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Pre-existing basement structure and its influence on continental rifting and fracture zone development along Australia's southern rifted margin

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Abstract: Palaeogeographical reconstructions of the Australian and Antarctic margins based on matching basement structures are commonly difficult to reconcile with those derived from ocean-floor magnetic anomalies and plate vectors. Following identification of a previously unmapped crustal-scale structure in the southern part of the early Palaeozoic Delamerian Orogen (Coorong Shear Zone), a more tightly constrained plate reconstruction for these margins is proposed. This reconstruction places the Coorong Shear Zone opposite the Mertz Shear Zone in Antarctica and lends itself to a revised interpretation of continental rifting along Australia's southern margin in which rift basin architecture, margin segmentation and the formation of ocean-floor fracture zones are all linked to pre-existing basement structure and the reactivation of a few deep-rooted crustal structures inherited from the Delamerian Orogeny in particular. Reactivation of the Coorong Shear Zone and other basement structures (Avoca–Sorell Fault Zone) during the earlier stages of rifting was accompanied by the partitioning of extensional strain and formation of late Jurassic–Early Cretaceous normal faults and half-graben in the Bight and Otway basins with opposing NE–SW and NW–SE structural trends. Previously, the Mertz Shear Zone has been correlated with the Proterozoic Kalinjala Mylonite Zone in the Gawler Craton but this positions Australia 300–400 km too far east relative to Antarctica prior to breakup and fails to secure an equally satisfactory match in both basement geology and the superimposed extension-related structures.

Pre-existing basement structures and fabrics have long been known to exert a strong influence on the formation and geometry of rifted continental margins and may have controlled the position of some ocean fracture zones (Wilson 1965; Choi *et al*. 2008). Basement control is particularly evident in the case of the west African and NE Brazilian transform margins where opening of the central Atlantic basin in Early Cretaceous time was accompanied by intracontinental shearing and reactivation of an older (600 Ma) Pan-African suture. This inherited structure predetermined not only the future location and geometry of continental breakup but also the orientation of the transform faults bounding these margins (Benkhelil *et al*. 1995; Mascle *et al*. 1997; Mohriak & Rosendahl 2003; de Castro *et al*. 2012). These transform faults strike east–west, parallel to the trace of the older suture, and merge seaward into a network of oceanic fracture zones.

For many other fracture zones, and more particularly those not obviously associated with a continental transform margin, no major reactivated basement structure is evident along strike and the case for basement control is far less certain. Indeed, some researchers have argued that no such control exists and that ocean fracture zones may nucleate spontaneously (Stoddard & Stein 1988; Taylor *et al*. 2009). It is nevertheless evident from bathymetric images that many fracture zones assume a pattern that closely mirrors the shape and orientation of the adjacent continental margin, pointing to a shared origin and control by the same crustal weaknesses that predetermined the location and geometry of continental breakup (McClay & Khalil 1998; Khalil & McClay 2001; Choi *et al*. 2008). Here, we present the results of a combined geological and geophysical study into basement structure along Australia's southern rifted margin that addressed this issue and led to the identification of a previously unmapped crustal-scale basement shear zone (the Coorong Shear Zone) positioned along strike from the George V Fracture Zone (Fig. 1). This shear zone originally extended from SE Australia into the opposing Antarctic continental margin and serves both as an additional constraint on palaeogeographical reconstructions of the Australian and Antarctic conjugate rift margins and as an important test of existing models for continental breakup in which relative plate motion between Australia and Antarctica (Tikku & Cande 1999; Whittaker *et al*. 2007; Williams *et al*. 2011) does not always accord with the pattern and direction of extension deduced from the surrounding sedimentary basins (Norvick & Smith 2001; Krassay *et al*. 2004; Totterdell & Bradshaw 2004; Blevin & Cathro 2008). No less importantly, identification of this structure provides new insights into how pre-existing basement structure influenced the geometry of continental rifting and related fracture zone development along Australia's southern rift margin.

Basement units and tectonic elements in SE Australia

Continental rifting and the separation of Australia from Antarctica was a protracted process, commencing in the Middle to Late Jurassic and progressing from west to east through successive stages of crustal extension, basement-involved synrift faulting and thermal subsidence until the Cenozoic (Norvick & Smith 2001; Totterdell & Bradshaw 2004; Blevin & Cathro 2008). Pre-rift basement rocks disrupted during this process strike broadly north–south and encompass an older cratonic unit (Gawler Craton) bounded to the east by rocks of the early to mid-Palaeozoic Delamerian and Lachlan fold belts (Fig. 1).

Gawler Craton

This tectonic element was formerly contiguous with the Mawson Craton in Antarctica (Fig. 1) and comprises mainly supracrustal

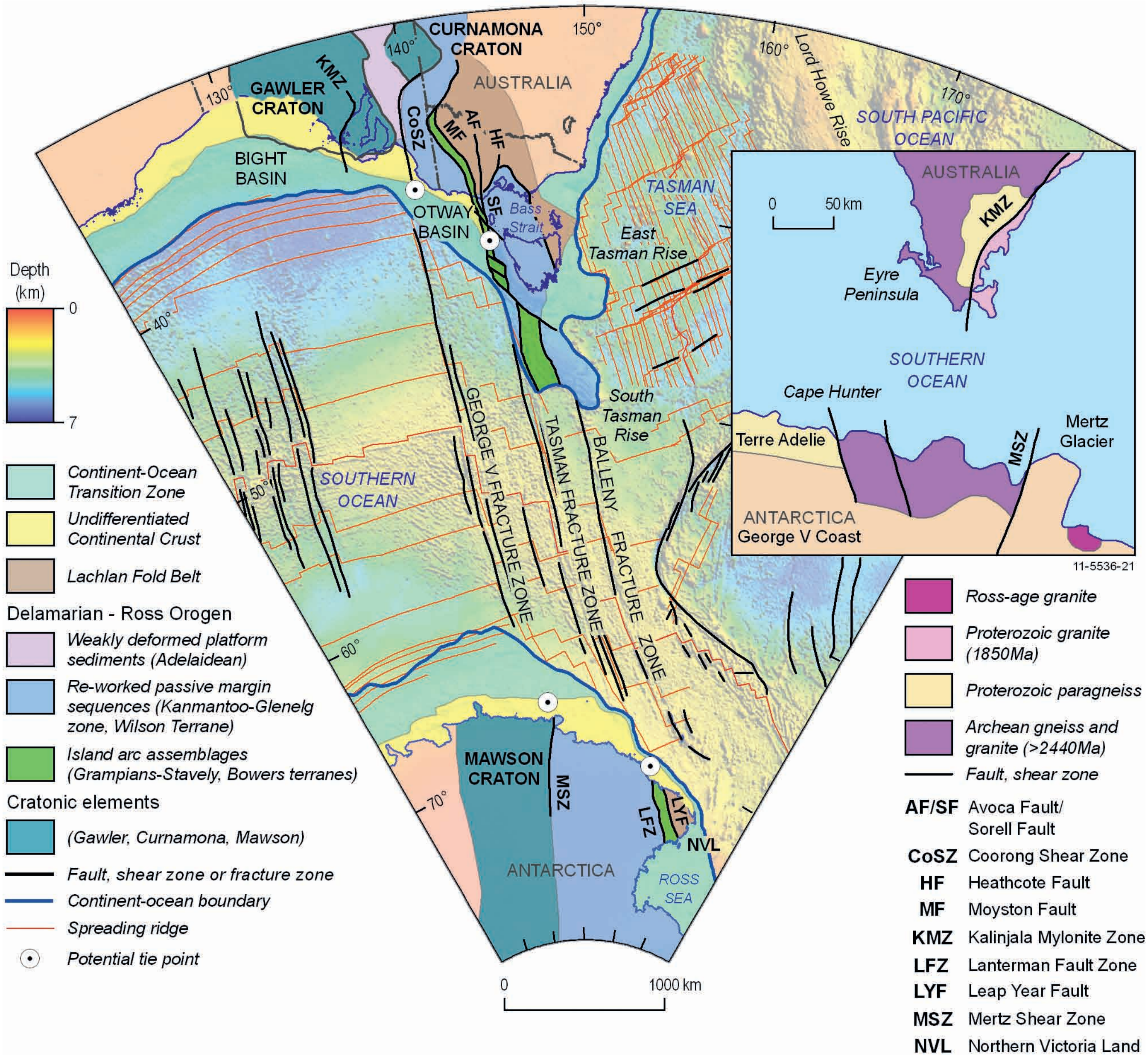

Fig. 1. Tectonic elements map for conjugate Australian and Antarctic continental margins showing major basement structures and geological units used in palaeogeographical reconstructions. Geological boundaries are adapted from several sources, including Cayley *et al*. (2002), Cowley (2006), Boger (2011) and Gibson *et al*. (2011). The significant width of the continent–ocean transition zone and adjacent expanse of submerged continental crust along each margin, which makes for considerable uncertainty in the reconstructions, should be noted. Inset shows previously proposed correlation between Kalinjala Mylonite Zone in South Australia and Mertz Shear Zone in Antarctica (modified after Di Vincenzo *et al*. 2007; Goodge & Fanning 2010).

rocks of Mesoarchaean to Mesoproterozoic age metamorphosed up to the granulite facies (Swain *et al*. 2005; Hand *et al*. 2007; Fraser *et al*. 2010; Szpunar *et al*. 2011; Reid & Hand 2012). Except for a few scattered localities, these rocks are not well exposed and mapping of their internal structure and boundaries relies heavily on interpretation of geophysical images derived from gravity and aeromagnetic data (Daly & Fanning 1993; Ferris *et al*. 2002; Cowley 2006). One such image is reproduced here (Fig. 2a) and shows the Gawler Craton cut by a dense network of faults and shear zones across which there are marked contrasts in magnetic character (Ferris *et al*. 2002). These faults and shear zones are of several different orientations and generations, some of which extend offshore all the way to the continental margin. They include: (1) east–west-striking structures (Fig. 2a), such as the 1590 Ma Yerda Shear Zone (Fraser & Lyons 2006), that were reactivated during the early stages of continental rifting and served as the northern limit of crustal extension and normal faulting in the Bight Basin (Stagg *et al*. 1992; Totterdell & Bradshaw 2004); (2) NW–SE-striking shear zones of late Palaeoproterozoic or younger age (Fig. 2a) that controlled intrusion of the 830 Ma Gairdner Dyke Swarm (Wingate *et al*. 1998) and whose earlier reactivation may also have influenced the overall trend of the co-located late Mesoproterozoic Carriewerloo Basin (Fig. 2b); (3) mylonitic and variably magnetized NE–SW-trending shear zones (Tallacootra, Karari and Coorabie shear zones; Fig. 2a) dating from *c*. 1450 Ma or earlier (Fraser & Lyons 2006); (4) north–south- to NNE–SSW-trending structures that

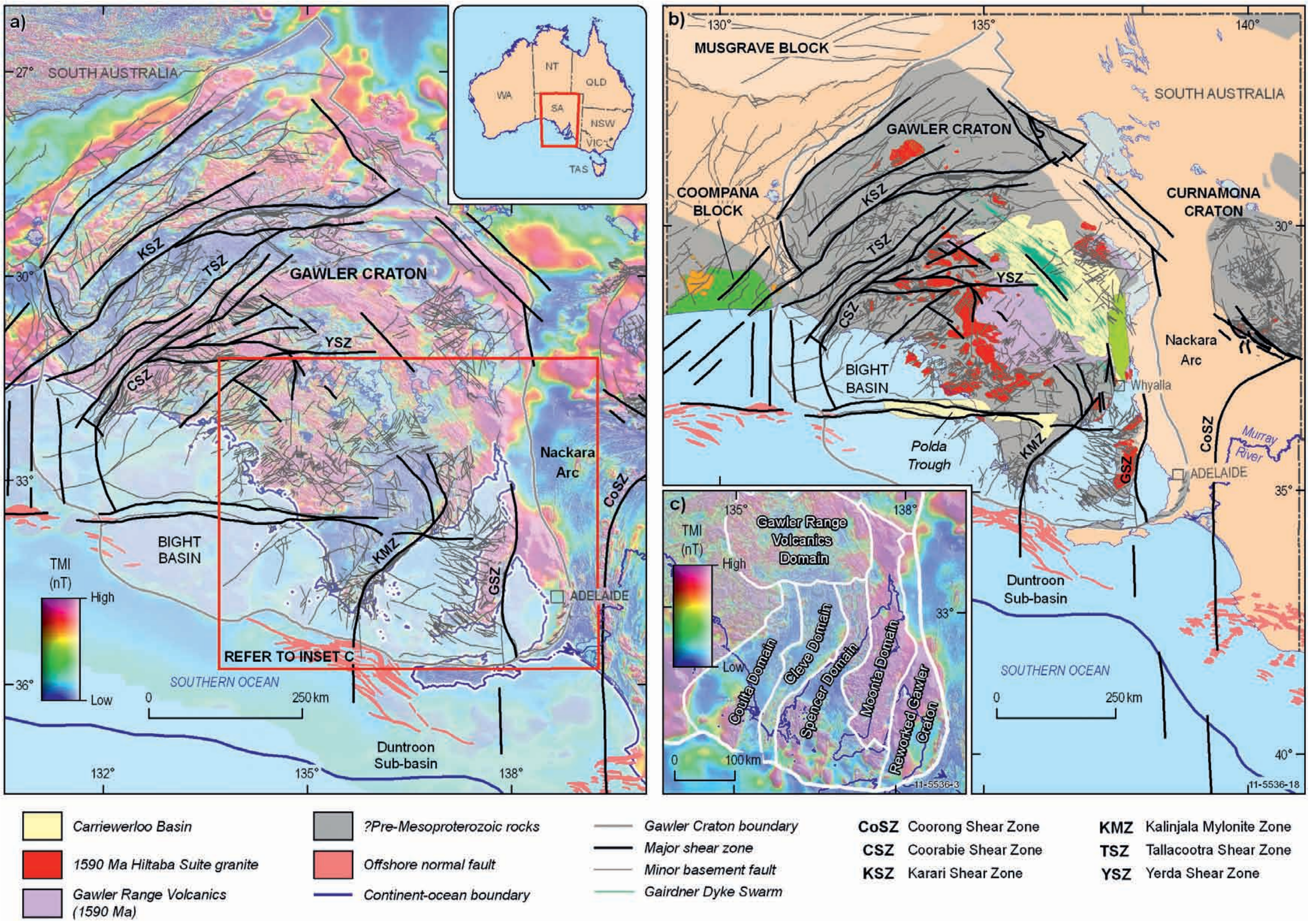

Fig. 2. (**a**) Total magnetic intensity image of Gawler Craton and environs with major faults and shear zones superimposed. (**b**) Geological map based on (**a**) showing major structural elements and fabrics, including the NW–SE-striking Mesoproterozoic Carriewerloo Basin and 830 Ma Gairdner Dyke Swarm. The predominance of NE–SW- and NW–SE-striking faults and shear zones in the west and north–south-striking structural elements in the east should be noted. Offshore normal faults in Bight Basin (bottom left) and Duntroon sub-basin (bottom) follow the same general trend as onshore basement structures in the adjacent craton. The boundary between the Cleve and Spencer magnetic domains in the south of the Gawler Craton (inset) corresponds to the Kalinjala Mylonite Zone in (**a**).

include the *c*. 300 km long Kalinjala Mylonite Zone (Parker 1980) and subdivide the southern part of the Gawler Craton into fault-bounded structural domains (Fig. 2b; inset). The Kalinjala Mylonite Zone originated during the 1740–1690 Ma Kimban Orogeny (Vassallo & Wilson 2002; Hand *et al*. 2007; Reid & Hand 2012) and is of particular interest here because it is one of the few major structures in southern Australia for which an Antarctic equivalent has previously been proposed (Mertz Shear Zone; Figs 1 and 3). It has recently been interpreted as a former subduction zone or palaeosuture (Betts & Giles 2006; Howard *et al*. 2006) and separates early Mesoarchaean–Palaeoproterozoic basement gneisses and granites in the east (Spencer Domain) from a younger Cleve Domain (Fig. 2b) in the west made up of Palaeoproterozoic metasedimentary rocks (Hutchison Group) overlying an older late Neoarchaean metasedimentary and volcanic succession deformed during the *c*. 2400 Ma Sleaford Orogeny (Parker 1980; Swain *et al*. 2005; Hand *et al*. 2007; Fraser *et al*. 2010).

Delamerian and Lachlan Fold Belts

The Cambro-Ordovician Delamerian Fold Belt (Fig. 1) is partially built on attenuated crust of the Gawler Craton and encompasses a multiply deformed Neoproterozoic continental platform sequence overlain in the east by an equally intensely deformed succession of late Neoproterozoic–early Cambrian, shallow- to deep-water clastic sediments and subordinate basaltic rocks represented by the Normanville and Kanmantoo Groups (Preiss 2000; Foden *et al*. 2006). Similarly reworked passive margin sequences make up much of the contemporaneous and formerly contiguous Ross Orogen in Antarctica (Fig. 1) and, in common with their Australian counterparts, preserve a comparable record of late Cambrian–earliest Ordovician high-temperature–low-pressure metamorphism accompanied by widespread granite magmatism (Stump *et al*. 1986; Borg & DePaolo 1991; Flottmann *et al*. 1993; Gibson *et al*. 2011).

Platform sequences of the Adelaide Supergroup are best preserved in the Nackara Arc (Fig. 2a) whereas the Kanmantoo Group and its correlatives make up the Kanmantoo–Glenelg zone and extend eastwards into western Victoria, where they are tectonically juxtaposed against the Grampians–Stavely terrane (Fig. 1). The Grampians–Stavely terrane incorporates remnants of an island arc–forearc assemblage (VandenBerg *et al*. 2000; Kemp 2003) and is bounded on the east by the Moyston Fault, long identified (VandenBerg *et al*. 2000) as the boundary between the Delamerian

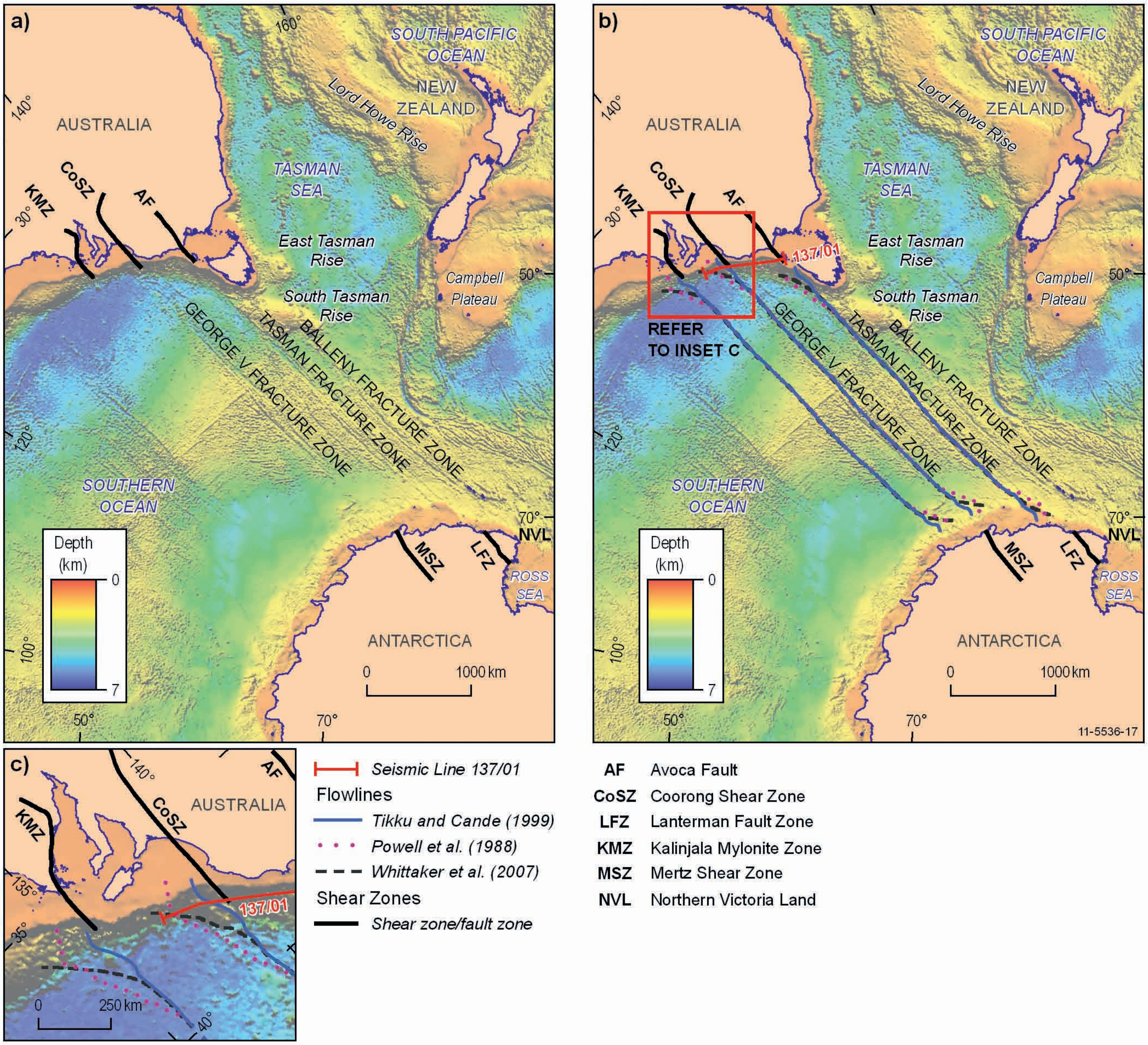

Fig. 3. (**a**) Bathymetric map of the Southern Ocean showing major fracture zones and their inferred along-strike basement equivalents in the adjacent Australian and Antarctic continents. (**b**) Flow lines show relative plate motion determined by various researchers for successive stages of rifting and crustal extension (adapted from Williams *et al*. 2011). The absence of a common plate vector during the earlier stages of rifting reflects differences in the assumed direction of extension prior to 47 Ma, at which time the north–south fracture zones began to develop. The red line shows the location of deep seismic reflection survey p137–01.

and Lachlan fold belts (Fig. 1). Rocks of the Lachlan Fold Belt were not deformed until mid-Palaeozoic time and comprise mainly deep-water, quartz-dominated turbidite sequences of Cambro-Ordovician age floored by older *c*. 500 Ma oceanic crust (VandenBerg *et al*. 2000; Squire *et al*. 2006). These turbidite sequences, together with the Grampians–Stavely terrane, extend offshore for some considerable distance and underlie much of the continental shelf off the west coast of Tasmania (Fig. 1). Weakly deformed quartz-rich turbidite sequences of comparable to slightly younger age occur widely in eastern Tasmania and northern Victoria Land east of the Leap Year Fault, and most probably represent a continuation of the Lachlan Fold Belt into these two regions (Fig. 1).

In contrast, the rocks of western Tasmania show greater affinity with the Delamerian Orogen (Fig. 1) and include a tectonically reworked Neoproterozoic–early Cambrian passive margin sequence overlying continental crust of Mesoproterozoic or older age (Berry *et al*. 1997, 2008; Meffre *et al*. 2000). Slices of mafic and ultramafic rock overlying this deformed passive margin sequence (not shown in Fig. 1), and bearing a striking resemblance to the island arc–forearc assemblage preserved in the Grampians–Stavely terrane farther west, have been interpreted as parts of a tectonically dismembered ophiolite complex (Crawford *et al*. 2003). However, neither this dismembered ophiolite nor the underlying passive margin sequence has any obvious physical connection to the rest of the Delamerian Fold Belt. Several faults and a strip of Lachlan Fold Belt intervene (Fig. 1). This has led several researchers to conclude that the rocks of western Tasmania represent an allochthonous crustal block that has been tectonically transported into its present position from elsewhere either through collision and accretion from the east (Cayley 2011) or through orogen-parallel strike-slip faulting from the south during the closing stages of the Delamerian Orogeny (Gibson *et al*. 2011). Irrespective of which interpretation is correct, the rocks of western Tasmania are clearly bounded in the west by the Sorell Fault, a reactivated early Palaeozoic basement structure whose along-strike onshore counterpart is the west-dipping Avoca Fault (Fig. 1).

The northern limits of the Tasmanian crustal block are unknown although deep seismic reflection data for the southern part of the Lachlan Fold Belt in central Victoria (Cayley *et al*. 2011) support the idea that rocks of Tasmanian affinity are not restricted to the region south of Bass Strait but continue northward in the subsurface for some significant distance beneath parts of southern Victoria (Fig. 1). The western limits of this buried Tasmanian crust (Selwyn Block) are defined by the west-dipping Heathcote Fault, which farther south terminates against the Avoca Fault, thereby juxtaposing rocks of the Delamerian Orogen directly against those of the younger Lachlan Fold Belt (Fig. 1). The Avoca Fault and its along-strike offshore equivalent (Sorell Fault) might therefore be expected to constitute a boundary of some considerable tectonic significance across which there was a commensurate and equally abrupt change in crustal rheology and mechanical behaviour at the time of continental breakup between Australia and Antarctica. No less importantly, from the perspective of this paper, is the observation that this crustal boundary merges southward into the Tasman Fracture Zone (Figs 1 and 3).

Geological setting of Tasman and George V fracture zones

The Tasman Fracture Zone is part transform boundary and evolved from a late Mesozoic–early Cenozoic intra-continental shear zone located above an even older reactivated Palaeozoic basement structure previously identified as the Woorndoo (Foster & Gleadow 1992) or Moyston Fault (Fig. 1; Hill *et al*. 1995; Miller *et al*. 2002) but interpreted here to be the Avoca–Sorell Fault Zone (Figs 1 and 3). Bathymetric images (Fig. 3) show various strands of this fracture zone continuing southward all the way to the ocean–continent boundary in Antarctica, where they assume a position directly along strike from two of the most important basement structures in northern Victoria Land, the steeply dipping Lanterman and Leap Year faults (Fig. 1). Both of these structures originated in the early Palaeozoic but have since been modified by several phases of later deformation, including an episode of strike-slip faulting in the Cenozoic that affected much of northern Victoria Land and has the same sense of dextral shear (Figs 1 and 3) as the Tasman Fracture Zone offshore (Salvini *et al*. 1997; Capponi *et al*. 1999; Rossetti *et al*. 2002; Kleinschmidt & Läufer 2006; Storti *et al*. 2007). The Lanterman Fault preserves an even earlier phase of late Cambrian–early Ordovician strike-slip faulting and now separates island arc rocks (Bowers terrane) from older continental crust to the west (Wilson terrane) (Weaver *et al*. 1984; Capponi *et al*. 1999; Gibson *et al*. 2011). It is has been widely interpreted as a former subduction zone or palaeosuture (Weaver *et al*. 1984; Gibson & Wright 1985; Rocchi *et al*. 1998; Tessensohn & Henjes-Kunst 2005), which, together with the Leap Year Fault farther east, is one of the principal structures along which the terranes of northern Victoria Land were assembled and accreted onto the east Gondwana margin (Weaver *et al*. 1984; Gibson & Wright 1985; Capponi *et al*. 1999; Tessensohn & Henjes-Kunst 2005).

The George V Fracture Zone is the most westerly of the large-offset, dextral fracture zones that span the entire Southern Ocean between SE Australia and Antarctica (Fig. 1) and marks a sharp break from east–west-trending, normally rifted continental margin between the Great Australian Bight and Terre Adélie–Wilkes Land in Antarctica and a generally NNW–SSE-oriented continental margin farther east (Fig. 3) in which oblique- and strike-slip segments developed between Tasmania and George V Land (Stagg & Reading 2007). It is no less prominent than the Tasman Fracture Zone but thus far no suggestion has ever been made that it too may be located along strike from a major reactivated basement structure in SE Australia. Published geological maps for this part of Australia (e.g. Cowley 2006) show no such basement structure, although the same cannot be said of Antarctica, where a 5 km wide mylonite zone (Mertz Shear Zone) separating late Archaean–Palaeoproterozoic cratonic basement from early Palaeozoic rocks of the Ross Orogen occurs directly along strike from this same fracture zone (Fig. 1; inset). However, its inferred correlative in South Australia is the late Palaeoproterozoic Kalinjala Mylonite Zone (Talarico & Kleinschmidt 2003; Di Vincenzo *et al*. 2007; Goodge & Fanning 2010) and lies much too far west to be collinear with the George V Fracture Zone. Published flow lines for relative plate motion (Fig. 3) between Australia and Antarctica (Powell *et al*. 1988; Tikku & Cande 1999; Williams *et al*. 2011) would also appear to be incompatible with this correlation.

The alternative is to argue for a different palaeogeographical reconstruction in which the Mertz Shear Zone is matched against a different structure in southern Australia. Possibilities include the Gawler Shear Zone and hitherto previously unmapped Coorong Shear Zone in the southern part of the Delamerian Fold Belt (Fig. 4). The Coorong structure occurs along strike from the George V Fracture Zone (Figs 1 and 3) and extends northwards as far as the Curnamona Craton (Fig. 1), where it overlaps a parallel, and presumably temporally related, structural discontinuity (Anabama–Redan Shear Zone) for which a Rodinia breakup age has been proposed (Preiss 2000). It would appear to be the more important structure but owing to little or no outcrop along its length, is best mapped and characterized through geophysical data (Fig. 4) and the interpretation of deep seismic reflection data collected across the structure offshore (Fig. 5). The Gawler Shear Zone is even less well exposed and lies wholly within the southern Gawler Craton (Figs 2 and 4), where it defines the western edge of a basement tilt block upon which shallow water shelf sediments (Ardrossan Shelf) were subsequently deposited (Belperio *et al*. 1998).

Geological and geophysical evidence for Coorong Shear Zone

Aeromagnetic signature of shear zone

Aeromagnetic data for the Coorong Shear Zone and surrounding region, including part of the adjacent continental shelf, are presented as an image in Figure 4. This image is a vertical derivative of the total magnetic intensity aimed at capturing 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. 4). To the west of this shear zone are inverted and tightly folded platform sequences of the Adelaide Supergroup (Nackara Arc) in which structural fabrics generally strike north–south to NNW–SSE, whereas to the east and south are even more intensely deformed rocks of the Kanmantoo Group and its correlatives in which structures trend NNE–SSW (Fig. 4). Cutting across this NNE–SSW fabric, and intruded into

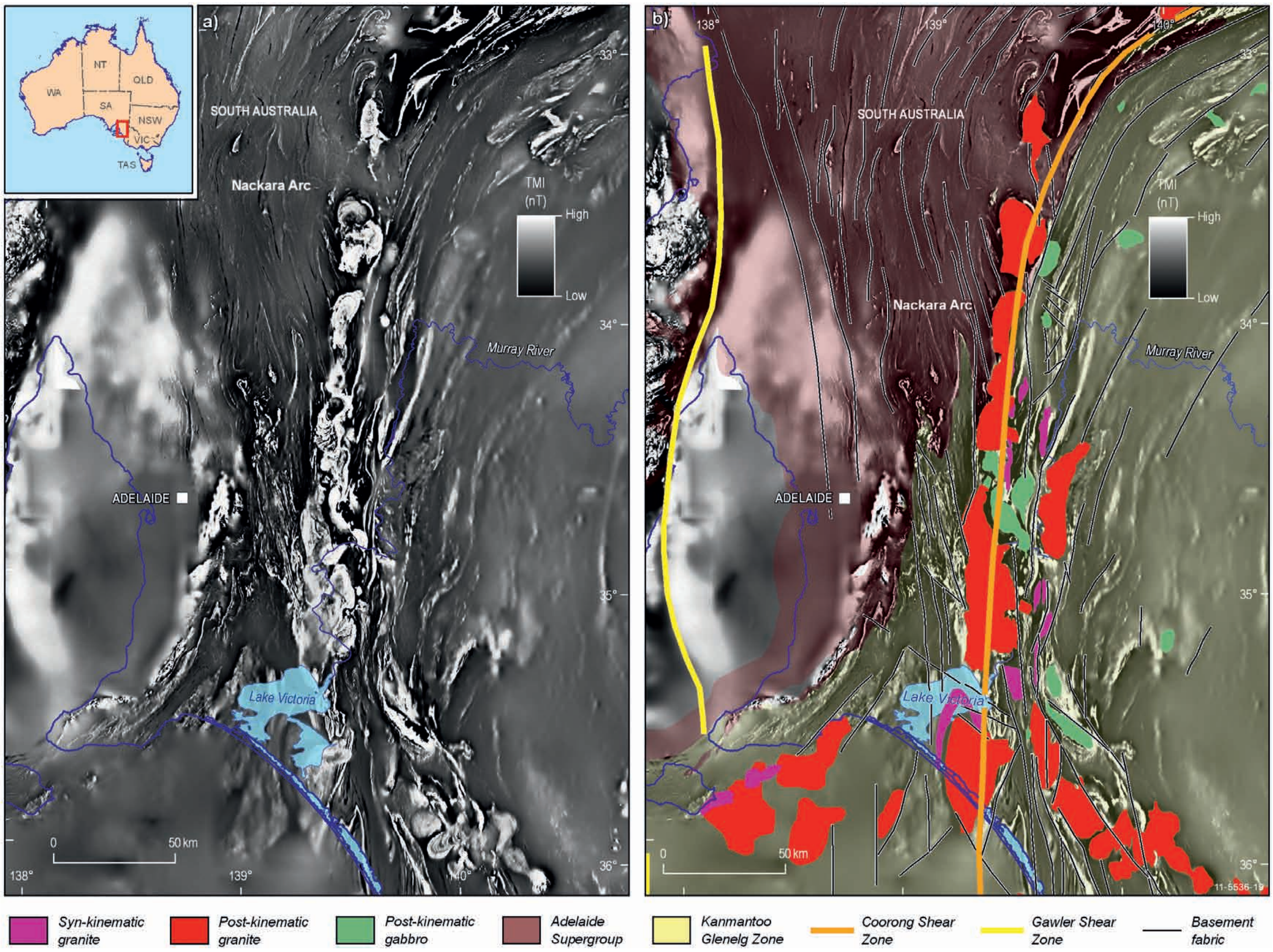

Fig. 4. (**a**) Uninterpreted and (**b**) interpreted aeromagnetic images (0.5 vertical derivative) of the Coorong Shear zone and immediately adjacent parts of the Delamerian Orogen. Concentrically zoned plutonic bodies intruded along the entire length of the shear zone and the differently oriented fabrics developed on either side of it should be noted. The ovoid anomaly bounded by the Gawler Shear Zone to the west of the Coorong structure corresponds to a basement block that has been rotated and downthrown to the west, and then buried beneath sediments of the Ardrossan Shelf.

the Kanmantoo Group and its correlatives, are variably magnetized post-kinematic granites and minor gabbro for which a late Cambrian–early Ordovician age has been determined (Foden *et al.* 2002*a*). Magmatic rocks of comparable age and magnetic character have also intruded along the Coorong structure itself (Fig. 4), indicating that this structure is no younger in age than late Cambrian–early Ordovician and served as a conduit for post-orogenic magmatic intrusion. Geochemical and isotopic data further indicate that the granites were sourced from the Kanmantoo Group, which evidently extends to considerable depth beneath this part of the Delamerian Fold Belt (Foden *et al.* 2002*a*,*b*).

In contrast, granites of post-Delamerian age are not widely developed west of the Coorong Shear Zone and none have been mapped in the Nackara Arc (Fig. 4). A few granite outcrops occur between the Coorong and Gawler shear zones farther south but they are hosted by the Kanmantoo Group (Belperio *et al.* 1998) and far removed from the linear belt of post-tectonic granites and subsidiary gabbro intruded along the Coorong structure (Fig. 4). Indeed, except for this one area, the Coorong Shear Zone would appear to serve not only as the western limit of late Cambrian–early Ordovician bimodal magmatism in the Delamerian Fold belt but also as an important crustal boundary within the original sedimentary basin across which there was an abrupt change from platform (Adelaide Supergroup, Normanville Group) to deeper water sedimentary facies (Kanmantoo Group). Early Cambrian mafic magmatism is similarly much more common east of the Coorong Shear Zone (Belperio *et al.* 1998), further supporting the idea that the Coorong Shear Zone is a much older inherited structure that first became active during deposition of the Kanmantoo Group.

Seismic imaging and vertical extent of Coorong Shear Zone

Seismic reflection data collected off the coast of southern Australia by Geoscience Australia (Fig. 3; line p137-01) 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 a significant thinning of the middle to lower crust (Fig. 5a). This structure has produced significant offsets in some of the more prominent horizons making up the Early Cretaceous synrift section of the Otway Basin, indicating some degree of reactivation at the time of basin formation (Fig. 5a). However, its more obvious attribute and defining feature is its steep to subvertical attitude (Fig. 5a). This attitude, combined with the considerable strike-length observed in

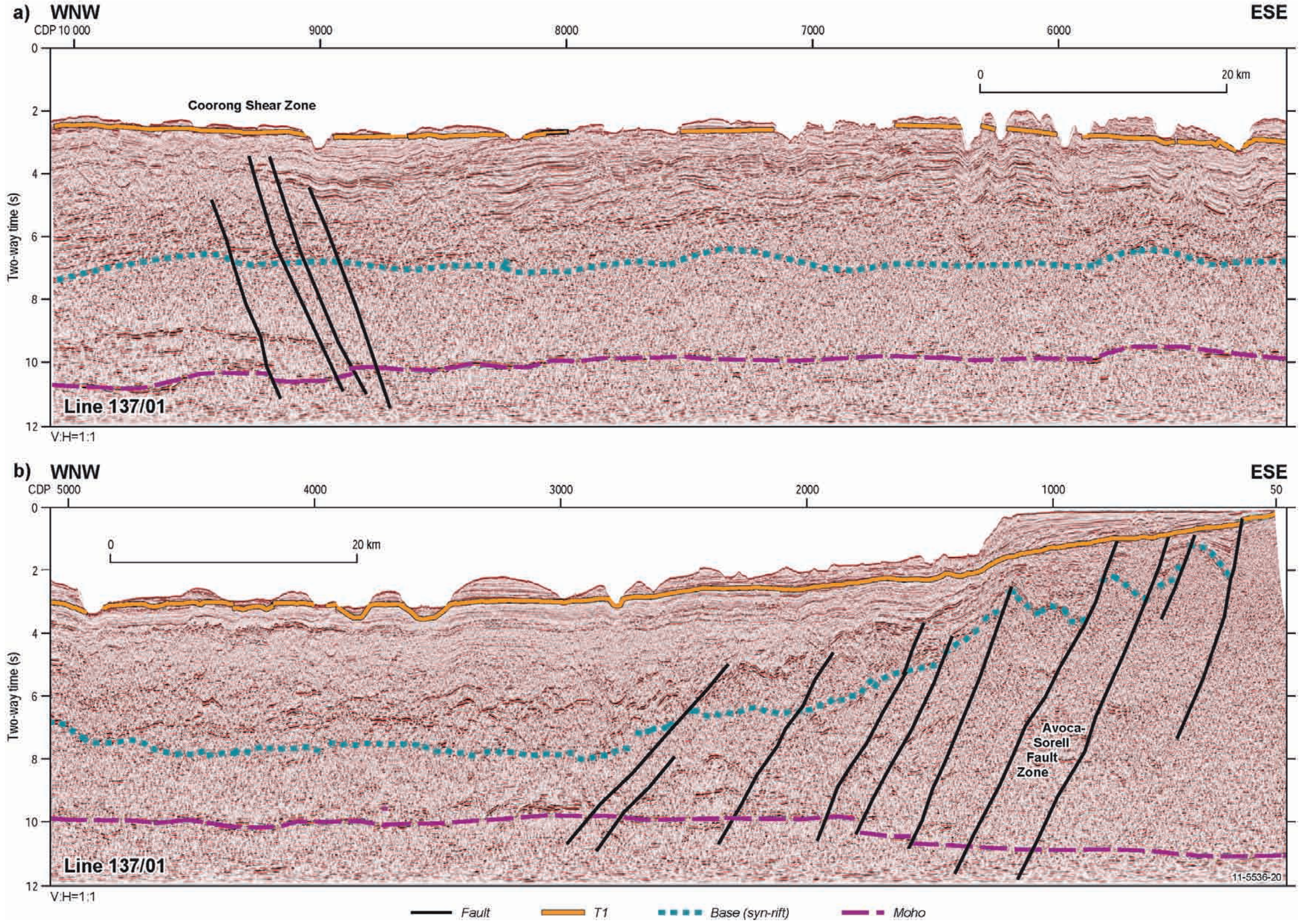

Fig. 5. Coorong and Avoca–Sorell shear zones captured in seismic reflection profile p137–01 oriented parallel to the Otway coast and orthogonal to structures of interest (for location of profile see Fig. 3). The thinning of the middle to lower crust beneath the deepest part of the sedimentary (Otway) basin should be noted. The basin profile and stratigraphic surfaces are constrained by additional unpublished seismic sections oriented at a high angle to p137–01.

the aeromagnetic image (Fig. 4), indicates that the Coorong Shear Zone is unlikely to be related to the west-vergent thrust faults identified by others (Flöttmann & Cockshell 1996) in earlier offshore seismic surveys conducted by the South Australian Department of Mines and Energy. These faults sole out at much shallower depths in the crust (Flöttmann & Cockshell 1996). The Coorong Shear Zone is an entirely separate structure, the vertical and lateral dimensions of which are more consistent with a strike-slip origin. In keeping with this interpretation, no single planar surface can be identified in the seismic data (Fig. 5a) and strain has instead been distributed over several parallel and subvertical structures as is expected of a major strike-slip shear zone. A strike-slip origin has already been proposed for the equally steep Anabama–Redan Fault in the northern part of the Delamerian Fold Belt (Preiss 2000).

Previous structural studies of the Delamerian Fold Belt have emphasized 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 *et al*. 1994; Flöttmann & James 1997). An east-dipping and downward-flattening basement ramp was thought to exist in this area along which there had been significant strain partitioning during and subsequent to sedimentary basin formation (Flöttmann *et al*. 1994; Belperio *et al*. 1998). However, if any such ramp or basement structure does indeed lie at depth beneath the Kanmantoo Group, it is not immediately obvious from the seismic section interpreted here (Fig. 5a), either because this structure does not extend sufficiently far eastward or because it steepens before reaching the Coorong Shear Zone. In either case, this basement ramp and the Coorong Shear Zone are not one and the same structure even though both would appear to date from the time of Rodinia breakup and both are rooted in basement beneath some of the highest grade and most intensely deformed metasedimentary rocks in the Delamerian Fold Belt.

Farther east, seismic line p137-01 (Fig. 3a) crosses a reactivated basement structure identified here and elsewhere (Gibson *et al*. 2011) as the Avoca–Sorell Fault Zone (Fig. 5b) and with which the Coorong Shear Zone might be usefully compared. The Avoca–Sorell Fault Zone shares the same steep dip as the Coorong Shear Zone and is associated with an even more pronounced step in the Moho, along with a corresponding increase in crustal thickness landward (Fig. 5b). This is accompanied at higher structural levels by a decrease in the thickness of the overlying Mesozoic sedimentary basin sequences (Fig. 5b). As with the Coorong Shear Zone, strain has been distributed across several different structures and the Avoca–Sorell Fault Zone cannot strictly be regarded as a single discrete subvertical structure (Fig. 5b). Both it and the Coorong Shear

Zone share a common north–south orientation and both are continuous along strike with prominent fracture zones (Tasman and George V fracture zones) that can be traced all the way to Antarctica (Fig. 3). However, whereas the Avoca–Sorell Fault Zone has an obvious correlative in either the Lanterman or Leap Year fault in northern Victoria Land (Fig. 1), the Coorong structure is best matched with the Mertz Shear Zone, which up till now has been regarded as a correlative of the Kalinjala Mylonite Zone (Talarico & Kleinschmidt 2003; Di Vincenzo *et al*. 2007; Goodge & Fanning 2010).

Correlation of Coorong and Mertz shear zones. Other than a few isolated outcrops of mylonite, the north–south-striking Mertz Shear Zone (Figs 1 and 3) is mainly known from well-documented differences in the age and geological history of rocks exposed on either side of the structure (Talarico & Kleinschmidt 2003; Ménot *et al*. 2007; Di Vincenzo *et al*. 2007; Goodge & Fanning 2010). Neoarchaean–Mesoproterozoic rocks exposed west of the shear zone (Fig. 1) are geologically indistinguishable from formerly contiguous parts of the Gawler Craton (Fitzsimons 2003; Goodge & Fanning 2010; Boger 2011) although neither they nor any of the mylonitic rocks preserve any record of Delamerian–Ross deformation and metamorphism (Di Vincenzo *et al*. 2007; Ménot *et al*. 2007). Reported $^{40}Ar/^{39}Ar$ cooling ages for these mylonitic rocks are 1500 Ma or older (Di Vincenzo *et al*. 2007). By way of comparison, rocks immediately east of the Mertz Shear Zone are host to a significant volume of Cambro-Ordovician granite (Fanning *et al*. 2002; Di Vincenzo *et al*. 2007; Goodge & Fanning 2010) and form part of the Delamerian–Ross Orogen (Fig. 1). An important crustal boundary of early Palaeozoic age evidently occurs in this region and would appear to be the Antarctic equivalent of the Coorong Shear Zone in that both structures mark or closely approximate the western limits of Delamerian–Ross orogenesis in their respective continental margins (Fig. 4). In contrast, the Kalinjala Mylonite Zone lies well to the west of the currently accepted limits of Delamerian-age magmatism and deformation in SE Australia based on geochronological as well as geological grounds (Swain *et al*. 2005).

Recently published *c*. 3150 Ma ages for gneissic granite in the Spencer Domain (Fraser *et al*. 2010) further indicate that basement of known Archaean age extends east of the Kalinjala Mylonite Zone and is of even greater antiquity than Neoarchaean crust exposed farther west in the neighbouring Cleve Domain (Fig. 2b). Unlike the Mertz Shear Zone, the Kalinjala Mylonite Zone is wholly entrained within older cratonic basement and for this reason might be better compared with a structure in Antarctica that is similarly bounded on either side by Archaean crust. The region west of the Mertz Shear Zone is host to several such structures (Fig. 1) and comprises Neoarchaean crust overlain by a late Palaeoproterozoic metasedimentary cover sequence whose record of 1700 Ma metamorphism and deformation followed by granite magmatism at 1590 Ma closely matches that of similar sequences in formerly adjacent parts of the Gawler Craton (Peucat *et al*. 2002, 1999; Ménot *et al*. 2005; Goodge & Fanning 2010). Equally significantly, this cover sequence and its inferred metasedimentary counterparts in the Gawler Craton yield near-identical Sm–Nd data and detrital zircon ages consistent with derivation of their protoliths from a source region with a common *c*. 3.2–3.1 Ga age (Oliver & Fanning 2002; Ménot *et al*. 2005). Either the Spencer Domain, along with its 3150 Ma granitic gneisses, was proximal to the metasedimentary sequences developed in both regions or rocks of Mesoarchaean age are more widely developed in Antarctica than existing geochronological data would suggest. In either case, geological reconstructions of the Australian and Antarctic margins (Talarico & Kleinschmidt 2003; Di Vincenzo *et al*. 2007; Goodge & Fanning 2010) based on matching the Kalinjala and Mertz shear zones are no longer likely to be tenable and produce an interpretation of continental rifting increasingly at odds with observed extensional basin geometries and continental fits based on other criteria such as ocean-floor fabrics and magnetic anomalies (e.g. Powell *et al*. 1988; Tikku & Cande 1999).

Reconstruction of the Australian–Antarctic margin

Several researchers have commented on the difficulties of reconciling reconstructions of the Australian and Antarctic continental margins based on ocean-floor fabrics and plate-tectonic considerations as opposed to geological grounds (Powell *et al*. 1988; Hill *et al*. 1995; Royer & Rollet 1997; Whittaker *et al*. 2007; Williams *et al*. 2011). Part of the problem stems from uncertainties in matching geological structures across ocean–continent transition zones for the two conjugate margins that are not only exceptionally wide in some places (Fig. 1) but also preserve little or no magnetic record of the direction of extension. Mismatches are particularly 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 were aligned with similarly verging basement-cored structures developed along the western margin of the Delamerian Fold Belt in SE Australia. Such reconstructions placed 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.

Later reconstructions (Royer & Rollet 1997; Hill & Exon 2004) avoided this problem by placing northern Victoria Land, along with formerly contiguous parts of the South Tasman Rise, much closer to Tasmania. This had the effect of aligning the Bowers and Grampians–Stavely terranes (Finn *et al*. 1999) whilst maintaining some connection between west-vergent, craton-directed structures in the Wilson terrane and relevant parts of SE Australia (Gibson & Nihill 1992; Flottmann *et al*. 1993, 1998). A recurrent problem with these more geologically constrained reconstructions was the amount of overlap between the different crustal elements farther east, including Tasmania and the South Tasman Rise (Tikku & Cande 1999, 2000).

More recently, other plate-tectonic reconstructions have been proposed in which the Australian plate is located farther east with respect to Antarctica (Whittaker *et al*. 2007; Williams *et al*. 2011). In these reconstructions, the Mertz Shear Zone is restored to a position between the Kalinjala Mylonite Zone and Coorong Shear Zone at 84 Ma (Fig. 6). Yet on geological grounds, an alignment of this shear zone with the Coorong structure might be expected. The Kalinjala Mylonite Zone lies some 300–350 km west of the Coorong structure (Figs 1–3), indicating that Antarctica, along with the Mertz Shear Zone, has been rotated too far west in these reconstructions. A westward shift of near-identical magnitude is also evident in reconstructions for the Lanterman Fault Zone which, at 84 Ma, should have restored to a position along strike from the Avoca (Sorell) Fault (Fig. 6).

This discrepancy in the relative lateral motion of Australia versus Antarctica has been raised before (Tikku & Direen 2008) and put down to differences in the choice of rotational (Euler) pole compared with some previous reconstructions (Tikku & Cande 1999, 2000). More specifically, Tikku & Direen (2008) argued that the *c*. 400 km westward shift in Antarctica could be eliminated from the Whittaker *et al*. (2007) reconstruction by adopting the previously proposed Tikku & Cande (2000) Euler pole along with the original fracture zone pick upon which this pole was calculated (compare Fig. 6c and d).

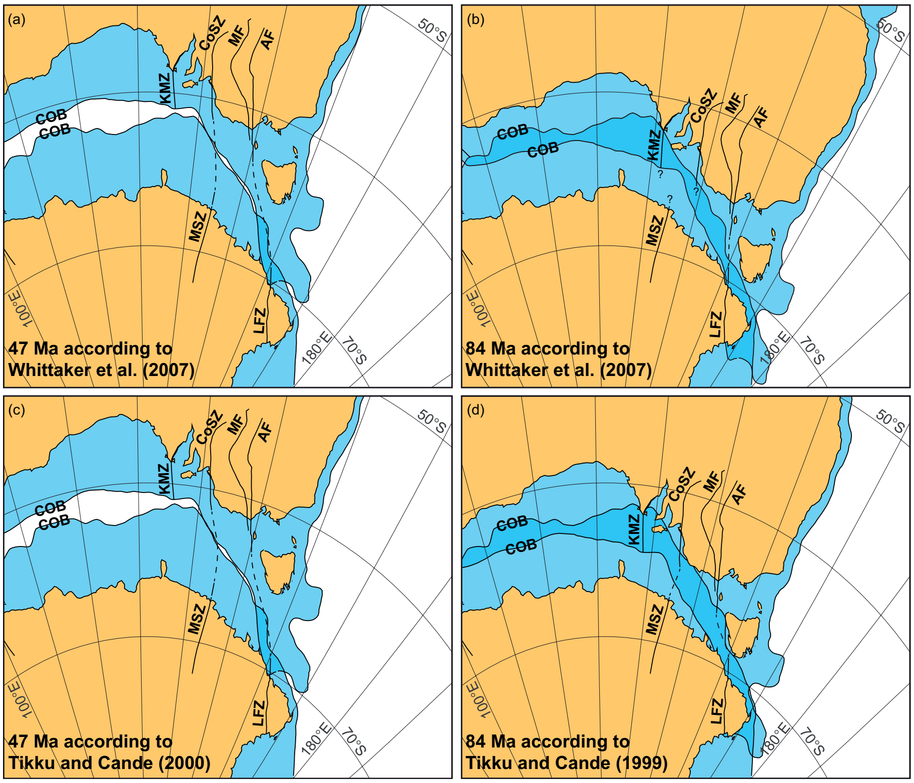

Fig. 6. Alternative reconstructions of the Australian and Antarctic conjugate margins showing restored positions of major basement structures at 47 Ma and 84 Ma based on the rotational poles for Australia obtained from (**a**, **b**) Whittaker *et al*. (2007) and (**c**, **d**) Tikku & Cande (1999, 2000). In each restoration, Australia is rotated relative to an arbitrarily fixed Antarctic plate. At 47 Ma, the reconstructions are essentially the same (**a**, **c**) and position the Coorong Shear Zone (CoSZ) opposite the Mertz Shear Zone (MSZ) with the Avoca Fault (AF) conjugate to the Lanterman Fault Zone (LFZ). At 84 Ma, the two reconstructions are considerably different (**b**, **d**). The Whittaker *et al*. (2007) rotational pole produces a reconstruction (**b**) in which the MSZ could be conjugate to either the CoSZ or the Kalinjala Mylonite Zone (KMZ) whereas the Tikku & Cande (1999) rotational pole of at 84 Ma (**d**) secures a good fit between the MSZ and the CoSZ, and the LFZ and AF. The Moyston Fault (MF) and continent–ocean boundary (COB) for each plate are also shown. These reconstructions were created with the Pplates tectonic reconstruction software developed at The Australian National University (http://rses.anu.edu.au/tectonics/projects/p-plates/). Euler pole ages were adjusted according to the internationally agreed geological time scale (Gradstein *et al*. 2004).

Tikku & Cande (2000; see also Tikku & Cande 1999) matched the Leeuwin (Perth) fracture zone (Australia) with the Vincennes fracture zone (Antarctica) whereas Whittaker *et al*. (2007) matched the Leeuwin and Perth South fracture zones. However, even where preference is given to the former, problems persist as shown by the reconstruction of Williams *et al*. (2011) in which Antarctica is rotated even farther west with respect to Australia.

The Whittaker *et al*. (2007) and Williams *et al*. (2011) reconstructions are both based on the premise that crustal extension barely deviated from its initial NW–SE or NNW–SSE trajectory during the earlier stages of rifting before assuming a north–south azimuth in the Cenozoic (Fig. 3). Seismic and sequence stratigraphic studies along Australia's southern margin (Norvick & Smith 2001; Krassay *et al*. 2004; Totterdell & Bradshaw 2004; Blevin & Cathro 2008) indicate that this assumption is unwarranted and point to a more complicated record of rifting wherein NW–SE or NNW–SSE extension in the Bight Basin was superseded by NNE–SSW extension in the Otway Basin during the latest Tithonian (*c*. 145 Ma). Basin architecture and observed patterns of normal faulting along Australia's southern margin are more in accord with this more complicated history of rifting and serve to emphasize the importance of basement structure and the role structural inheritance played in determining the location and geometry of continental breakup.

Discussion and conclusions

As with most other rifted continental margins, Australia's southern margin is segmented and subject to marked changes in orientation along strike (Figs 1 and 3). These changes are manifest in both the shelf-break and more distal continent–ocean boundary, and find maximum expression in the prominent re-entrant developed off western Tasmania, where the continental margin undergoes an abrupt change of strike from NW–SE to north–south across the Tasman Fracture Zone (Figs 1 and 3). This fracture zone is continuous along strike with the Avoca–Sorell Fault Zone, which was not only optimally oriented for reactivation as a transform boundary during north–south rifting (Hill *et al*. 1995; Gibson *et al*. 2011) but also represents the boundary (Fig. 1) between basement blocks of contrasting rheology as reflected in their very different origins and crustal histories. More specifically, whereas rocks to the west of this boundary belong to the Lachlan Fold Belt and comprise mainly rheologically weaker, Cambrian–Ordovician turbidites floored by oceanic crust, western Tasmania on the other side of the Avoca–Sorell Fault Zone is predominantly made up of mechanically stronger Precambrian cratonic basement overlain by reworked Neoproterozoic–early Palaeozoic cover rocks (Fig. 1). An analogous transform margin and re-entrant in the Gulf of Guinea off west Africa have similarly been interpreted in terms of pre-existing basement structure and reduced mechanical strength inherited from rocks tectonically reworked between two more rigid crustal blocks during an earlier deformational event (Benkhelil *et al*. 1995; Mascle *et al*. 1997).

In contrast, no re-entrant or transform boundary developed in the vicinity of the Coorong Shear Zone despite its north–south orientation and many other similarities to the Avoca–Sorell Fault Zone. Some other limiting factor would seem to be involved. One possibility is that the Coorong Shear Zone is stitched along nearly its entire length by post-kinematic magmatic intrusions (Fig. 4) whose emplacement inhibited future reactivation because any inherited structural anisotropy or pre-existing crustal weakness was removed or at least significantly reduced. However, if this were the case, it is difficult to see how this structure could have influenced the location and development of the George V Fracture Zone along strike to the south (Figs 1 and 3), let alone have any bearing on later rifting and margin geometry.

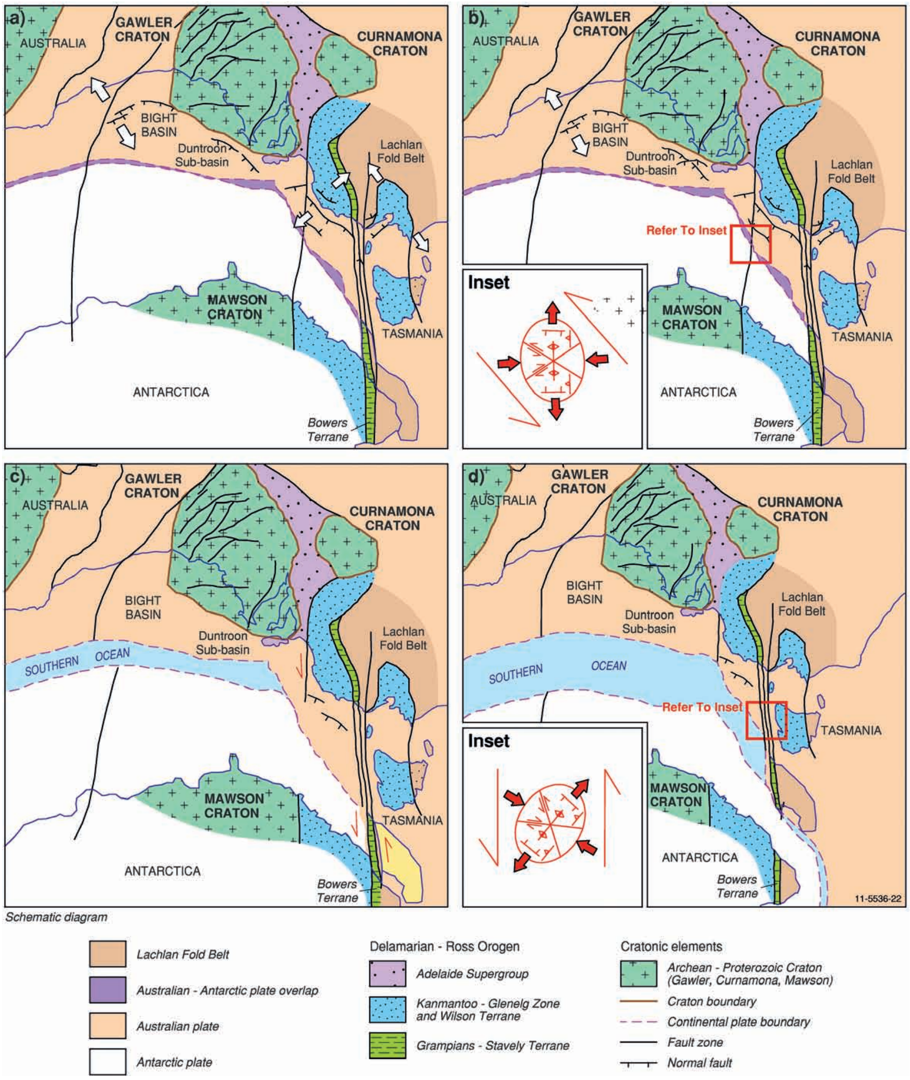

Fig. 7. Simplified representation of continental breakup between Australia and Antarctica, showing how differently oriented basement structures may have been reactivated during successive stages of rifting and crustal extension: (**a**) Late Jurassic–Early Cretaceous; (**b**) Early Cretaceous with NW-SE-directed extension in Bight Basin and onset of intracontinental shearing between Australia and Antarctica; (**c**) Late Cretaceous and NNE–SSW-directed extension leading to reactivation of north–south-striking Palaeozoic basement structures, including Coorong and Avoca–Sorell shear zones; (**d**) Early Cenozoic and onset of north–south rifting with formation of ocean–continent transform boundary off western Tasmania and South Tasman Rise. Insets show anticipated sense of displacement on reactivated basement structures in regions dominated by transform faulting during different stages of rifting.

Yet this structure was clearly an important boundary during rifting and ensuing continental breakup because late Jurassic–Early Cretaceous normal faults and half-graben in the Bight and Otway basins on either side of the structure show very different orientations and formed under different extensional regimes. Extensional structures in the Bight Basin mainly formed in response to NW–SE- or NNW–SSE-directed crustal extension and typically strike west–east or NE–SW (Norvick & Smith 2001; Bradshaw *et al*. 2003; Totterdell & Bradshaw 2004; Blevin & Cathro 2008), parallel to basement structures in the adjacent Gawler Craton (e.g. Tallacootra and Karari shear zones), which were presumably favourably oriented for reactivation through tensile failure or left-lateral shear (Fig. 7a and b). In contrast, normal faults and half-graben in the western Otway Basin dominantly strike NW–SE and formed in response to NNE–SSW-directed extension (Krassay *et al*. 2004; Blevin & Cathro 2008). Basement control on the orientation of these structures is not immediately obvious, although it has long been speculated that rocks of the Gawler Craton occur at depth beneath this region, albeit in highly attenuated form following breakup of the Rodinia supercontinent (Preiss 2000; Teasdale *et al*. 2003). It may therefore be the case that basement beneath the western Otway Basin shares a similar history of fault reactivation to other parts of the eastern Gawler Craton, including repeat movements on NW–SE-trending structures that occurred both before and during rifting along Australia's southern margin. In either event, it is difficult to escape the conclusion that extensional strain has been compartmentalized or partitioned across the Coorong Shear Zone so as to produce opposing fault geometries in extensional basins that appear not too dissimilar in age. A late Callovian–earliest Berriasian (160–140 Ma) age is generally accepted for early crustal extension in the Bight Basin (Totterdell & Bradshaw 2004) whereas extensional structures in the western Otway Basin date back to the latest Jurassic–Early Cretaceous (145–125 Ma) (Norvick & Smith 2001; Krassay *et al*. 2004; Blevin & Cathro 2008). Significantly, this same age pattern and geometry is observed in extensional structures on either side of the Avoca–Sorell Fault Zone (Fig. 7a), consistent with the observation made repeatedly here that these two structures share many similarities, including near-vertical attitudes and an origin that involved strike-slip faulting at a continental scale during and subsequent to the Delamerian–Ross Orogeny (Fig. 5).

As formerly contiguous parts of the same fold belt, the Delamerian and Ross orogens preserve a common record of Neoproterozoic continental breakup and passive margin formation followed by plate convergence, arc–continent collision and strike-slip faulting in the Cambro-Ordovician (Weaver *et al*. 1984; Rossetti *et al*. 2002; Tessensohn & Henjes-Kunst 2005; Gibson *et al*. 2011). The Coorong and Avoca–Sorell fault zones both date from the closing stages of orogenesis and, from seismic reflection data, are clearly deep-rooted, extending downward all the way to the Moho (Fig. 5). Moreover, given their considerable strike-lengths, there is no reason to believe that either structure terminates in the deep crust and does not continue downward into the underlying lithospheric mantle. Teleseismic tomography studies (Rawlinson *et al*. 2011) support such an interpretation and reveal significant changes in mantle P-wave velocities across discontinuities near the base of the lithosphere (150 km) that could represent 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 Palaeozoic 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 ($92 \pm 10\,\mathrm{mW\,m^{-2}}$) 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 Mesoarchaean age (Fraser *et al*. 2010; Neumann *et al*. 2000). 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. 6). 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 also during 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 that some pre-existing thermal weakness may also have helped localize deformation along this structure in Antarctica (Talarico & Kleinschmidt 2003; Di Vincenzo *et al*. 2007; Goodge & Fanning 2010).

Some researchers (Willcox & Stagg 1990; Norvick & Smith 2001) have argued that early rifting between Australia and Antarctica was largely accommodated by *c*. 300 km of left-lateral displacement on a NW–SE-trending continental transform fault that extended all the way from the Bight Basin to the South Tasman Rise (Fig. 7b). Basement terranes in the western part of the South Tasman Rise are commonly offset in a sinistral sense (Fig. 1), consistent with development of such a transform fault, although the amount of displacement on single structures is significantly less than the predicted 300 km and could just as easily have occurred during later strike-slip faulting accompanying reactivation of the Avoca–Sorell Fault Zone (Fig. 7c and d). The second interpretation is preferred here in keeping with the proposition that the western part of the South Tasman Rise originally lay farther north and was not transported into its present position against the rest of the terrane until *c*. 55 Ma (Hill & Exon 2004). Prior to that time, the western part of the South Tasman Rise formed part of the Antarctic rather than Australian plate (Royer & Rollet 1997; Hill & Exon 2004) and so any strike-slip faulting along the nascent Tasman Fracture Zone by which the two parts of the South Tasman Rise were juxtaposed would have to occurred later and thus post-date any postulated early transform faulting between Australia and Antarctica. This is not to say that early transform faulting did not occur but that its influence may have been more localized than previously thought and confined for the most part to the Bight Basin and adjacent Duntroon Sub-basin whose orientation and narrow, elongate character are at least consistent with formation of a depocentre located at the releasing bend of a NW–SE-trending continental transform fault as in northern Anatolia (Aksu *et al*. 2000).

Notwithstanding such caveats, sea-floor spreading in the Bight Basin commenced no later than 83 Ma (Sayers *et al*. 2001) and by *c*. 47 Ma had seemingly failed to propagate any farther east because no oceanic crust older than this is known to occur off the Otway Basin (Norvick & Smith 2001; Whittaker *et al*. 2007). The first oceanic crust and fabrics to form in this region did not eventuate until well after the onset of north–south rifting at 67 Ma (Krassay *et al*. 2004) or 61 Ma (Tikku & Cande 1999), and some 35–40 Myr after sea-floor spreading commenced in the Bight Basin. The most likely explanation for this hiatus from the point of view of this paper is that sea-floor spreading had stalled against a major basement structure represented by the Coorong Shear Zone. Following subsequent breaching of this structure, the locus and pattern of ocean-floor fabric development abruptly changed and the spreading axis underwent a succession of short, right-lateral jumps eastward along the margin, coincidently bringing about a change in the orientation of this margin from east–west to NW–SE (Figs 1 and 3). However, immediately prior to this stage of continental breakup and eastward shift in spreading, the Coorong Shear Zone lay directly opposite the Mertz Shear Zone (Fig. 6a), either because these two structures had remained contiguous throughout the earlier stages of rifting or because any offset induced by initial NW–SE-directed extension had been restored during later NNE–SSW rifting (Fig. 3b). Irrespective of which interpretation is correct, fracture zone development in the Southern Ocean off the Otway Basin is not uniformly distributed but reaches its maximum expression and intensity directly along strike from the Coorong and Avoca–Sorell fault zones (Figs 1 and 3), indicating some form of basement control. This in turn would imply that not all fracture zones develop spontaneously (Stoddard & Stein 1988; Taylor *et al*. 2009), but owe their location and origin to the existence of appropriately oriented pre-existing basement structures that are rooted in the deep crust and lithospheric mantle.

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