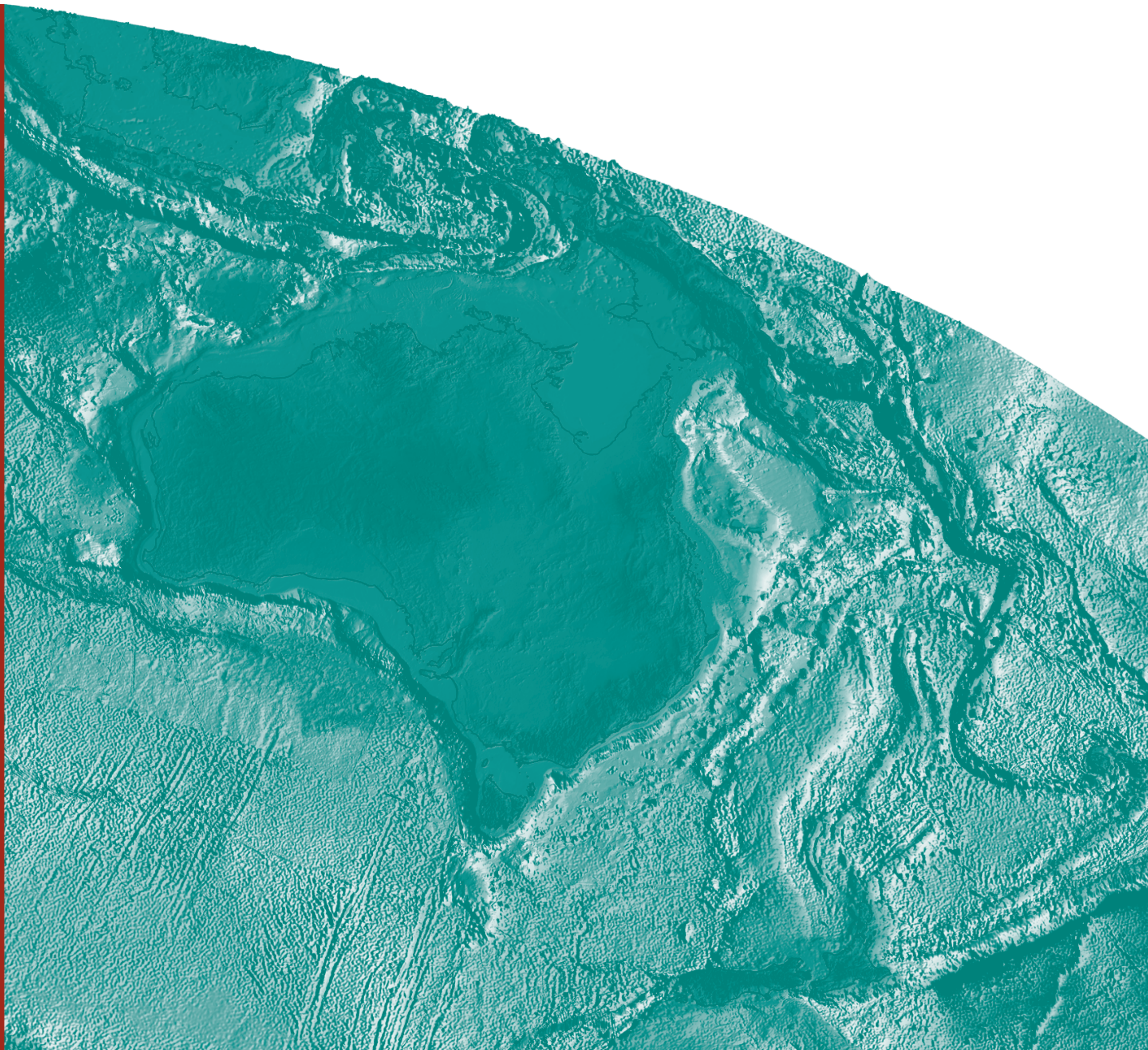

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

Basement structure and its influence on the pattern and geometry of continental rifting and breakup along Australia's southern rift margin

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by

Gibson, G. M., Totterdell, J. M., Morse, M. P., Goncharov, A., Mitchell, C. H. and Stacey, A.R.

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Contents

Executive Summary

Continental rifting and the separation of Australia from Antarctica commenced in the Middle-Late Jurassic and progressed from west to east through successive stages of crustal extension, basement-involved syn-rift faulting and thermal subsidence until the Cenozoic. Early syn-rift faults in the Bight Basin developed during NW-SE directed extension and strike mainly NE and E-W, parallel to reactivated basement structures of Paleoproterozoic or younger age in the adjacent Gawler Craton and Albany-Fraser Orogen. This extension was linked to reactivation of NW-striking basement faults that predetermined not only the locus of breakup along the cratonic margin but the position and trend of a major intracontinental strike-slip shear zone along which early displacement between Australia and Antarctica was accommodated.

Following a switch to NNE-SSW extension in the Early Cretaceous, the locus of rifting shifted eastwards into the Otway Basin where basin evolution was increasingly influenced by transtensional displacements across reactivated north-south-striking terrane boundaries of Paleozoic age in the Delamerian-Ross and Lachlan Orogens. This transtensional regime persisted until 55 Ma when there was a change to north-south rifting with concomitant development of an ocean-continent transform boundary off western Tasmania and the South Tasman Rise. This boundary follows the trace of an older Paleozoic structure (Avoca-Sorell Fault Zone) optimally oriented for reactivation as a strike-slip fault during the later stages of continental breakup and is one of two major basement structures for which Antarctic equivalents are readily identified.

The other major basement structure is the previously unrecognised early Paleozoic Coorong Shear Zone. This shear zone is the Australian equivalent of the Mertz Shear Zone in Antarctica and provides an important first-order constraint on paleogeographic reconstructions of the Australian-Antarctic continent. Previously, the Mertz Shear Zone was held to be a correlative of the Paleoproterozoic Kalinjala Mylonite Zone in the Gawler Craton but this leads to a very different continental fit in which Australia is positioned 300-400 km too far east with respect to Antarctica. Along with the Avoca-Sorell fault system, this basement structure was reactivated during continental breakup between Australia and Antarctica, and served as a major tectonic boundary during the Early Cretaceous across which the direction of extension changed from NW-SE to NNE-SSW. Both it and the Avoca-Sorell Fault Zone are particularly well imaged in aeromagnetic data and seismic sections, and have near-vertical attitudes consistent with formation as crustal-scale strike-slip faults that cut all the way down to the Moho. As such, their reactivation had a particularly profound influence on both the pattern and geometry of continental breakup, and the degree to which the southern rift margin was segmented. These structures would also appear to have controlled the location of some offshore ocean fracture zones with which they share a common strike and into which they appear to merge oceanward.

Introduction

Pre-existing basement structures and fabrics have long been known to exert a strong influence on the geometry of continental rifting and the formation of extensional basins in general. Particularly influential in this respect have been studies of active or recently extended continental rifts such as the Gulf of Suez (Younes and McClay, 2002), East African rift system (Bosworth, 1992; Contreras and Scholz, 2001; Morley, 1999; Morley et al., 1990; Ring, 1994; Rosendahl, 1987) and North American Rio Grande Rift (May and Russell, 1994), where it has proved to be mechanically more efficient to reactivate favourably oriented pre-existing structures and fabrics than create new ones in crystalline basement. For example, in the Tanzanian segment of the East African rift, extensional deformation is locally strongly partitioned into lines of pre-existing crustal weakness with basin development controlled by the structural grain of Proterozoic mobile belts, bypassing the adjacent Archean basement blocks (Morley et al., 1990; Rosendahl, 1987). In other parts of the rift system (e.g. Gulf of Suez), along-strike reversals in basin polarity and normal fault attitudes coincide with major basement faults and shear zones identified at depth in seismic reflection profiles (Younes and McClay, 2002). Such reversals are common to all continental rifts, not only bringing about a compartmentalisation or segmentation of the rift system into separate sub-basins (Faulds and Varga, 1998; Lambiase and Bosworth, 1995; McClay et al., 2002), but lending themselves to indirect mapping of structural anisotropies in basement even where the latter is not exposed (e.g. Rio Grande Rift, May & Russell, 1994).

A similar degree of basement control has been proposed for many continental rift margins and is particularly evident in the case of continental transform (sheared) margins. These margins typically evolve from transform faults located along strike from pre-existing basement structures and intra-continental shear zones (Bird, 2001; Lorenzo, 1997). A sharp re-entrant in the continental margin marks the site of the pre-existing basement structure. The opposing mid-Atlantic West African and northern Brazil transform margins both evolved from such a shear zone (Benkhelil et al., 1995; Mascle et al., 1997) and much the same type of basement structure is thought to have controlled basin architecture and formation of the transform margin off western Tasmania (Fig. 1) along Australia's southern rift margin (Gibson et al., 2011; Hill et al., 1995; Hill and Exon, 2004). In both these examples, rifting failed to propagate across a pre-existing basement structure which, instead, became the locus of strike-slip faulting with consequent migration of the rift axis seaward along the resulting continent-ocean transform boundary. In fully mature ocean basins, such boundaries commonly translate along strike into ocean fracture zones and only ceased being active once the opposing continental blocks achieved full and final separation. Thus, the west Tasmanian transform margin (Fig. 1) remained active until Antarctica broke free from Australia shortly after 33.4 Ma (Hill and Exon, 2004). Thereafter, this boundary evolved into a fully oceanic transform fault or fracture zone along which further separation between Australia and Antarctica took place.

Other fracture zones (e.g. George V Fracture Zone off South Australia) are no less prominent than the Tasman Fracture Zone off western Tasmania (Fig. 1) and might be expected to exhibit a comparable degree of basement control. However, to date little or no consideration has been given to the possibility that this equally prominent bathymetric feature might be similarly linked to pre-existing basement structure in the opposing continental margins. Here, we assess the influence of basement structure on the origin of this and many other features of Australia's southern margin, including the pattern and geometry of continental breakup and the location and distribution of the sedimentary rift basins that resulted from this process. Many of the basement structures described here have been identified before but others have little or no obvious surface expression and are reported for the first time. They include lithospheric-scale structures developed on both opposing continental margins whose position not only serves as an important constraint on paleogeographic reconstructions of the Australian-Antarctic continent margin but appears to have controlled the degree to which the continental margin is segmented and changes orientation along strike.

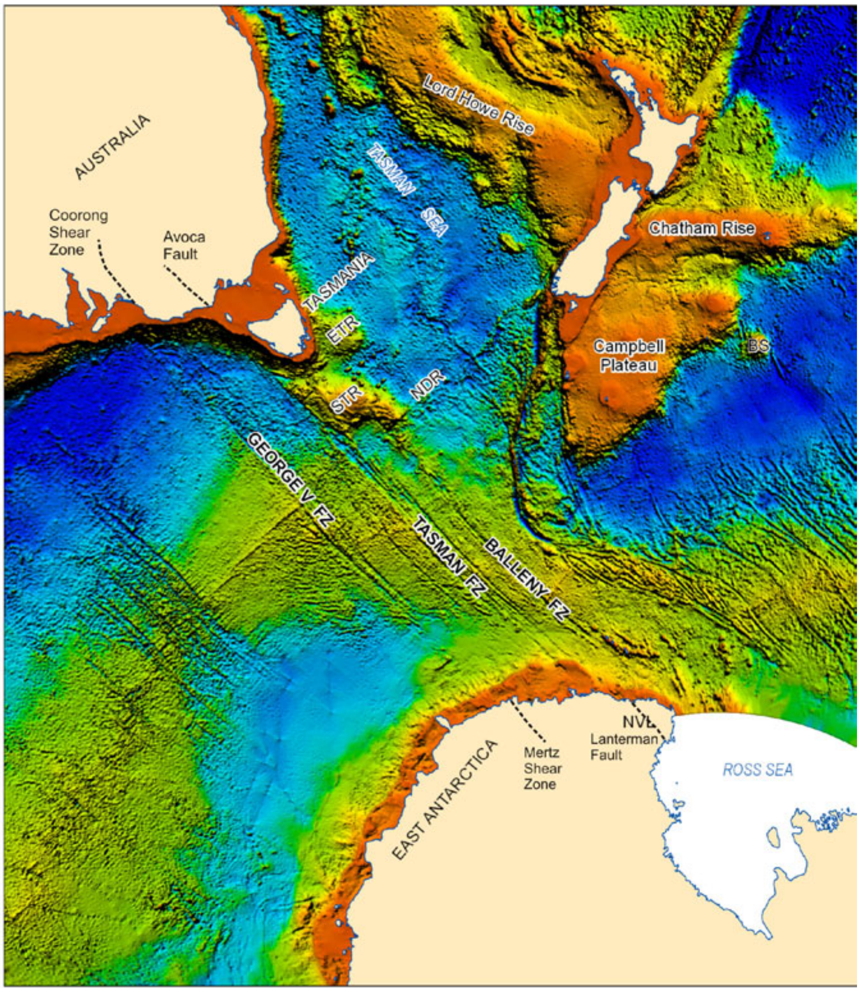

***Figure 1**. Bathymetric map of Southern Ocean off SE Australia showing ocean fracture zones, collinear basement structures and transform margin off west Tasmanian coast. NVL = northern Victoria Land; STR = South Tasman Rise; ETR = East Tasman Rise.*

Basement tectonic elements & crustal provinces

Shaw et al. (1996) subdivided the Australian continent into eight major crustal provinces or tectonic mega-elements based on shared geophysical and geological characteristics. Four of these mega-elements are represented in southern Australia although only three are retained here: the Pinjarra, West Australian and Tasman (Tasmanides) mega-elements (Figs. 2 & 3). The other mega-element (South Australia) is demonstrably composite (Fig. 3) and can be further subdivided into smaller crustal domains on the basis of isotopic and compositional heterogeneities within their respective basements (Shaw et al., 1996). These smaller subdivisions include the Mesoproterozoic Albany-Fraser Orogen and Archean-Mesoproterozoic Gawler Craton (Fig. 2), both of which have counterparts in Antarctica and originally formed part of much more regionally extensive basement terranes (Boger, 2011; Fitzsimons, 2003). Along with formerly contiguous parts of the East Antarctic Shield, the Gawler Craton makes up much of the Mawson Continent or Craton (Fanning et al., 1999). Its constituent domains (Figs. 3 & 4) have since been revisited and updated in the light of new and better quality geophysical and geological data (Hand et al., 2007) but for the most part retain their originally defined positions and boundaries (Shaw et al., 1996), many of which are structural (Cowley, 2006). The Tasman mega-element (Tasmanides) is similarly composite (Fig. 3) and, like the Gawler Craton, once extended without interruption into Antarctica (Fig. 2).

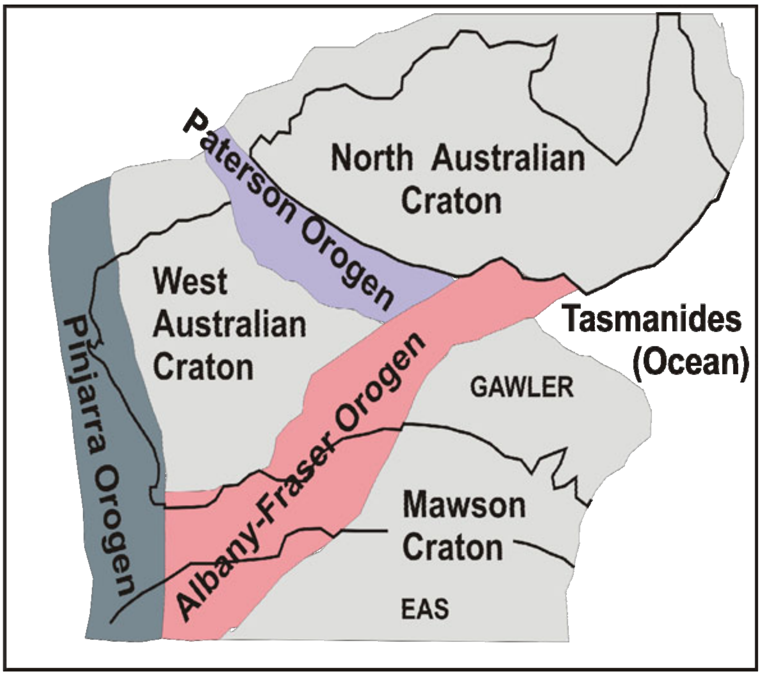

Figure 2. Major tectonic elements in a reassembled late Mesoproterozoic to early Neoproterozoic Australian-Antarctic continent. The Gawler Craton and East Antarctic Shield are combined into a single crustal entity to form the Mawson Continent or Craton (Fanning et al., 1999) bounded to the east by an ocean basin that will become the future Paleozoic-Mesozoic Tasmanides. The Mesoproterozoic Albany-Fraser Orogen is truncated in the south by the younger north-south-trending Neoproterozoic Pinjarra Orogen (modified after Shaw et al., 1996; Fitzsimons & Buchan, 2005). EAS = East Antarctic Shield.

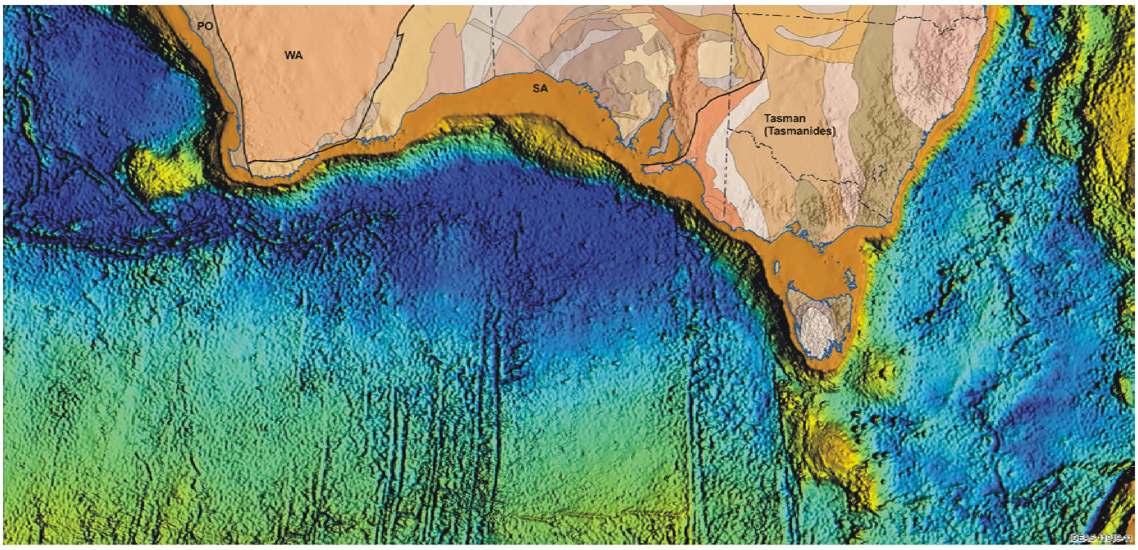

Figure 3. Mega-elements (heavy outlines) subdivided into smaller crustal domains (after Shaw et al., 1996) and superimposed upon a bathymetric image of southern ocean. PO = Pinjarra Orogen; WA = West Australian mega-element; SA = South Australian mega-element.

More recently, the Gawler Craton (Fairclough et al., 2004) has been redefined to include poorly exposed Mesoproterozoic rocks in the Coompana Block (Figs. 3 & 4) and adjoining regions around the periphery of the craton, and renamed the Gawler Province (Cowley, 2006). Unlike the Gawler

Craton, the Gawler province extends westwards for a considerable distance beneath lower Paleozoic sediments of the Officer Basin into Western Australia and is not geographically restricted to South Australia. In this respect the Gawler Province has a more restricted geographic distribution and is not entirely synonymous with the SA mega-element of Shaw et al. (1996).

Basement of Mesoproterozoic age is also believed to lie at depth beneath parts of the Tasmanides in SE Australia (e.g. Selwyn block; Cayley et al., 2002) but has only limited exposure in western Tasmania and adjacent offshore regions (Berry et al., 1997; Berry et al., 2008). Its presence nevertheless had a significant influence on rift basin geometry and evolution at the southeastern extremity of Australia's southern rift margin (Gibson et al., 2011; Hill et al., 1995; Hill and Exon, 2004; Palmowski et al., 2004). The West Australia mega-element (WA) lies at the other extremity (Figs. 2 & 3), comprising two Archean crustal blocks (Yilgarn and Pilbara Cratons) stitched together by the late Paleoproterozoic Capricorn Orogen (Cawood, 2005). It lies wholly inboard of the Australian continental margin and has no counterpart in Antarctica (Fig. 2). Rather, it is bounded to the west and south by late Neoproterozoic mobile belts (Pinjarra and Albany-Fraser Orogens) that isolate this crustal element from the continental margin (Fig. 2). These mobile belts are included in the Pinjarra and SA mega-elements respectively (Shaw et al., 1996) and mark the position of former sutures along which the Rodinia supercontinent was assembled (Cawood, 2005; Fitzsimons, 2003; Fitzsimons and Buchan, 2005). Major thrust faults in the Albany-Fraser Orogen dip southeast and strike northeast-southwest, parallel to the dominant gravity anomalies in this region.

FABRICS AND STRUCTURE WITHIN INDIVIDUAL TECTONIC ELEMENTS

Previous studies of Australia's southern continental margin have emphasised the importance of basement structure on rift basin architecture (Blevin and Cathro, 2008; Bradshaw et al., 2003; Totterdell and Bradshaw, 2004) and it is not intended here to repeat what has already been reported or is widely accepted. Rather, this section is more concerned with identifying the dominant structural trends in each of the major tectonic elements and determining how they influenced the rifting process during successive stages of crustal extension and continental breakup. A brief description of each major tectonic element is presented below. Further details for the terranes of the western Tasmanides can be found in Appendix A.

Pinjarra tectonic mega- element (orogen)

The Pinjarra mega-element or Orogen (Fig. 5) is separated from the WA crustal element by the north-south-trending, 1500 km-long Darling fault zone (Myers, 1990) and incorporates Mesoproterozoic rocks that underwent metamorphism and deformation up to granulite facies at 1080 Ma (Pinjarra Orogeny) and 550 Ma (Fitzsimons, 2003; Myers, 1990). Granulite facies rocks are reasonably well exposed in the Leeuwin Complex but for the most part the Pinjarra Orogen lies buried beneath Phanerozoic sediments of the Carnarvon and Perth basins. Rocks of comparable age and character (Fig. 2) occur in the Denham Glacier region of Wilkes Land in East Antarctica (Fitzsimons, 2003) and represent the inferred continuation of the Pinjarra Orogen into the opposing continental margin (Zhao et al., 1992). No equivalent structure to the Darling fault zone has yet been unambiguously identified in Antarctica although the Antarctic segment of the Pinjarra Orogen has been widely identified as an important crustal boundary in East Antarctica (Boger, 2010), separating Australo-Antarctic and Indo-Antarctic domains with different Proterozoic geological histories. Juxtaposition of these domains occurred through strike-slip faulting in late Neoproterozoic time (Fitzsimons, 2003). The Darling fault zone is similarly characterised by late Neoproterozoic strike-slip faulting and, in geophysical images for southwestern Australia, abruptly truncates fabrics developed in both the Yilgarn Craton (West Australian mega-element) and Albany-Fraser Orogen (South Australian mega-element) (Figs. 2 & 5).

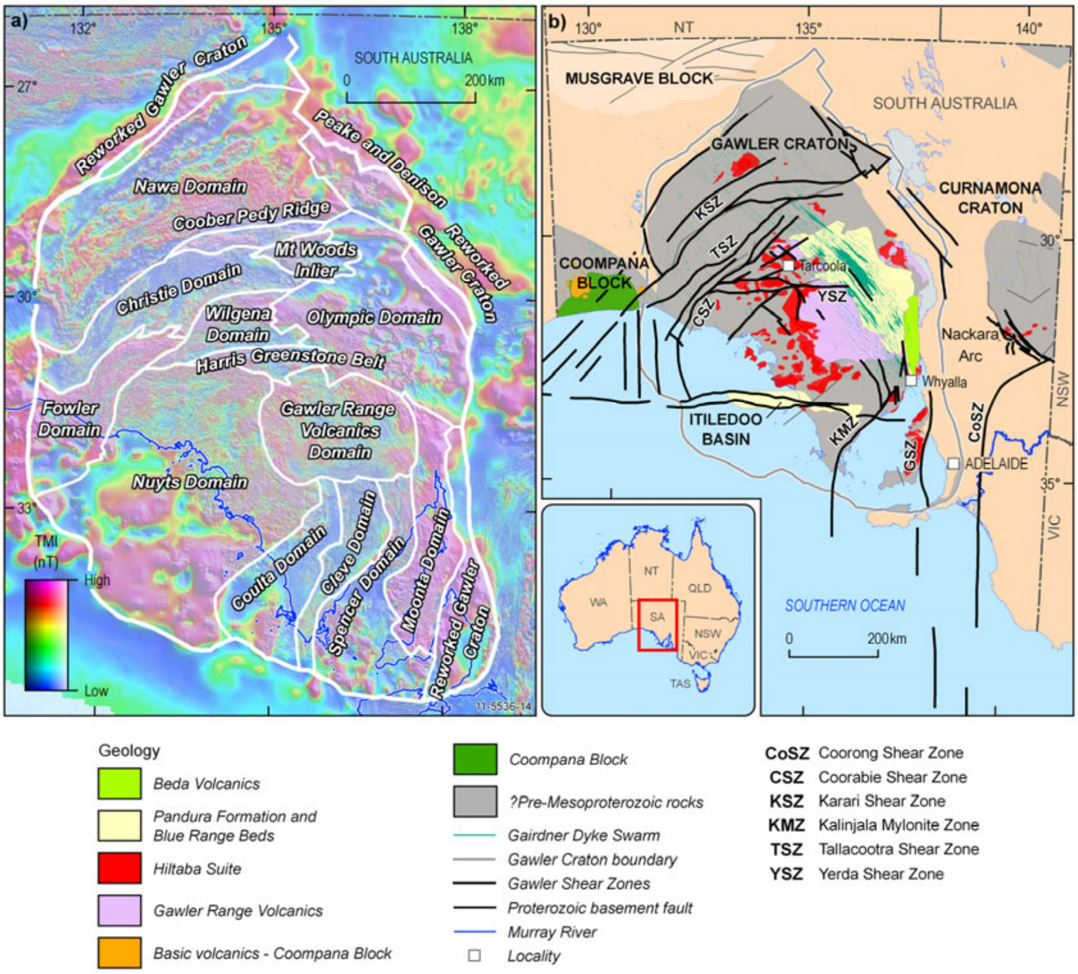

Figure 4. *(a) Gawler crustal domains superimposed upon total magnetic intensity image (after Ferris et al., 2002). Note that many domain boundaries are coincident with magnetic anomalies or changes in magnetic character. (b) Major shear zones in the Gawler Craton and surrounding region. The poorly exposed Coompana Block lies immediately west of the craton (see also figure 3) and forms part of a greater Gawler crustal province (Cowley, 2006).*

Albany-Fraser Orogen & adjacent Coompana Block

Except for a few coastal exposures, neither the Albany-Fraser Orogen (Fig. 5) nor adjacent Coompana Block (Figs. 3 & 4b) is well exposed so that only a limited amount of information is available about their internal structure and fabrics. Thrust faults and structures in the Albany-Fraser Orogen typically strike NE-SW (Fig. 5) and thus have broadly determined the trend of the southern West Australian coast and the sedimentary rift basins that lie offshore (Bremer and Eyre Sub-basins). A strong basement control on fault orientation and basin architecture in the Bremer Sub-basin has long been recognised (Nicholson and Ryan, 2005; Totterdell and Bradshaw, 2004) and includes normal faults with NE-SW trends that follow the dominant structural grain of the underlying orogenic belt (Fig. 5). This pattern of basement-controlled NE-SW oriented normal faulting continues farther east into the main part of the Bight Basin whose underlying basement rocks form part of the Coompana Block or greater Gawler Province (Fig. 4b). Other basin structures for which basement control seems likely are WNW- to NW-trending normal faults in the Bremer Sub-basin; they share the same NW orientation as late-stage strike-slip faults that cut across the southwest corner of the Yilgarn Craton and extend into the adjacent Albany-Fraser Orogen (Bradshaw et al., 2003).

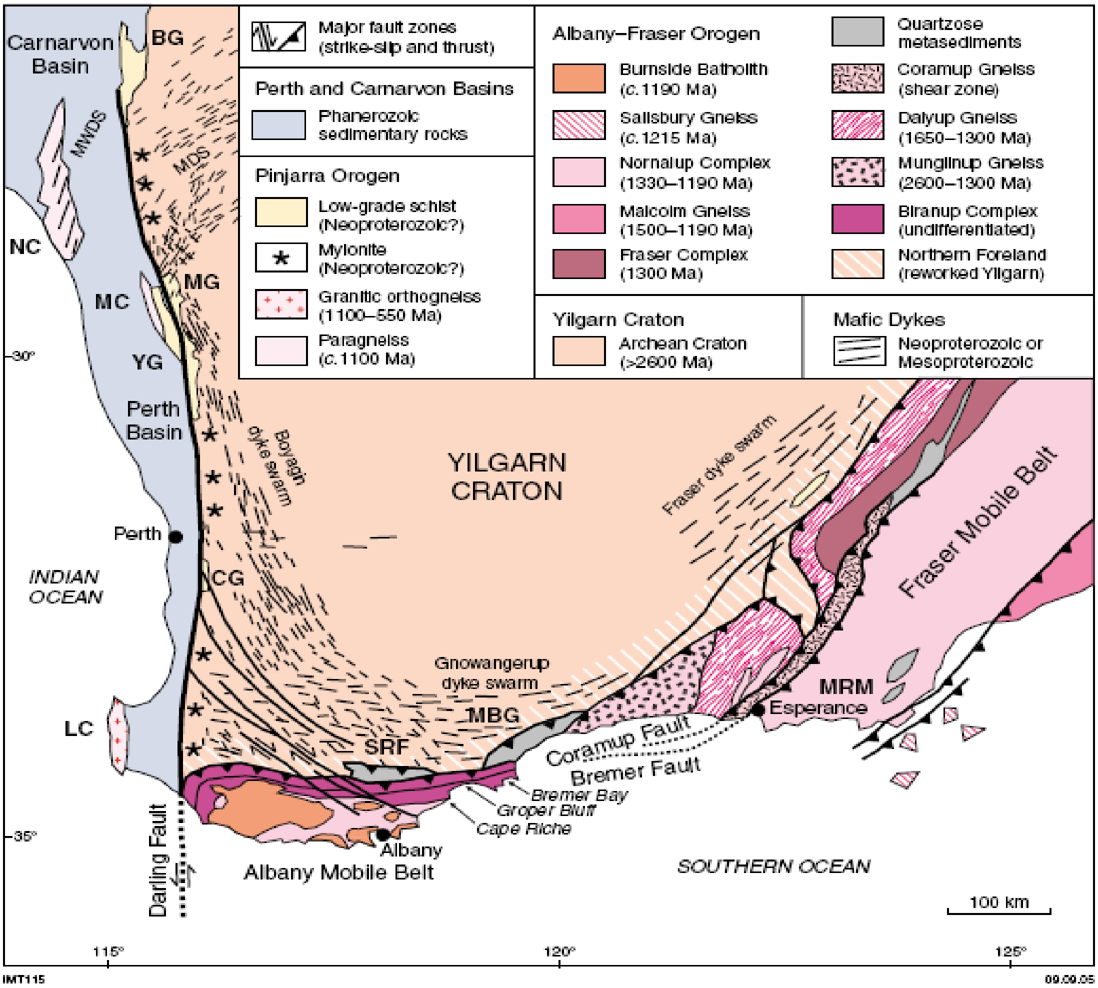

Figure 5. *Basement geology and structure of southwest Australia (after Fitzsimons & Buchan, 2005) based on regional mapping of Myers (1990), Clark (1999) and Fitzsimons (2003). Note strong NE structural grain defined by Fraser Dyke Swarm and structures of Albany-Fraser Orogenic Belt. NW-striking structures in southern Yilgarn Craton do not stop at coast but continue offshore into Bight Basin. BG = Badgeradda Group; CG = Cardup Group; LC = Leeuwin Complex; MGB = Mount Barren Group; MDS = Muggamurra Dyke Swarm; MWDS = Mundline Well Dyke Swarm; MRM = Mount Ragged Metasedimentary rocks; NC = Northampton Complex; SRF = Stirling Range Formation; YG = Yandanooka Group.*

Gawler Craton

The Gawler Craton (Figs. 4 & 6), comprising mainly supracrustal rocks metamorphosed up to the granulite facies and ranging in age from Mesoarchean to Mesoproterozoic (Fraser et al., 2010b; Hand et al., 2007; Swain et al., 2005; Szpunar et al., 2011), is the single most regionally extensive basement unit, occupying most of South Australia. It extends offshore for a considerable distance, underpinning much of the eastern Bight and Duntroon sedimentary basins (Fig. 7) as well as parts of the adjacent Delamerian-Ross Fold Belt farther east (Fig. 8). Its geological equivalent in Antarctica

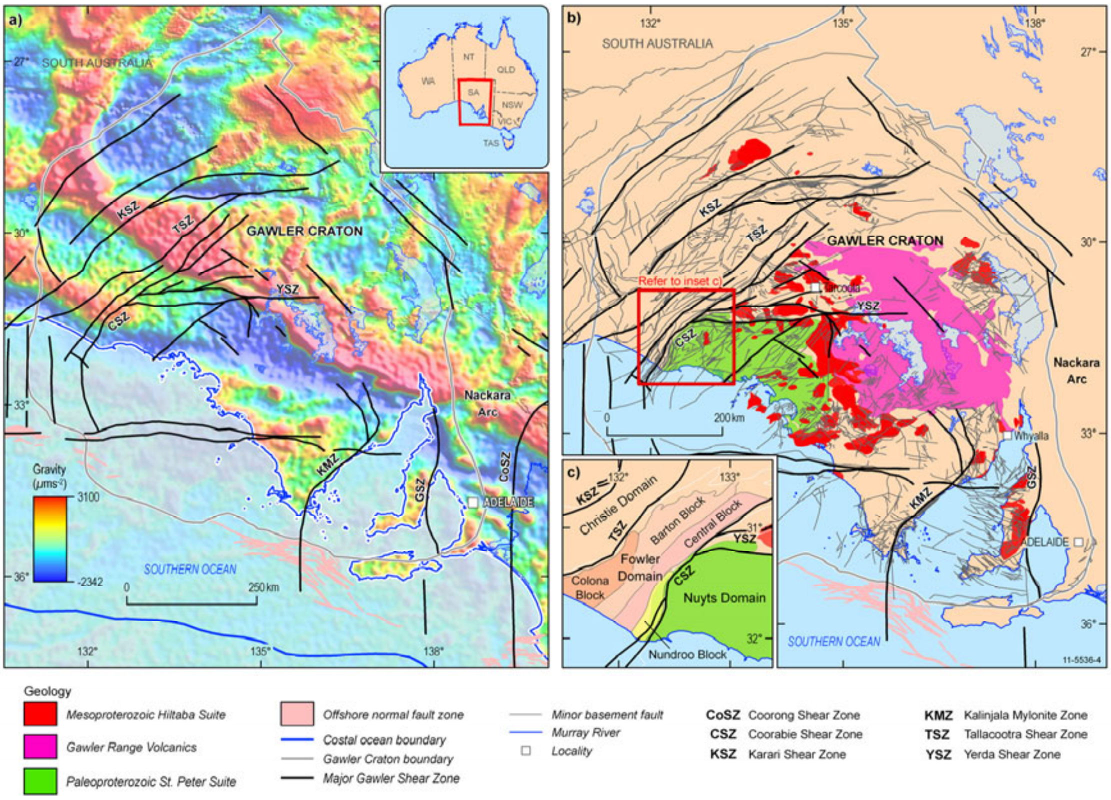

Figure 6. *(a) Major faults and shear zones in the Gawler Craton superimposed on a gravity image. (b) Dominant structural trends in the Gawler Craton defined by all faults and shear zones. Note predominance of NE- and NW-trending structures along with the west-east oriented structures that not only serve as the northern boundary of the Nuyts Domain (see inset) but appear to have locally controlled intrusion of the 1590 Ma Hiltaba Suite granites.*

is the East Antarctic shield which, together with the Gawler Craton, formed a core tectonic element (Mawson continent; Figs. 2 & 8) within the Rodinia supercontinent (Fanning et al., 1999).

Outcrop in the Gawler Craton is generally poor and mapping of its internal structure and constituent geological units relies heavily on the interpretation of geophysical images derived from gravity and aeromagnetic data (Cowley, 2006; Daly and Fanning, 1993; Ferris et al., 2002). These images reveal a complex mosaic of disparate geological units or domains (Fig. 4a) centred on an Archean nucleus around which several younger Paleo- and Mesoproterozoic domains are distributed in a crudely concentric fashion (Cowley, 2006; Hand et al., 2007; Kositcin, 2010; Szpunar et al., 2011). Boundaries between adjacent domains (Fig. 4a) are based on contrasting magnetic character and typically follow the trace of regionally significant magnetic anomalies interpreted to be major faults or shear zones (Ferris et al., 2002). This network of faults and shear zones formed during successive deformational events and includes structures along which there have been multiple episodes of reactivation (Figs. 4b & 6b). Northeast-, northwest- and east-west-oriented structures are particularly well represented (Fig. 6a & b) and include individual faults and shear zones of sufficient magnitude and lateral extent that they not only have an offshore expression but may have had an impact on the pattern and direction of continental breakup along Australia's southern margin:

- East-west-striking structures like the Yerda Shear Zone dated at ca. 1590 Ma (Fraser and Lyons, 2006) and which have been intruded syn-kinematically by 1590-1575 Ma granites (McLean and Betts, 2003). This shear zone is one of the oldest recognisable structures in the central Gawler Craton and separates highly deformed late Archean to early Paleoproterozoic gneisses of the Wilgena Domain at its core from younger 1690-1610 Ma rocks of the Nuyts

Domain (Fig. 6b). Farther south, structures of the same age and orientation have been reactivated to produce the east-west-trending Itledoo Basin and co-located offshore Polda Trough (Figs. 4b & 7) whose sedimentary fill ranges in age from late Neoproterozoic to Jurassic (Stagg et al., 1990).

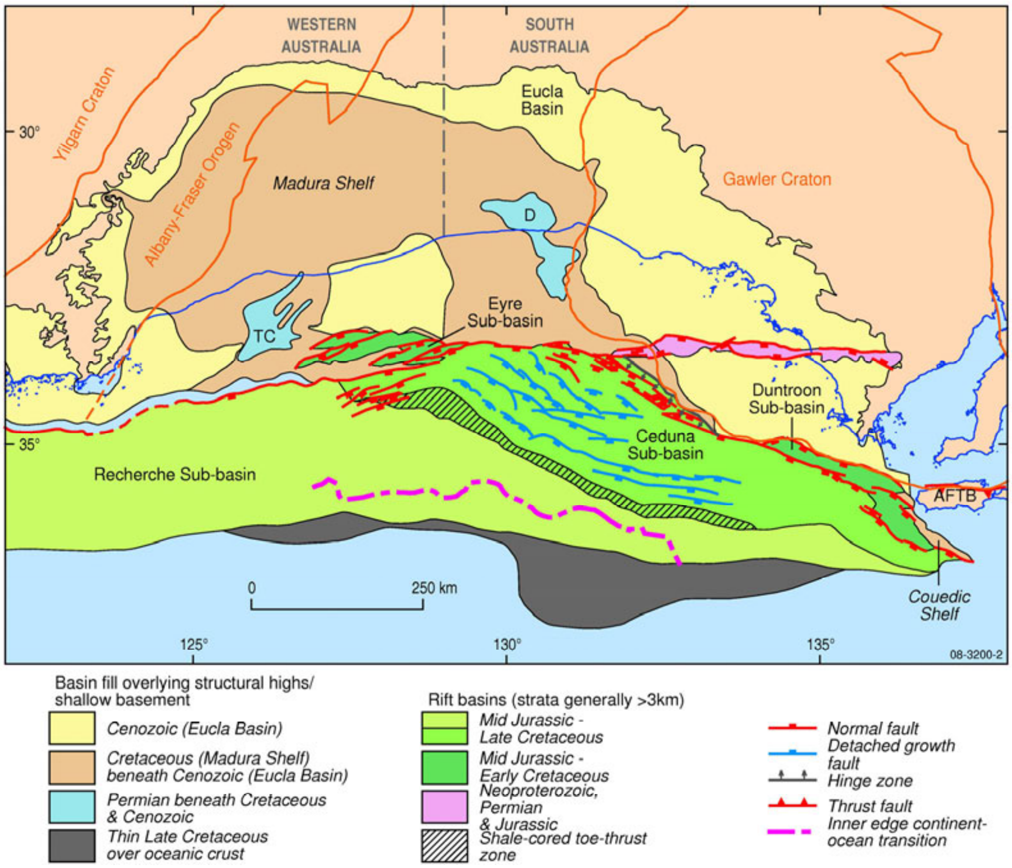

Figure 7. *Location of eastern Bight Basin, including Ceduna and Duntroon Sub-basins, with respect to underlying basement crustal elements (after Bradshaw et al., 2003). Note east-west-trending basement structure (s) that served as a northern limit to late Jurassic-early Cretaceous normal faulting in the Ceduna-Sub-basin and whose reactivation controlled sedimentation during formation of the co-located Neoproterozoic Itledoo Basin and Jurassic times Polda Trough (pink).*

- Northeast-trending faults and shear zones with strike lengths of several hundred kilometres that truncate and overprint the east-west structures and are among the most laterally extensive structures in the whole craton (Figs. 4 & 6). These structures separate the dominantly late Archean Christie Domain from the adjacent Paleoproterozoic Nawa and Fowler-Nuyts domains (Fig. 6b). They include the strongly mylonitic and variably magnetised Tallacootra, Karari and Coorabie shear zones which were last active at ca. 1450 Ma but could have originated much earlier (Fraser and Lyons, 2006). A significant amount of dip-slip displacement has occurred on the Karari Shear Zone whereas the other two structures exhibit mainly strike-slip movement (Fraser and Lyons, 2006; Teasdale et al., 2003). Both the Karari and Coorabie structures extend offshore, and once continued southward into Antarctica.

- Northwest-trending faults and shear zones of seemingly limited lateral extent that are not particularly well represented at the regional or crustal scale (Fig. 6b). Some of the best developed structures occur along the northeastern margin of the craton and may have contributed to its overall shape and northwest trend (Fig. 4b). Reactivated basement structures with this orientation may also be implicated in formation of the late Mesoproterozoic Carriewerloo Basin and intrusion of the 830 Ma Gairdner Dyke Swarm (Cowley, 2006; Wingate et al., 1998). They both share the same northwest trend and occur at a scale (Fig. 6b) commensurate with the presence of a northwest-trending basement fabric that is much more pervasively developed and of far greater lateral extent than existing geological maps might suggest (Cowley, 2006). Such a fabric would have greatly facilitated rifting and breakup of the Mawson continent in the Mesozoic which initially followed a similar NW-SE trajectory (Totterdell and Bradshaw, 2004; Whittaker et al., 2007; Willcox and Stagg, 1990).

- North-south oriented shear zones of limited distribution and best developed in the southern part of the craton (Fig. 6b) where they subdivide basement into Coulta, Cleve and Spencer Domains (Fig. 4a). They include the ca. 300 km-long Kalinjala Mylonite Zone (Parker, 1980) formed during the 1740-1690 Ma Kimban Orogeny (Hand et al., 2007; Vassallo and Wilson, 2002). It has recently been interpreted as a former subduction zone or paleosuture (Betts and Giles, 2006) and separates late Mesoarchean-Paleoproterozoic basement gneisses and granites in the east (Spencer Domain) from a younger Cleve Domain in the west. The Cleve Domain comprises mainly Paleoproterozoic metasedimentary rocks (Hutchinson Group) overlying an older late Neoarchean metasedimentary and volcanic succession that was deformed during the ca. 2400 Ma Sleaford Orogeny (Fraser et al., 2010a; Hand et al., 2007; Parker, 1980; Swain et al., 2005). Mylonitic fabrics along the trace of the Kalinjala Shear Zone vary in attitude from steep to subvertical in the south (Parker, 1980; Vassallo and Wilson, 2002) to moderately east-dipping in the north where it has been imaged in seismic reflection data (Fraser et al., 2010a).

Delamerian Fold Belt (Orogen)

The Gawler province (Mawson craton) is bounded on the east (Figs. 3 & 8) by various Neoproterozoic-early Paleozoic passive margin sequences and accreted terranes whose geological affinities range from continental to oceanic (Glen, 2005; VandenBerg et al., 2000). Together with adjacent parts of the Gawler Craton, these rocks were subjected to widespread deformation and metamorphism during the Cambro-Ordovician Delamerian and mid-Paleozoic Lachlan orogenies (Glen, 2005; Gray and Foster, 2004; Hand et al., 2007) and make for a geologically diverse basement in SE Australia characterised by marked differences in crustal structure, lithology, and rheological properties along strike.

The Delamerian Fold Belt (Orogen) abuts directly against the Gawler Craton (Fig. 3) and is of middle Cambrian-earliest Ordovician age, deforming Neoproterozoic rift-related sedimentary and minor volcanic rocks of the Adelaide Supergroup (Fig. 8), along with a progressively eastward-deepening passive margin sequence dating from Rodinia breakup in Neoproterozoic time (Glen, 2005; Preiss, 2000). Rift-related basins typically strike northwest or northeast and were incised into cratonic basement (Preiss, 2000). They make up much of the north- to northeast-trending Nackara Arc (Fig. 4) and have since been inverted along with their bounding normal faults to produce a west-vergent fold and thrust belt that is conspicuously narrower and more intensely developed in the south compared to the north (Flöttmann et al., 1994; Paul et al., 1999). Folds and thrusts in the Nackara Arc (Fig. 4) are believed to be cored by basement rocks representing an eastward extension of the Gawler Craton (Paul et al., 1999) but only in the southern part of the Delamerian Fold belt is gneissic basement actually exposed; it is of Paleo- to Mesoproterozoic age and occurs in thrust-bound inliers along the western margin of the fold belt (Flöttmann and James, 1997; Flöttmann et al., 1994; Szpunar et al., 2007).

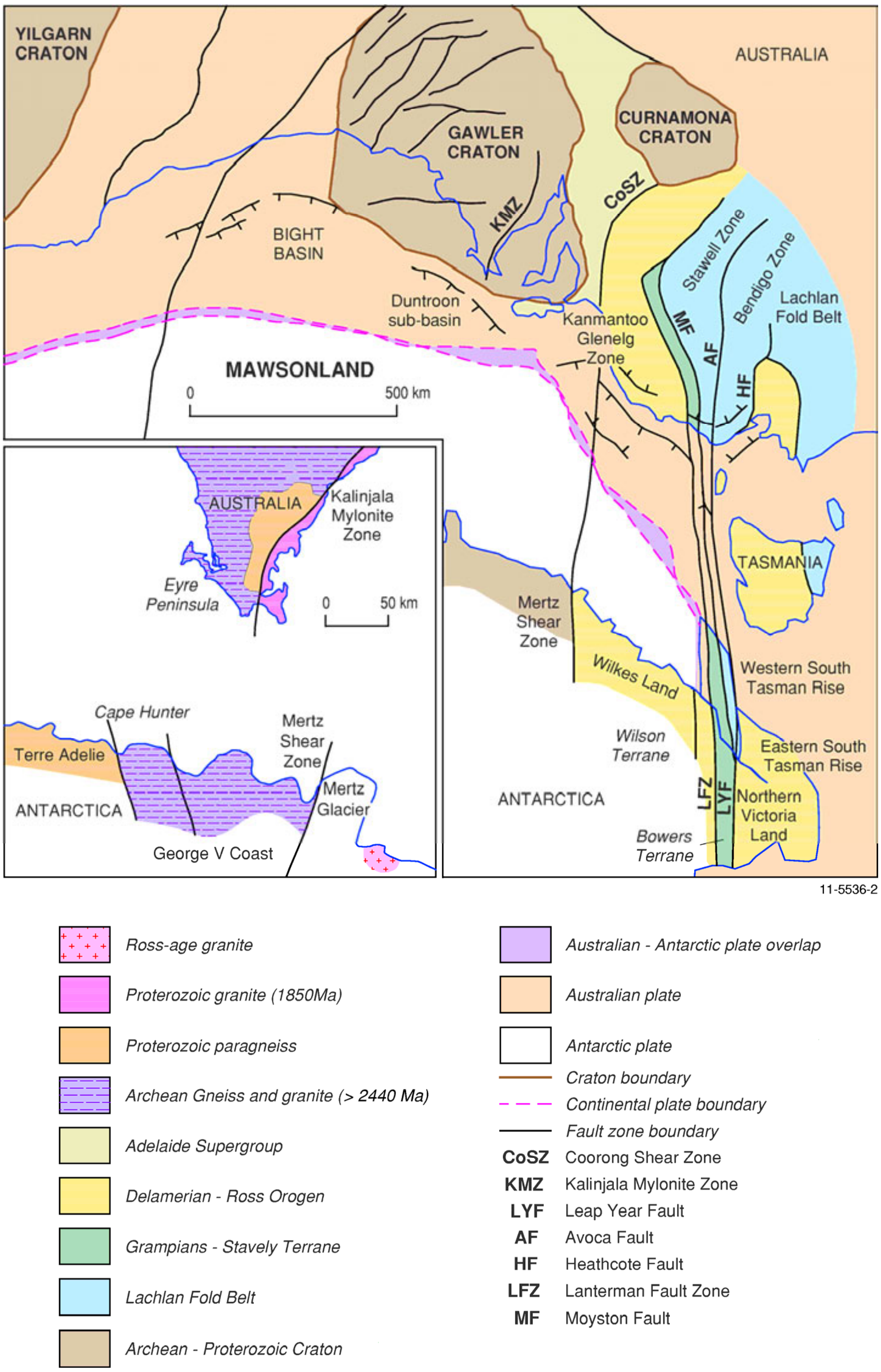

***Figure 8**. Reconstructed eastern margin of Gondwana with greater Gawler Province continuing into Antarctica as part of the Mawson continent (Mawsonland). The Delamerian Orogen similarly continues southward into Antarctica but as the Ross Orogen. Inset shows Paleoproterozoic Kalinjala Mylonite Zone as the proposed Australian correlative of the Mertz Shear Zone in Antarctica.*

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Resting disconformably on the Adelaide Supergroup (Fig. 8), but still forming part of the Delamerian Fold Belt, is a variably deformed and metamorphosed, dominantly clastic, shallow to deep water succession of late Neoproterozoic-early Cambrian sediments with minor intercalated basaltic rocks included in the Normanville and Kanmantoo Groups (Preiss, 2000). These rocks share a similar record of west-directed folding and thrusting to the Adelaide Supergroup but have been intruded by far greater amounts of Cambro-Ordovician granite and minor gabbro. Correlatives of the Kanmantoo Group extend eastwards as far as the Glenelg Zone in western Victoria (Figs. 3 & 8) where they have been tectonically juxtaposed against an early Cambrian forearc-island arc complex represented by mafic and ultamafic rocks of the Dimboola Igneous Complex in the Grampians-Stavely terrane (Gibson et al., 2011; Kemp et al., 2002; Morand et al., 2003; VandenBerg et al., 2000). No basement to this metasedimentary succession is exposed anywhere in the Glenelg zone although sequences of equivalent age exposed in western Tasmania (Berry et al., 2007; Berry et al., 1997) and formerly contiguous parts of Antarctica (Gibson et al., 2011; Gibson and Nihill, 1992; Stump et al., 1986; Tessensohn and Henjes-Kunst, 2005) are underlain by older continental crust that ranges back in age to the late Mesoproterozoic or older (Fitzsimons, 2003; Goodge and Fanning, 2010).

Lachlan Fold Belt

Continental crust of Delamerian and older age (Selwyn Block; Fig. 8) is also thought to extend northward at depth across Bass Strait into the Melbourne zone in the central part of the turbidite-dominated Lachlan Fold Belt (Cayley et al., 2002; Cayley, 2011; Gibson et al., 2011). Recently published seismic data through this part of the Lachlan Fold Belt support this interpretation (Cayley et al., 2011) and show that this older continental crust terminates at the Heathcote Fault Zone and does not extend westwards into the neighbouring Bendigo and Stawell zones (Fig. 8). Rather, these two terranes comprise mainly quartz-dominated turbidite sequences floored by oceanic crust of late Neoproterozoic-Cambrian age (VandenBerg et al., 2000). Their bounding structures are all major crustal discontinuities and include at least one paleosuture as well as the boundary between the Delamerian and Lachlan Fold belts. A position to the east of the island arc assemblage in the Grampians-Stavely terrane is generally accepted for this boundary although opinion is divided as to whether this coincides with the Moyston Fault (Cayley et al., 2002) or farther east along the boundary (Avoca Fault) between the Stawell and Bendigo zones (Cayley et al., 2002; Glen, 2005). Both faults are important terrane boundaries (Fig. 8) and both have been implicated in formation of the Tasman Fracture Zone (Gibson et al., 2011; Hill et al., 1995; Miller et al., 2002). A more detailed description of these terranes and their bounding structures is presented in Appendix A and Figures A.1-A.2.

Basement control on rift geometry

Pre-existing basement structure not only influenced rift basin architecture and fault geometry but had an equally profound effect on development of ocean floor fabrics in the Southern Ocean and the fracture zones in particular (Fig. 1). These fabrics are most spectacularly developed south of the Otway Basin and include the Spencer-George V and Tasman fracture zones (Fig. 1), both of which harbour important clues about the magnitude and relative importance of the basement structures that controlled the direction and pattern of continental breakup. For this reason these two fracture zones and their tectonic setting are described first before turning to an analysis of the major basement structures themselves.

TASMAN AND SPENCER-GEORGE V FRACTURE ZONES

Crustal extension and rifting along the Australian continental margin initially took place in a NW-SE to NNW-SSE direction (Willcox and Stagg, 1990), progressing through NNE-SSW-directed extension before assuming a north-south trajectory (Hill and Exon, 2004). North-South directed rifting produced both the Tasman and Spencer-George V fracture zones and imparted a strong north-south fabric (Fig. 1) on oceanic crust younger than 47 Ma (Whittaker et al., 2007). A prominent re-entrant in the Australian continental margin marks the position of the Tasman Fracture Zone. This structure is part transform boundary (Fig. 1) and evolved from a late Mesozoic-early Cenozoic intra-continental shear zone located above an even older reactivated Paleozoic basement structure in southeast Australia, variously identified as the Woorndoo (Foster and Gleadow, 1992), Moyston (Hill et al., 1995; Miller et al., 2002) or Avoca Fault (Gibson et al., 2011). Bathymetric images (Fig. 1) show various strands of this fracture zone continuing southward all the way to ocean-continent boundary in Antarctica where they assume a position directly along strike from some of the most important basement structures in northern Victoria Land (Figs. 1 & 8). The most westerly of these structures is the early Paleozoic Lanterman Fault Zone (Figs. 8 & A.1), long interpreted as a former subduction zone or paleosuture (Gibson and Wright, 1985; Rocchi et al., 1998; Tessensohn and Henjes-Kunst, 2005; Weaver et al., 1984), but along which there have been several episodes of subsequent strike-slip faulting and shearing, including one in the Cenozoic that affected much of northern Victoria Land and shares the same sense of shear as the Tasman Fracture Zone offshore (Capponi et al., 1999; Rossetti et al., 2002; Storti et al., 2007). This structure (Figs. 8 & A.1) now separates island arc rocks (Bowers terrane) from older continental crust (Wilson terrane). The eastern boundary of this same island arc terrane is the steeply-dipping Leap Year Fault which shares a similar history of late strike-slip reactivation. Together, the Leap Year and Lanterman fault zones constitute the main boundaries along which the terranes of northern Victoria Land were finally assembled and accreted onto the East Antarctic Shield (Capponi et al., 1999; Gibson et al., 2011; Rossetti et al., 2002; Weaver et al., 1984).

Unlike the Tasman Fracture Zone, the Spencer-George V Fracture Zone is not associated with any obvious re-entrant in the Australian continental margin. It is nevertheless an important boundary, coinciding with a change of direction in ocean floor fabrics from NW-SE to north-south (Whittaker et al., 2007), and marking a sharp break from east-west trending, normally rifted continental crust between the Great Australian Bight and Terre Adelie/Wilkes Land in Antarctica to a grossly NNW-SSE oriented continental margin farther east in which oblique- and strike-slip segments developed between Tasmania and George V Land (Stagg and Reading, 2007). It is the most westerly of the set of large-offset, dextral fracture zones that span the entire Southern Ocean between southeast Australia and Antarctica (Fig. 1) and, except for the absence of an obvious reactivated basement structure along strike in Australia, is not dissimilar to the Tasman Fracture Zone in terms of character and magnitude (Fig. 1). A more substantive 5 km-wide shear zone (Mertz Shear Zone), separating late Archean-Paleoproterozoic cratonic basement from early Paleozoic rocks of the Ross Orogen (Fig. 8, inset), occurs along strike in the opposing Antarctic margin but its proposed correlative in southern Australia is the late Paleoproterozoic Kalinjala Mylonite Zone in the eastern Gawler Craton (Di Vincenzo et al., 2007; Talarico and Kleinschmidt, 2003) and lies much too far west to be co-linear with the Spencer-George V Fracture Zone (Fig. 1).

The alternative is to argue for a different palaeogeographic reconstruction in which the Mertz Shear Zone is matched against a hitherto previously unmapped basement structure in southern Australia identified and named here as the Coorong Shear Zone (Figs. 1 & 8) and which partially overlaps the Anabama-Redan Shear Zone of Preiss (2000) at its northern extremity. This structure lies much farther east than the Kalinjala Mylonite Zone and better accords with the position and orientation of the Spencer-George V Fracture Zone (Fig. 1). Owing to little or no outcrop along its length, this structure is best characterised through geophysical mapping supported by the interpretation of deep seismic reflection data collected offshore by Geoscience Australia (Figs. 9 & 10). An interpretation of these datasets is presented below.

Coorong Shear Zone in aeromagnetic and seismic reflection images

Aeromagnetic data for the Coorong Shear Zone and surrounding region, including part of the adjacent continental shelf, are presented as an image in Figure 9. This image is based on the 0.5

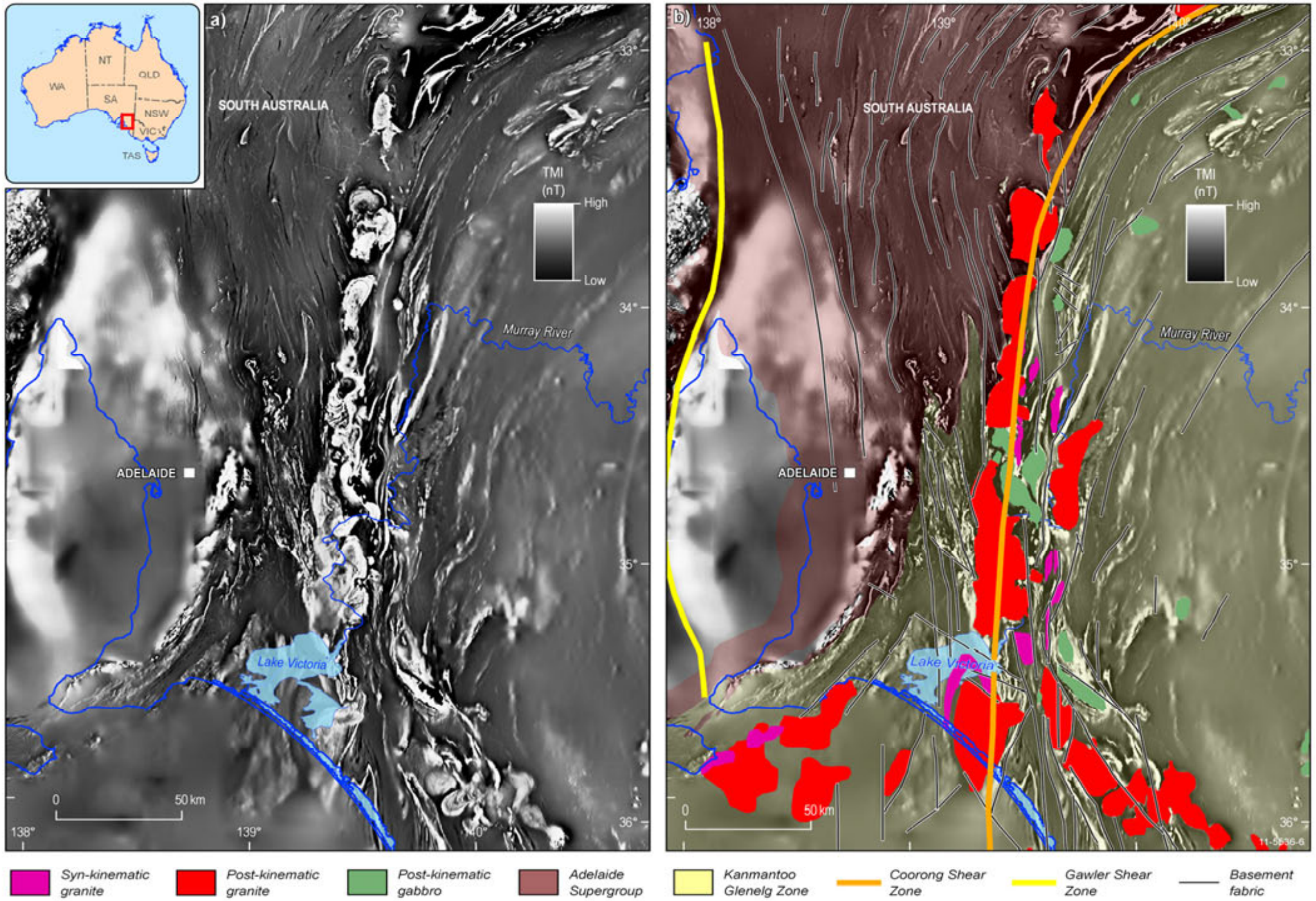

Figure 9. *(a) Uninterpreted and (b) interpreted aeromagnetic images (0.5 vertical derivative) of the Coorong Shear zone and immediately adjacent parts of the Delamerian Orogen, including the Ardrossan Shelf. The shear zone forms the boundary between structural domains with differently oriented fabrics and is intruded along its length by undeformed, commonly concentrically zoned, early Paleozoic plutons. The ovoid anomaly west of the Coorong structure is a block of basement buried beneath sediments of the Ardrossan Shelf. This basement block has been rotated and downthrown to the west on a structure labelled here as the Gawler Shear Zone.*

vertical derivative of the total magnetic intensity and captures abrupt changes in the potential field gradient that might reveal the presence of major geological structures or discontinuities. The Coorong Shear Zone is particularly conspicuous in this image and juxtaposes two domains with opposing structural trends (Fig. 9; see also Fig. 6). Moreover, this shear zone is not restricted to the mainland but continues offshore. To the west of this shear zone in the north are inverted and tightly folded basinal sequences of the Adelaide Supergroup (Nackara Arc) in which structural fabrics generally strike north to northeast whereas to the east and south are even more intensely deformed rocks of the Kanmantoo Group and its correlatives in which structures trend NNE (Fig. 9). Intruded into the Kanmantoo Group, and cutting across this NNE fabric, are variably magnetised post-kinematic granites and minor gabbro of late Cambrian-early Ordovician age (Foden et al., 2002). Granite geochemistry and isotopic data further indicate that rocks of the Kanmantoo Group extend to considerable depth and represent the source region from which the granitic melts were derived (Foden et al., 2002a; Foden et al., 2002b). They and their host rocks can be traced southward in the aeromagnetic image as far as the continental shelf (Fig. 9) and eastwards into the Glenelg zone (Fig. 8 & A.1).

In contrast, granites of post-Delamerian age are not widely developed in Adelaidean rocks west of the Coorong Shear Zone and appear to be completely absent from the Nackara Arc (Fig. 9). For most of its length, this structure marks the western limits of late Cambrian-early Ordovician magmatic intrusion and has itself been intruded by a large number of undeformed, concentrically zoned granites and subsidiary gabbro. It served as a conduit for post-orogenic magmatic intrusion and is constrained by these same magmatic rocks to be no younger than late Cambrian-early Ordovician in age. A maximum age is provided by truncation and juxtaposition of the inverted Delamerian structures on either side of the structure although this makes no provision for the possibility that the Coorong Shear Zone is a much older reactivated structure that predates both orogenesis and deposition of the Kanmantoo Group. Indeed, it is not inconceivable that this structure dates back to the time of Rodinia breakup and had a strong influence on Neoproterozoic-early Cambrian sedimentary depositional patterns. A pre-Delamerian age is consistent with the observation that the Coorong structure is broadly coincident with the western limits of Kanmantoo deposition and concomitant transition from platform (Adelaide Supergroup) to deeper water turbidite sedimentary facies (Preiss, 2000). If this interpretation is correct, it follows that deformation along the Coorong Shear Zone commenced long before onset of the Delamerian Orogeny whose age has been variously estimated at ca. 523 Ma (Gibson et al., 2011) or 514 Ma (Foden et al., 2006). This in turn would imply that the Coorong Shear Zone constitutes a long-lived crustal weakness into which strain was repeatedly partitioned during subsequent deformational events. No less importantly, because this structure continues offshore beneath Early Cretaceous sediments of the western Otway Basin, aspects of its character and movement history should be amenable to investigation through seismic reflection data acquired off the South Australia coast.

Seismic imaging and vertical extent of Coorong Shear Zone

Seismic reflection data collected offshore by Geoscience Australia directly along strike from the Coorong Shear Zone, but more particularly along line p137-01 (Fig. 10), confirm the presence of a crustal-penetrating structure in this general location and show that it coincides with a prominent step in the Moho as well as an abrupt thinning of the middle to lower crust to the east. This structure has also effected significant offsets in some of the more prominent horizons making up the Early Cretaceous syn-rift section of the sedimentary basin, indicating some degree of reactivation at the time of basin formation (Fig. 10). However, its more obvious attribute and defining feature is its steep to subvertical attitude (Fig. 10). This attitude, combined with the considerable strike-length observed in the aeromagnetic image, indicates that the Coorong Shear Zone is unlikely to be directly related to the west-vergent thrust faults identified in other offshore seismic surveys (e.g. DME93-01; Flöttmann and Cockshell, 1996) and which typically sole out at much shallower depths in the crust.

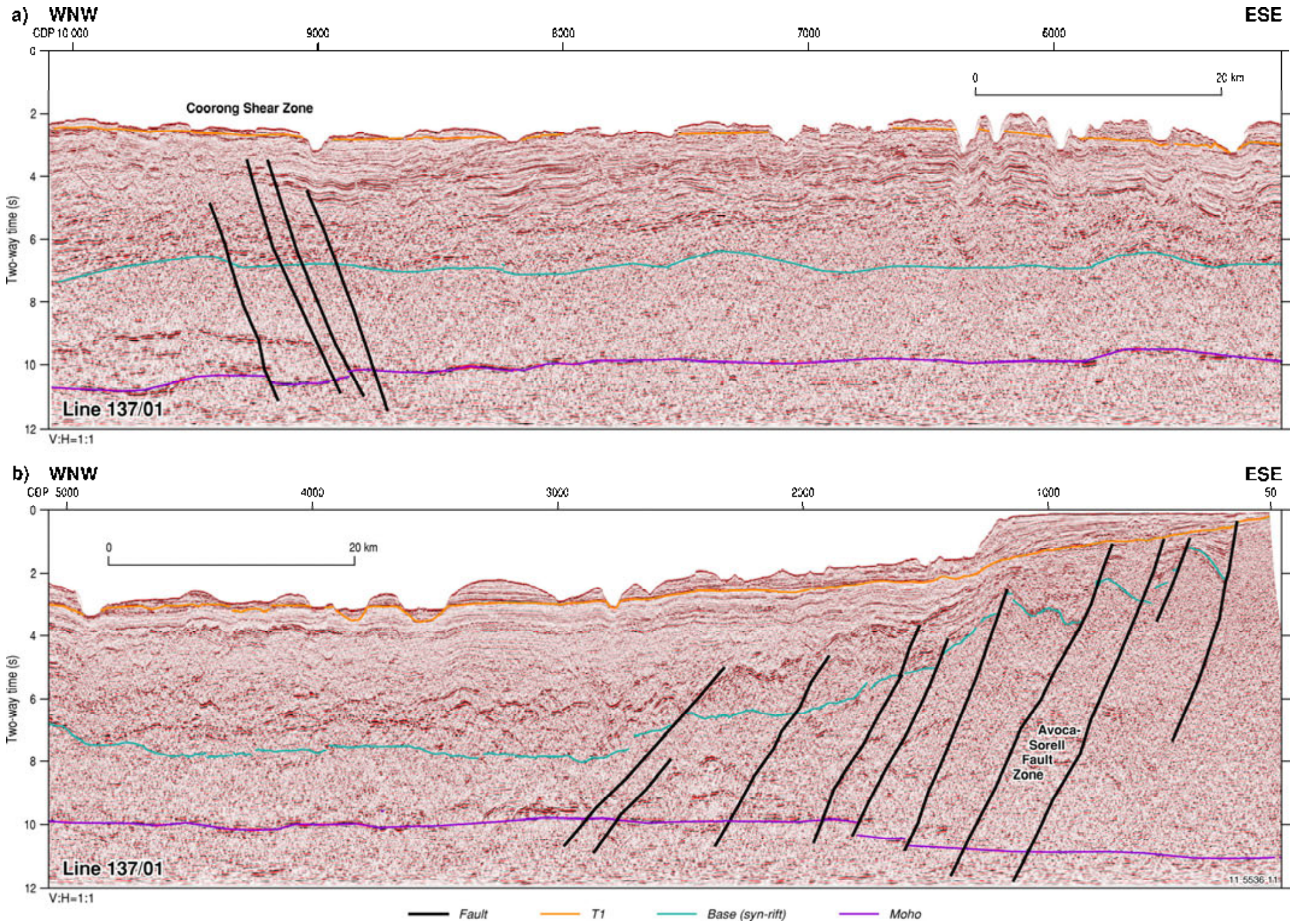

Figure 10. *Coorong and Avoca-Sorell shear zones captured in seismic reflection profile p137-01 off southern Australia (for location of profile see Figure 11). Note thinning of middle to lower crust beneath deepest part of sedimentary (Otway) basin. Basin profile and stratigraphic surfaces (Base of Cretaceous = base of syn-rift and Base of Cenozoic = T1) constrained by additional seismic sections oriented at high angle to p137-01.*

Rather, the Coorong Shear Zone is an entirely separate structure, the vertical and lateral dimensions of which are more in keeping with a strike-slip origin.

A strike-slip origin has already been proposed for the parallel and presumably temporally related Anabama Fault near the northern end of the Coorong structure. However, this need not imply that the Coorong Shear Zone and main locus of Delamerian thrusting are unconnected. Previous structural studies of the Delamerian Fold Belt have emphasised that crustal shortening during orogenesis was largely taken up on basement-involved footwall shortcut thrusts and inverted normal faults located along, or close to, the original western margin of the deep water Kanmantoo Basin (Flöttmann and James, 1997; Flöttmann et al., 1994). Among the largest of these structures is the Williamstown-Meadows Fault in the central part of the Delamerian Fold Belt which still preserves some component of its original normal displacement (Flottman and James, 1997). Its position and that of other regional-scale thrust faults is thought to have been controlled by a basement ramp along which there has been significant strain partitioning during and subsequent to sedimentary basin formation (Flottman et al., 1994). This ramp was interpreted to be broadly listric in shape and assume sub-horizontal dips at shallow crustal depths. No such basement ramp has been identified in this study although it is clear from the description and proposed position of this structure that it is not far removed from the Coorong Shear Zone and broadly corresponds to the zone of maximum basin inversion near the western margin of the Delamerian Fold Belt. More importantly, the Coorong Shear Zone penetrates to much greater crustal depths and shows clear evidence for reactivation during the Cretaceous that persists for some distance offshore and most likely continued in the opposing Antarctic margin.

A similar history of basement reactivation is evident along the Avoca-Sorell fault zone farther east where there is an even more pronounced step in the Moho and corresponding increase in crustal thickness to the east (Fig. 10). This is accompanied at higher structural levels by a decrease in the thickness of the overlying Mesozoic sedimentary basin sequences (Fig. 10). This fault zone shares the same steep dip as the Coorong structure and, like the latter, originated in the early Paleozoic as a strike-slip fault with the same north-south orientation (Fig. 8). It was once part of a much more regionally extensive fault system that extended into Antarctica and much the same might be expected of the Coorong structure with which it shares a common history of strike-slip faulting.

Correlation of Coorong and Mertz Shear Zones

Correlation of the Coorong and Mertz Shear Zones at either end of the Spencer-George V Fracture Zone (Figs. 1 & 8) makes for an additional constraint on paleogeographic reconstructions of the Australian-Antarctic continent that is directly amenable to testing through comparisons of basement geology in the two opposing continental margins (Fitzsimons, 2003; Goodge and Fanning, 2010). Particularly important in this context is the observation that both the Coorong and Mertz shear zones serve as the western limit of Cambrian-early Ordovician granite magmatism in their respective continental margins (Di Vincenzo et al., 2007; Fanning et al., 2002) whereas the Kalinjala Mylonite Zone is located within the interior of the Gawler Craton (Fig. 8) and well to the west of the presently accepted limits of Delamerian-age deformation and magmatism in SE Australia based on geochronological as well as geological grounds (Swain et al., 2005). Indeed, deformation and magmatism of this age is not known to extend much beyond the western limits of the Nackara Arc and Torrens Hinge Zone (Fig. 9).

Posing further difficulties for the previously proposed correlation are recently published ca. 3100 Ma ages for gneissic granites in the Spencer Domain to the east of the Kalinjala Mylonite Zone (Fig. 8; inset), indicating that crystalline basement in this part of the Gawler Craton is not only considerably older than previously supposed but extends much farther east (Fraser et al., 2010b). It forms part of the substrate upon which ca. 1700 Ma metamorphosed sedimentary sequences in the eastern Gawler Craton were originally deposited and, compared to basement beneath the central Gawler Craton, is characterised by a different bulk composition as evidenced by its elevated heat flow (Neumann et al.,

2000) and by the fact that Hiltaba-age granites intruded into these Paleoproterozoic metasedimentary sequences (Fig. 6b) are isotopically more evolved (avg. εNd_{1590} -5.9) than those of identical age (avg. εNd_{1590} -3.4) intruded farther west (Hand et al., 2007).

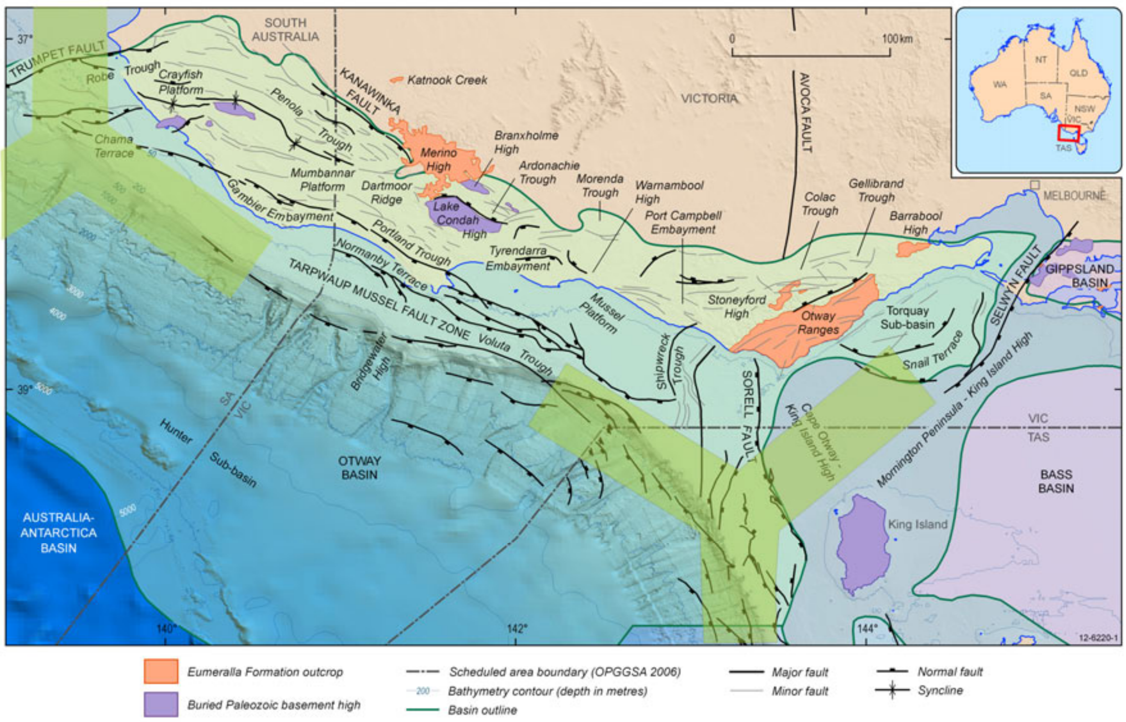

Figure 11. *Principal structural elements of Otway Basin (modified after Krassey et al., 2004). Note change of orientation in normal faults on either side of the Avoca-Sorell Fault Zone which on reactivation formed one arm of a triple junction centred to west of King Island (light green shading). Another arm of this triple junction continued northwest along the Tartwaup-Mussel Fault Zone and Portland Trough whereas the failed northeast arm extended into the Torquay Sub-basin. A second triple junction (light green shading) is inferred at the western extremity of the Otway Basin centred on the Coorong Shear Zone (failed northern arm).*

Rocks metamorphosed contemporaneously with intrusion of 1590 Ma Hiltaba-age granites have also been identified as thrust-bounded basement inliers along the western margin of the Delamerian Fold Belt (Szpunar et al., 2007), indicating that this more evolved basement province may extend eastwards at depth beneath rift-related sediments of the Adelaide Supergroup, and possibly all the way to the Coorong Shear Zone. Previously, Archean basement rocks were thought to extend no farther east than the Kalinjala Mylonite Zone along the eastern margin of the Cleve Domain (Fig. 4a), thereby providing seemingly good grounds for correlation of these rocks with similarly aged Neoarchean basement in Antarctica immediately west of the Mertz Shear Zone (Di Vincenzo et al., 2007; Talarico and Kleinschmidt, 2003). As is the case with the Cleve Domain (Sleaford Complex), Neoarchean basement in Antarctica is unconformably overlain by metasedimentary sequences deformed and metamorphosed in the late Paleoproterozoic (Ménot et al., 2005; Peucat et al., 1999). Notwithstanding such similarities, the weight of evidence presented in this paper favours correlation of the Mertz Shear Zone with the Coorong structure even though exposed basement of equivalent Mesoarchean age to the Spencer Domain in the Gawler Craton has yet to be identified in this part of Antarctica. In this regard it is worth noting that late Proterozoic metasedimentary sequences in both Australia and Antarctica yield Sm-Nd data and detrital zircon ages consistent with derivation of their protoliths from a source region with a common ca. 3.2-3.1 Ga age (Fanning et al., 2002; Ménot et al., 2005), identical to that recently reported for Mesoarchean basement in the eastern Gawler Craton (Fraser et al., 2010).

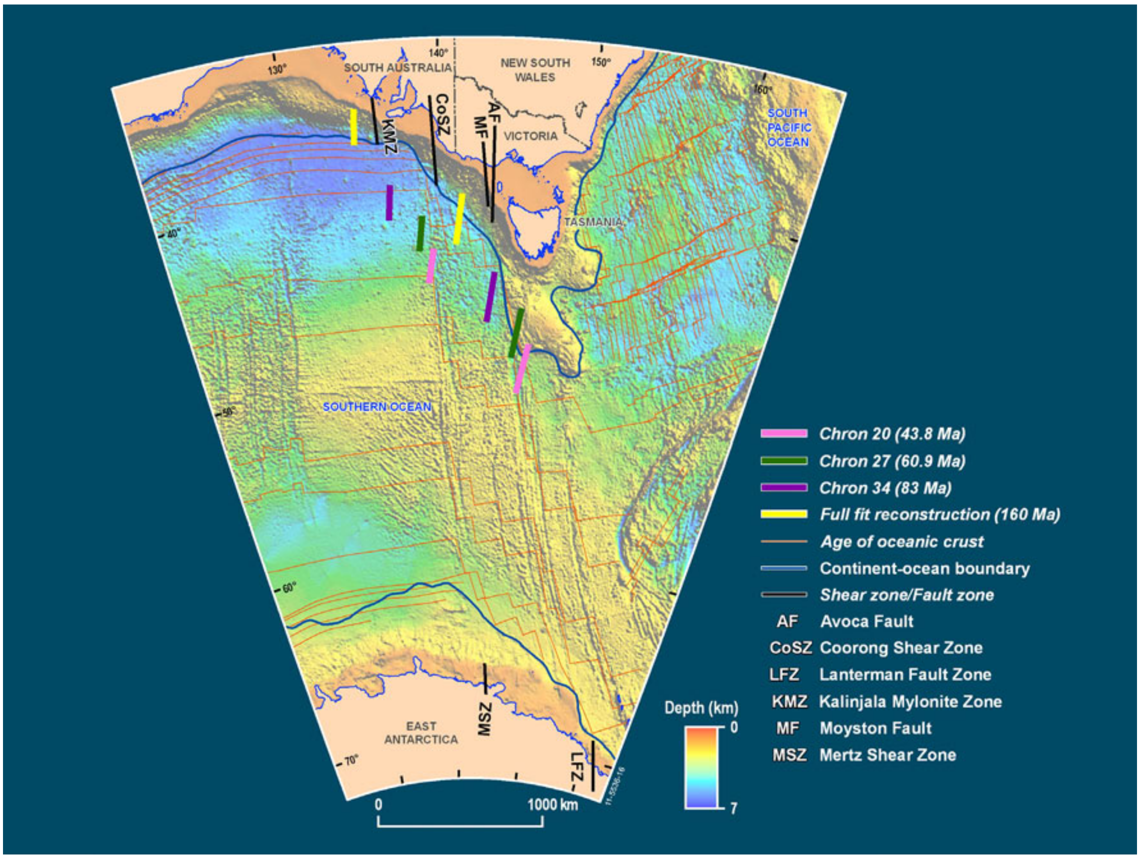

Figure 12. *Australian and Antarctic shear zones (bold coloured lines) restored back to selected times and magnetic anomalies using GPlates software (modified after Whitaker et al., 2007) showing that while the Lanterman Fault Zone (Antarctica) sensibly aligns with the offshore extension of the Avoca Fault at 83 Ma, the Mertz Shear Zone projects to a position between the Kalinjala Mylonite Zone and Coorong Shear Zone. At full fit (all extensional strain removed), the match is even worse with the Mertz Shear Zone restoring to a position several hundred kilometres west of the Coorong structure. Continent-ocean boundaries from published source (Stagg and Reading, 2007).*

Australian & Antarctic margins reconstructed

Several researchers have commented on the difficulties of reconciling reconstructions of the Australian and Antarctic continental margins based on ocean floor magnetic anomalies and plate tectonic considerations as opposed to geological grounds (Gaina et al., 1998; Hill et al., 1995; Royer and Rollet, 1997; Veevers, 2012; Whittaker et al., 2007). Mismatches are equally evident in some of the earlier geologically-based reconstructions (e.g. Flottman et al., 1993) in which major basement thrust faults of Delamerian-Ross age in northern Victoria Land (Fig. 8) are aligned with similarly verging basement-cored structures developed along the western margin of the Delamerian Fold Belt in SE Australia. This reconstruction places northern Victoria Land much too far west of Tasmania to achieve a correspondingly good fit between island arc-forearc assemblages of near identical age in the Bowers and Grampians-Stavely terranes. In other reconstructions (Gaina et al., 1998; Hill and Exon, 2004; Royer and Rollet, 1997; Tikku and Cande, 1999, 2000), northern Victoria Land, along with formerly contiguous parts of the South Tasman Rise, is placed much closer to Tasmania (Fig. 8), thereby aligning the Bowers and Grampians-Stavely terranes (Finn et al., 1999) whilst still preserving some correspondence between west-vergent, craton-directed structures in the Wilson terrane and relevant parts of SE Australia (Flottmann et al., 1993; Flottmann et al., 1998; Gibson and Nihill, 1992; Morand et al., 2003).

More recent plate tectonic based reconstructions (Whittaker et al., 2007) offer yet another fit between Australia and Antarctica in which the Mertz Shear Zone is restored to a position opposite the Kalinjala Mylonite Zone (Fig. 12), as in some geologically-based reconstructions (e.g. Talarico and Kleinschmidt, 2003; Goodge and Fanning, 2010; Veevers, 2012). This reconstruction assumes that the Leeuwin (= Perth, SW Australia) and Perth South (Antarctica) fracture zones in the far west are correlatives of each other but this correlation has since been disputed (Tikku and Direen, 2008). In accord with previous researchers (Tikku and Cande, 1999, 2000), Tikku and Direen (2008) argued that the Leeuwin (Perth; SW Australia) fracture zone was best matched with the Vincennes Fracture Zone (Antarctica). This lead to a revised reconstruction of Australia and Antarctica (Williams et al., 2011) but, as with Whitakker et al. (2007), this reconstruction fails to bring about a match between the Mertz and Coorong shear zones, and positions Australia too far east with respect to Antarctica, particularly for the full fit reconstruction in which all extensional strain is removed (Fig. 12). To a lesser extent, this same westward shift is also evident in the Lanterman Fault Zone which at 67 Ma should have restored to a position directly opposite the Avoca Fault. The reasons for these discrepancies are not immediately apparent but are unlikely to lie in the assumed pattern of continental rifting during the period of north-south seafloor spreading from about 47 Ma onward as this is well constrained by magnetic anomalies, bathymetry and the ocean floor fabrics, including the Tasman and George V fracture zones (Norvick and Smith, 2001; Whittaker et al., 2007). The problem more likely lies in the earlier and less well understood stages of continental rifting for which there is much less control from ocean floor fabrics and magnetic anomalies, and there is ongoing uncertainty about the identity and orientation of the basement structures across which the extensional strain was partitioned and/or accommodated as rifting progressed.

Discussion

Following a review of the timing, architecture and distribution of sedimentary facies in the Otway Basin, Hill et al. (1995) listed the three most important factors controlling continental rifting and breakup between SE Australia and Antarctica as:

- Shifts in global plate movements, driven by mantle processes
- Subduction along the east Gondwana plate boundary, and
- Pre-existing basement fabric.

Only the third factor is considered in any detail here as it clearly had a major influence not only on the pattern of continental rifting and breakup but the very process by which the continental margin achieved its present shape. As with most other continental margins, Australia's southern margin is segmented and made up of differently oriented sections that reflect real changes in basement geology, structure and rheology. This segmentation is best appreciated from the bathymetric image (Fig. 1) which shows an east-west-striking continental margin in the Bight Basin giving way successively to NW-SE and N-S trending segments farther east (Fig. 1). This same pattern is followed by the more distal continental-ocean boundaries in each segment (Fig. 12) and, at the grossest scale, broadly corresponds to the distribution of the major crustal blocks, and the position of the two cratonic blocks in particular (Gawler and Selwyn/Tasmania blocks). However, whilst this might initially be taken as evidence that boundaries between adjacent continental margin segments are coincident with the eastern and western margins of the Gawler and Tasmanian cratonic blocks respectively (Fig. 8), this conclusion is not entirely justified and ignores the very real possibility that Gawler crystalline basement does not terminate at the mapped boundary but extends eastward for some considerable distance beneath a progressively eastward-thickening cover of Adelaidean rocks.

Only in western Tasmania is crystalline basement unequivocally bounded by an older reactivated structure. It takes the form of the early Paleozoic Avoca-Sorell fault zone (Fig. 8) which was not only optimally oriented for reactivation during north-south rifting between 55 Ma and 47 Ma but subsequently evolved into the ocean-continent transform boundary off western Tasmania (Fig. 12).

In contrast, there is no corresponding transform boundary evident along strike from the exposed eastern margin of the Gawler Craton and nor is it immediately obvious that segmentation along this part of the continental margin is linked to this exposed boundary. Rather, the primary control on segmentation would appear to lie slightly farther east and correspond to either the Gawler or Coorong shear zone (Figs. 4 & 6), both of which share the same north-south strike as the Avoca-Sorell fault zone and were thus no less well oriented for reactivation during north-south rifting. The Coorong Shear Zone is deemed to be the more significant structure into which strain was partitioned at this time although, compared to the Avoca-Sorell Fault Zone, there are few aeromagnetic and seismic reflection data to indicate that this structure has undergone more than limited amounts of reactivation since it first formed in the early Paleozoic (Fig. 10). Cenozoic movement has been identified (Preiss, pers. comm..) on several other north-south oriented faults in the immediate neighbourhood of the Coorong Shear Zone (e.g. Morgan Fault) but these typically dip west and appear to be unrelated to the east-dipping structure described here. Why the Coorong Shear Zone failed to reactivate is not immediately clear although it may stem from the fact that this structure is stitched by post-kinematic granites and gabbro and, unlike the Avoca-Sorell Fault Zone, is bounded on either side by crust of entirely continental origin. Given this degree of magmatic intrusion, any pre-existing anisotropy or inherited structural weakness in the crust may have been lost or at least reduced to the extent that reactivation along this structure was inhibited during subsequent continental rifting.

The other possibility is that the Coorong structure was originally associated with a triple junction but lay along the arm that subsequently failed and so never evolved into a transform boundary. Instead, rifting progressed along the other two arms of the triple junction, and the southeast arm in particular (Figs. 8 & 11). This arm extended into the Otway Basin and had a northwest strike (Fig. 11) whereas the third arm trended west-east to WSW-ENE. Offshore sedimentary basins and normal faults in the extreme western part of the Otway Basin have a configuration consistent with this scenario and show that their change in orientation does indeed occur across the Coorong Shear Zone (Fig. 8). However, even if this scenario were correct, it can only apply to the earliest stages of continental rifting because, throughout at least part of the Early Cretaceous, basin formation and extension in the neighbouring Bight Basin was accompanied by sinistral shear on a major NW-SE trending continental transform fault (Fig. 13) that acted as a temporary boundary between the Australian and Antarctic plates (Norvick and Smith, 2001; Willcox and Stagg, 1990). This transform fault passed to the south of the nascent Otway Basin and extended all the way to the South Tasman Rise where it was associated with limited amounts of rifting and crustal extension between the latter and Tasmania (Fig. 13b). Basement structures in the Delamerian and Lachlan fold belts cut by this structure are consistently offset in a sinistral sense, including the Avoca-Sorell Fault Zone (Fig. 8). The Coorong Shear Zone is also likely to have been displaced across this structure but as yet had not undergone significant amounts of reactivation. It nevertheless remained an important basement structure and retained the capacity to influence basin architecture and rift geometry along the continental margin as evidenced by the fact that the George V Fracture Zone lies immediately offshore and directly along strike from it (Fig. 1). As with the Tasman Fracture Zone, a pre-existing basement structure has influenced the formation and location of a fracture zone in the adjacent ocean basin. In view of some of the similarities between the Avoca-Sorell and Coorong structures, this is perhaps not surprising. Both structures originated as orogen-parallel strike-slip faults in the early Paleozoic and both are of sufficient lateral and vertical extent (Figs. 9 & 10) to have an expression at the lithospheric scale.

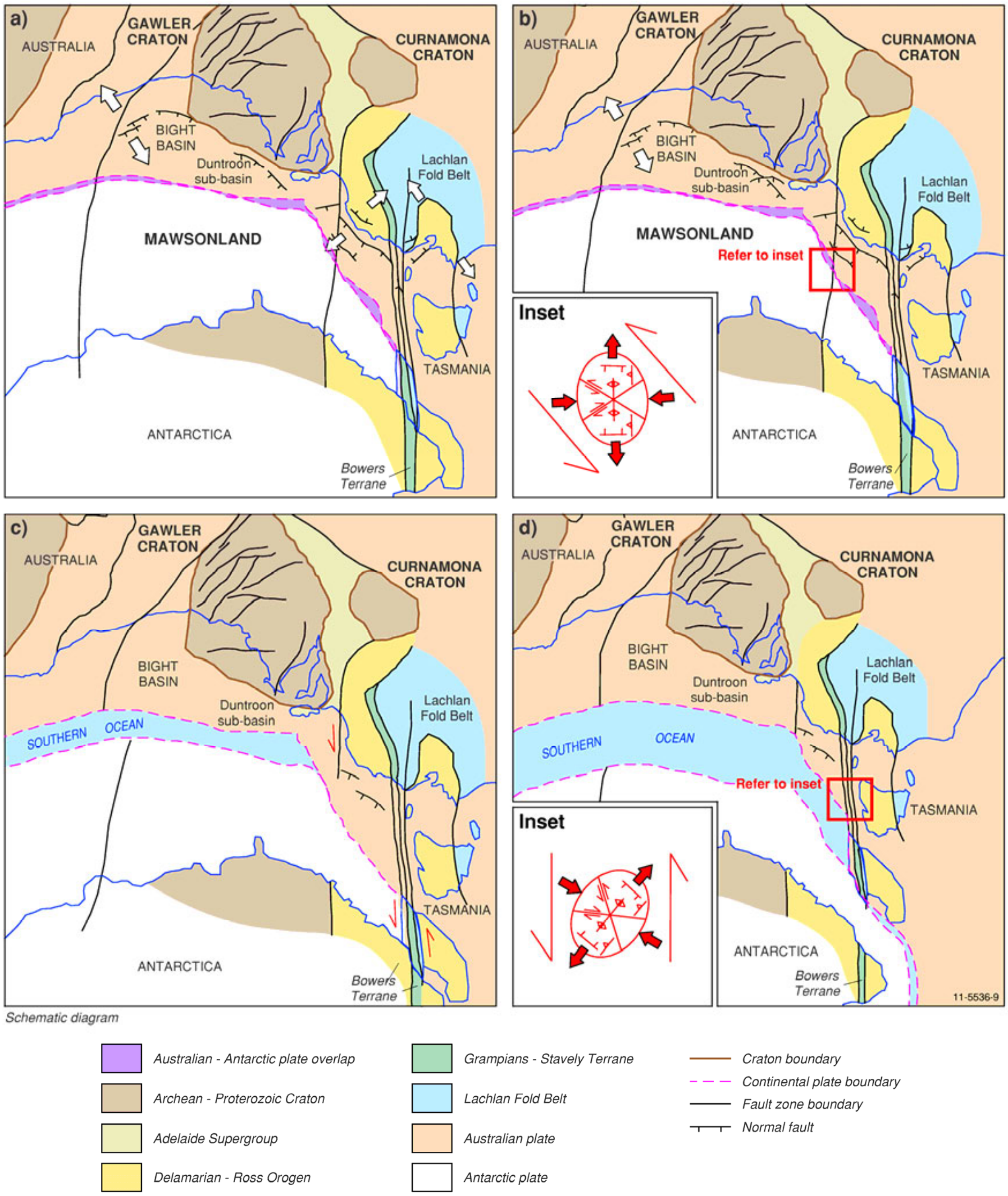

Figure 13. *Schematic representation of successive stages in separation of Australia from Antarctica with geometry of rifted margin governed by the interplay between reactivated basement structures and a progressively changing extensional direction. (a) Late Jurassic-Early Cretaceous; (b) Early Cretaceous with NW-SE directed extension in Bight Basin and onset of intra-continental shearing between Australia and Antarctica (Trans-Antarctic Shear); (c) Late Cretaceous and NNE-SSW directed extension leading to reactivation of N-S-striking Paleozoic basement structures, including Coorong and Avoca shear zones; (d) Early Cenozoic and onset of N-S rifting with formation of ocean-continent transform boundary off western Tasmania and South Tasman Rise. Insets show orientation of structures anticipated to occur in regions dominated by strike-slip displacement during rifting.*

Support for this interpretation comes from recent teleseismic tomography studies (Rawlinson et al., 2011) showing significant changes in mantle p-wave velocities across discontinuities near the base of the lithosphere (150 km) that could be deeper level expressions of both these structures. An eastward change from higher to lower wave speeds in western Victoria is consistent with the position of the Avoca Fault and the predicted change (Cayley et al., 2002; Gibson et al., 2011) from cold Neoproterozoic lithospheric mantle of continental affinity beneath the Delamerian Orogen to Paleozoic lithospheric mantle of oceanic affinity beneath the western part of the Lachlan Fold Belt. More surprising is the westward decrease in wave speed across the Coorong Shear Zone into lithospheric mantle underlying the Gawler craton that might be expected to return higher velocities owing to its greater antiquity and correspondingly lower temperature. Anomalously high surface heat flow values (92 ± 10 mWm^{-2}) have been reported for the eastern Gawler craton and correlative basement rocks buried beneath the neighbouring Adelaide Supergroup (Neumann et al., 2000) but any associated thermal anomaly is interpreted to be confined to the continental crust and not extend down into the underlying mantle (Neumann et al., 2000). These higher heat flow values correspond to the 250 km wide South Australia Heat Flow Anomaly and owe their existence to higher than usual concentrations of U and Th in basement granites of Proterozoic and Mesoarchean age (Neumann et al., 2000; Fraser et al., 2010). This enrichment and resulting elevated heat production are likely to have had an adverse effect on crustal strength even where mantle temperature remained depressed. Moreover, this effect is predicted (Sandiford et al., 1998) to be greatest wherever basement has been subjected to deep burial beneath a thick insulating blanket of sedimentary rocks as is the case along the eastern margin of the Gawler craton. Maximum depths of burial in the present instance were achieved beneath sediments of the Kanmantoo Group and so it is probably no accident that deformation has been preferentially partitioned along the Coorong Shear Zone, together with a significant amount of magmatic intrusion (Fig. 9). The Coorong Shear Zone lies at or close to the eastern margin of the South Australia Surface Heat Flow Anomaly and, once formed and buried beneath Kanmantoo sediments, would have remained in a structurally and thermally weakened state during subsequent deformational events. It consequently served as a locus for repeated basement reactivation not only during the Delamerian Orogeny but later continental breakup and the separation of Australia from Antarctica. Similar conditions might also pertain along the formerly contiguous Mertz Shear Zone but as yet there are no equivalent heat flow data available from Antarctica to test this hypothesis. It is nevertheless significant that the Mertz Shear Zone occupies an analogous position to the Coorong Shear Zone in that it too lies at, or close to, the western limits of Cambro-Ordovician granitic magmatism, indicating some pre-existing thermal weakness may also have helped localise deformation along this particular structure in Antarctica (Di Vincenzo et al., 2007; Goodge and Fanning, 2010; Talarico and Kleinschmidt, 2003).

Tasman Fracture Zone: a reactivated basement fault

The effects of pre-existing basement fabric on the geometry and orientation of rifting in the Otway Basin are especially evident off western Tasmania where reactivation of the early Paleozoic Avoca (-Sorell) Fault (cf. Foster and Gleadow, 1992; Hill et al., 1995; Miller et al., 2002), led to formation of an ocean-continent transform boundary (Gibson et al., 2011). This older basement structure dips steeply basinward in seismic reflection images (Fig. 10) and represents a former strike-slip fault along which oceanic and continental crust were juxtaposed in the late Cambrian-earliest Ordovician (Gibson et al., 2011). It initially served as the locus for rifting along one arm of a triple junction that continued to evolve whereas the arm extending northeast through Bass Strait failed (Fig. 13), presumably because it was underlain by older and stronger Tasmanian continental crust compared to the already extensively faulted and rheologically weaker strike-slip zone to the west (see also Teasdale, 2003). A greater propensity for failure along this structure also accords with the observation made elsewhere in this paper that the Avoca-Sorell fault zone extends to mantle depths so that any inherited structural weakness would not have been confined to the crust but have been lithospheric in scale (Fig. 10). The third arm of the triple junction extended northwest along what is now the western Otway Basin (Fig. 11) and became the main depocentre for sedimentation in the early-late Cretaceous (Hill et al., 1995; Krassey et al., 2004).

Influence of basement structure on basin geometry

As formerly contiguous parts of Rodinia and eastern Gondwana (Figs. 8 & 13a), the continental margins of Australia and Antarctica share a common legacy of Neoproterozoic rifting and passive margin formation followed by plate convergence, ocean basin closure and orogenesis in the early to mid-Paleozoic (Gibson et al., 2011; Glen, 2005; Rossetti et al., 2002; Tessensohn and Henjes-Kunst, 2005; Weaver et al., 1984). The Coorong and Mertz Shear Zones both date from these events and represent only two of the more obvious basement structures that had a strong influence on the geometry of rifting and subsequent plate margin. No less important are the variously oriented deep-cutting basement structures farther west that controlled the direction of normal faulting associated with Mesozoic rifting and basin formation within and adjacent to the older Gawler Craton (Figs. 4 & 6). The most obvious of these structures trend west-east or northeast (e.g. Karari and Tallacootra shear zones) and were manifestly reactivated during the earliest stages of rifting (Fig. 13a) because structures with these orientations (Fig. 7) bound half-graben of late Jurassic and/or early Cretaceous age in the Polda (Itiledoo) and Bight basins (Stagg et al., 1992; Stagg et al., 1990; Totterdell and Bradshaw, 2004). NE-trending intra-basinal faults are equally evident farther west in the Bremer Sub-basin off the south coast of Western Australia (Bradshaw et al., 2003) where basement is similarly dominated by rocks having a NE-oriented structural grain (Albany-Fraser Orogen; Fig. 5). Indeed, in many parts of the greater Bight Basin, this structural trend would appear to be dominant and developed to the exclusion of all others. Given that crustal extension during this period was directed NW-SE in the Bight Basin (Fig. 14), the predominance of NE-trending intra-basinal structures is not altogether surprising as many deep-cutting basement structures with this particular trend would have been optimally oriented for reactivation through tensile failure. Significantly, this phase of continental rifting in the Bight Basin was also characterised by subdued rates of extension, culminating in the formation of a magma-poor hyper-extended continental margin in which sub-continental lithospheric mantle was exhumed at the seafloor.

Delamerian-age thrust faults on nearby Kangaroo Island share the same east-west trend as some Jurassic-Early Cretaceous structures in the Duntroon Sub-basin (Figs. 7 & 15), indicating that early Paleozoic deformation in this part of the fold belt was as much controlled by older pre-existing basement structure as the younger intra-basinal faults. Indeed, it has already been suggested (Preiss, 2000) that the anomalous east-west trends in this part of the Delamerian Fold belt are due to the presence of a pre-existing failed rift that dates back to at least the time of Rodinia breakup (Neoproterozoic). However, this failed rift may itself have been influenced by a much older east-west-trending basement structure of the type exposed farther north in the Gawler craton (Figs. 4 & 6).

Significantly, this pattern of crustal failure and normal faulting along west-east and northeast directions is limited to the region west of the Coorong Shear Zone and does not extend eastward into the western Otway Basin where half-graben and their bounding normal faults predominantly strike northwest (cf. Figs. 7 & 11) and formed during NE-directed extension (Fig. 14). The Duntroon Sub-basin shares this same northwest trend but it is probably of strike-slip (transtensional) origin and developed during the same extensional event that produced the Bight Basin farther west (Fig. 15). Extensional strains would appear to have been partitioned across the Coorong structure, reinforcing the conclusion made elsewhere in this paper that the Coorong Shear Zone is not only a crustal structure of fundamental importance but one which had considerable influence over the location and manner in which continental rifting and breakup took place. This change in extensional direction and basin geometry along the Australian continental margin has been noted before (Blevin and Cathro, 2008; Totterdell and Bradshaw, 2004; Willcox and Stagg, 1990) but, in the absence of any previously mapped major basement structure like the Coorong Shear Zone (this study), has largely gone unexplained.

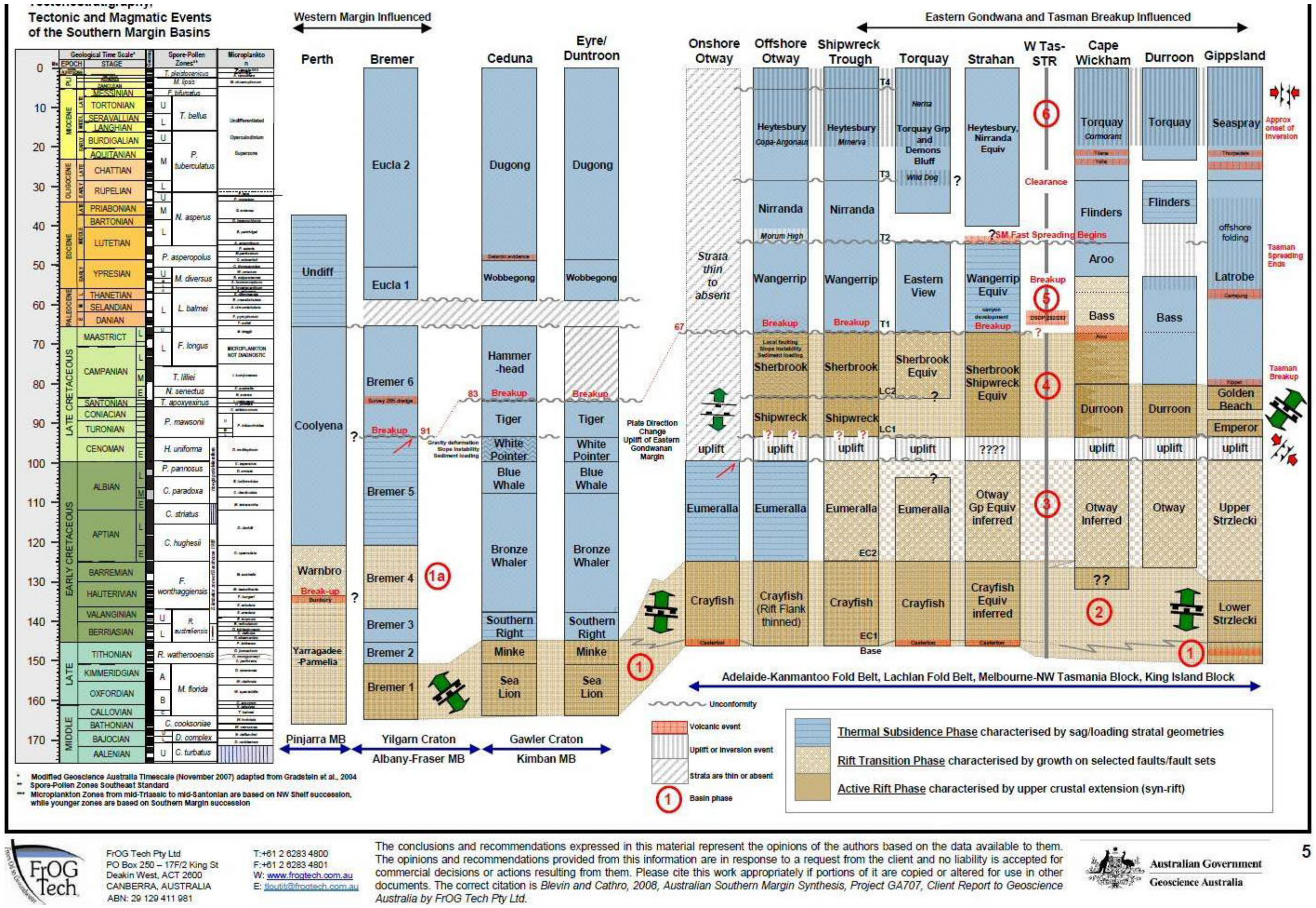

Figure 14. *Time-space plot & tectonic synthesis for the Australian southern rift margin (from Blevin and Cathro, 2008). Note change in extensional direction from west to east as margin evolved.*

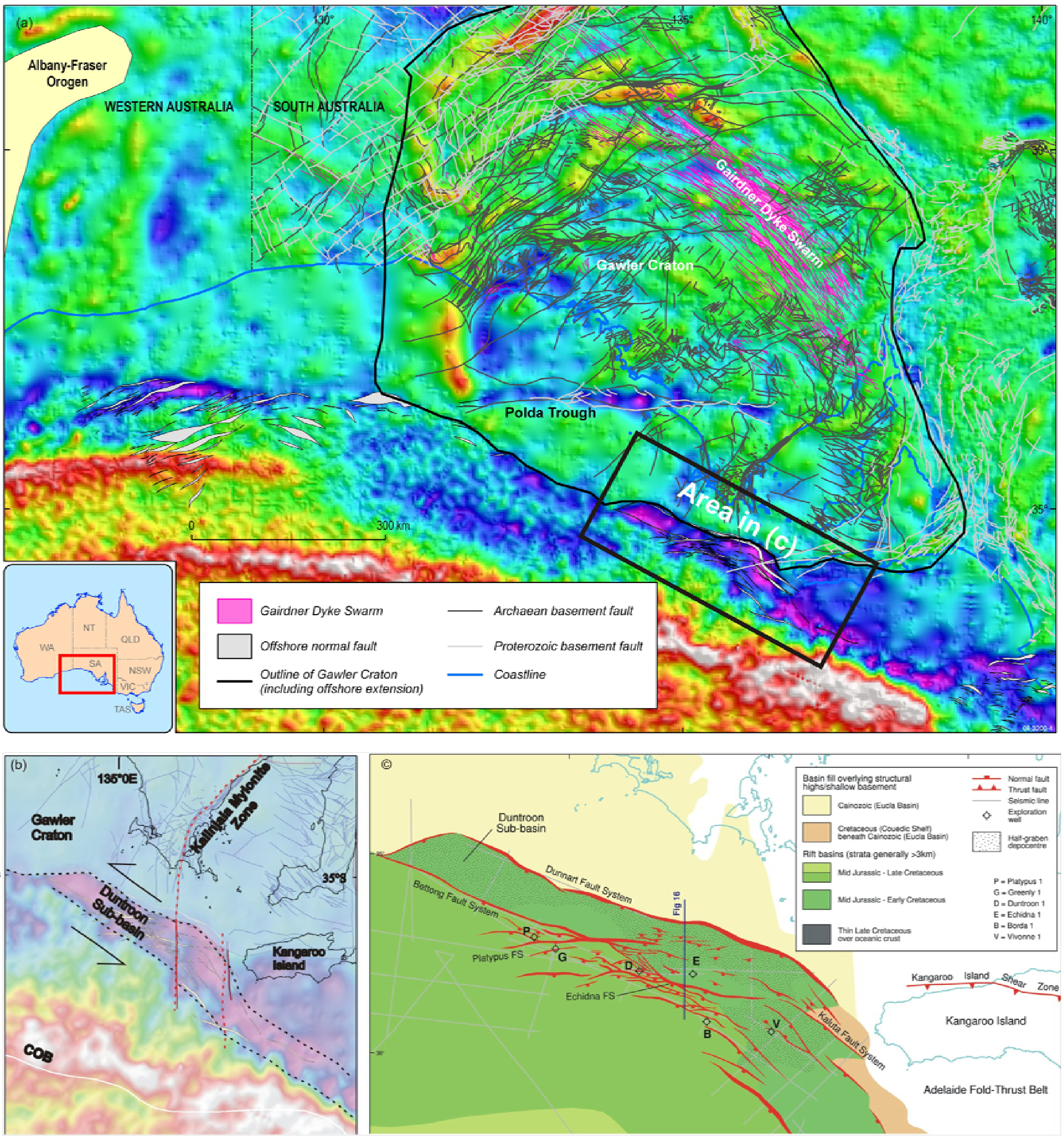

Figure 15. *Residual gravity image (a) in which the onshore and offshore gravitational responses are levelled to a common datum. Normal faults within the Bight Basin do not extend north of the reactivated west-east-trending basement fault that also controlled formation of the Polda Trough. The Duntroon Sub-basin is located within an indentation along the southern margin of the Gawler Craton (b). Basement faults in the adjacent Gawler Craton (a) share the same northwest orientation as the sub-basin and its bounding faults (c), suggesting that basin geometry may have been controlled by reactivation of the former. The southern margin of the basin merges southward into the continent-ocean boundary (b) along which there was considerable transtensional shear (Willcox and Stagg, 1990) prior to formation of the first oceanic crust at 83 Ma. Basin boundaries in the Duntroon Sub-basin are offset where affected by the Kalinjala Mylonite Zone and related north-south-trending basement structures. Note parallelism between younger east-west-trending normal faults in sub-basin and thrust fault of Delamerian age on Kangaroo Island (c). Map of Duntroon Sub-basin is from Bradshaw et al. (2003).*

An analogous change in basin geometry and extensional direction occurs across the Avoca-Sorell fault zone (Figs. 11 & A.2), indicating that this basement structure was no less influential in controlling the pattern of rifting and continental breakup, and is probably developed at a comparable crustal, if not lithospheric, scale (Gibson et al., 2011; Miller et al., 2002). In keeping with this interpretation, seismic profiles across the offshore extension of this structure northwest of Tasmania reveal a steep to near-vertical fault extending all the way down to the mantle (Fig. 10). This same steep to near vertical attitude is also evident in the transform boundary off the South Tasman Rise farther south (Fig. 17) and which is taken here to be a southern extension of the Avoca-Sorell fault system. As with most other transform boundaries, this boundary dips steeply oceanward and is

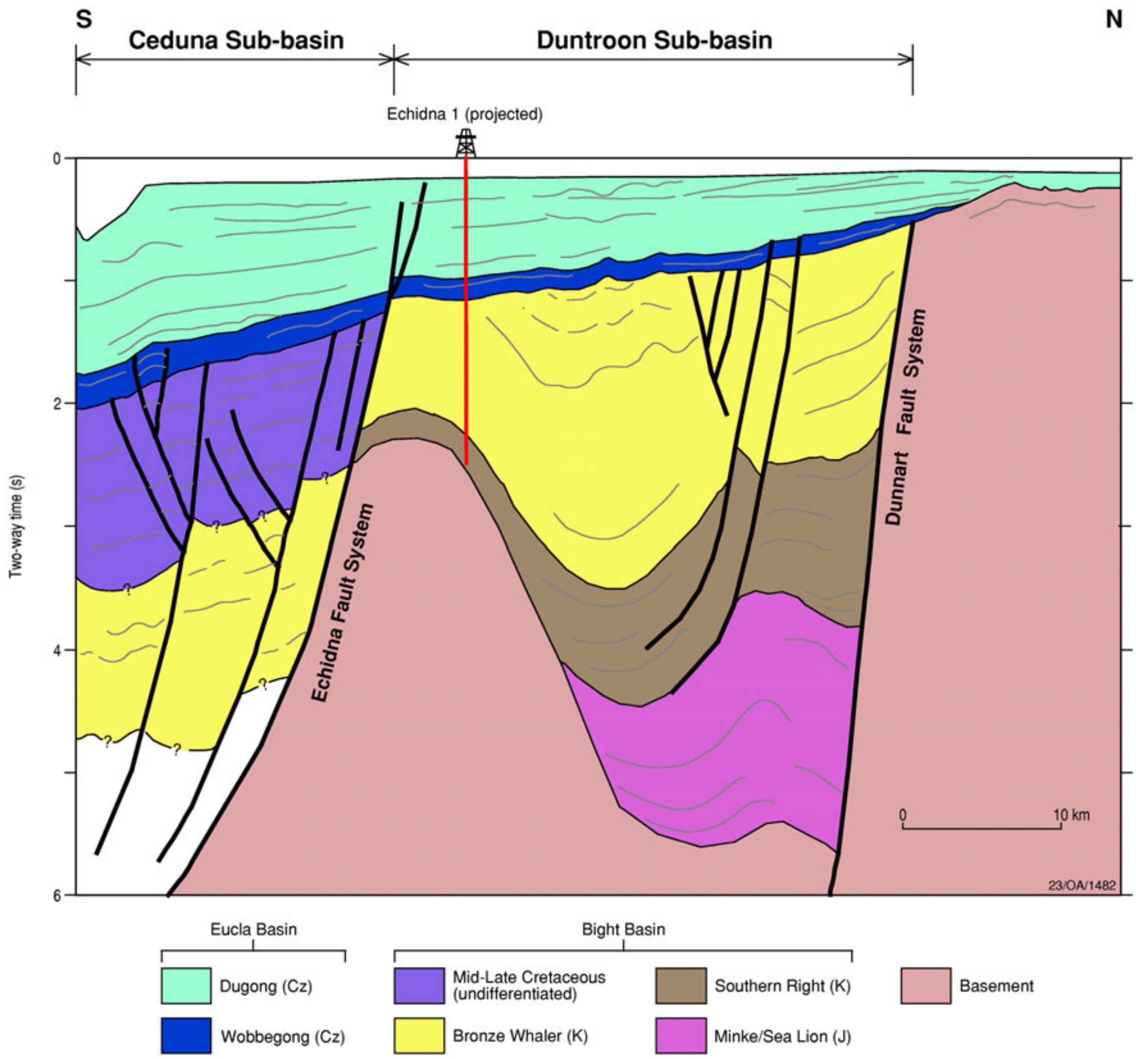

Figure 16. *Interpreted seismic section (Bradshaw et al., 2003) through Duntroon Sub-basin showing its narrow character, Jurassic – Early Cretaceous syn-rift basin fill (Southern Right and Minke/Sea Lion) and thickening of this fill against the sub-vertical Dunnart Fault System on northeast side of the basin. This basin-bounding fault system is interpreted here to be primarily of strike-slip origin and temporally linked to formation of the Trans-Antarctic Shear (see Fig. 15 for location of seismic line).*

associated with an outer basement high against which a narrow sedimentary basin has developed (Fig. 17). Interestingly, both the Avoca-Sorell and Coorong shear zones are also the only two basement structures along the Australian margin for which there is good evidence that structural inheritance played a recognisable role in formation of the along-strike ocean floor fabric, and the George V and Tasman fracture zones in particular (Fig.1).

A late Callovian-earliest Berrisian (160-140 Ma) age is generally accepted for initial rifting (Fig. 14) in the Bight Basin (Totterdell and Bradshaw, 2004) whereas in the Otway Basin early rifting dates back to the latest Jurassic-Early Cretaceous (145-125 Ma) (Blevin and Cathro, 2008; Krassay et al., 2004; Norvick and Smith, 2001). Thus, unless strain was actively partitioned across a pre-existing basement structure such as the Coorong Shear Zone, Early Cretaceous extensional faults might be expected to overprint older normal faults and basinal structures in the Bight Basin. The general absence of such overprinting structures supports the case for strain partitioning although this need not imply that strain partitioning during the earlier stages of rifting was confined to any one basement structure or even involved the Coorong structure. Indeed, according to Willcox and Stagg (1990; see also Norvick and Smith, 2001), early rifting between Australia and Antarctica was largely accommodated by ca. 300 km of left-lateral displacement on a NW-trending transform fault (Trans-Antarctic Shear) that extended all the way from the Bight Basin to the South Tasman Rise (Fig. 13b). If this interpretation is correct, any such transform fault, no matter how transitory, would have cut and displaced the Coorong Shear Zone along with any other basement structures by a comparable amount. This would have produced a major disconnect between the Coorong and Mertz shear zones that would have persisted until ~ 83 Ma (84 Ma according to new time scale (Gradstein et al., 2004)) when further changes in the plate vector brought them back into alignment (Fig. 13c). Importantly, this is the exact same time that seafloor spreading commenced in the Bight Basin (Sayers et al., 2001) and when Australia and Australia may have first began to separate on a more northerly trajectory.

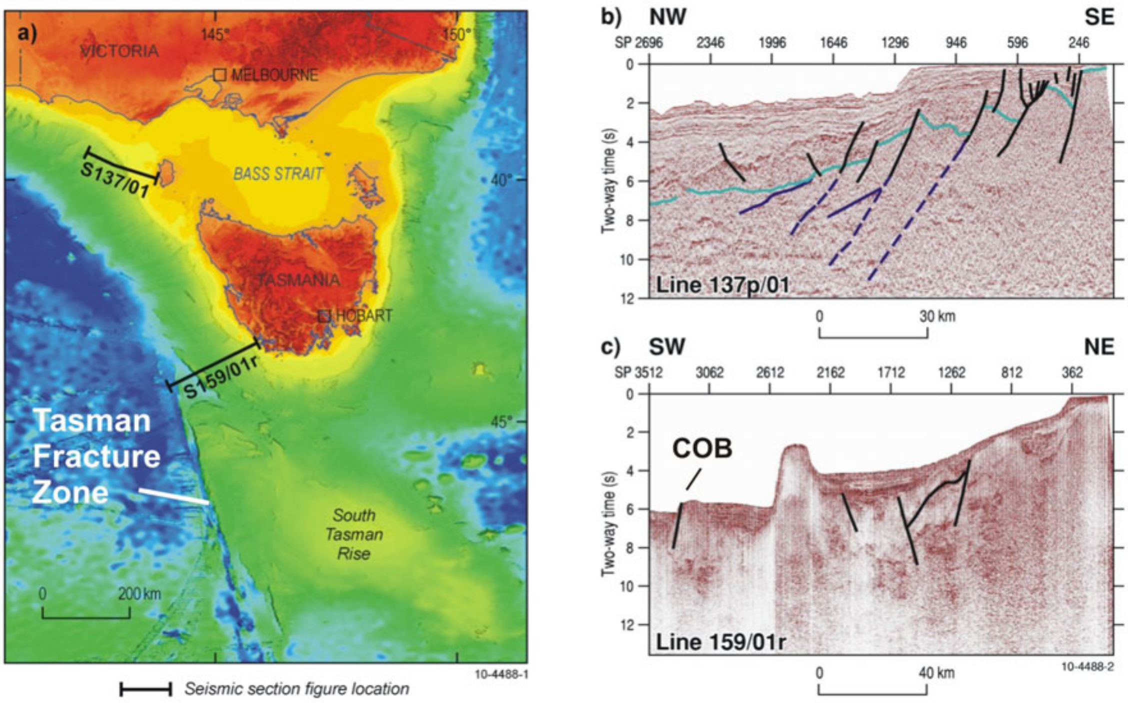

Figure 17 *.Bathymetric Map for Tasmania and South Tasman Rise showing location two seismic sections across the Avoca-Sorell fault system and its extension southward into the Tasman Fracture Zone. In both seismic sections the major crustal-penetrating faults dip oceanward. Note perched sedimentary basins on landward side of outer basement highs. COB = Continent-ocean boundary.*

By this time (83 Ma) displacement on the Trans-Antarctic Shear would have ceased and extensional strain would have been increasingly accommodated by left-lateral movement on the Coorong and Avoca-Sorell fault zones (Fig. 13c). Similarly, basin development concluded in the northwest-striking Duntroon Sub-basin which up until that time lay along strike from the Trans-Antarctic Shear and had evolved into a narrow, elongate basin with all of the characteristics of a depocentre formed at the releasing bend of a continental transform fault (Aksu et al., 2000). Shear sense for basin formation is sinistral (Fig. 15) and thus in the same direction as that proposed for the Trans-Antarctic

Shear. Major basement-involved faults in the Duntroon Sub-basin, and farther north along the eastern margin of the Ceduna Sub-basin, strike mainly northwest (Figs. 7 & 15), parallel to basement fabrics of inferred 830 Ma or older age that controlled regionally extensive dyke intrusion (Gairdner Dyke Swarm) in the neighbouring Gawler Craton (Fig. 4). Dyke intrusion occurred during late Neoproterozoic extension accompanying the initial stages of Rodinia breakup and may be symptomatic of an even older northwest-trending basement fabric that not only controlled formation of the Duntroon Sub-basin and Trans-Antarctic Shear but the direction of plate fragmentation along the southern margin of the Gawler Craton itself (Fig. 15). In this scenario, interaction between the Coorong Shear Zone and northwest-trending structures is likely to have impacted not only on the location and direction of plate breakup but the very fabric of the adjacent ocean floor.

Following the cessation of intra-continental shearing between Australia and Antarctica, and a return to NNE-SSW-directed extension in the late Cretaceous (Fig. 14), a mainly transtensional tectonic regime developed in the more outboard part of the Otway Basin, presumably in response to far-field stresses linked to subduction rollback and continental breakup farther east in New Zealand and the Lord Howe Rise (Norvick and Smith, 2001). Both the Coorong and Avoca-Sorell shear zones were now subject to left-lateral strike-slip displacement (Fig. 13c). This regime persisted through successive events until 55 Ma or maybe even earlier (67 Ma?) when there was a major reorganisation of global plate movements with the result that rifting between Australia and Antarctica assumed a north-south direction, and displacement on both structures became almost wholly strike-slip (Fig. 13d). In the Otway and Sorell basins, this led to further east-west faulting and sinistral offset of basement structures on northwest-trending shear zones (Fig. A. 1).

Conclusions

Pre-existing basement structure, combined with along-strike differences in crustal composition and rheology, had a profound influence on the geometry of continental rifting along Australia's southern margin, determining not only the locus and direction of breakup but the degree to which the margin is segmented. A three-fold segmentation of the margin is recognised.

The western segment strikes broadly west-east and is centred on the Bight Basin in which extension was initially directed NW-SE, leading to widespread reactivation of NE-striking basement faults and shear zones in the Albany-Fraser Orogen and neighbouring Gawler Craton. Late Jurassic-Early Cretaceous sedimentary basins and normal faults formed offshore during this phase of rifting share the same NE trend and were coupled to an episode of sinistral transtensional shear between Australia and Antarctica that produced the NW-trending Duntroon Sub-basin. This segment extends no farther east than the early Paleozoic Coorong Shear Zone across which extensional strain was strongly partitioned and there was a change from NW-SE to NNE-SSW extension. This change occurred in the Early Cretaceous, giving rise to the western Otway Basin and a very differently oriented segment of continental margin in which the majority of rift structures strike NW. The remaining segment strikes north-south and owes its orientation to reactivation of an older early Paleozoic structure (Avoca-Sorell Fault Zone) that that shared the same north-south strike and subsequently evolved from a continental transform boundary into the Tasman Fracture Zone.

The Tasman and George V Fracture Zones both owe their origin and location to the presence of pre-existing lithospheric-scale basement structures optimally oriented for reactivation during Mesozoic-Cenozoic continental rifting. They are identified here as the early Paleozoic Avoca-Sorell Fault Zone and Coorong Shear Zone respectively, both of which have identifiable correlatives along strike in Antarctica that necessitate some revision of existing paleogeographic reconstructions of the opposing Australian and Antarctic continental margins based on non-geological criteria. During continental breakup, extensional strain was partitioned across the Coorong Shear Zone such that it now separates sedimentary basins formed broadly contemporaneously with each but under opposing extensional directions. Plate reconstructions that match the Mertz Shear Zone against the Coorong structure are preferable to previously published reconstructions in which the former was matched with the Kalinjala Mylonite Zone in the Gawler Craton.

Appendix A

Included here is a more detailed description of the principal basement terranes and structures that make up the western Tasmanides in SE Australia and for which temporal equivalents have been identified in Tasmania and Antarctica (Flottmann et al., 1993; Flottmann et al., 1998; Gibson and Ireland, 1996; Munker and Crawford, 2000). From dredge samples and seismic reflection studies, these rocks are also known to extend offshore beneath Australia's southern rift system where they form basement to sedimentary basins of latest Jurassic-early Cenozoic age (Berry et al., 1997; Blevin and Cathro, 2008). An older late Mesoproterozoic gneissic component identified (Berry et al., 1997) in dredge samples from the South Tasman Rise (Fig. A.1) derives from even deeper structural levels within this same basement and probably represents a westward extension of similarly aged metamorphic rocks exposed in western Tasmania (Tyennan block) and on neighbouring King Island in Bass Strait (Berry et al., 2007; Meffre et al., 2000; Seymour et al., 2007). These rocks underwent metamorphism at 1290 Ma and 920 Ma, and intrusion by granite at 1050 Ma (Berry et al., 2008) and are different to most other basement rocks in SE Australia in preserving Grenville ages. They are thought to extend at depth from Tasmania northwards beneath Bass Strait and into central Victoria where they make up the deeper structural levels of the unexposed Selwyn block (Cayley et al., 2002; VandenBerg et al., 2000).

Kanmantoo-Glenelg zone

Late Neoproterozoic–Early Cambrian rift-related sequences developed during Rodinia breakup and ensuing development of the east Gondwana passive margin (Glen, 2005) are widely distributed in South Australia and neighbouring western Victoria where they make up the bulk of the Kanmantoo-Glenelg zone. This zone comprises mainly sediments of shallow and deep water origin deposited on a variably magnetised basement of attenuated continental crust of Paleo- to Mesoproterozoic age (Preiss, 2000). Stratigraphic sequences represented include the Adelaide Supergroup and overlying Normanville and Kanmantoo Groups (Preiss, 2000). Basement of Grenville age as occurs in western Tasmania is completely unknown although 800-900 Ma granites dating from the earliest stages of Rodinia breakup have recently been reported from South Australia (Preiss et al., 2008). Much more common are granites of Cambrian-early Ordovician age that were intruded into their passive margin sedimentary host rocks during or immediately following the Delamerian Orogeny. Granites of this age are often strongly magnetic and include both I- and A-type varieties (Fig. 9); they extend eastwards as far as the Moyston fault and were in part derived through the interaction of mantle-derived basaltic melts with crustal sources, particularly in the west where the granites are best exposed (Foden et al., 1999). These granites include the 514 ± 5 Ma Rathjen Gneiss for which a pre- or early syntectonic origin has been proposed, and which carries an inherited zircon population (Foden et al., 1999) identical in age to that observed in detrital zircons from the adjacent Kanmantoo metasedimentary rocks (Ireland et al., 1998). Granites and gabbros hosted by the Coorong Shear Zone are similarly strongly magnetic and were emplaced after the cessation of Delamerian deformation and metamorphism.

Rift-related alkaline to tholeiitic basaltic rocks with well developed aeromagnetic signatures (Fig. A.2) and ages between 525 Ma and 510 Ma (Preiss, 2000 and references therein) occur widely throughout the Kanmantoo-Glenelg zone (Gibson and Nihill, 1992; Morand et al., 2003). They become increasingly abundant towards the base of the stratigraphic sequence (Gibson and Nihill, 1992) and exhibit within-plate or E-type MORB (mid-ocean ridge basalt) compositions. Along with their sedimentary host rocks, these rocks preserve a record of polyphase deformation and metamorphism, including an episode of low pressure (P)-high temperature (T), greenschist to amphibolite facies metamorphism linked to granite intrusion at 490-480 Ma (Anderson and Gray, 1994; Gibson and Nihill, 1992; Morand et al., 2003).

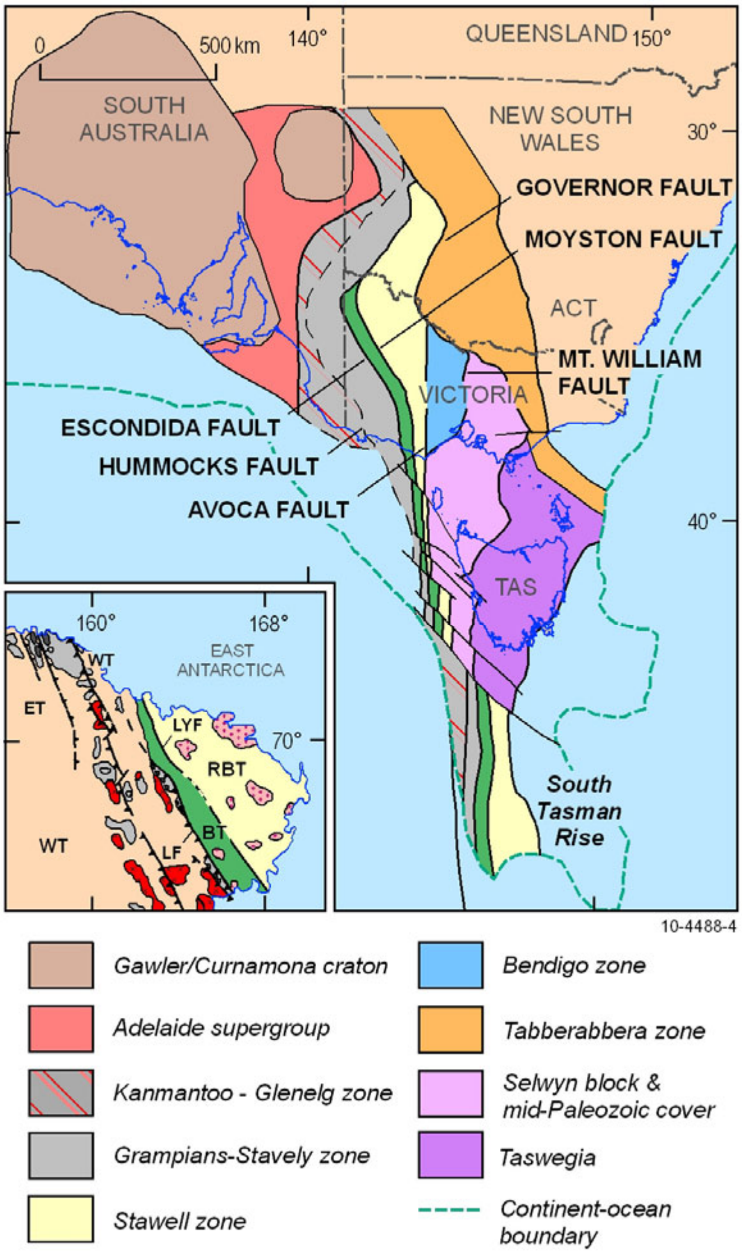

Figure A.1. *Basement terrane map for SE Australia and proposed equivalents in northern Victoria Land, Antarctica (after Gibson et al., 2011). WT = Wilson terrane; BT = Bowers terrane; RBT = Robertson Bay Terrane; ET = Exiles Thrust; LF = Lanterman Fault; LYF = Leap Year Fault.*

Wilson terrane (northern Victoria Land)

Like the Kanmantoo-Glenelg terrane with which it is commonly compared, the Wilson terrane (Fig. A.1) preserves a record of polyphase deformation, low P-high T metamorphism and granite intrusion at 520-480 Ma (Borg and DePaolo, 1991; Palmeri et al., 2003; Stump et al., 1986). Granitic rocks give isotopic signatures consistent with increased amounts of crustal contamination westwards (Borg and DePaolo, 1991) and intrude a metasedimentary sequence in which pods and lenses of variably retrogressed amphibolite and eclogite are locally embedded (Di Vincenzo et al., 1997; Palmeri et al., 2003). Such pods and lenses are best known from the Lanterman Range along the eastern margin of the Wilson terrane and exhibit transitional to E-MORB-type compositions typical of tholeiitic basalts injected into thinned continental crust or an incipient ocean basin (Di Vincenzo et al., 1997). Their composition is not too dissimilar to that of rift-related basalts in the Kanmantoo-Glenelg zone and could be taken as evidence of a common origin and formation in the same tectonic environment. More rarely, metsedimentary rocks in the Lanterman Range contain pods of unretrogressed 508 Ma coesite-bearing eclogite formed at pressures in excess of 2.9 GPa (Di Vincenzo et al., 1997; Ghiribelli et al., 2002; Palmeri et al., 2003). Their mineralogy predates low P-high T metamorphism in the Lanterman Range and can only have formed in crust carried to mantle depths in a subduction zone.

Bowers and Grampians-Stavely terranes

Continuity of the volcanic-dominated early Paleozoic Bowers terrane with the Grampians-Stavely zone in western Victoria (Fig. A.1) has been proposed many times owing to similarities in their deformational, magmatic and sedimentary records (Flottmann et al., 1998; Foster and Gleadow, 1992; Gibson and Nihill, 1992; Munker and Crawford, 2000). Particularly important in this respect are the variably sheared and strongly magnetised tholeiitic basalts, boninitic lavas and boninitic cumulate-derived ultramafites and serpentinites of the Dimboola Igneous Complex (VandenBerg et al., 2000) thought to have formed in an oceanic supra-subduction setting (Crawford et al., 2003a). Their equivalent in northern Victoria Land forms part of the Glasgow Volcanics in the Bowers terrane where gabbro and basaltic rocks with tholeiitic-boninitic affinities are also known to occur (Rocchi et al., 2011; Tribuzio et al., 2008; Weaver et al., 1984).

Lying immediately east of the Grampians-Stavely zone (Fig. A.1), and exhumed in the hangingwall of the Moyston Fault, are early Cambrian metabasaltic rocks (Magdala Volcanics) and amphibolites of the tectonically reworked and more highly metamorphosed Moornambool Metamorphic Complex dated at ca. 500 Ma (Crawford et al., 2003a; Foster et al., 2009; Miller et al., 2005; Squire et al., 2006). These rocks have the composition of back-arc basalts (Squire et al., 2006) and represent the deepest exposed structural levels within both this zone and the immediately adjacent Bendigo zone (Gray and Foster, 1998; Gray and Foster, 2004; VandenBerg et al., 2000). Quartz-rich turbidites of Cambro-Ordovician age overlie these basalts in the Stawell zone (VandenBerg et al., 2000) and are widely thought to be correlatives of turbidites of similar age and composition making up the bulk of the Robertson Bay terrane in northern Victoria Land (Tessensohn and Henjes-Kunst, 2005; Weaver et al., 1984). Except for an isolated outcrop of ca. 510 Ma granite in the eastern part of the terrane (Fioretti et al., 2005), basement to Robertson Bay terrane is unexposed and no equivalent of the Magdala Volcanics or Moornambool Metamorphic Complex has ever been reported from this part of northern Victoria Land. The Bendigo zone has no known correlative in Antarctica and encompasses a thick sequence of turbidites no older than Ordovician in age (VandenBerg and Stewart, 1992; VandenBerg et al., 2000).

Tasmania - Selwyn basement block

Other than an exposed older Mesoproterozoic basement in which granites of 790-750 Ma and Grenville age are entrained (Berry et al., 1997; Berry et al., 2008), western Tasmania (Taswegia; Fig. A.1) shares many geological similarities with western Victoria and the Wilson terrane, including a late Neoproterozoic-Cambrian continental margin sequence comprising shallow to deep water sediments with lesser amounts of intercalated rift-related basaltic rocks (Crawford and Berry, 1992; Direen and Crawford, 2003; Seymour et al., 2007). As in northern Victoria Land, metamorphism in these rocks locally reached eclogite facies conditions, consistent with substantial amounts of tectonic loading and burial of some parts of the continental margin to subcontinental depths (Meffre et al., 2000; Palmeri et al., 2009). Peak metamorphic pressures in these rocks are estimated at 1.5 GPa (Palmeri et al., 2009) and were attained no later than ca. 505 Ma (Foster et al., 2005; Meffre et al., 2000) in response to a major tectonothermal event involving island arc-continent collision and the superposition of the leading edge of this island arc over the adjacent continental margin. Early Cambrian (ca. 516 Ma) mafic-ultramafic rocks of tholeiitic and boninitic composition interpreted as parts of a forearc complex occur widely throughout western Tasmania, and were transported into their present position on a major detachment that originally dipped eastwards and had its roots in the Tamar or Tiers fracture zone (Crawford and Berry, 1992; Crawford et al., 2003b; Foster et al., 2005). Metamorphism in these rocks took place at significantly lower temperature-pressure conditions than in the underlying continental margin sequences and produced mainly greenschist facies mineral assemblages (Crawford and Berry, 1992).

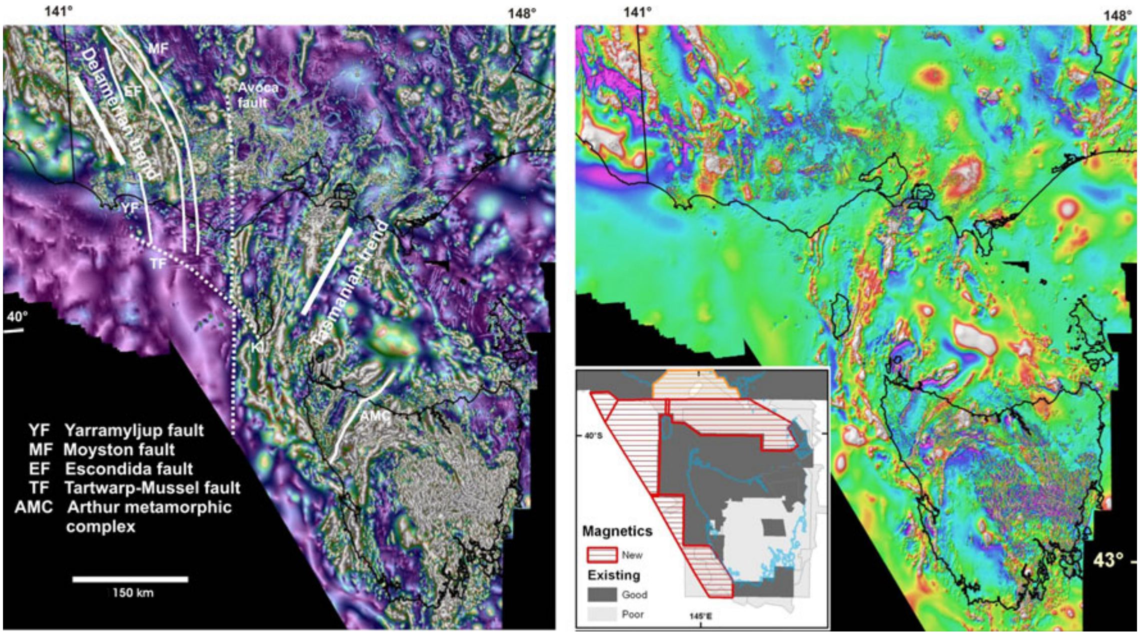

Figure A.2. *Aeromagnetic images for SE Australia based on (a) phase and amplitude components of the analytical signal, and (b) total magnetic intensity (TMI). The former accentuates and sharpens anomalies sourced from magnetic bodies lying at shallow to mid-crustal depths (Morse et al., 2009) allowing the margins and contacts of these bodies to be mapped more precisely than from the TMI image alone. Note continuation of Avoca Fault offshore. Image (a) incorporates a linear colour stretch from 60,500 nT (magenta) to 60,900 nT (white); colours represent amplitude; phase is represented by degree of background colour. Anomalies in TMI image range from 58,000 nT to 68,000 nT. Both images combine pre-existing and newly acquired (2009) high resolution aeromagnetic data (inset; horizontally ruled areas). PI=Phillip Island; WB=Waratah Bay; KI=King Island.*

Avoca-Sorell fault system

Separating the NNW-trending rocks of western Victoria from a Tasmania-Selwyn block in which NNE-trending basement structures predominate is the Avoca Fault (Figs. 10 & A.1–A2). It is the single most obvious structure identified in aeromagnetic data (Fig. A.2) and presently serves as the boundary between the Stawell and Bendigo zones (Fig. A.1). Recently acquired deep seismic reflection data (Korsch et al., 2008) and published magnetotelluric data for central Victoria (Cull et al., 2008) support the idea of a major crustal-penetrating structure in the vicinity of the Avoca Fault and show that it dips steeply westwards. Its along strike equivalent offshore is the Sorell Fault (Fig. 11) across which there is an abrupt change in the orientation of normal faults (Fig. A.2) in the Late Cretaceous-Cenozoic Otway Basin (cf. Miller et al., 2002).

Moyston and Escondida faults

Prominent among the NNW-trending structures are the Moyston and Escondida Faults (Fig. A.1). They both dip eastwards and, except for minor modifications made to their northern extremities, occupy the same positions as determined in previous studies (Moore and Maher, 2006; VandenBerg et al., 2000). The Escondida Fault truncates the west-dipping Yarramyljup Fault at its northern end (Fig. A.1) and has magnetite-bearing mafic and ultramafic rocks of the Dimboola Igneous Complex exposed in its hangingwall (Cayley et al., 2002; VandenBerg et al., 2000). Together, these two faults form a western boundary to the mainly volcanic-dominated Grampians-Stavely terrane or structural zone (Fig. A.1).

The Moyston Fault separates the Grampians-Stavely terrane from the Stawell zone (Fig. A.1) and, as befits a major crustal boundary, has an estimated vertical displacement in excess of 20 km (Cayley et al., 2002). It emplaces weakly metamorphosed Cambrian low-K basalts of the Magdala Volcanics over lower grade rocks of the Grampians-Stavely zone (Cayley et al., 2002; Miller et al., 2005). Due to masking of the analytical signal by a thick wedge of Cretaceous sediments, neither these rocks nor the Dimboola Igneous Complex are well imaged offshore and their continuation southward beneath sediments of the Otway Basin is more speculative (Fig. A.1).

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