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Nicholas G. Direen, Howard M. J. Stagg, Philip A. Symonds and Ian O. Norton

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Notes

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NICHOLAS G. DIREEN[1,2]*, HOWARD M. J. STAGG[3], PHILIP A. SYMONDS[4] & IAN O. NORTON[5]

[1]*Institute for Marine and Antarctic Studies, and School of Earth Sciences, University of Tasmania, TAS 7001, Australia*

[2]*FrOG Tech Pty Ltd, Blackmans Bay, TAS 7052, Australia*

[3]*Retired, Canberra, ACT2601, Australia*

[4]*Geoscience Australia, Canberra, ACT 2601, Australia*

[5]*Jackson School of Geosciences, Institute for Geophysics, University of Texas at Austin, TX 78758-4445, USA*

**Corresponding author (e-mail: n_direen@utas.edu.au)*

Abstract: We present a synthesis based on the interpretation of two pairs of deep seismic reflection crustal sections within the Southern Rift System (SRS) separating Australia and Antarctica. One pair of sections is from the conjugate margins between the Great Australian Bight (GAB) and Wilkes Land, in the central sector of the SRS, which broke up in the Campanian. The second pair of conjugate sections is located approximately 400 km further east, between the Otway Basin and Terre Adélie, which probably broke up in Maastrichtian time. Interpretations are based on an integrated synthesis of deep multi-channel seismic, gravity and magnetic data, together with sparse sonobuoy and dredging information, and the conjugate sections are presented with the oceanic crust removed beyond the continent–ocean boundary (COB).

At first order, both conjugate pairs show a transition from thinned continental crust, through a wide and internally complex continent–ocean transition zone (COTZ), which shows features in common with magma-poor rifted margins worldwide, such as basement ridges interpreted as exhumed subcontinental mantle. In the central GAB sector, the COTZ is symmetric around the point of break-up and displays a pair of mantle ridges, one on each margin, outboard of which lies a deep-water rift basin. Break-up has occurred in the centre of this basin in this sector of the SRS. In contrast, the Terre Adélie margin is nearly 600 km wide and shows an abandoned crustal megaboudin, the Adélie Rift Block. This block is underlain by interpreted middle crust, and appears to have a mantle ridge structure inboard, as well as an outboard exhumed mantle complex from which mylonitized harzburgite has been dredged. The conjugate margin of the Beachport Sub-basin is relatively narrow (*c.* 100 km wide) and does not appear to contain an exhumed mantle ridge, as observed along strike in the GAB.

These observations from a single rift spreading compartment show that radically different break-up symmetries and margin architectures can result from an essentially symmetric rifting process involving multiple, paired detachment systems. This indicates the need for caution in interpreting causative mechanisms of rifting from limited conjugate sections in other rifts. We speculate that the underlying crustal composition, rheology and structural preconditioning play a significant role in partitioning strain during the transition to break-up.

As highlighted by Manatschal *et al.* (2009), research into the formation of continental rifted margins is currently undergoing a paradigm shift, driven by the discovery of exhumed continental mantle in many margins worldwide, but particularly in the North Atlantic (e.g. Boillot *et al.* 1980; Manatschal 2004; Müntener & Manatschal 2006; Péron-Pinvidic *et al.* 2007; Reston & Pérez-Gussinyé 2007; Sibuet *et al.* 2007; Crosby *et al.* 2008; Péron-Pinvidic & Manatschal 2009; Reston 2009; van Avendonk *et al.* 2009). Undoubtedly, the intensive study of the Iberian rifted margin and its Newfoundland conjugate (e.g. Péron-Pinvidic *et al.* 2007; van Avendonk *et al.* 2009), especially through multiple Ocean Drilling Program (ODP) drilling legs (e.g. Boillot *et al.* 1985; Whitmarsh *et al.* 1998; Tucholke & Sibuet 2007), together with deep seismic reflection and refraction acquisition (e.g. Pickup *et al.* 1996; Sawyer *et al.* 1997; Funck *et al.* 2004; Henning

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et al. 2004; Hopper *et al.* 2004; Lau *et al.* 2006*a*, *b*), has led to major advances in the understanding of rifting and break-up processes in magma-poor continental margins.

These types of margins are defined by a range of features, such as a wide continent–ocean transition zone (COTZ – defined below), unroofed mantle peridotite rocks exposed at the palaeo-sea floor, relatively flat-lying, serpentinized detachment faults and low volumes of magmatic rocks (Boillot & Froitzheim 2001; Whitmarsh *et al.* 2001; Huismans & Beaumont 2011). These defining features have been reinforced by data from field studies of analogue sites in the Alps (e.g. Manatschal 2004; Manatschal *et al.* 2009) and numerical modelling (e.g. Lavier & Manatschal 2006; Harry & Grandell 2007; Huismans & Beaumont 2007).

However, study of other magma-poor margins worldwide (e.g. Aslanian *et al.* 2009; Direen *et al.* 2011) has revealed anomalous observations that do not fit either within the older paradigms for continental rifting (e.g. McKenzie 1978; Wernicke 1985; Lister *et al.* 1986, 1991) nor easily with the new concepts developed from Iberia–Newfoundland and their Alpine analogues. In particular, some sections from the Southern Rift System, the Mesozoic rift between Australia and Antarctica (Stagg *et al.* 1990), display a pronounced – but not ubiquitous – symmetry, and spatially variable evidence for mantle exhumation to the sea floor, as recently highlighted by Direen *et al.* (2007, 2011).

In this paper, we review two pairs of approximately conjugate sections from the central sector of the Southern Rift System that show a high variance in conjugate margin symmetry. In doing so, we aim to highlight the major differences in mechanical behaviour that can arise even in a single rift spreading compartment and, therefore, urge a degree of caution in the interpretation of underlying rifting mechanisms based on single conjugate pairs of sections.

In the ensuing discussion, we follow Colwell *et al.* (2006) in defining two terms that are often used confusingly in studies of rifted continental margins:

- *continent–ocean transition zone* (COTZ): a region on the continental margin that lies between the outboard edge of highly attenuated, unequivocal continental crust, and the inboard edge of unequivocal oceanic crust. The COTZ includes both sedimentary and magmatic components in proportions that vary both along and across the margin, and may include areas of failed sea-floor spreading. Note that this definition is similar, but not identical, to the term *ocean–continent transition* (OCT) as used by Manatschal (2004, p. 439) for 'the transition from the distal continental margin to the first oceanic crust'.
- *Continent–ocean boundary* (COB): this marks the inboard edge of unequivocal oceanic crust.

Study area

The Southern Rift System (SRS: Fig. 1) was defined by Stagg *et al.* (1990), and encompasses the broad zone affected by Jurassic–Tertiary rifting and oceanic spreading along the southern margin of Australia. The definition was later expanded to include the Antarctic conjugate margin (Stagg *et al.* 2005; Direen *et al.* 2011). The SRS extends for approximately 4000 km, between Broken Ridge and Naturaliste Plateau in the Indian Ocean, to the South Tasman Rise on the Australian–Indian Plate; and as far west as the Bruce Rise, the southern Kerguelen Plateau and the Williams Ridge, and east to the Balleny Fracture Zone on the Antarctic Plate.

The SRS formed during the break-up of Mesozoic east Gondwana, by the separation of Australia and Antarctica (Willcox 1990; Willcox & Stagg 1990; Sayers *et al.* 2001). From the Middle Jurassic, the proto-Southern Rift System was undergoing mechanical extension with syn-rift sequence deposition (Totterdell *et al.* 2000; Norvick & Smith 2001). Continued extension during the Cretaceous led to break-up (Sayers *et al.* 2001), with postulated spreading ridge propagation from west to east (Mutter *et al.* 1985) but with very slow initial oceanic spreading (Cande & Mutter 1982; Sayers *et al.* 2001). This produced a diachronous break-up (Mutter *et al.* 1985) with different initial spreading ages recorded in various compartments within the rift (Sayers *et al.* 2001; Stagg *et al.* 2005, 2006; Tikku & Direen 2008; Direen 2012), and the spreading ridge itself cut by numerous transform fracture zones (Figs 2 & 3). Although some authors have suggested mostly synchronous break-up around 85–83 Ma (Santonian: e.g. Whittaker *et al.* 2007: and Fig. 3b after Müller *et al.* 2008), at the western end of the SRS, south of Naturaliste Plateau, break-up is recorded at approximately 93–87 Ma (Turonian–Coniacian: Chatin *et al.* 1998; Beslier *et al.* 2004; Halpin *et al.* 2008). In the Bremer Basin, break-up is inferred from a regional Turonian unconformity and Ar/Ar dating of break-up-related volcanics to have occurred at around 91 Ma (Blevin & Cathro 2008). In the central Great Australian Bight and conjugate Wilkes Land area, break-up is interpreted from analysis of magnetic spreading anomalies to have occurred from 83 Ma (Santonian) to potentially as young as 71 Ma (Campanian) (Sayers *et al.* 2001; Tikku & Direen 2008). In the Otway–Bass–Sorell basin margins, conjugate to

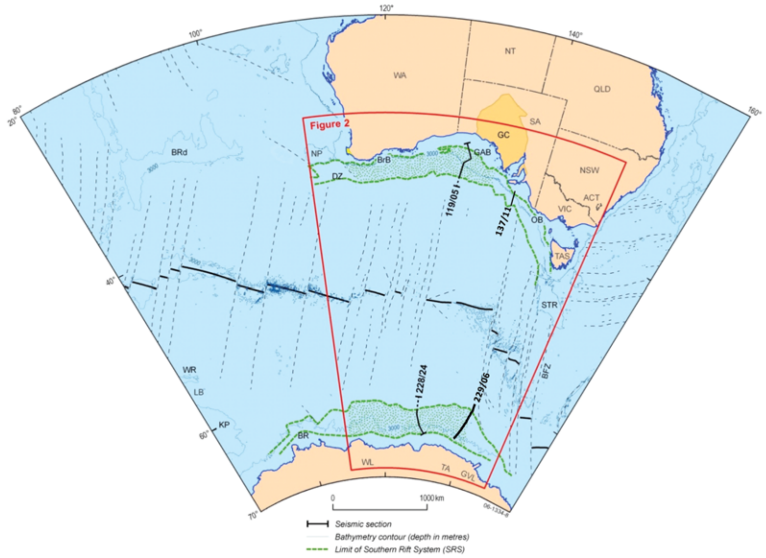


Fig. 1. Regional tectonic elements of the Southern Rift System, after Direen *et al.* (2011), showing the location of interpreted reflection seismic and potential field profiles; portions of these profiles on oceanic crust are shown dashed. The 3000 m bathymetric contour is shown to highlight the general form of the continental margins, as well as the Southeast Indian Ridge (shown by the heavy black line) and other major bathymetric features. Stippling within the Southern Rift System indicates the approximate area of the symmetrical part of the extensional system. Major oceanic fracture zones shown dashed. Abbreviations: BRd, Broken Ridge; NP, Naturaliste Plateau; DZ, Diamantina Zone; BrB, Bremer Basin; GAB, Great Australian Bight; GC, Gawler Craton; OB, Otway Basin; STR, South Tasman Rise; BFZ, Balleny Fracture Zone; WR, Williams Ridge; LB, Labuan Basin; KP, (southern) Kerguelen Plateau; BR, Bruce Rise; WL, Wilkes Land; TA, Terre Adélie; GVL, George V Land.

George V Land (Stagg & Reading 2007), break-up is interpreted at about 67 Ma (Maastrichtian) based on stratigraphic onlaps (Krassay *et al.* 2004), or even younger (Palmowski *et al.* 2004) (Fig. 3b). Break-up at the far eastern end of the SRS was very oblique (*c.* 55° between the spreading azimuth and the rift-bounding structures in the Otway margin, to around 15° in the Sorell margin), with strike-slip separation producing transtensional basin bounding faults at high angles to the main east–west rift (Stagg *et al.* 1990; Willcox & Stagg 1990; Stagg & Reading 2007) (Fig. 2). In the central Great Australian Bight (GAB) and conjugate Wilkes Land sector, break-up produced a complex but near-symmetrical magma-poor margin system, marked by a wide COTZ with distinctive paired conjugate basement ridges (Direen *et al.* 2011). These features are interpreted to comprise exhumed serpentinized mantle and magmatic products from decompression melting of the upper continental mantle (Sayers *et al.* 2001; Colwell *et al.* 2006). Further east, between the Beachport Terrace of the western Otway Basin and Terre Adélie, break-up appears to be more asymmetric, with a wide COTZ and interpreted peridotite ridge documented on the Antarctic margin (Colwell *et al.* 2006). However, no equivalent features are apparent on the conjugate section of the Australian margin (cf. Moore *et al.* 2000), despite possible exhumed mantle ridges being interpreted further to the east (Palmowski *et al.* 2004). It is the comparison between two conjugate sections within the central spreading compartment of the SRS that will be the focus of this study.

Data

The data discussed here are from deep multi-channel seismic reflection surveys GA228, GA229, L1–84-AN and ATC, and high-speed seismic reflection survey GA227 on the Antarctic margin, and from deep multi-channel seismic reflection surveys GA137 and GA199 on the Australian margin. These seismic data are complemented by open file geophysical grids of the satellite free-air gravity (Fig. 3a) (Sandwell & Smith 2009) and interpreted age of oceanic lithosphere (Fig. 3b, after Müller *et al.* 2008).

Figures 3 and 4 show the locations of the chosen profile segments, in present-day (Fig. 3a) and two syn-break-up (50 Ma: Fig. 4a; 75 Ma: Fig. 4b)

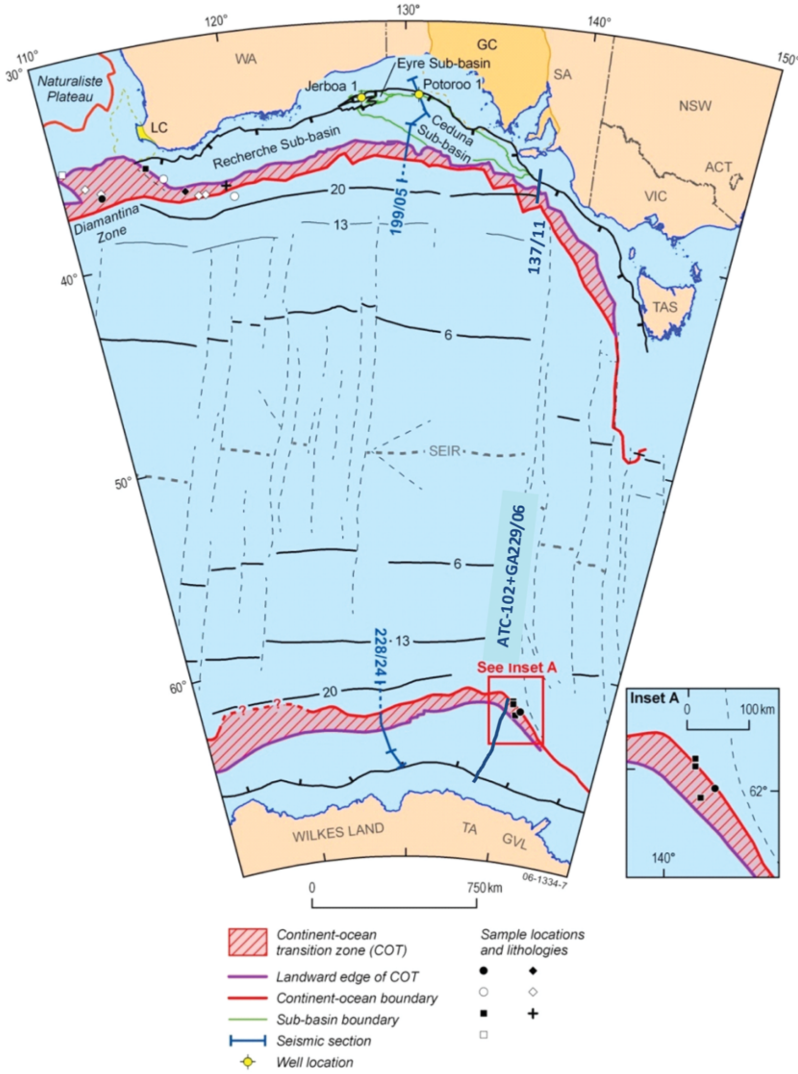


Fig. 2. Key sample and seismic line locations off Australia and Antarctica, with key sea-floor spreading magnetic anomalies (bold, numbered lines) and oceanic fracture zones (dashed lines) identified (after Direen *et al*. 2011). Portions of interpreted profiles over oceanic crust are shown dashed. Details of relevant dredges are contained in Table 1. The COT (hachured) is derived from Sayers *et al.* (2001), Blevin & Cathro (2008) and Colwell *et al.* (2006). The interpreted offshore extents of continental basement are shown as dashed lines. Dredge haul compositions include mixed continental crustal and supracrustal rocks (solid square); mixed supracrustal and transitional mafic rocks (cross); mixed continental crustal and transitional basaltic rocks (open square); transitional basaltic rocks (open diamond); peridotite, harzburgite and gabbros (solid circle); peridotites and transitional basaltic rocks (open circle). Full catalogues for each haul are given in Table 1. Normal fault symbol (ticked line) is the margin rift-bounding fault system downthrowing to the ocean. SEIR, Southeast Indian Ridge; TA, Terre Adélie; GVL, George V Land.

configurations, using the UTIG PLATES software and rotation parameters from Royer & Rollet (1997).

On the Antarctic margin, lines GA228/24 and GA229/06 are 36-fold deep multi-channel seismic reflection data that were recorded during Geoscience Australia surveys 228 and 229 in 2001 and 2002, respectively. They are part of a series of 90 km-spaced lines extending from the continental slope into the deep ocean basin, typically with profile lengths of 300–450 km. Further details of the acquisition and processing parameters for these data can be found in Close *et al.* (2007).

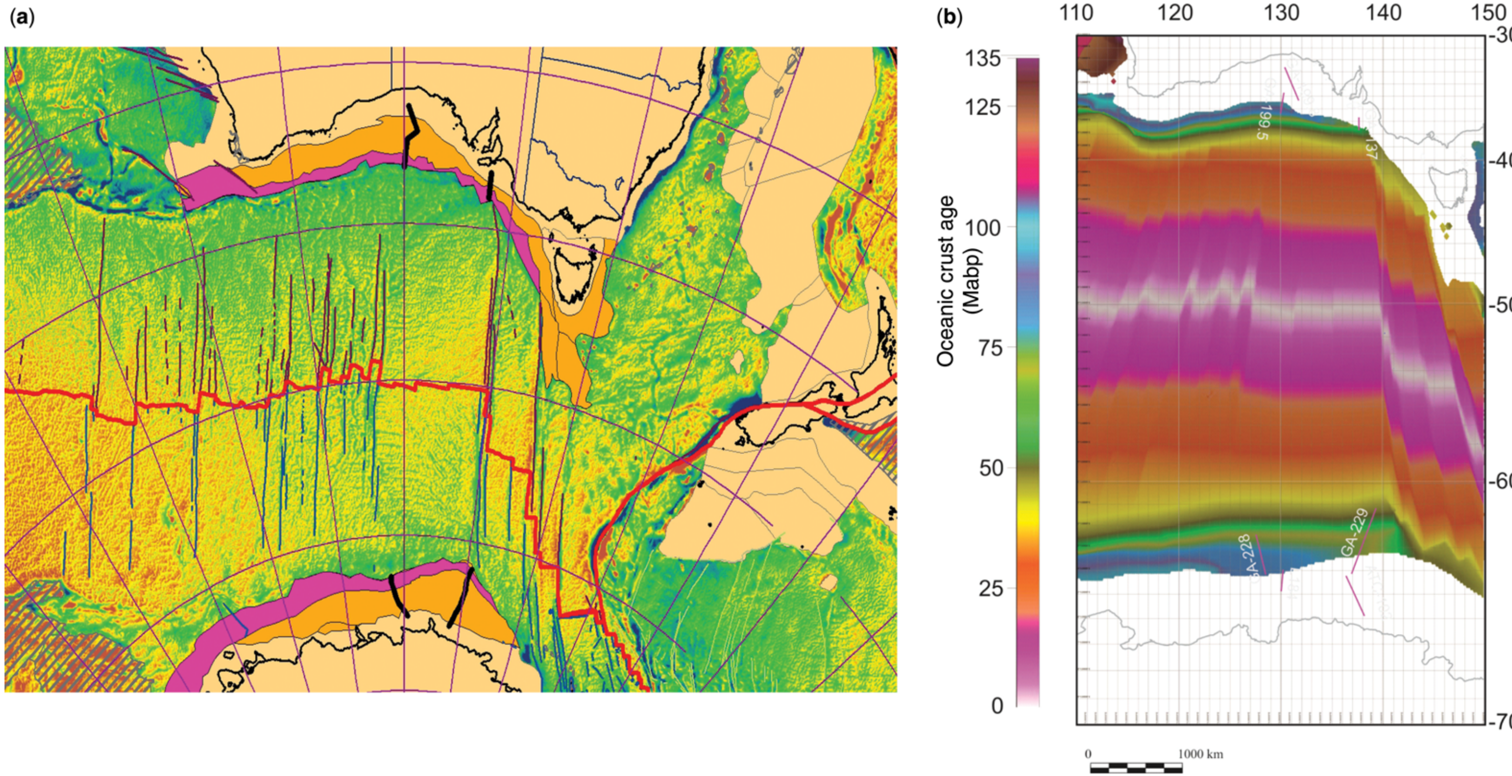


Fig. 3. Mercator projection geophysical grid images overlain by approximately conjugate line positions in this study. (**a**) Satellite Free-Air (FA) grid (Sandwell & Smith 2009), with an original grid spacing of 0.01″ (lat/long) resolution from the National Geophysical Data Center (NGDC). Continental crust is shown in light brown, transitional crust in orange and the COTZ in magenta. Black crosshatching is the areal distribution of large igneous provinces (LIPs). Heavy black lines are seismic profile locations discussed in this paper. The Southeast Indian spreading ridge is shown by the heavy red line. Geographical co-ordinates, WGS84 datum. (**b**) Digital-interpreted age of oceanic lithosphere of the world, from Müller *et al.* (2008). Heavy black lines are seismic profile locations.

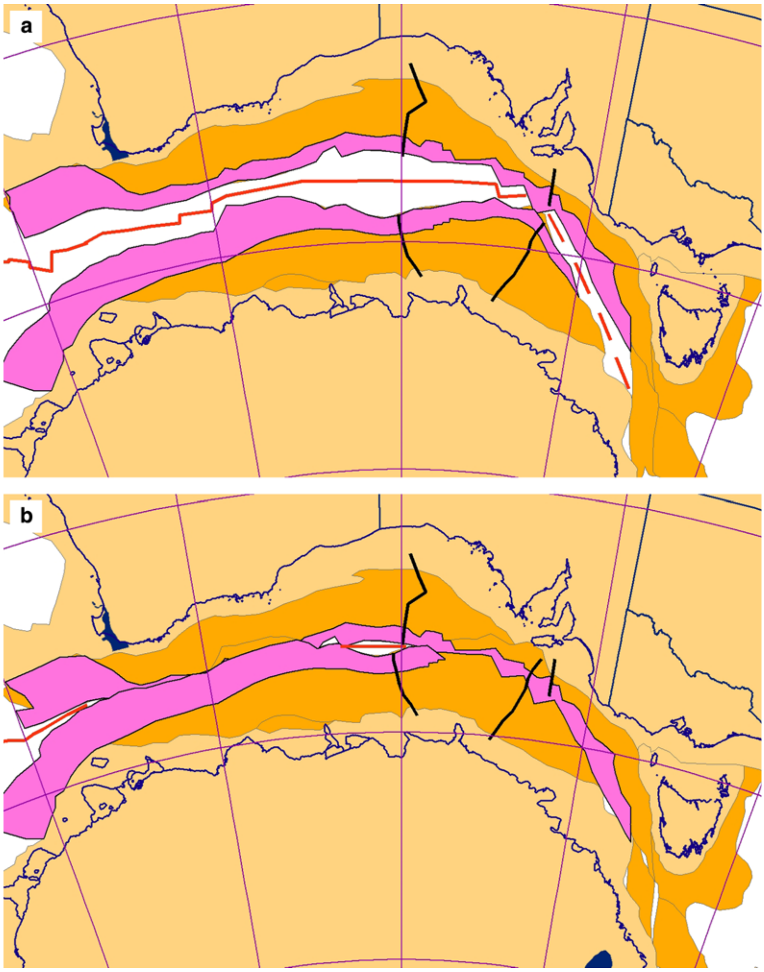


Fig. 4. (**a**) Reconstructed Middle Eocene (Lutetian: 50 Ma) locations of seismic lines (black lines). Symbology as in Figure 3a. (**b**) Reconstructed Late Cretaceous (Campanian: 75 Ma) position of lines at syn-break-up time. Rather than a uniform west to east progression of onset of spreading as postulated by Mutter *et al.* (1985), spreading initiated off Naturaliste Plateau–Bruce Rise (93–87 Ma: Beslier *et al.* 2004; Halpin *et al.* 2008), then in the outer Bremer Basin (*c*. 91 Ma: Blevin & Cathro 2008). Break-up in the central Bight region occurred at 83–75 Ma, with later separation in the western Bight at about 65 Ma (not shown in these figures), and only at about 50 Ma in the Terre Adélie–Otway region (Fig. 4a). Reconstructions were made using the PLATES high-resolution global plate model and PaleoGIS reconstruction software.

Expendable sonobuoys were also recorded on these lines, to provide velocity data for the sedimentary and crustal sections. Sonobuoys 228/SB11 and 228/SB15 were recorded on line GA228/24, and sonobuoys 229/SB10, 229/SB11 and 229/SB12 were recorded on line GA229/06. Specific locations and velocity models of these data are documented in Stagg *et al.* (2005). Although these sonobuoys were not reversed, the geometry of the key crustal refractors is constrained by the interpretation of deep-seismic reflection data.

Line L184-1 was acquired in 1984 by the USGS (US Geological Survey) Antarctic Survey, as part of 1800 km of 24-fold multi-channel seismic reflection survey L1–84–AN in 130°–146°E (Eittreim & Smith 1987). Line L184–1 has been sourced from the Antarctic Seismic Data Library System (SCAR 1992).

Line ATC-102 was acquired in 1982 for the Institut Français du Petrole, as part of the 3190 km ATC-82 24-fold multi-channel seismic reflection reconnaissance survey of the Terre Adélie margin.

It has been tied to line GA228/24, and also ties to Deep Sea Drilling Program (DSDP) site 269 via line ATC-101 (Wannesson *et al.* 1985; Stagg *et al.* 2005). Line ATC-102 has also been sourced from the Antarctic Seismic Data Library System (SCAR 1992).

On the southern Australian margin, lines GA199/05 and GA199/08 are part of a regional set of 48-fold deep multi-channel seismic reflection data recorded on Geoscience Australia survey GA 199 in the central Great Australian Bight in 1997 (Sayers *et al.* 2001, 2003). Both are tied to extensive industry seismic data coverage on the continental slope, allowing the ages and depositional environments of the major sedimentary packages to be extrapolated into deep water (Totterdell *et al.* 2000; Krassay & Totterdell 2003). Velocity control of the sedimentary and crustal sections is provided by two non-reversed sonobuoys (11 and 12) on line GA 199/05, described and interpreted in Sayers *et al.* (2001).

Line GA 137/11 (Moore *et al.* 2000; also referred to as Line 137/1100 in Blevin *et al.* 1995) was acquired as part of a regional two-dimensional (2D) grid of 48-fold deep multi-seismic reflection recorded on Geoscience Australia survey GA 137 in the deep-water Otway Basin in 1995 (Blevin *et al.* 1995). It is also tied to an extensive industry seismic data and well coverage on the continental slope (Moore *et al.* 2000). No sonobuoy data were acquired on this transect.

Both margins have also been the focus of dredging, to sample crustal basement outcrops present in deep water (e.g. Beslier *et al.* 2004, Halpin *et al.* 2008). Particularly relevant to this paper is the dredging by Japanese expeditions of seamount outcrops on the margin of Terre Adélie and George V Land (Fig. 2). These rocks included granite, slate and diorite (Tanahashi *et al.* 1997), and also subcontinental mantle peridotite reported by Niida & Yuasa (1995) and Yuasa *et al.* (1997).

Here, we report on dredges from the SW slope of a feature informally named Seamount 'B' (Yuasa *et al.* 1997) off Terre Adélie during the JNOC (Japan National Oil Company) *Hakurei Maru* cruise TH93 (Table 1); there is no published report of that cruise. Seamount 'B' is located approximately 125 km east of SP 5300 on line GA 229/06 (see Fig. 2) (Stagg *et al.* 2005, plate 7). Samples were acquired from the Geological Survey of Japan Antarctic collection in Tsukuba, Japan. Dredge haul D1402 from this cruise included cobbles of quartzite, amphibolite and granite, and dredge haul D1403 recovered granite, quartz–biotite–potassic feldspar phyric dacite, and protomylonitic or cataclasized harzburgite (sample GSJ R78137) (Fig. 5). Dredge material from this seamount was considered by Yuasa *et al.* (1997) to be *in situ* owing to the significant free-air gravity anomaly associated with the feature, indicating that it is primarily composed of dense, crystalline rocks. All dredge fragments were examined using

Table 1. *Summary of dredge hauls from Terre Adélie*

Dredge/sample(s)	Latitude	Longitude	Depths (m)	Rocks recovered
TH91D1201 (Seamount 'B')	−62.1333°	141.3667°	N/A	Deformed harzburgite (Yuasa *et al.* 1997)
TH 92 D1301/ GSJ R78127	62°50′25″S (start), 62°51′28″S (end)	140°49′18″E (start), 140°49′18″E (end)	3260 − 3009 m	Greywacke (A–C); dolerite/gabbros (D)
TH 92 D1302/ GSJ R78128	62°09′02″S (start), 62°08′19″S (end)	141°9′02″E (start), 141°19′30″E (end)	3476–3050 m	Serpentinized harzburgite
TH93D1402/GSJ R78133	62°05′49″S (start), 62°06′50″S (end)	141°14′18″E (start), 141°16′00″E (end)	3416–2950 m	Quartzite, granite
TH93D1403/GSJ R78136	62°08′01″S (start), 62°07′38″S (end)	141°14′00″E (start), 141°14′54″E (end)	3476–3115 m	Quartz-biotite phyric dacite; granite; cataclasized harzburgite
TH95D1601 (Seamount 'A')	−61.6936° (start), −61.82003° (end)	140.5450° (start), 140.5783° (end)	N/A	Granite, gneiss, diorite, calcareous ooze, manganese nodule (Tanahashi *et al.* 1997)
TH95D1602 (Seamount 'C')	−62.3153° (start), −62.3164° (end)	140.9400° (start), 140.9117° (end)	N/A	Granite, gneiss, slate, calcareous ooze, manganese nodule and crust (Tanahashi *et al.* 1997)

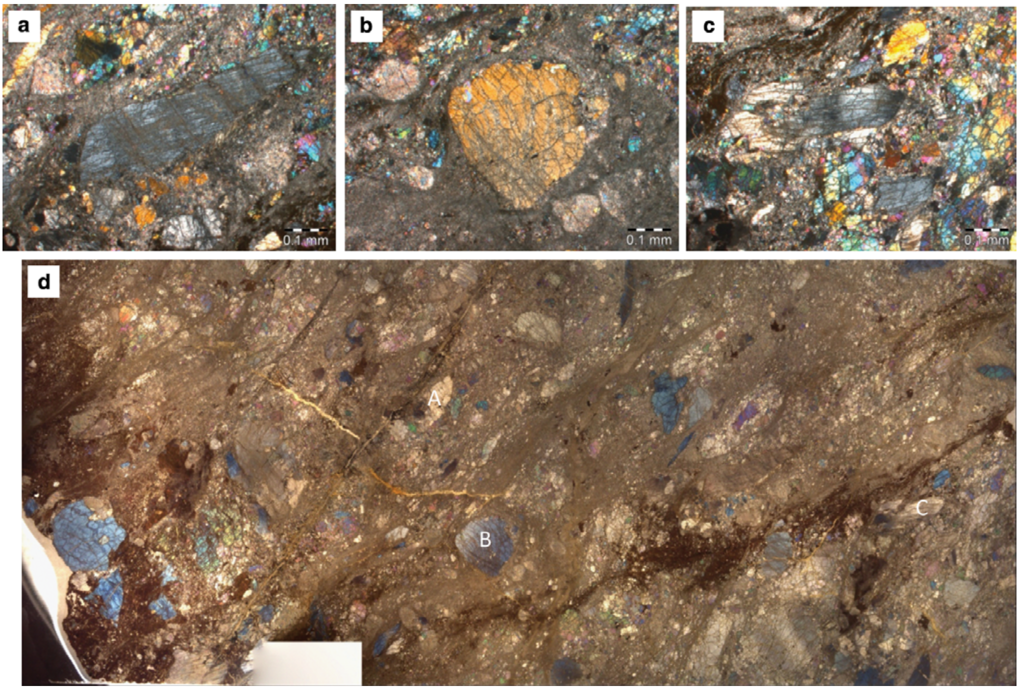


Fig. 5. (**a**) Photomicrograph of unoriented 25 μm-thickness thin section under polarized light from sample TH93D1403-6 (GSJ R78136), off seamount 'B', offshore Terre Adélie. The photograph shows rounded and tectonically milled olivine grains (**b**) and deformed orthopyroxenes (opx) with kinked twinning (**c**, **d**). The opx grains are clearly elongated in the anastomosing fabric defined by fine crystalline domains trending from the top right to the bottom left of the slide at about a 45°–50° angle. (b) Detail under cross-polarized light of olivine grain (b & c): detail under polarized light of orthopyroxene grain (c & d) detail under polarized light of orthopyroxene grain (d).

optical petrography on standard coverless 25 μm-thin sections.

Interpretation

The purpose of this paper is to provide a new view of the distribution of rifting symmetry in the SRS from multiple comparable sections, by employing a synthesis of existing datasets. Consequently, existing interpretations of all the data herein can already be found, albeit scattered through diverse literature. Conjugate transect GA228/24–GA 199/05 has already been discussed in detail by Direen *et al.* (2011), to which the reader is referred for a detailed analysis, including results from gravity and magnetic forward modelling. Only the main features will be summarized here.

Line ATC-102 has been discussed by Wannesson *et al.* (1985) and also by Stagg *et al.* (2005); line GA 229/06 was interpreted in detail, including coincident gravity and magnetic forward modelling, by Colwell *et al.* (2006). Line GA 137/11 has been interpreted by Moore *et al.* (2000). None of these lines, however, have been published as part of a conjugate transect. Our interpretation of such a synthesis is presented here.

Figure 6 shows conjugate, uninterpreted time sections from Terre Adélie to the Beachport Terrace (Otway Basin), joined at the COB so that the oceanic crust is removed. Overall, this section shows final break-up asymmetry across the rift system.

On the Beachport margin, from the high-angle, landward-bounding headwall fault to oceanic crust is only approximately 50 km wide (Fig. 7). Sedimentary basin development is limited to the narrow continental slope, but the section images more than 4 s TWT (two-way time: *c*. 6 km) of faulted and rotated syn- and pre-rift sedimentary section in this zone. The overlying cover sequences are sediment starved, and are less than 300 m thick (Moore *et al.* 2000). The boundary with oceanic crust is located near the outer margin, which appears to lack a syn-rift section, with a post-break-up sag section deposited directly on normally listric-faulted, exceedingly thinned, middle crust basement.

In contrast, the conjugate Terre Adélie margin is nearly 600 km wide. The most prominent features of

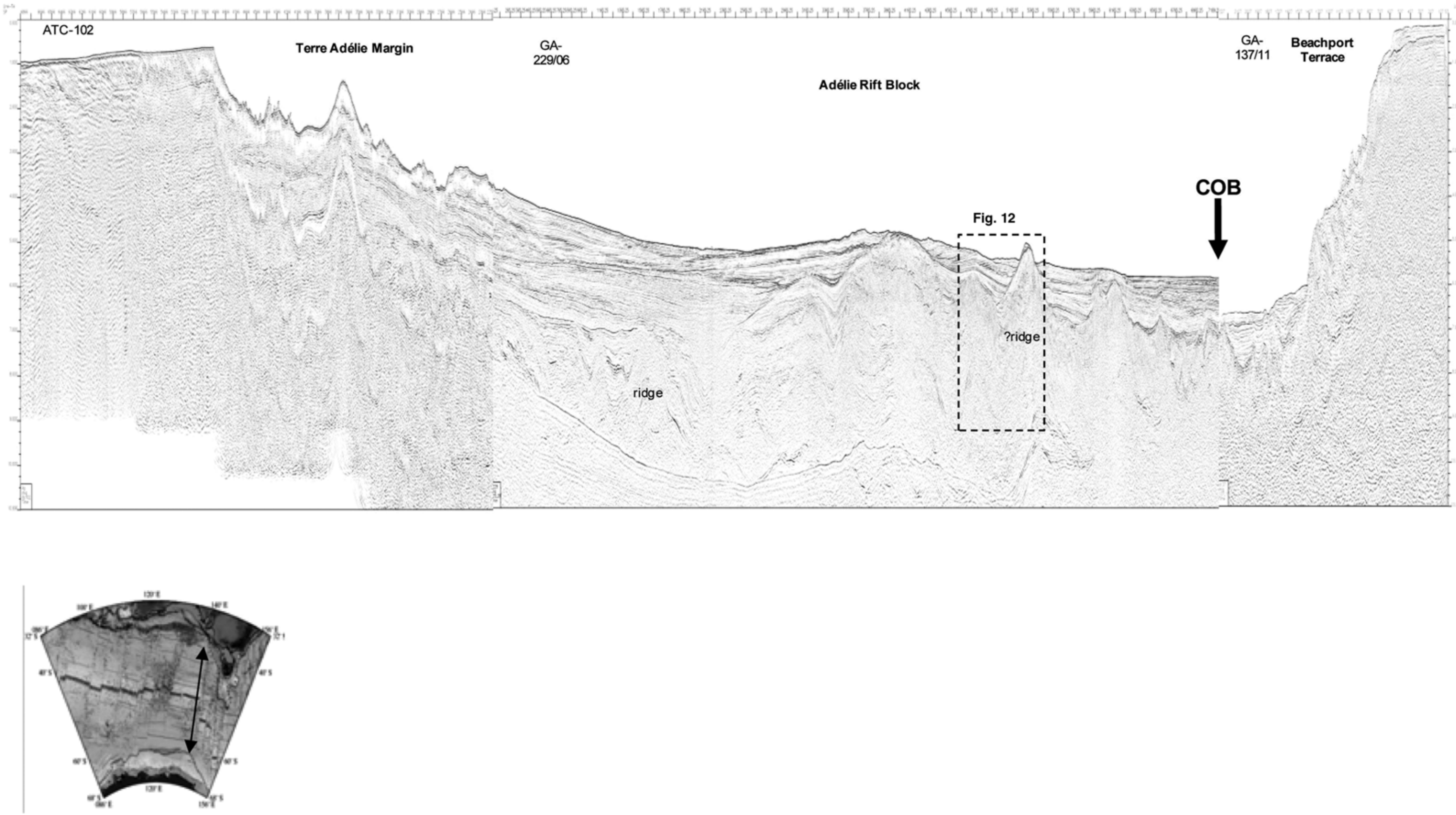


Fig. 6. Conjugate seismic profiles in two-way time from Terre Adélie and the Beachport Terrace (Otway Basin) continental margins, with the principal geological features annotated. The profiles are joined at the continent–ocean boundary. The stronger multiples on the Antarctic margin are a function of the shorter seismic streamer that was used on survey GA229.

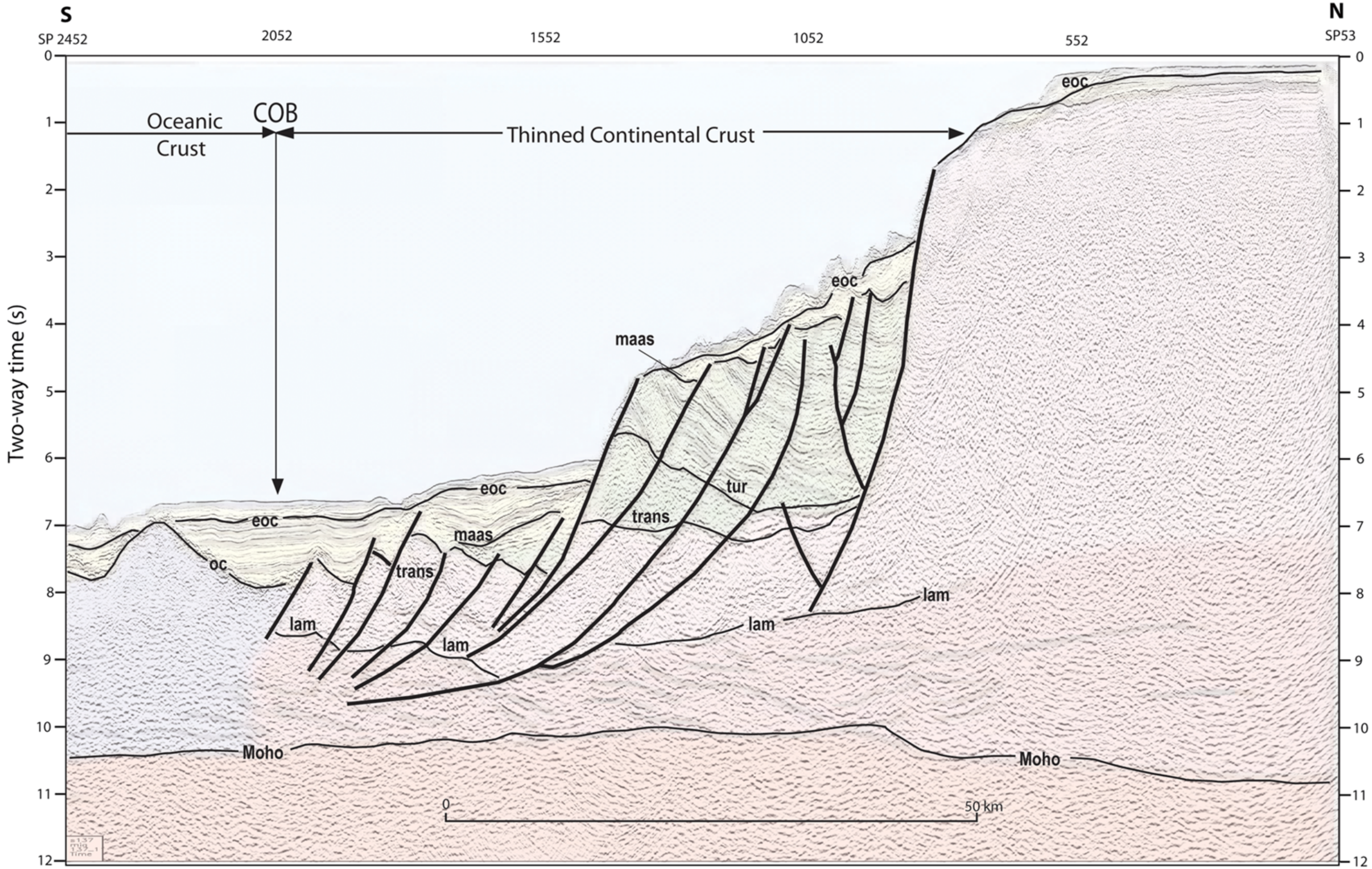


Fig. 7. Full-length seismic reflection profile for line GA 137/11, modified after Moore *et al.* (2000), from the southern edge of the Beachport Terrace (right-hand end) to the oceanic crust of the Australian–Antarctic Basin. Oceanic crust (oc) is marked by a bright upper reflector, and generally low internal reflectivity. Moho, top Moho reflection; lam, top of laminated lower continental crust; trans, top of transparent continental middle crust; tur, base Turonian; maas, Maastricthian break-up unconformity; eoc, mid Eocene unconformity.

this section are a series of 4 − 5 km amplitude, 20 − 40 km wavelength megaboudins in the lower crust, and the associated deformation of the thick Cretaceous (?and Jurassic) mid-crustal rocks (Figs 6 & 8). Supracrustal deformation is focused around a single megaboudin, termed the Adélie Rift Block (Colwell *et al.* 2006: herein, ARB; SP 2200–6000), interpreted to be comprised of crystalline crust on the basis of its density, magnetic, seismic reflection and velocity characteristics (Stagg *et al.* 2005; Colwell *et al.* 2006). This block is bound on the southern side by a major landward-dipping, mantle-penetrating normal fault system, and oceanward by igneous rocks of the COTZ. The pinch-and-swell structure of the lower crust and the major fault system at the inner edge of the Adélie Rift Block controls the distribution of the post-rift section above the pronounced Turonian(?) break-up unconformity. Another prominent feature of the Adélie section is the major topography on the bright reflector beneath the ARB. Gravity and magnetic forward modelling in Colwell *et al* (2006) suggests that this reflector is the top of the altered/serpentinized mantle. A basement ridge at around SP 1500 pierces the middle crust, and is likewise interpreted as a serpentinized mafic–ultramafic ridge located at the point of maximum necking of the crust, and analogous to the ridge interpreted on line GA 228/24. The COB off Terre Adélie is marked by a change in the seismic character from this structurally complex and diverse seismic character, to the distinctive generally low-reflectivity, rugose upper-surface seismic character of the oceanic crust (Fig. 8).

Figure 9 shows conjugate uninterpreted time sections from Wilkes Land to the Great Australian Bight, again joined at the COB with oceanic crust removed. Ignoring the difference in post-rift depositional sediment volumes, as explained in Direen *et al.* (2011), this section shows overall apparent break-up symmetry.

Both conjugate margins in this transect are characterized by a high-velocity, basement ridge at the outboard edge of highly attenuated and thinned continental crust. These ridges are seismically and structurally complex, and are highly magnetized. The upper parts of these ridges are capped by noisy, discontinuous, high-amplitude reflections interpreted as mafic volcanics (see Sayers *et al.* 2001; Colwell *et al.* 2006). Internal seismic reflections beneath the caps show little coherence, although some planar faults can be interpreted. The seismic character of the ridges, particularly their unusual internal structure, is similar to structures off Newfoundland (Lau *et al.* 2006*a*) and Iberia (Pickup *et al.* 1996; Henning *et al.* 2004), where Ocean Drilling Program drilling has confirmed these ridges to be comprised of serpentinized, subcontinental mantle peridotites.

The ridge on the GAB margin was analysed by Sayers *et al.* (2001), who interpreted it to be one of a number of similar strike features, composed of serpentinized peridotites and subordinate mafic intrusions.

Dredging of the Terre Adélie ridge complex at its intersection with the Spencer Fracture Zone has been previously reported by Niida & Yuasa (1995) and Yuasa *et al.* (1997), who described 'slickensided', partially serpentinized, spinel lherzolite to harzburgite (containing up to 29% coarse to megacrystic orthoenstatite). These rocks appear to have been deformed plastically, with deformed exsolution lamellae in orthopyroxene reported (Yuasa *et al.* 1997).

Sample GSJ R78137, reported here, also from Seamount 'B', is a protomylonitic or cataclasized olivine–orthopyroxene–spinel (± serpentine, talc, and magnetite) harzburgite (Fig. 5). It is petrologically and geochemically (Niida & Yuasa 1995) very similar to rocks reported by Beslier *et al.* (2004) from the Diamantina Zone, a domain of exhumed continental mantle on the SW Australian margin (Chatin *et al.* 1998; Beslier *et al.* 2004).

Outboard of the basement ridge, but inboard of unambiguous slow-spreading oceanic crust (Figs 10 & 11), both the GAB and Wilkes margins are characterized by a 60–80 km-wide basin. Seismically, this basin is characterized by a thick (up to 4 km), well-layered sedimentary sequence that is cut by approximately parallel, oceanward-dipping, listric and planar normal faults; these cut down to one or more bright, subhorizontal reflectors, interpreted as extensional detachment faults (Direen *et al.* 2011). Intermittent, discontinuous, high-amplitude reflectors suggest that some volcanics or intrusions are also present in this basin. However, the basin is generally characterized by overall low-amplitude gravity and magnetic signatures, consistent with its sediment-dominated interpretation, and suggesting that the volume of volcanics and intrusions is low.

Colwell *et al.* (2006), tying to the Australian margin using distinctive seismic reflectors, dated the erosional unconformity and marked the termination of rifting in this basin on the Antarctic margin as Turonian (base Tiger Supersequence of Totterdell *et al.* 2000: *c.* 90 Ma), although it could be as young as latest Santonian (base Hammerhead Supersequence of Totterdell *et al.* 2000: *c.* 83 Ma). While there are uncertainties in well–horizon ties over long distances, and additional uncertainties in (and revisions to) the geological timescale (e.g. Gradstein *et al.* 1994, 2004; Young & Laurie 1996), initial break-up and cessation of rifting between the central GAB and Wilkes Land is interpreted to have occurred at approximately 83 Ma (Campanian) by Sayers *et al.* (2001).

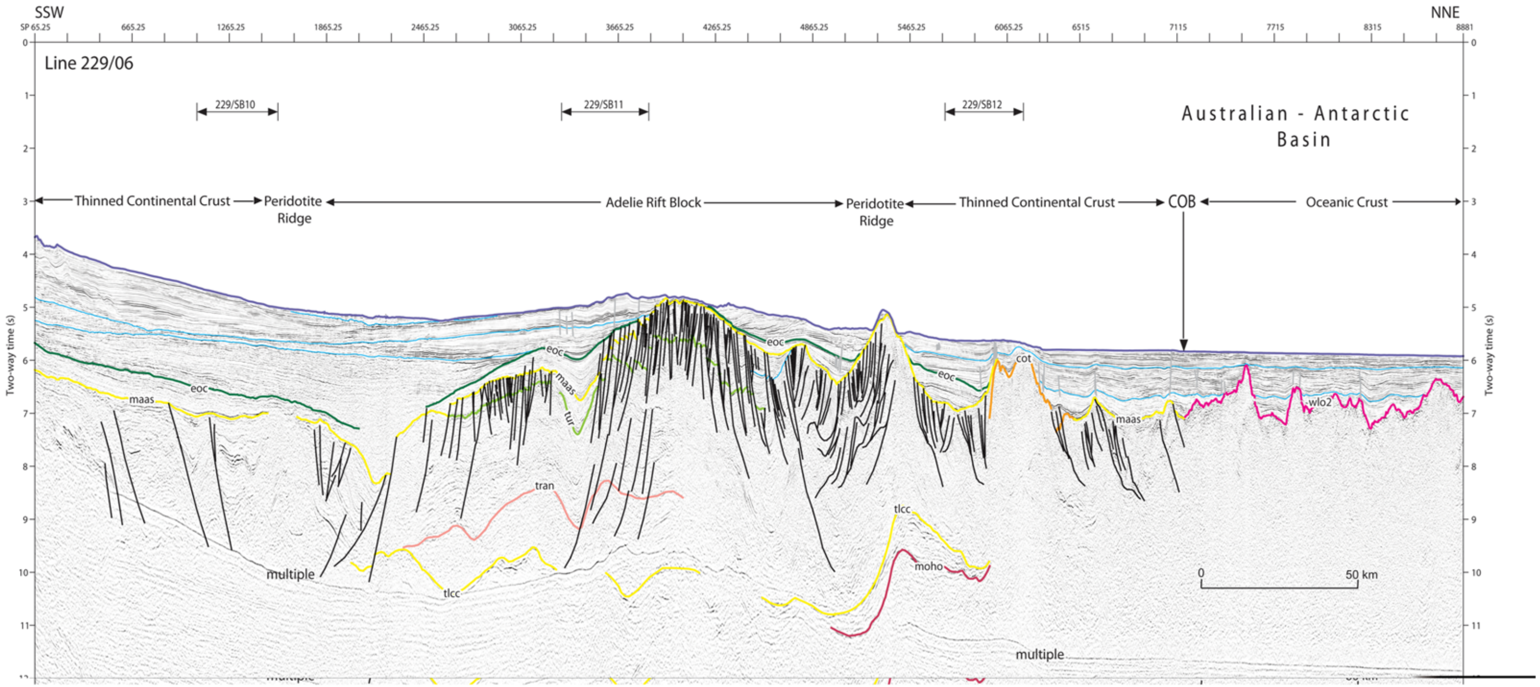


Fig. 8. Full-length seismic reflection profile for line GA 229/06, modified after Stagg *et al.* (2005), from Terre Adélie (left-hand end) to the oceanic crust of the Australian–Antarctic Basin, with the interpreted COB according to Colwell *et al.* (2006) marked at about SP 7115. Positions of unreversed sonobuoys 229/SB10, 229/SB11 and 229/SB12 (Stagg *et al.* 2005) are marked, and give velocity boundaries within continental crust, and the inner and outer flanks of the ARB, respectively. Oceanic crust is marked by a bright upper reflector, which marks a rugged, faulted upper crust, with generally low internal reflectivity. *K*, undifferentiated Cretaceous horizon; trans, top of transparent continental lower crust; Moho, top Moho reflection; Tur, Turonian rifting unconformity; COT, COTZ transitional crust; eoc, mid Eocene unconformity; maas, top Maastrichtian; tlcc, top laminated continental crust. After Colwell *et al.* (2006).

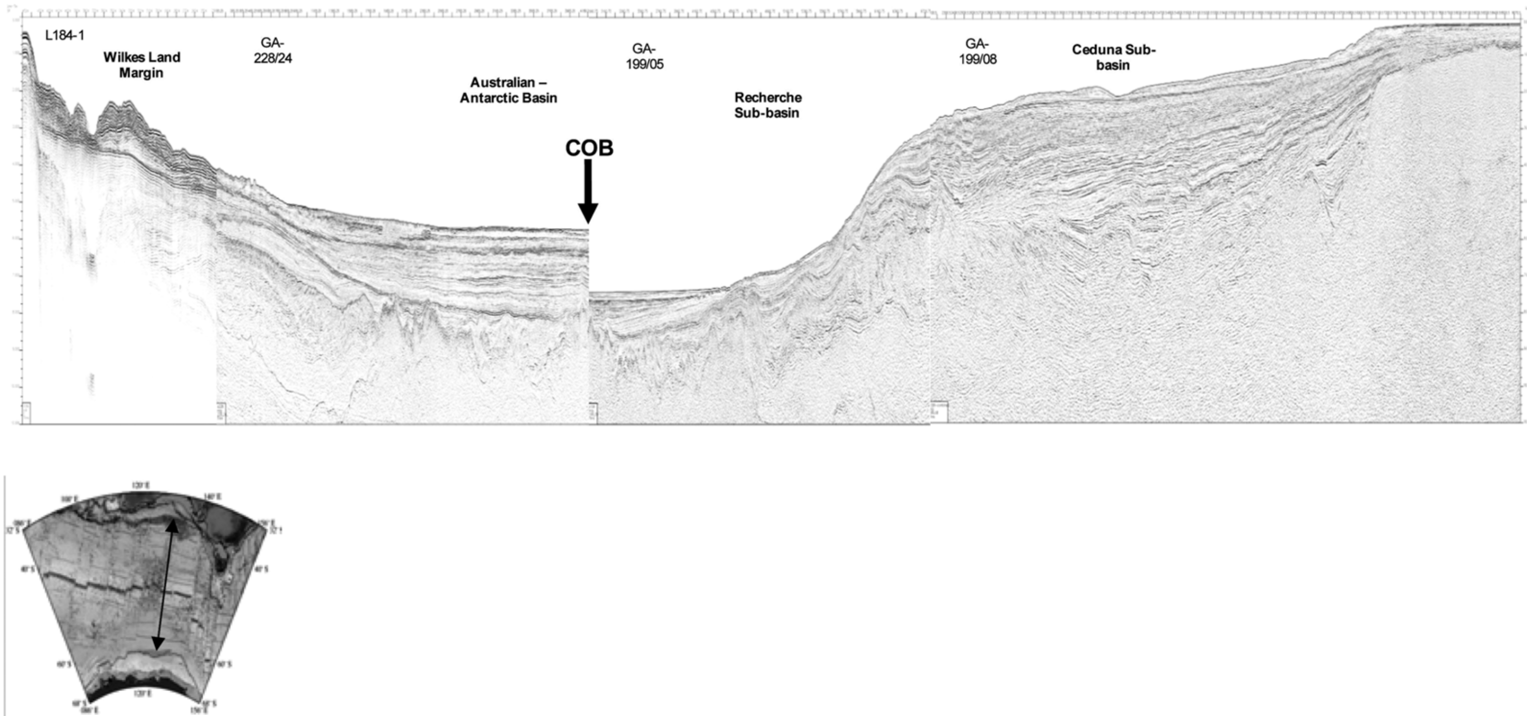


Fig. 9. Seismic detail, line GA229/06, showing the thick folded and faulted? Cretaceous sedimentary section of the Adélie Rift Block immediately inboard of the continent–ocean transition. The location is shown in Figure 6. The projected positions of the dredges on Seamount 'B' are shown, and the possible position of the underlying exhumed mantle ridge indicated. Note the internal bright reflectors in this structure.

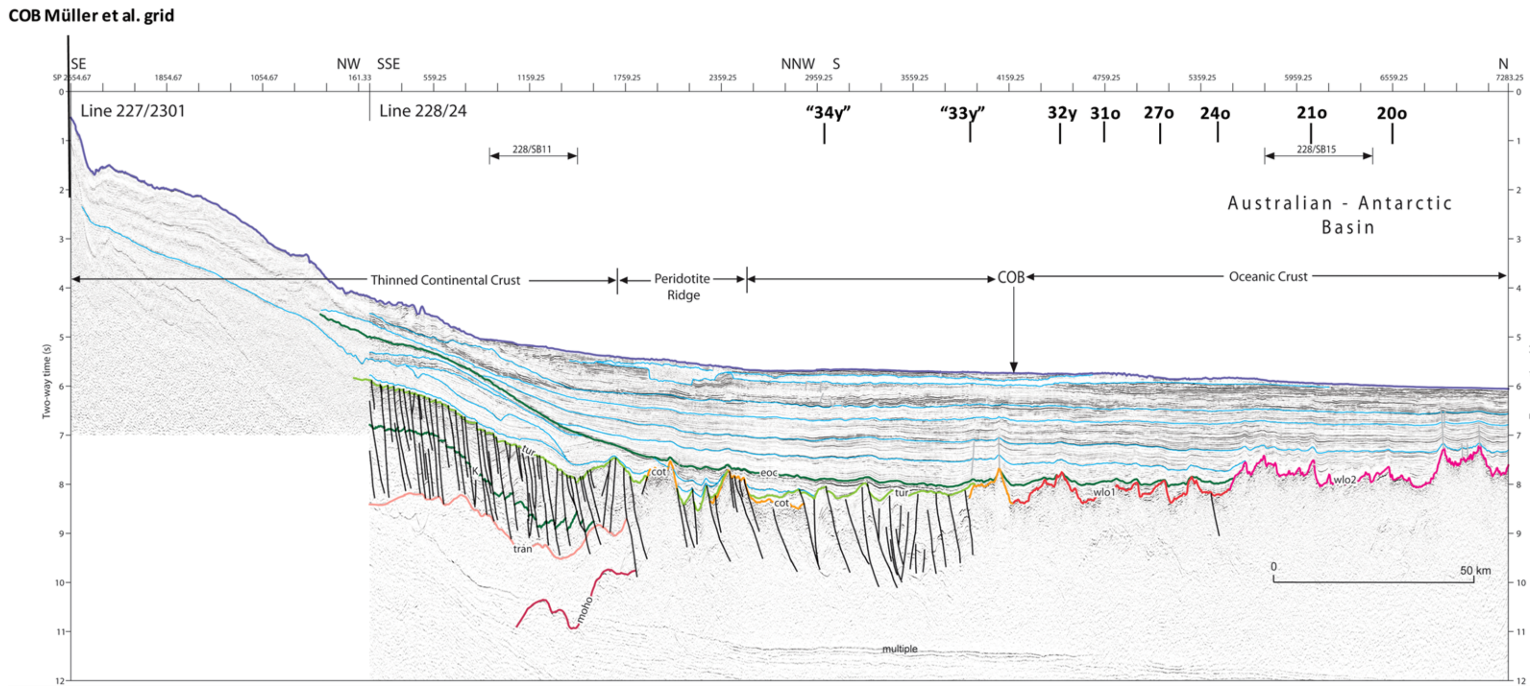


Fig. 10. Full-length composite seismic reflection profile for lines GA227/2301 and 228/24, modified after Stagg *et al.* (2005) from the Wilkes Land continental shelf (left-hand end) to the oceanic crust of the Australian–Antarctic Basin, with interpreted COB according to Colwell *et al.* (2006) marked at about SP 4000. Positions of unreversed sonobuoys 228/SB11 and 228/SB15 (Stagg *et al.* 2005) are marked, and give velocity boundaries within continental and oceanic crust, respectively. Oceanic crust is generally marked by a bright upper reflector, which marks a rugged upper surface interpreted to be the result of post-eruption mechanical extension, and generally low internal reflectivity. Two types of oceanic basement were recognized (wlo1 and wlo2) separated by an oceanwards step-up in basement level at approximately SP 5500. The base level change of approximately 0.4 s TWT (*c.* 600 m) correlates closely with interpreted magnetic Chron 24o (Early Eocene) and marks the interpreted change in spreading rate from an ultra-slow 1.5 mm year^{-1} to a slow 6.5 mm year^{-1} (Tikku & Cande 1999). Abbreviations as for Figure 8. After Colwell *et al.* 2006.

Top basement beneath this basin lies at 9.5–10 s TWT (*c.* 12 km depth), and was interpreted by Direen *et al.* (2011) as altered upper mantle. The remainder of the basement beneath this outer basin is characterized seismically by very bright, discontinuous high-amplitude reflections, mostly dipping landwards. Below these levels, the reflection character is chaotic, but landward-dipping planar offsets can be identified. We interpret the upper surface as a deformed detachment between the middle crust and upper mantle. Below this are altered (?serpentinized) and extended upper continental mantle peridotites, lacking stratification, consistent with the dredging results, and the gravity and magnetic forward modelling presented in Direen *et al.* (2011), Colwell *et al.* (2006), Stagg *et al.* (2005) and Sayers *et al.* (2001).

Discussion

Comparison of Figures 6 and 9 highlights significant differences and some similarities in gross basin architecture and symmetry within the Southern Rift System. These can be broken down into five major features (Figs 6–12).

Width of each conjugate pair

The Terre Adélie margin is wider than its conjugate by a factor of about 12, but the GAB margin is only slightly wider than the Wilkes margin by a factor of approximately 1.3 (*c.* 550 v. *c.* 430 km), when measuring the lateral distances between the main headwall faults and the COB.

Number of ridges

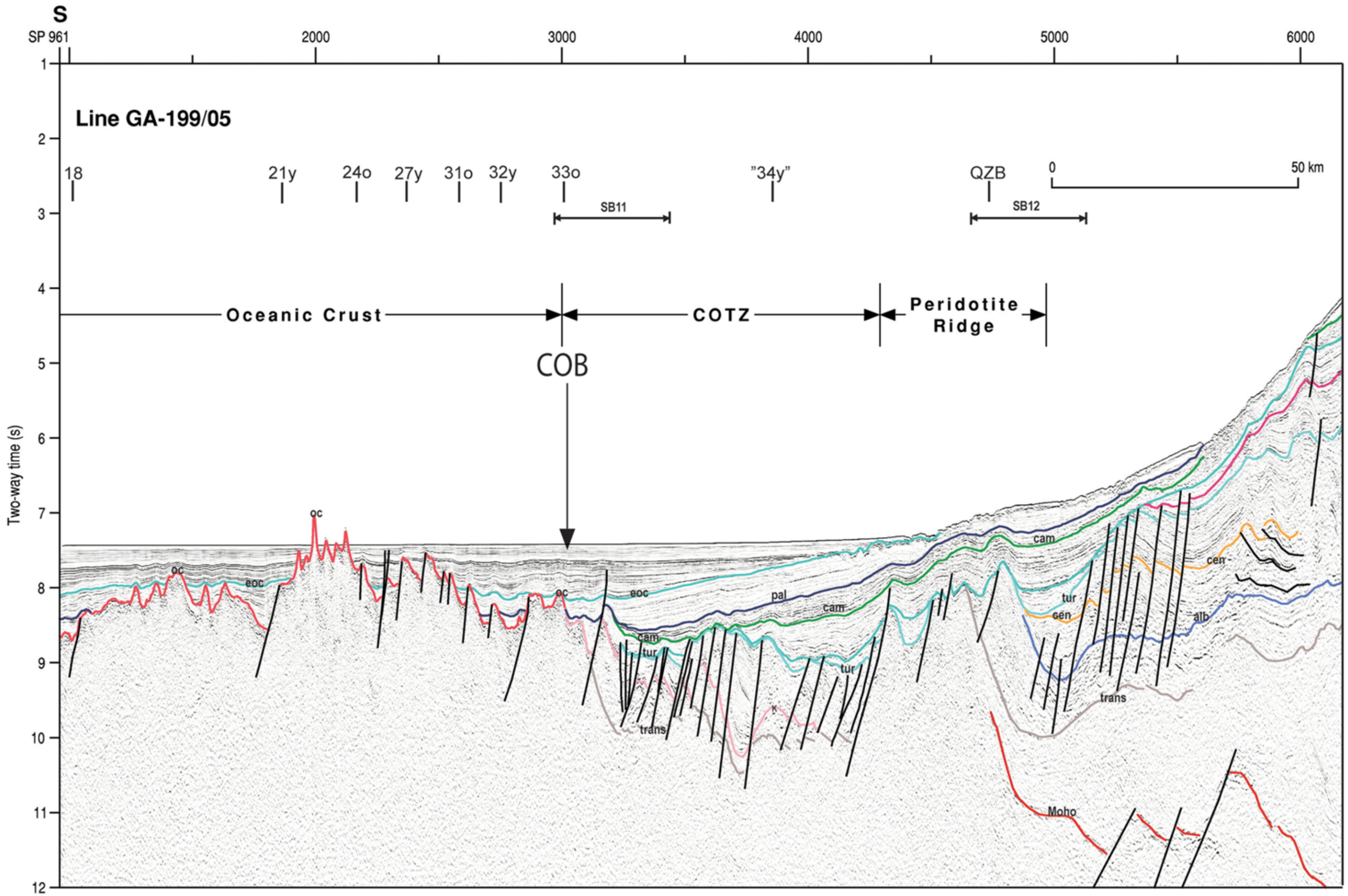
The eastern SRS has a buried ridge complex inboard of the Adélie Rift Block (at around SP 2500 on Line GA 229/06: Colwell *et al.* 2006), with no evidence of any similar structure on the Beachport Terrace margin. However, the recovery of protomylonitized harzburgite from Seamount ‘B’ in dredge D1403-6 (and also the findings reported in Yuasa *et al.* 1997 from dredge D1201 on the oceanward side of the same feature) suggests that a *second*, ridge structure, fully exhumed at Seamount ‘B’, may also exist at around SP 5300 on Line GA 229/06. It is noteworthy that there is a seamount at this location on line 229/06 (Fig. 12) that is mantled by Cretaceous (Maastrichtian) sediments but internally is characterized by bright planar reflectors and has a clearly mafic or serpentinized ultramafic core (inferred density 2.85 t m^{-3}, susceptibility 0.05 SI: Colwell *et al.* 2006; P wave velocity 6.82 km s^{-1} at 9.66 km depth: Stagg *et al.* 2005). This feature, if it is the strike continuation of Seamount ‘B’, implies multiple sites of mantle exhumation have developed on the Antarctic margin. Unlike the Adélie–Beachport profile, the GAB–Wilkes margins have an interpreted mantle ridge structure on each side of the position of the spreading ridge axis, as highlighted by Direen *et al.* (2011).

Point of final separation

The eastern SRS broke up outboard of the Adélie Rift Block, and very close to the Beachport Terrace, whereas the central SRS broke up almost in the centre of the basin lying between the paired mantle ridge structures. The point of final separation in each transect must reflect the location of the time-integrated maximum weakness in the crust. This difference between the two margins suggests a major difference in finite crustal strength between them. Of potential significance is the difference in orientation of crustal fabrics in the relatively strong (i.e. load-bearing) upper crust between the two margin segments: the upper crust in the central GAB (and presumably the conjugate Wilkes margin) is formed by NE–SW-striking Proterozoic fold belts at the westernmost margin of the Gawler Craton (e.g. Direen *et al.* 2005*b*; Thomas *et al.* 2008), whereas the upper crust off the Beachport Terrace comprises an east–west-striking segment of the Cambrian Delamerian orocline (e.g. Flöttmann *et al.* 1995; Direen *et al.* 2005*a*). In the Beachport sector, Late Cambrian thrust faults invert slightly older Cambrian strike-slip basin-margin faults (Flöttmann *et al.* 1995; Marshak & Flöttmann 1996) with northerly vergence. This means that NNW–SSE-directed Jurassic–Cretaceous extension was optimally oriented to reactivate these faults, in contrast to the NNE–SSW-striking faults in the western Gawler Craton margin. That is, there is a significant relative upper-crustal strength anisotropy between the two marginal transects imparted by the orientation of pre-existing upper-crustal fabrics. The extreme asymmetric break-up geometry has developed where the existing fabric was aligned subparallel to the rifting axis, where a relative weakness exists in the load-bearing upper crust. Significantly, the point of Cretaceous break-up in the eastern SRS may be focused by the location of a near-vertical, Early Cambrian east–west-striking strike-slip fault (Flöttmann *et al.* 1995). In the central GAB, the locus of break-up is at a newly formed east–west (Cretaceous) fault, cutting across the older (Proterozoic) north–south fabrics.

Mechanism of thinning

Both margins can be inferred to contain significant sets of extensional detachment faults, in some


S
SP 961
2000
3000
4000
5000
6000
Line GA-199/05
18
21y
24o
27y
31o
32y
33o
"34y"
QZB
0
50 km
SB11
SB12
Oceanic Crust
COTZ
Peridotite Ridge
COB
Two-way time (s)
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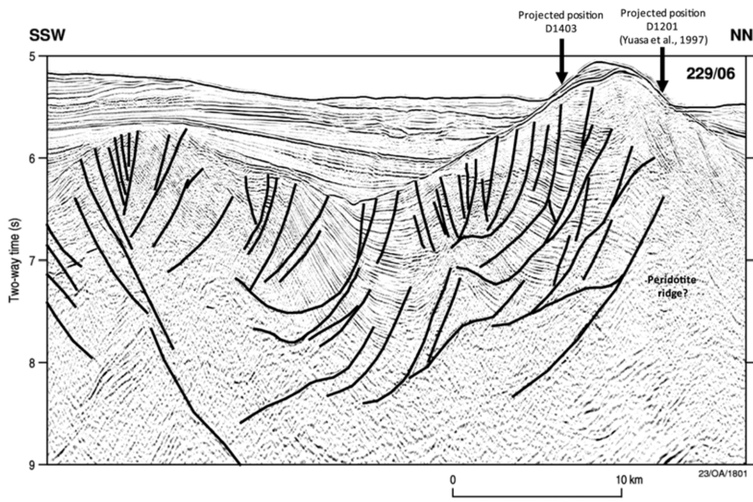

Fig. 12. Conjugate seismic profiles in two-way time from the central Wilkes Land and the Great Australian Bight continental margins, with the principal geological features annotated. The profiles are joined at the continent–ocean boundary. The stronger multiples on the Antarctic margin are a function of the shorter seismic streamer that was used on survey GA228. Modified from *Antarctica: Contributions to Global Earth Sciences*. Chapter 6.6. The Structure of the Continental Margin off Wilkes Land and Terre Adelie Coast, East Antarctica. 2006. Colwell, J. B., Stagg, H. M. J., Direen, N. G., Bernardel, G., Borissova, I. Figure 6.6.-8. Copyright, Springer-Verlag, 2006. With kind permission of Springer Science+Business Media.

places imaged as undulating bright reflectors (Figs 6 & 9). Overall, the pattern of the detachments – at the base of the middle crust, lower crust–top mantle, bounding the exhumed ridges, and underlying the central basin in the central SRS and the ARB in the eastern SRS – are very similar. Both margins display radical thinning and necking of the lower crust. The main difference is the removal of the middle crust almost entirely in the GAB–Wilkes margin, whereas in the Terre Adélie margin it remains as a megaboudin in the form of the lower part of the ARB. Prima facie, this bulk elastic behaviour suggests the middle crust in the eastern SRS is stronger than that in the central SRS, which has behaved in a more ductile manner.

Elevation of the Moho

Figure 13 shows the patterns of mantle elevation (and exhumation) between the two parts of the margin. In the eastern SRS, the Moho elevation shows a double culmination, all located on the southern side of the point of break-up, flanking the ARB. As discussed above, there is a buried mantle ridge to the south of the ARB, and very probably an exhumed or near-outcropping mantle ridge to the north. Both ridges are likely to be associated with significant extensional detachment faults, to elevate the upper mantle from its regional elevation at approximately 40 km depth (Reading 2004), to pierce through the middle and lower crust to now sit at depths of about 6 km. In the central SRS, as

Fig. 11. Full-length seismic reflection profile for line GA 199/05, modified after Direen *et al.* (2007), from the southern edge of the Ceduna Terrace (right-hand end) to the oceanic crust of the Australian–Antarctic Basin, with the interpreted COB according to Sayers *et al.* (2001) marked at about SP 3000. Positions of unreversed sonobuoys SB11 and SB12 (Sayers *et al.* 2001) are marked, and give velocity boundaries within the exhumed peridotite ridge complex and continental crust, respectively. Interpretation follows the scheme of Totterdell & Bradshaw (2004). Oceanic crust (oc) is generally marked by a bright upper reflector that marks a rugged upper surface interpreted to be the result of post-eruption mechanical extension, and generally low internal reflectivity. Moho, top Moho reflection; trans, top of transparent continental crust; K, Jurassic–Cretaceous (Ju–K) pre-rift sequence (Minke); alb, upper Albian (base Blue Whale); cen, base Cenomanian (White Pointer); tur, base Turonian (base Tiger); cam, base Campanian (base Hammerhead) break-up unconformity; eoc, mid Eocene unconformity (base Wobbegong).

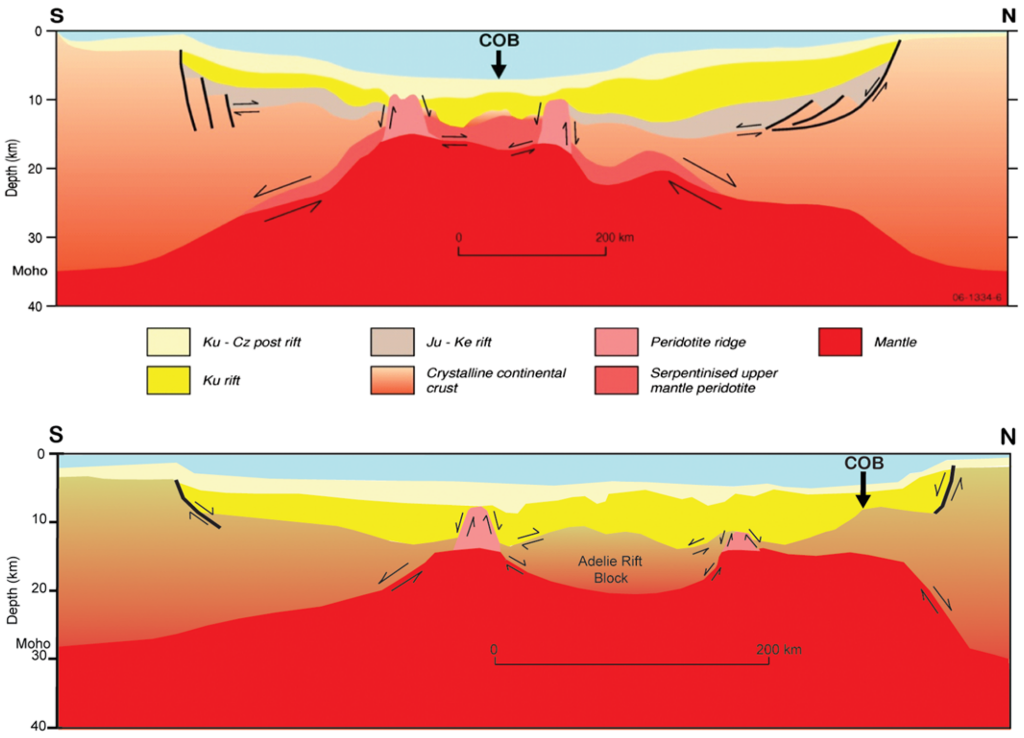

Fig. 13. Conceptual, lithospheric-scale cross-sections of the full rift in the two conjugate sections with the oceanic crust removed. Arrow shows the locus of break-up on each pair. The vertical exaggeration is approximately 10:1. Kinematic indicators show the relative material flow across different crustal interfaces; no mechanism is implied. Abbreviations: Ku–Cz, Upper Cretaceous to Cenozoic; Ku, Upper Cretaceous; Ju–Ke, Jurassic to Lower Cretaceous.

discussed by Direen *et al.* (2011), the mantle shows a more 'compact' symmetrical pattern of elevation, with a (non-outcropping) ridge culmination on either side of the point of final break-up.

Implications

Neither margin examined here shows evidence for a seismically reflective major concave-down detachment fault as imaged in parts of the Iberian–Newfoundland margin system (Whitmarsh *et al.* 2001). Therefore we conclude that even in conjugate margins that show geometric asymmetry after break-up, such as the Terre Adélie–Beachport pair that might have developed a 'Zone of Exhumed Continental Mantle' (ZECM), the final 'exhumation mode' of crustal thinning mechanism hypothesized by Manatschal (2004) and Lavier & Manatschal (2006) does not appear to have operated. Specifically, this implies that paired systems of detachments can operate within a rift, leading to either final geometric symmetry or asymmetry of break-up (Figs 6, 9 & 13). This is in contrast to a rift whose late stages are dominated by a single master detachment fault (e.g. Wernicke 1985; Lister *et al.* 1986; Whitmarsh *et al.* 2001; Manatschal 2004; Huismans & Beaumont 2011) that will necessarily result in an asymmetric break-up geometry. More generally, these observations challenge the ubiquity of the Alpine–Iberian model of non-volcanic rifting hypothesized by Whitmarsh *et al.* (2001), Manatschal (2004) and Lavier & Manatschal (2006), and suggest that modifications or alternatives to the emerging paradigm (Manatschal *et al.* 2009; Huismans & Beaumont 2011) should be examined in the light of a wider range of observational data – a point also highlighted by Aslanian *et al.* (2009). In particular, it may be that multiple ridges observed on the southern part of the Iberia margin (Henning *et al.* 2004) are also found in other rifts.

The key difference between the points of break-up with respect to the location of the pair of ridges in the two margins is highly significant. It strongly suggests that the locus of mantle exhumation is incidental, and does not have a *determining* role in the location of eventual sea-floor spreading. Such an observation seems at least partially consistent with the findings of Ranero & Pérez-Gussinyé (2010), who attributed final break-up to sequential faulting, with strain eventually migrating to a single fault 'defining the basin centre' (Ranero & Pérez-Gussinyé, p. 296) (i.e. the point of break-up as defined by Cowie *et al.* 2005). We speculate that if the sequence of faulting was modulated by crustal strength variations – including temperature variations in the mid-crust (Nagel & Buck 2007; Direen *et al.* 2011) and also retardation of fault growth by, or, alternatively, hard linkage to, variably oriented pre-existing basement structures – the variations on the asymmetric model recently postulated by Ranero & Pérez-Gussinyé (2010) could arise. The locus of final break-up is clearly more complex than envisioned by earlier models based on single detachment systems; for example, Lister *et al.* (1991).

If the position of the COB is related to faulting and migration of fault activity, as postulated by Ranero & Pérez-Gussinyé (2010), then a further implication arises. We examine this below in a thought experiment.

Faults have to do work to break the lithosphere (Cooke & Murphy 2004). In Newtonian classical mechanics, the total work budget can be described by $W = Fs\ \cos\theta$, where a force, F, is acting to break rocks over some distance, s. In real situations, neither s, nor θ, the angle between the vectors F and s, are constant owing to physical, structural (Versfelt & Rosendahl 1989) and thermal (Holford *et al.* 2011) inhomogeneities in the crust and their spatial anisotropies. This mechanical formalism may appear trivial; however, it has a definite geological meaning: subjected to the same (constant) forces and energy budgets supplied by the tectonic system, different pieces of crust will rift at different rates, even in a single rift compartment, owing to their inherent anisotropies – as evidenced by the results of Holford *et al.* (2011). As the work done on the crust by faulting proceeds, it would be normal to expect that break-up would occur at different times in different places. In the system examined, we observe deflections of the pre-existing anisotropies in the rifting crust that trend through 90° – thus, the term $\cos\theta$, between the Great Australian Bight and the Beachport terraces, changes from 0 to 1, significantly changing the amount of work that the faults do between these transects. It is therefore unsurprising to observe a significant difference in the age of break-up between these transects (Fig. 4a).

More subtly, however, the same logic can be applied to any two points in the rift system. Given that no two pieces of the crust are the same, it is therefore unsurprising that the point of final separation, the COB, changes its age from place to place along the rift. This has been recently highlighted by Tikku & Direen (2008) and Direen (2012), and is illustrated in Figure 4a, b. However, a less obvious corollary of this result is that it is highly unlikely that the age of break-up can therefore be defined using an isochron. For example, comparing the age defined COB of the Müller *et al.* (2008) grid – based on picking magnetic isochrons – to the geological sections in Figures 10 & 11, with the isochron picks of Tikku & Cande (1999) annotated, there is a discrepancy in the age at the COB in the grid as it lies over stretched continental crust. Thus, following Colwell *et al.* (2006) and Stagg *et al.* (2005), we recommend that all datasets, including reflection seismic data where available, be used to pick the COB, rather than simple reliance on isochron picks from magnetic data. In general, the radical changes in width of the COTZs imaged here also have significant ramifications for continental reconstructions, as highlighted by Gohl (2008).

Conclusions

We have presented a new synthesis of previously published deep multi-channel seismic reflection data, sonobuoy and dredge information for two conjugate profiles through a single spreading ridge segment in the Southern Rift System between Australia and Antarctica. This is a Jurassic–Late Cretaceous rift system, with a variable age of break-up from west to east.

The two conjugate pairs of sections show significant differences in symmetry about the point of final break-up. In particular, the GAB–Wilkes pair broke up in the centre of a basin bounded by a pair of similar, exhumed, but not outcropping, basement ridges interpreted to be serpentinized peridotites, rooting into the upper mantle. The point of break-up, which was perhaps modulated by temperature variations due to radiogenic granites in the middle crust (Direen *et al.* 2011), has left a ridge stranded on each margin. In contrast, the Terre Adélie–Beachport margin pair broke up on the northern side of an apparently strong middle crustal megaboudin, the Adélie Rift Block. Our interpretation of seismic and dredge data suggests that the ARB has an exhumed mantle ridge on each side of it, and that, on the northern side, the mantle crops out at a group of seamounts that have been dredged to reveal deformed continental mantle harzburgites. However, the point of break-up, perhaps modulated by hard linkage to pre-existing? Cambrian strike-slip faults in the middle and upper crust, has left both ridges stranded on the southern side of the rift axis spreading centre.

These observations are at variance with features observed on the archetypal Iberia – Newfoundland magma-poor margin, and challenge some of the recent hypotheses about how such margins form mechanically. This calls for a degree of caution in the broader application of such models to margins worldwide, and further suggests that a wider range of margin architectures needs to be used to inform and test such models.

The results also suggest the need for revisions in some places to the global digital isochron map (Müller *et al.* 2008) owing to errors in associating the location of final break-up with age determinations from magnetic isochron picking. This in turn has significant ramifications for continental reconstructions (Gohl 2008).

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