Developing a consistent sequence stratigraphy for the Wilkes Land and Great Australian Bight margins

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Abstract

The conjugate margins of Wilkes Land, Antarctica, and the Great Australian Bight (GAB) are amongst the least understood continental margins. Breakup along the GAB–Wilkes Land part of the Australian–Antarctic margin commenced at approximately 83 Ma. Using recent stratigraphic interpretations developed for the GAB, we have established a sequence stratigraphy for the Wilkes Land margin that will, for the first time, allow for a unified study of the conjugate margins. By reconstructing the two margins to their positions prior to breakup, we were able to identify comparable packages on the Wilkes Land margin to those recognised on the GAB margin. Excluding the glacial sediments on the Antarctic margin, the sedimentary sequence along the Wilkes Land margin is very thin compared to the GAB margin, which has substantially more syn- and post-rift sediments. Despite the differences in thickness, the syn-rift sedimentary package on the Wilkes Land margin exhibits a similar style of extensional faulting and seismic character to its GAB margin counterpart. In comparison, post-rift sequences on the Wilkes Land margin are markedly different in geometry and seismic character from those found on the GAB margin. Isopach mapping shows substantial differences in the thickness of the post-breakup sediments, suggesting different sediment sources for the two margins. The Late Cretaceous interval termed the "Hammerhead Supersequence" provides much of the post-rift thickness for the GAB margin as a result of large sediment influx into the basin. This supersequence is characterised by a thick progradational succession and was deposited in fluvio-deltaic and marine environments. The equivalent succession on the Wilkes Land margin has a different seismic character. It is thinner and aggradational, which is interpreted to represent a distal marine environment of deposition.

Introduction

Despite the key role the conjugate Great Australian Bight (GAB) and Antarctic margins play in understanding the Cretaceous–Cenozoic evolution of the Southeast Indian Ocean, no regional stratigraphic framework exists to allow for a consistent interpretation of sedimentary sequences across the two margins. Totterdell *et al.* (2000) previously identified ten supersequences from Late Jurassic to Holocene in the Bight and Eucla basins of the GAB margin that document the extension between Australia and Antarctica, and the subsequent breakup. The Bight Basin is a large Jurassic–Cretaceous basin extending from the Leeuwin Fracture Zone in the west and to Kangaroo Island in the east. The basin contains five main depocentres—the Ceduna, Duntroon, Eyre, Bremer and Recherche sub-basins (Bradshaw et al, 2003). To the north and east it is bounded by shallow, mostly Proterozoic basement with a thin covering of Cretaceous to Cenozoic sediments (Totterdell *et al.* 2000). The basin underlies the continental shelf and slope including the Eyre and Ceduna terraces, resulting in variable water depths over the basin. The younger Cenozoic aged Eucla Basin unconformably overlies the Bight Basin and consists of cool-water carbonates (Totterdell & Bradshaw 2004). The Bight Basin spans several different basement terranes from the Albany-Fraser Orogen in the west to the Gawler Craton in the east. The basement trends influenced the structural development and internal subdivision of the basin (Totterdell *et al.* 2000, Totterdell & Bradshaw 2004, Gibson *et al.* 2012). The basin was initiated during the breakup of eastern Gondwana and the separation of Australia and Antarctica, and developed through a series of rift and thermal subsidence phases. There are four basin phases identified by Totterdell *et al.* (2000) and Totterdell and Bradshaw (2004). The first phase was a period of upper crustal extension that was active during the Middle–Late Jurassic. Following this was a period of thermal subsidence during the Early Cretaceous. During the Albian, there was an increase in the subsidence rate and possible lower crustal extension and a final phase of thermal subsidence in the Late Cretaceous. Initial breakup of the two margins also coincided with uplift along the Eastern Highlands of Australia and the Transantarctic Mountains, which may have provided the principal sediment source areas for post-rift sedimentary sequences.

Compared with the GAB margin, the geology of the conjugate eastern Antarctic margin is poorly understood. Antarctica's Neogene evolution has been dominated by glacial processes giving the shelf and slope an incised and variable morphology that is different from typical passive margins (Close *et al.* 2007). The basement is interpreted by Colwell *et al.* (2006) to be of Archean–Proterozoic age. Other distinctive characteristics of the margin include an average continental slope depth of 5000 m and a commonly wide shelf and wide zone of ambiguous crust. The morphology of the Wilkes Land–Terre Adélie margin of Antarctica is controlled by the breakup of Australia and Antarctica. Along this margin, with a shelf width ranging from 100–200 km, there is a relatively consistent, symmetric morphology (Colwell *et al.* 2006, Direen *et al.* 2011). In this paper, we develop a sequence stratigraphic framework for the Wilkes Land margin following the interpretation of Totterdell *et al.* (2000) to evaluate both syn- and post-rift similarities and differences between this conjugate margin pair. .

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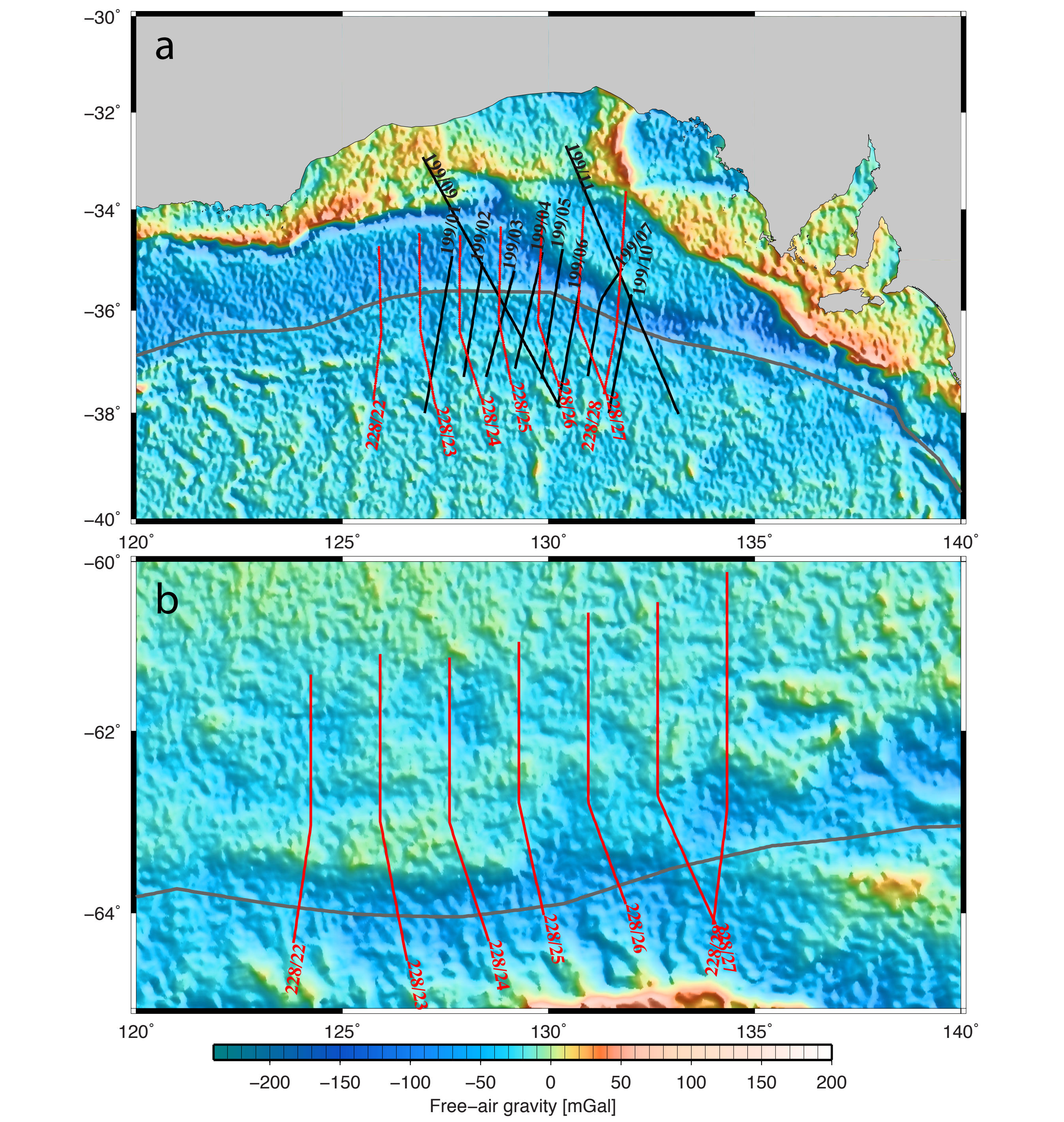

Figure 1. Seismic profile locations overlain on free-air satellite gravity anomalies, (a) Great Australian Bight with survey GA-199 profiles 1 to 11 (black) and GA-228 profiles 22 to 28 (red), reconstructed for breakup time at ~83 Ma around the Santonian–Campanian boundary. Because all profiles include substantial portions of oceanic crust, which did not yet exist at 83 Ma, they overlap in this reconstruction; (b) Wilkes Land GA-228 profiles 22-28 (red).

Data and methods

2D Seismic Seismic surveys GA-199 and GA-228 (Fig. 1), carried out in 1997 and 2001, respectively, provided the key data sets used to correlate the sedimentary successions on the conjugate GAB and Wilkes Land margins, and to build a stratigraphic framework for the latter margin. Seismic survey GA-199 (Figure 1) comprises eight profiles oriented perpendicular to the coast, and three oblique to the coast. Data from this survey was used to understand the geometry and distribution of sediments in the most distal parts of the Bight Basin, where the basin thins and eventually downlaps onto oceanic crust. Survey GA-228, located along the Wilkes Land coast of Antarctica (Fig. 1), covers a large area, and has a sparse seismic line spacing of approximately 90 km. The distance between seismic lines combined with the lack of stratigraphic control and tie-lines made horizon correlations between the lines challenging. Due to the presence of sea ice, Survey GA-228 was restricted to imaging the more distal units and structures of Wilkes Land; as a result, the older supersequences identified on inboard lines on the GAB margin are not imaged on this data set. The major unconformities along the Antarctic margin identified here follow the interpretation of Colwell *et al.* (2006) in principle, with additional horizons and sequences interpreted to correlate to the Bight Basin stratigraphy. Sub-division and correlation of post-breakup sequences was difficult as the margins no longer shared the same sediment source after breakup. Consequently, our interpretation of the Antarctic margin focuses on the Cretaceous sequences deposited prior to, and immediately after, breakup.

Seismic stratigraphic interpretation

Unlike the GAB margin, no exploration wells or age data are available on the Wilkes Land margin. While an attempt is made to correlate these sequences to the Bight Basin of the GAB margin (Table 1), there are inevitable differences, especially in the post-breakup sediments, caused by differences in accommodation and sediment supply. Therefore the seismic stratigraphy along the Wilkes Land margin was established based on the identification of key horizons and changes in seismic character.

Australian southern margin interpretation

Totterdell et al. (2000) identified ten supersequences within the Bight Basin, The sequences are variably developed and distributed in the different sub-basins of the Bight Basin. The Middle Jurassic–earliest Cretaceous rift phase and subsequent Early Cretaceous thermal subsidence phase sequences are best developed in the Eyre and Duntroon sub-basins; those sequences are not seen on the Wilkes Land seismic data (Fig. 2, interpretation key in Table 1). The younger (Albian-Maastrichtian) basin phases, including the post-breakup succession, are best developed in the Ceduna Sub-basin.

Sea Lion Supersequence

The Callovian-Kimmeridgian Sea Lion Supersequence is the oldest supersequence in the Bight Basin. In the exploration well Jerboa-1 in the Eyre Sub-basin, the supersequence is in faulted contact with meta-sedimentary basement (Totterdell *et al.* 2000). The supersequence comprises fluvial-lacustrine sandstone and mudstone deposited in a series of half-graben. The supersequence has a divergent wedge geometry and a low amplitude seismic character, with reflections generally diverging towards the bounding faults of half-graben and onlapping the hanging wall. This internal structure makes this supersequence easily distinguishable from the overlying sediments and the basement.

Minke Supersequence

The Minke Supersequence (Tithonian–E. Berriasian) directly overlies the Sea Lion Supersequence and forms the upper part of the extensional megasequence. The Minke Supersequence consists of retrogradational lacustrine claystone overlain by progradational claystone, siltstone and sandstone. The supersequence has a variable seismic character, comprising low to moderate amplitude reflections that onlap the sequence boundary on the hinge side of the half-graben.

Southern Right Supersequence

The Berriasian Southern Right Supersequence comprises a basal lowstand fluvial sandstone overlain by a thin layer of lacustrine claystone. Accommodation space for this sequence was created by thermal subsidence and compaction following the first phase of extension. The seismic character of the unit is quite variable suggesting significant lateral lithofacies changes within the supersequence.

Seismic horizon	Approx. age	Colour code
Oligocene unconformity	Late Oligocene	
Base Dugong S'seq.	base Middle Eocene	
Base Wobbegong S'seq.	base Palaeocene	
Hammerhead 3	intra-Campanian	
Hammerhead 2	base Campanian	
Base Hammerhead S'seq.	latest Santonian	
Intra-Tiger	base Santonian	
Base Tiger S'seq.	base Turonian	
Intra-White Pointer	intra-Cenomanian	
Base White Pointer S'seq.	near base Cenomanian	
Base Blue Whale S'seq.	late Albian	
Base Bronze Whaler S'Seq.	base Valanginian	
Base Southern Right S'seq.	near base Berriasian	
Base Minke S'seq.	base Tithonian	
Base Sea Lion S'seq.	intra-Callovian	

Table 1. Key for seismic horizons in the Bight Basin established from Survey GA-199 (Totterdell et al. 2000). Note that not all horizons are shown on all profiles.

Bronze Whaler Supersequence

The Valanginian–middle Albian Bronze Whaler Supersequence consists of a thick aggradational to progradational succession dominated by fine-grained fluvial and lacustrine deposits. In the easternmost parts of the Bight Basin, there is palynological evidence for intermittent marine conditions in the upper part of the succession. The seismic character of the Bronze Whaler Supersequence varies across the basin. In the Eyre Sub-basin reflections are low to moderate amplitude with higher-amplitude reflections near the top of the unit, possibly indicating the presence of coal. In the down-dip Recherche Sub-basin, reflections are of similar amplitude but are more continuous. In much of the Ceduna Sub-basin the unit cannot be identified as it lies beneath the seismically transparent Blue Whale Supersequence.

Blue Whale Supersequence

The mid Albian-Cenomanian Blue Whale Supersequence represents the first major marine flooding event in the Bight Basin. In wells, the unit consists of nearshore and restricted marine siltstones and exhibits an aggradational to progradational character. In the Eyre Sub-basin the Blue Whale Supersequence truncates and incises into the underlying Bronze Whaler Supersequence. In the Ceduna Sub-basin the Blue Whale Supersequence forms the mobile substrate for gravity-driven deformation (Figure 2a). Across much of the sub-basin, the unit has a relatively transparent seismic character consistent with overpressured, ductile mudstone and acts as a decollement surface for younger growth faults.

White Pointer Supersequence

In Bight Basin wells, which are largely located in the inboard parts of the basin, the Cenomanian White Pointer Supersequence consists of a dominantly aggradational succession of fluvial to lagoonal siltstone and mudstone with minor components of sandstone and coal. In the Ceduna Sub-basin the unit is characterised by growth strata associated with a series of listric faults that sole out in ductile mudstone of the underlying Blue Whale Supersequence. Growth faults are accompanied further down-

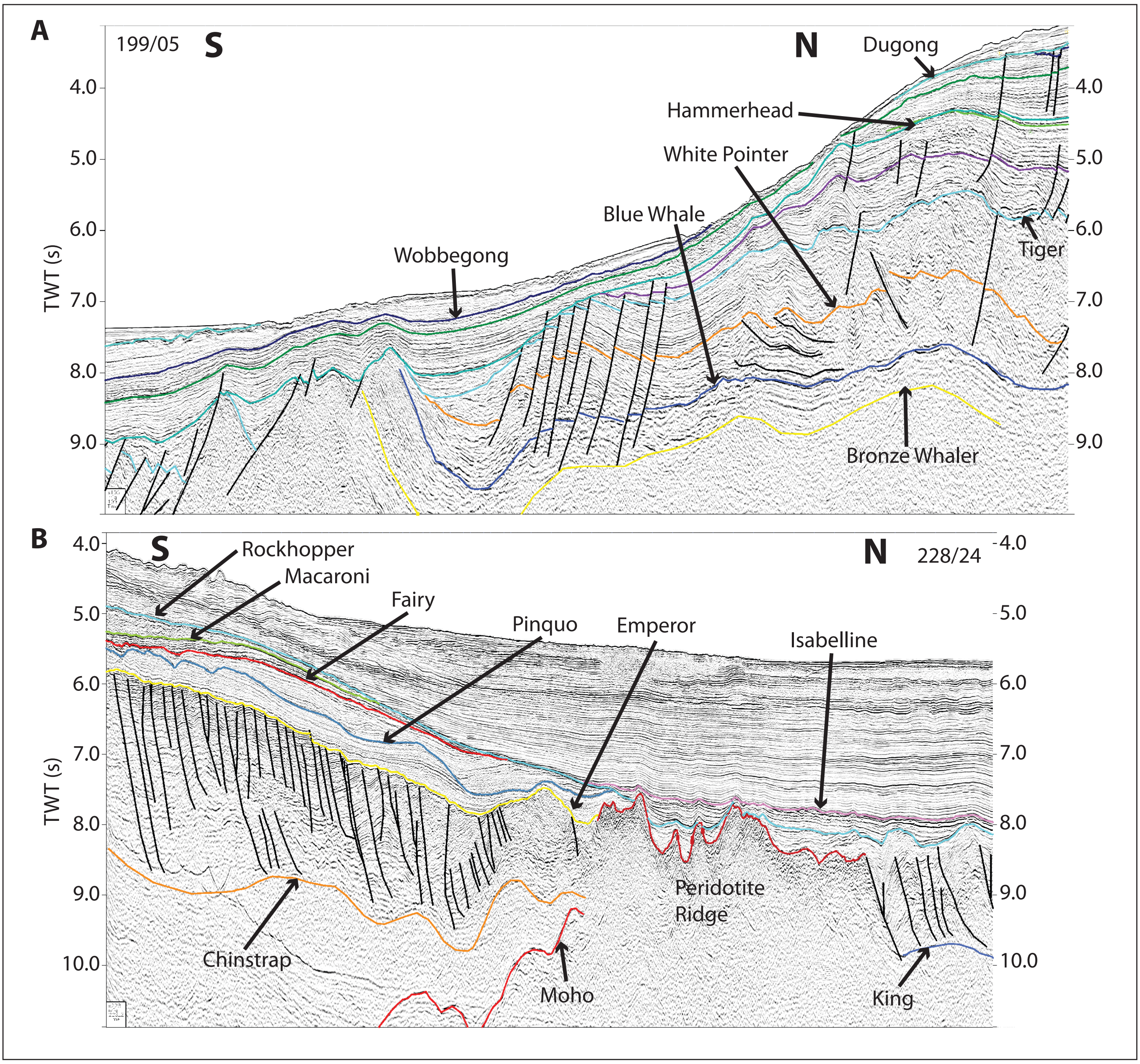

Figure 2. (a) Representative stratigraphy of the GAB margin, illustrated by a portion of seismic profile 199-05 (roughly northern half of profile shown on Figure 8). The oldest resolvable sedimentary sequence is the Bronze Whaler Supersequence, which terminates at a basement high, interpreted as a peridotite ridge (Sayers et al. 2001). (b) Detailed portion of seismic profile 228-24 on the Wilkes Land margin (shotpoints 65–3353). The syn-rift sequence is terminated by the base of the Emperor Sequence, interpreted to be correlative with the latest Santonian Hammerhead Supersequence on the Australian conjugate margin, roughly corresponding to magnetic anomaly 34 (~83 Ma). The profile exhibits a highly faulted basin at the landward end of the profile. Seaward of this basin, a prominent basement ridge is visible which is interpreted as a peridotite ridge.

dip by toe thrusts and contractional deformation (Figure 2a). A horizon has been mapped within the sequence separating sediments within the rotated fault blocks from overlying flat-lying strata. This horizon marks the end of movement along the growth faults, which could be due to the dewatering of overpressured shale. The White Pointer supersequence has a high-amplitude, high-continuity seismic character. The base of the succession, along the listric growth faults, has a generally chaotic or transparent seismic character.

Tiger Supersequence

The Turonian-Santonian Tiger Supersequence consists of predominantly marginal marine to marine mudstone and sandstone. In the Eyre and Duntroon sub-basins, the supersequence has been mostly eroded. An unconformity within the supersequence at the base of a widespread low-amplitude seismic unit divides the supersequence in to two distinct sequences. In the Ceduna Sub-basin the supersequence is extensively faulted, largely due to the reactivation of older faults. This reactivation is interpreted to coincide with the onset of seafloor spreading (Totterdell *et al.* 2000, Sayers *et al.* 2001). The seismic character is typical of an interbedded shale and sandstone and/or siltstone with flat-lying strata and continuous high to moderate-amplitude reflections.

Hammerhead Supersequence

The latest Santonian–Maastrichtian Hammerhead Supersequence is the first of the post-breakup sedimentary units.

The base of the supersequence is strongly erosional in places and marks the commencement of breakup (Totterdell *et al.* 2000, Krassay & Totterdell 2003). The Hammerhead supersequence marks the influx of coarse-grained deltaic sediments into the basin. The Hammerhead delta had a long-lived, sand-rich sediment supply related to the erosion of areas to the east and northeast (Krassay & Totterdell 2003). In the landward parts of the Ceduna Sub-basin, the succession exhibits a very incoherent seismic character of variable amplitudes and extremely discontinuous reflections consistent with poorly interconnected channel sandstones in a fluvial to delta plain setting. The presence of thin coal and siltstone interbedded with the sandstone suggest coaly marshes and small lakes in the interfluves regions. Further basinward, the supersequence is characterised by strongly developed shelf margin clinoforms. The overall character of the Hammerhead Supersequence is aggradational–progradational–retrogradational, and three third-order sequence sets can be identified (Figure 2a). Initial high sediment supply and/or low accommodation resulted in rapid progradation of the fluvio-deltaic sequences. During the Cenomanian–Maastrichtian, continued progradation and aggradation led to the build up of a thick sediment wedge at the shelf margin and eventually to slope instability and gravity-driven growth faulting (Krassay & Totterdell 2003).

Wobbegong Supersequence

The Wobbegong Supersequence, the basal unit of the offshore Eucla Basin, was deposited during the Paleocene–Early Eocene after a hiatus of 5–7 million years that produced an unconformity with the underlying Hammerhead succession. The Wobbegong Supersequence comprises marginal marine sandstones with minor siltstones. The seismic character of the Wobbegong Supersequence is very uniform with low-amplitude reflections that suggest that the unit is lithologically very consistent. In inboard parts of the basin, the unit is characterised by a distinct highstand systems tract comprising a series of progradational lobes. The unit is generally very thin, although in some locations a thick succession is present within large canyons, and a thick Wobbegong Supersequence lobe is present along much of the lower continental slope (Figure 2a).

Dugong Supersequence

The Middle Eocene–Holocene Dugong Supersequence consists of a basal coarse sandstone overlain by a thick cool-water carbonate succession. In outboard areas of the Bight Basin where the Wobbegong Supersequence is very thin, the base of the Dugong Supersequence can be difficult to distinguish seismically from the base of the Wobbegong Supersequence. Several sequence boundaries can be identified within the Dugong supersequence indicating a complex depositional history. Across the basin, the seismic character of the supersequence is highly variable, ranging from thick progradational units to reefal build-ups.

Wilkes Land interpretation

Our interpretation of seismic sequences along the Wilkes Land margin (Fig. 2b) is based on the identification of key horizons and changes in seismic character. Unlike the Bight margin, no exploration wells or age data are available on the Wilkes Land margin. Table 2 shows our suggested correlation of seismic sequences between the two margins.

GAB margin sequences (from Totterdell et al., 2000)	**Wilkes Land margin (this study)**
	Isabelline
	Rockhopper
	Macaroni
Base Dugong	*Fairy*
Base Wobbegong	Pinquo
Base Hammerhead	Emperor
Base Tiger	Gentoo
Base White Pointer	Chinstrap
Base Blue Whale	Not identified
Base Bronze Whaler	Not identified
Base Southern Right	Not identified
Base Minke	Not identified
Base Sea Lion	Not identified
	King*

Table 2. Identified seismic horizon boundaries from the Wilkes Land margin correlated against Totterdell et al. (2000) GAB supersequence boundaries. Italicised horizon names are not directly correlated with the nomenclature of the GAB margin as these sediments were deposited post-breakup.

* The King sequence identified on the Wilkes Land margin represents altered sedimentary rocks located seaward of the basement high.

Chinstrap Sequence

The base of the Chinstrap Sequence marks the base of resolvable sedimentary succession along the Wilkes Land margin. The sequence overlies basement that is interpreted to be the East Antarctic Shield. The sequence varies in thickness along the margin and is truncated seaward by the basement high. Syn-rift faulting within this unit is common (Fig. 2). To the east, some reverse faulting is observed along the flanks of a basement high. These reverse faults may be the result of gravity sliding. This sequence has a variable seismic character; for the most part, low-amplitude discontinuous reflectors predominate. In segments within individual fault blocks, the sequence exhibits higher amplitudes and more continuous reflections.

Gentoo Sequence

The Gentoo Sequence is interpreted to be the equivalent of the Tiger Supersequence in the Bight Basin. Like the Tiger Supersequence, in the outboard parts of the basin, the Gentoo Sequence is commonly eroded. Where the Gentoo Sequence is preserved, it overlies the Chinstrap Sequence within the closely spaced fault blocks at the southern end of the seismic lines. The base of the Gentoo Sequence is marked by a high-amplitude reflector within these fault blocks.

Emperor Sequence

The Emperor Sequence is characterised by low-amplitude, discontinuous reflections. A horizon similar to the base Emperor horizon was interpreted by Colwell *et al.* (2006) as Turonian in age. However, we consider this horizon to have stratigraphic and structural similarities to the base of the Hammerhead Supersequence in the outer Bight Basin (Figure 2a and b) and, therefore, interpret the base of the Emperor Sequence as latest Santonian–Campanian. This horizon marks the point of breakup with an unconformity that truncates the underlying Gentoo and Chinstrap sequences.

Pinquo Sequence

The base of the Pinquo Sequence is highly erosional (Fig. 2b). Though not directly comparable with any supersequence on the

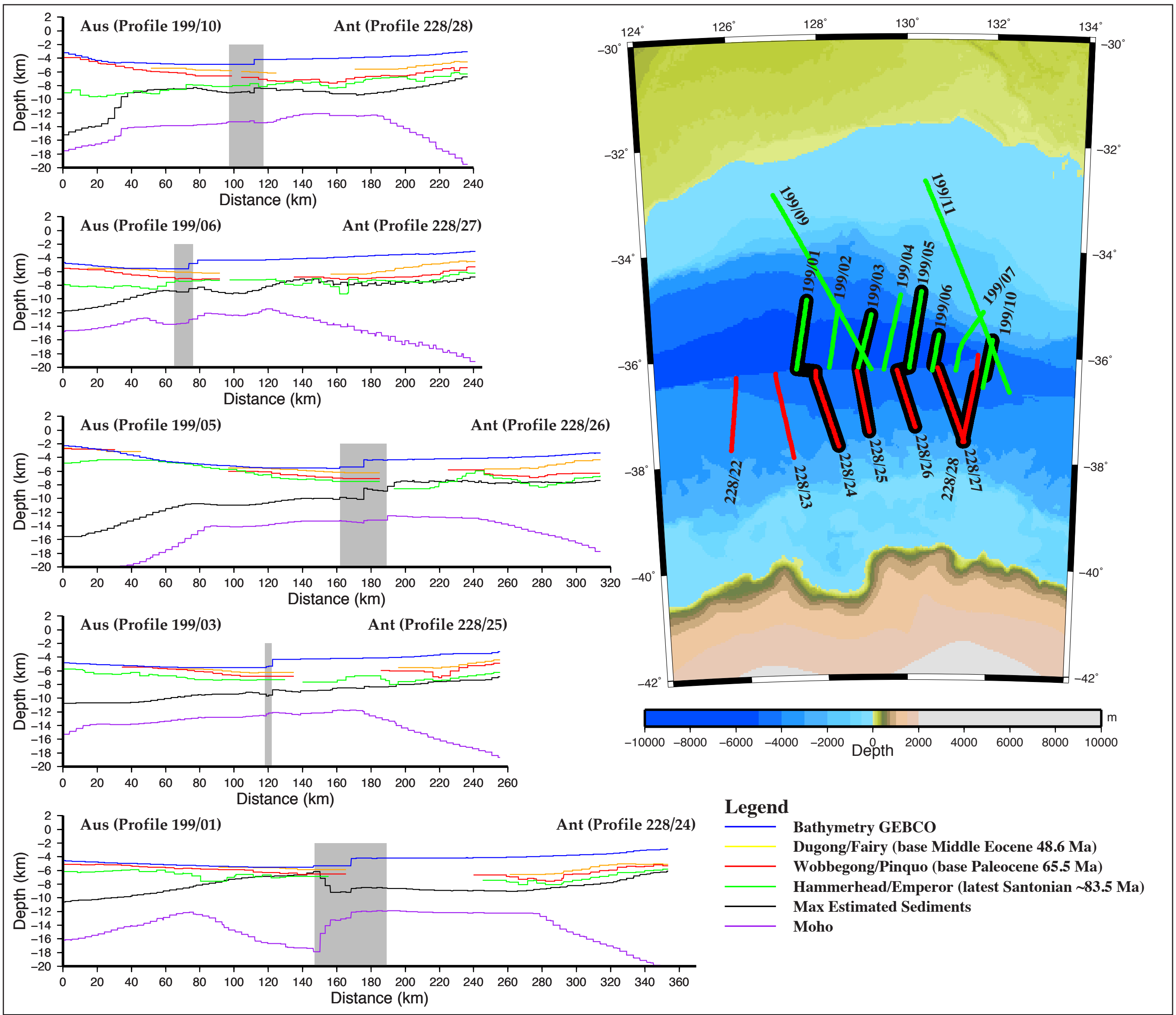

Figure 3. Profiles showing key sedimentary units, with arrows pointing to the unit bases, and crustal horizons along selected roughly conjugate profiles across the Australian-Antarctic margins reconstructed at continental breakup time (~83 Ma) in cross-section (left) and map view (right), overlain over reconstructed bathymetry. Grey shaded region on map indicates the connection between conjugate profiles. Paired profiles are highlighted with thick black lines in the map. For more detail regarding the maximum total sediment thickness and the Moho, see Whittaker et al. (2012).

GAB margin, the presence of canyons and incisions suggests that it was deposited as a result of changes in sea level, and may be loosely related to the Wobbegong Supersequence based on the similar timing of deposition. In the western part of the Wilkes Land margin, the upper part of the sequence is dominated by a series of seaward-dipping faults that sole out along the base of the sequence. The seismic character of the Pinquo Sequence is very similar to the underlying Emperor Sequence, and therefore may consist of a similar lithology.

Fairy Sequence

The Fairy Sequence blankets the underlying faults with a thin layer of sediments. The base of the Fairy Sequence is very distinct in the east, comprising a high-amplitude reflector overlying a faulted Pinquo Sequence. To the west this sequence becomes less distinct because the seismic character of the unit changes from low-amplitude reflections to higher amplitudes with some very bright reflectors that may indicate the presence of coal or volcanics. One possible explanation for the change in seismic character is a different sediment source. Despite the changes of the seismic character of the Fairy Sequence along the margin, the thickness of the unit remains constant.

Macaroni Sequence

Like the underlying Fairy Sequence, the Macaroni Sequence is also very thin and shares a similar seismic character with reflections of only slightly higher amplitude. A change occurs westward with reflectors becoming brighter. At the westernmost extent of the interpretated area, the Macaroni Sequence thickens dramatically, with continuous flat-lying strata exhibiting moderate-amplitude reflections overlying a section with the more discontinuous character that is typical of this unit along the margin.

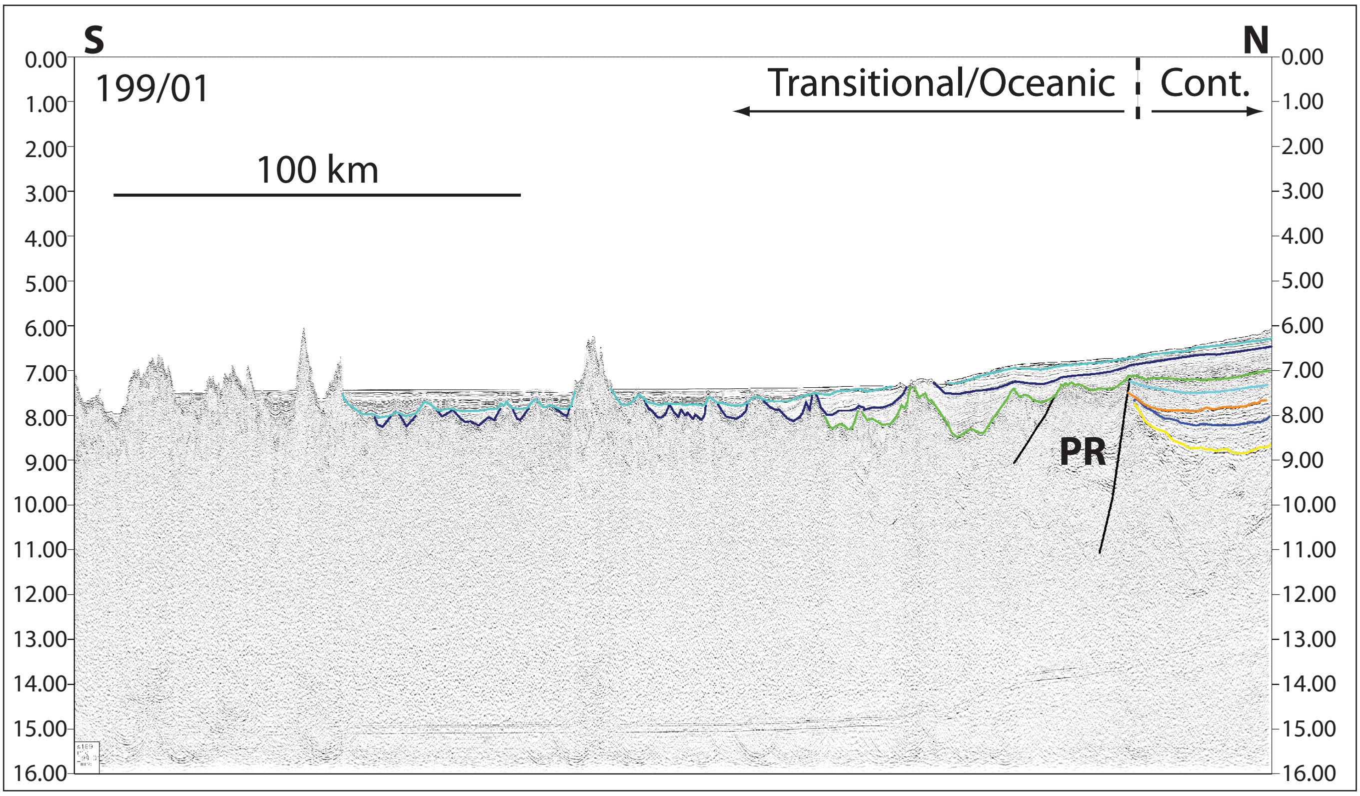

Figure 4. Seismic line 199/01 on the GAB margin. Interpretation by Totterdell et al. (2000). The basal Hammerhead boundary (bright lime green) is succeeded by the basal Wobbegong horizon (dark blue) in a southerly direction beyond the continental crust–transitional/oceanic crust boundary, indicative of younging of the basement in a southerly direction. Inboard of the Hammerhead Supersequence, the base of the section cannot be constrained well but is probably not much older than the base Bronze Whaler horizon (yellow). Note the rough topography of the oceanic basement including a number of large seamounts. PR—peridotite ridge.

Rockhopper horizon

The Rockhopper horizon marks a large-scale angular unconformity that separates the underlying strata from the younger flat lying glacial sediments (Fig. 2b). It was interpreted as Eocene age by Colwell *et al.* (2006) but its age is not well constrained. Extreme erosion of the underlying sediments is observed along the margin with post-breakup sequences being terminated by this boundary. In the west, the unconformity extends steeply upwards causing a thickening of the underlying Macaroni Sequence.

Isabelline horizon

The Isabelline horizon separates the younger flat-lying glacial sediments that onlap the Rockhopper horizon, from the older, more chaotic sediments that are found in the depressions of the Rockhopper horizon (Fig. 2b). The chaotic nature of the sediments suggests that these sediments are reworked and have been deposited as the result of gravity-driven mass movement.

King Sequence

The base of the King Sequence (Fig. 2b, northern portion of profile) marks the conservative interpretation of the base of sediments with the transitional basin that lies seaward of an interpreted peridotite ridge (Fig. 2b). It is a complex sequence with the lower parts being highly faulted, and contains bright discontinuous reflections indicating igneous intrusions (sills, dykes). Overlying the faulted component of the sequence is a zone of very low-amplitude, discontinuous reflections. The sediments within this sequence cannot be correlated with those on the landward side of the basement high because of their different seismic character.

Seismic sequences on conjugate profiles

Profile reconstruction

Seismic profiles from the conjugate margins were reconstructed at continental breakup time (~83 Ma) using the rotation from Williams *et al.* (2011) (Fig. 3). This reconstruction provides juxtapositions of profiles 199/01(Fig. 4) with 228/23 or 228/24 (Fig. 5 shows profile 228/24,), profiles 199/05 (Fig. 6) with 228/26 (Fig. 7) and 199/10 (Fig. 8) with 228/28 (Fig. 9). Major sedimentary and crustal horizons including the Moho were reconstructed along these profile pairs, as well as two additional pairs not shown here in detail (Fig. 3) to provide a simple graphical method of illustrating differences in juxtaposed sequences and crustal thicknesses. See Whittaker *et al.* (2012) for additional information on data and methods used in constructing crustal boundaries.

The GAB margin, Line 199/01

This profile (Fig 4) mostly displays oceanic crust, with a basement high, interpreted as a peridotite ridge based on potential field data, seismic reflection data, and a comparison with the

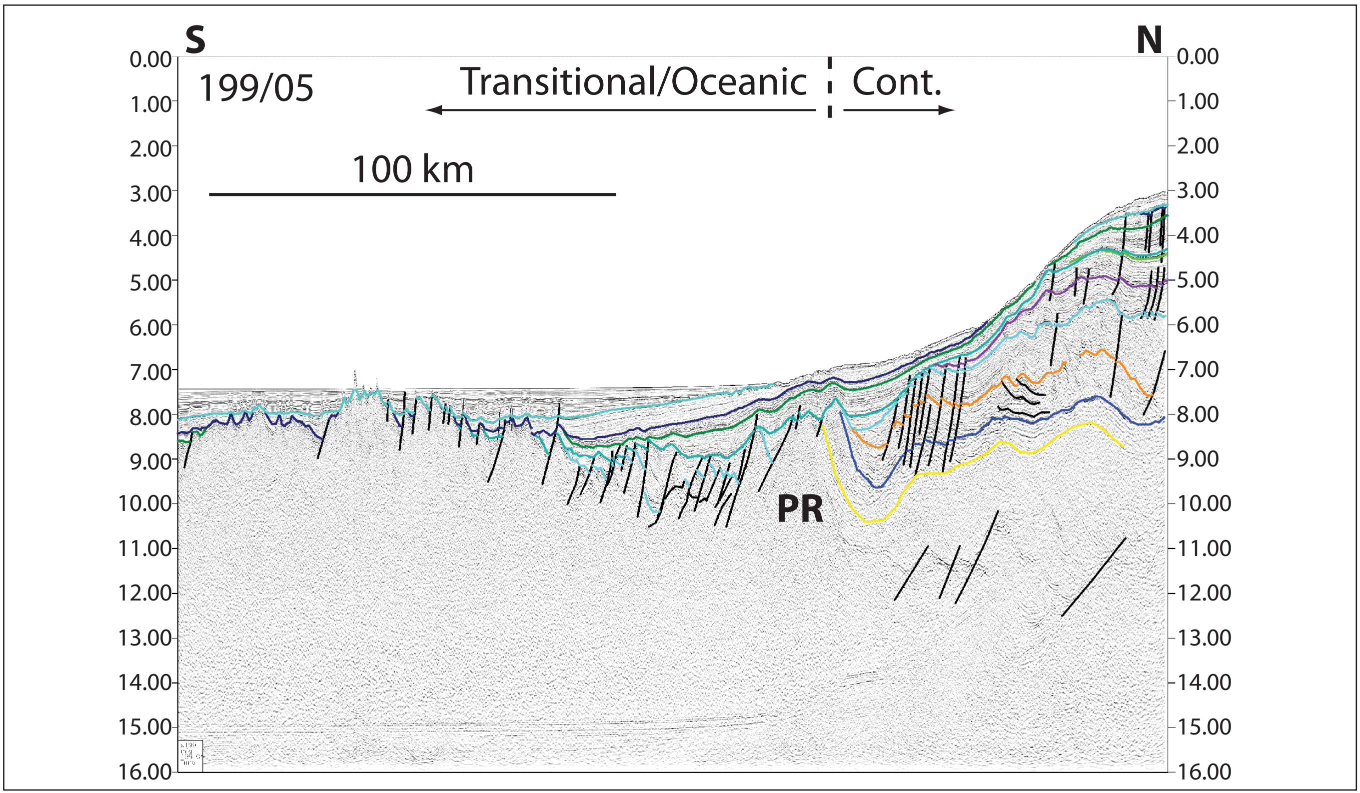

Figure 5. Seismic line 228/24 on the Wilkes Land margin, conjugate to line 199/01 (Fig. 4). The boundary between unambiguous continental crust and transitional/ ocean crust is shown. The small basin located seaward of the peridotite ridge is interpreted as reflecting extremely slow seafloor spreading, characterised by intermittent magmatic pulses separated by periods of oblique extension (Whittaker et al. 2010) between magnetic anomalies 34y (~83 Ma, breakup) and 33y (~73 Ma) (not shown here). Also note the pronounced rough topography of the oceanic basement. PR—peridotite ridge.

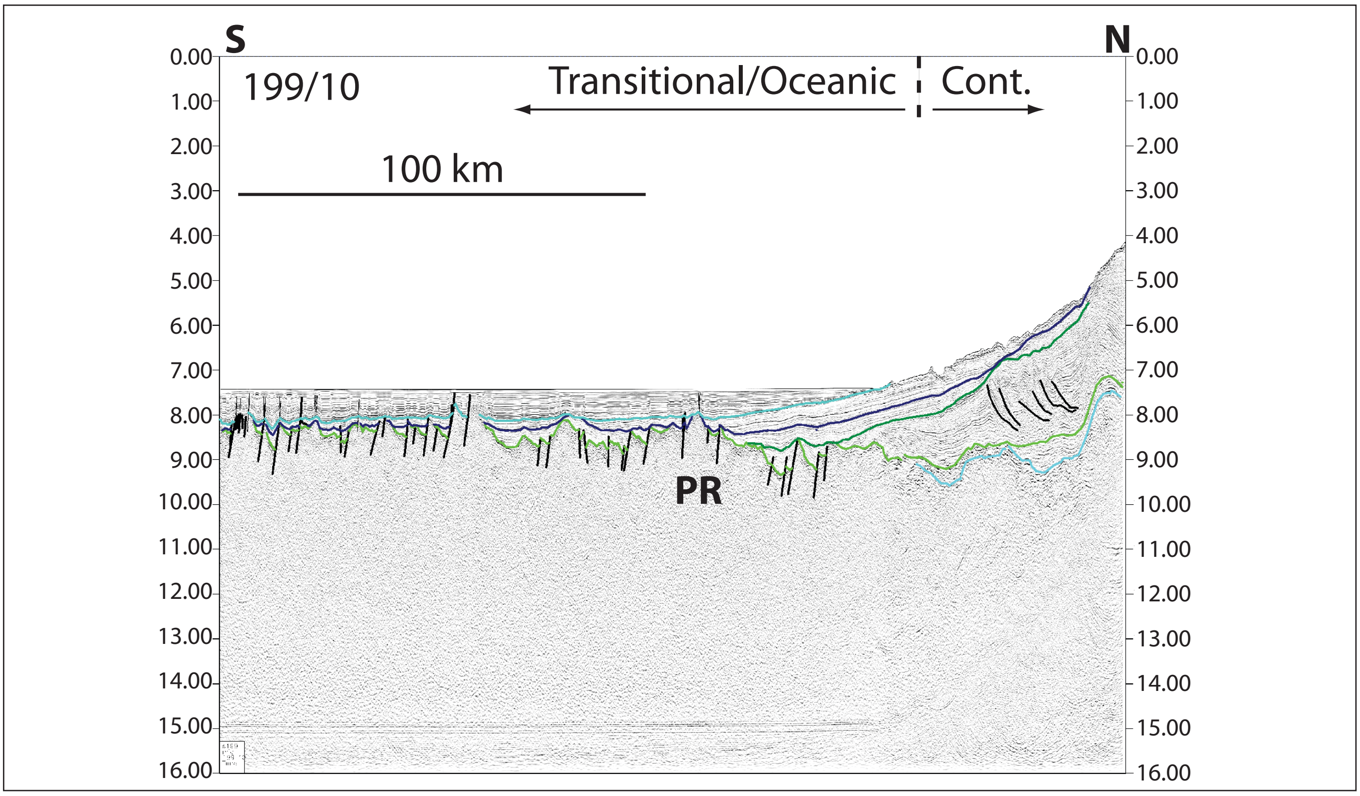

Figure 6. Seismic line 199/05 on the GAB margin. Interpretation by Totterdell et al. (2000). Inboard of the interpreted exhumed mantle peridotite ridge, the base of the section cannot be constrained, but is probably not much deeper than the base Bronze Whaler horizon (yellow). Outboard of the exhumed mantle peridotite the base Tiger (light blue) horizon is the oldest interpreted horizon, succeeded by intra-Hammerhead horizons (teal and green) and then by the base Wobbegong horizon (dark blue). We have interpreted a small half graben within oceanic crust filled with sediments corresponding to the uppermost Hammerhead sequence further seaward. PR —peridotite ridge.

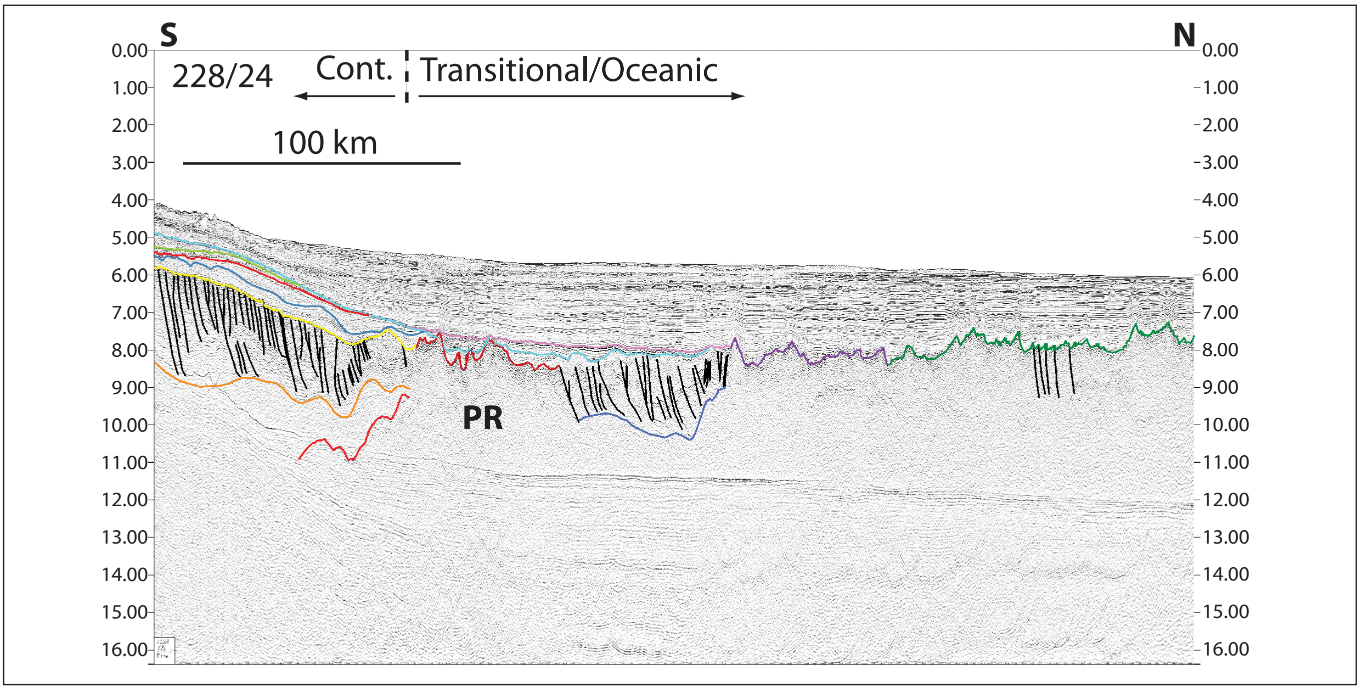

Figure 7. Seismic interpretation of 228/26 on the Wilkes Land margin, conjugate to line 199/05 (Fig. 6). Compared with Line 228/24 (Fig. 4) the peridotite ridge is less obvious. The oldest resolvable sedimentary horizon is the base Chinstrap horizon, which terminates at the peridotite ridge. Also note evidence for compressional fault reactivation in the main rift basin, affecting the Paleocene/Eocene Pinquo and Fairy sequences, equivalent to the Wobbegong and Dugong Supersequences on the GAB margin. Rough topography of the oceanic basement roughness is similar to that of Line 228/24. PR—peridotite ridge.

sampled mantle peridotites from the Iberian margin (Sayers *et al.* 2003), marking the boundary between unequivocal continental crust and transitional/ocean crust. It is not known whether this ridge represents unroofed continental or oceanic mantle. On this profile the basal post-rift Hammerhead Sequence is succeeded by the Wobbegong Sequence. The oceanic basement on this line is extremely rough, and includes a number of large seamounts.

The Antarctic margin, Line 228/24

Line 228/24 (Figure 5) is markedly different from the Wilkes Land margin profiles located further east, both in terms of sedimentary sequences and seismic character. Seaward of the main rift basin a prominent basement ridge is visible, which has been interpreted as a peridotite ridge based on potential field models (Colwell *et al.* 2006); as on the Australian side, this ridge could be composed of either continental or oceanic mantle. These two features mark the COB, in this context, reflecting the boundary between unambiguous continental crust and transitional/ocean crust. Post-breakup sediments show brighter reflections indicative of either coal or an interbedding of sandstones and mudstones, suggesting lateral variations in facies in the western portion of the Wilkes Land coast. The King Sequence, found in a confined basin seaward of the peridotite ridge, is interpreted to consist of sediments that were altered during mantle exhumation. Intrusions appear to be localised within the faulted section of the King Sequence and overlain by a bland zone with weak seismic reflections. The oldest oceanic crust is moderately faulted before becoming smoother seaward. The small basin located seaward of the peridotite ridge is interpreted as reflecting extremely slow seafloor spreading, characterised by intermittent magmatic pulses separated by periods of oblique extension (Whittaker *et al.* 2010) between magnetic anomalies 34y (~83 Ma, breakup) and 33y (~73 Ma).

The GAB margin, Line 199/05

On this profile (Figure 6) the oldest resolvable sedimentary sequence is interpreted to be a thin Bronze Whaler succession underlying the decollement at the base of the Blue Whale Supersequence. This section terminates at the basement high. Extensional faulting propagates downward from the Tiger Supersequence to the Blue Whale Supersequence and into the older sediments. While faulting is observed in all of the supersequences, there is an increase in faulting basinward, close to the location of the peridotite basement high. The Blue Whale and White Pointer supersequences at the landward edge of the basement form a depression before being folded up onto the basement high (Figure 6), presumably related to the exhumation of continental mantle to form the peridotite basement high. The thin Tiger Supersequence appears to onlap the basement high. This interpretation is supported by the geometry of the Moho, which can be seen underneath the continental crust rising rapidly towards the basement high, reinforcing the idea that the peridotite ridge may represent continental mantle. Seaward of the basement high, a small sedimentary basin is present (Figure 6). The Tiger Sequence in this basin is highly faulted and intruded. The geometry of this supersequence suggests that faulting occurred during and immediately after deposition with other faults being reactivated after breakup to produce the faulting within the Hammerhead Supersequence. The Hammerhead Supersequence is the first post-breakup unit on the margin. Totterdell *et al.* (2000) identify three different sequences within the Hammerhead (Table 1). The earliest oceanic crust is highly faulted, extending from the Wobbegong Supersequence through to the crust.

The Antarctic margin, Line 228/26

The oldest resolvable seismic horizon on line 228/26 (Figure 7) is the base Chinstrap horizon, which terminates at the basement

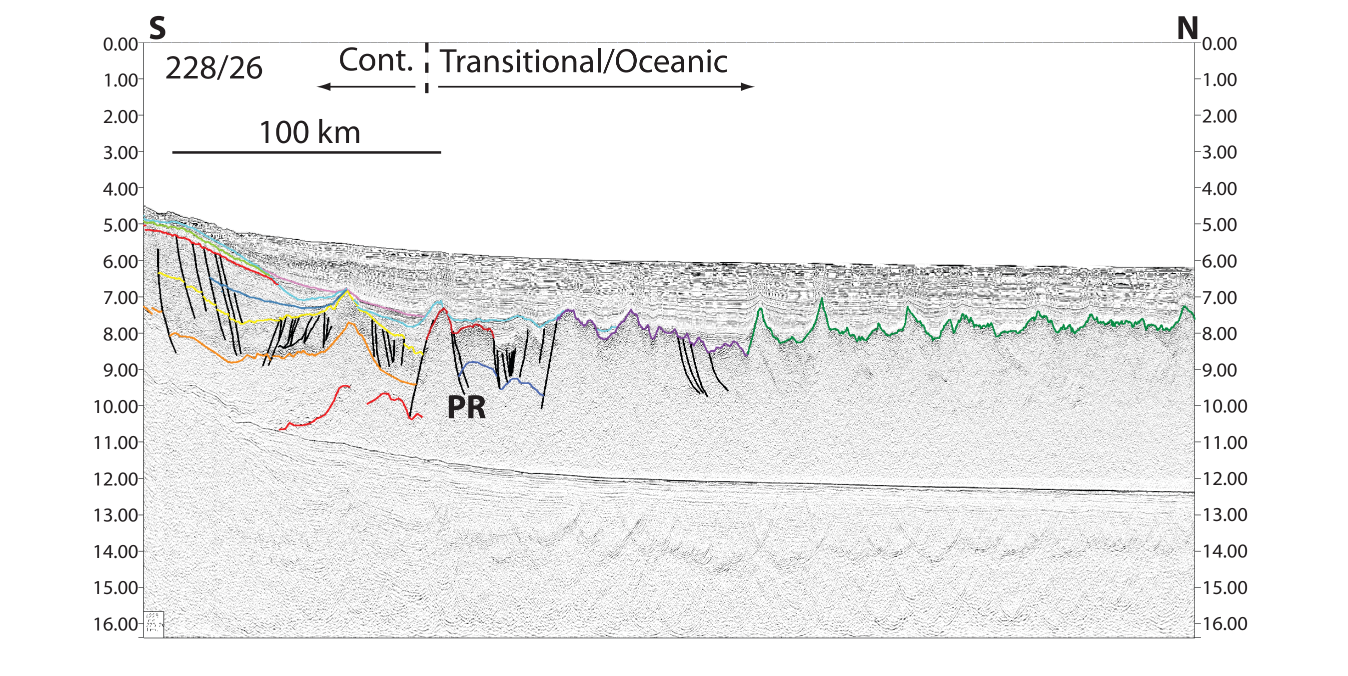

Figure 8. Seismic line 199/10 on the GAB margin. Interpretation by Totterdell et al. (2000). From the foot of slope, the basal Hammerhead Supersequence (bright lime green) directly overlies basement. Inboard of this region the basement cannot be interpreted well. Oceanic basement is considerably smoother than that shown on Line 199/01. PR—peridotite ridge.

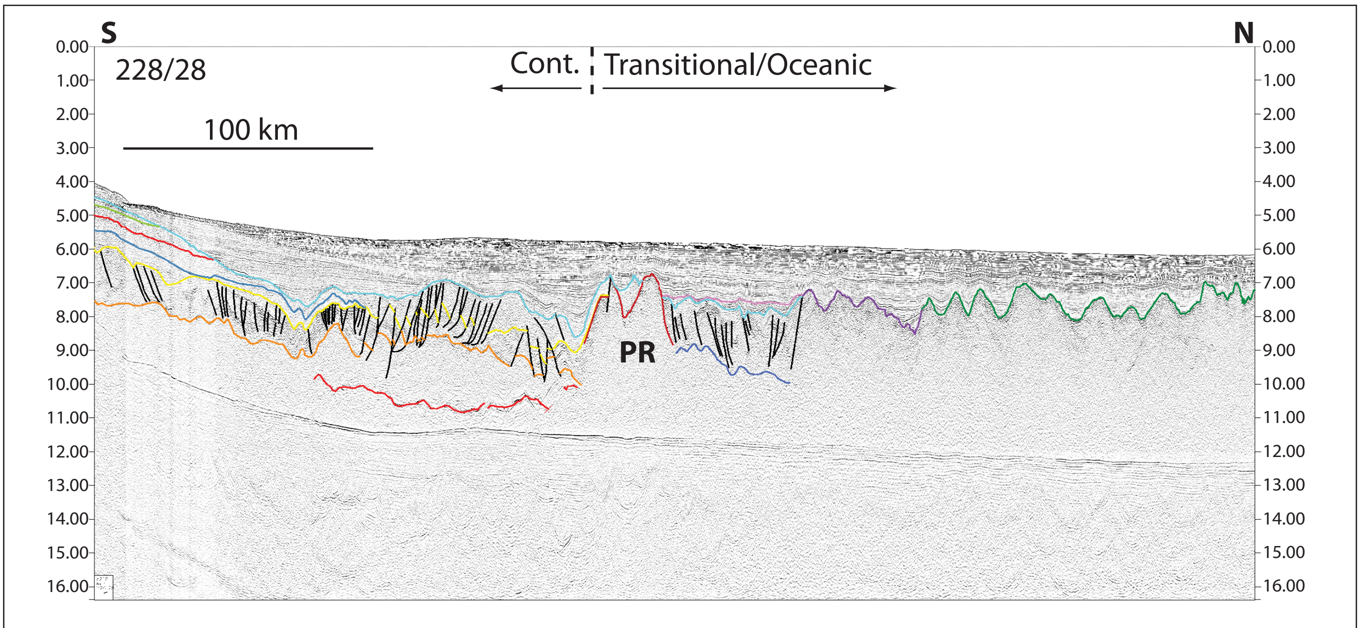

Figure 9. Seismic interpretation of 228/28 on the Wilkes Land margin, conjugate to line 199/10 (Figure 8). This profile overall is quite similar to 228/25 (Figure 7); however the oceanic basement is much smoother here. PR—peridotite ridge.

high. Landward of this point the Chinstrap Sequence is highly faulted. Underneath the Chinstrap Sequence, the Moho shallows towards the basement high. The faulting of the Chinstrap Sequence is significant and the overlying Gentoo Sequence is found only in the hinges of these faults, having been eroded before the overlying post-rift Emperor sequence was emplaced. There is evidence for post-rift reverse reactivation of syn-rift faults within the main rift basin, affecting the Emperor (~Campanian–Maastrichtian) and Pinquo sequences, terminating at the base Fairy horizon. The ?Eocene age (Colwell *et al.* 2006) Rockhopper Horizon is a very distinctive unconformity that extends out onto oceanic crust, with several older sequences being truncated by this horizon. Younger sediments are flat lying with minimal changes in amplitude and continuity.

The GAB margin, Line 199/10

Post-breakup sediments dominate along line 199/10 (Figure 8), with the oldest interpreted succession being the Tiger Supersequence. The overlying Hammerhead Supersequence is very thick in the north, but thins rapidly seaward. Toe-thrusts are seen in the thickest part of the sequence. Seaward, the lower part of the Hammerhead Supersequence is restricted to half-graben. The upper part of the supersequence, delineated by the Hammerhead-3 horizon, erodes the top of the underlying lower Hammerhead succession. The two Hammerhead successions are markedly different in their seismic character. The lower part of the Hammerhead Supersequence has moderate to high-amplitude reflectors, while the upper part has low-amplitude reflectors. The character of the base Hammerhead horizon also changes seaward. In the half-graben, its seismic character is translucent with low-amplitude, discontinuous reflectors.

The Wobbegong and Dugong supersequences maintain a fairly consistent thickness along the line. In the half-graben of seaward parts, the base of the Wobbegong Supersequence directly overlies the lower Hammerhead Supersequence. As there is no suggestion of an unconformity between the Wobbegong Supersequence and the underlying sediments landward of the fault blocks, it is likely that the upper Hammerhead succession did not extend as far seaward as the Wobbegong Supersequence. The Wobbegong Supersuccession thins seaward and is locally restricted to half-graben. Magnetic anomaly 34y (83 Ma) is not identified on this line suggesting a younger breakup age than along the lines further west, or perhaps a low-amplitude anomaly signature subdued by the thick sedimentary wedge. The majority of line 199/10 is occupied by a series of rotated fault blocks that are characteristic of slow oceanic spreading (Cannat 1993).

The Antarctic margin, Line 228/28

While this line is very similar overall to line 228/25, there are some obvious differences. The major difference is the character of the Chinstrap Sequence (Figure 9). The Chinstrap Sequence is characterised by bright, discontinuous horizons and closely spaced faults that change from being normally to reverse faulted within the southern portion of the profile, i.e. around the rift basin depocentre. The reverse faults originate in the Emperor Sequence and penetrate into the Chinstrap Sequence. The Rockhoppper horizon appears much more variable along this line. This is partly due to the underlying highly faulted sequences, but also due to the presence of the basement high which has a much higher relief here than along line 228/25. The King Sequence also appears very different from that seen along line 228/25. Faulting is not as extensive within the sequence and the seismic character indicates the presence of a number of intrusions and sills due to very bright discontinuous reflections. The oceanic crust on this line is much smoother than on profiles further west with a morphology akin to undulating hills.

Comparison of the Wilkes Land and GAB margins

The Wilkes Land and GAB margins exhibit very similar, largely symmetric crustal structures, as pointed out by Direen et al. (2011). Both margins show extended continental crust along the outer continental slope that has been excessively thinned, illustrated by the geometry of the Moho. The basement highs show a similar seismic character and morphology in both regions.

The main difference between the margins is in their sedimentary sequences. In particular, the Sea Lion–Bronze Whaler succession of the GAB margin is either not present or not imaged on the Wilkes Land margin. With the exclusion of the glacial sediments, the sedimentary sequence along the Wilkes Land margin is very thin compared to that of the GAB margin, which has substantially thicker syn- and post-rift sediments. The Hammerhead Supersequence provides much of the post-rift sediment thickness along the GAB margin, indicating a large sediment influx. The Emperor Sequence along the Wilkes Land margin is the correlative of the Hammerhead Supersequence, but is much thinner. The thickness, seismic character and style of syn-rift faulting on the Wilkes Land margin, which is generally extensional, with some post-rift compressional reactivation, correlates very well with deformation in the Blue Whale–White Pointer succession on the GAB margin. However, despite major differences in thickness, the syn-rift sedimentary package on the Wilkes Land margin exhibits a similar style of extensional faulting and seismic character to its GAB margin counterpart.

Both margins are characterised by confined sedimentary basins found immediately seaward of the basement high/peridotite ridge. Along the Wilkes Land margin, the base King horizon defines the base of resolvable, likely highly altered and intruded sediments within this small basin. This basin is a post-rift, and post-mantle exhumation feature. We interpret this feature as reflecting extremely slow, oblique seafloor spreading, characterised by intermittent magmatic pulses separated by periods of oblique extension (Whittaker *et al.* 2010) between magnetic anomalies 34y (~83 Ma, breakup) and 33y (~73 Ma). At this time the Australian–Antarctic rift system was extremely narrow with proximal sediment sources on both sides of the rift. On the GAB margin, Totterdell *et al.* (2000) have also interpreted the presence of post-rift sediments within the equivalent basin. The zone comprising peridotite ridge and transitional basin is much wider along the GAB margin than the Wilkes Land margin, but the reason for this difference is unclear.

Post-rift sequences on the Wilkes Land margin are markedly different in geometry and seismic character from those found on the GAB margin. Isopach mapping shows substantial differences in the thickness of the post-breakup sediments, particularly since the Oligocene, when there was an influx of glacially derived sediments to the Wilkes land margin (Close et al 2007). The Late Cretaceous Hammerhead Supersequence provides much of the post-rift thickness for the GAB margin as a result of large sediment influx into the basin. This supersequence is characterised by a thick progradational succession and was deposited in fluvio-deltaic and marine environments. The equivalent succession on the Wilkes Land margin has a different seismic character, being thinner and aggradational; this may be indicative of a more distal marine environment of deposition.

A major difference between the Wilkes Land and GAB post-rift sequences is that, on the Wilkes Land margin, syn-rift faults have been reactivated, resulting in reverse faults terminating at the Eocene Fairy horizon. De Santis et al. (2010) observed a contemporaneous Paleocene–Eocene phase of transpressional reactivation on the George V Land margin, causing uplift and inversion of previous rifted structures and folding in a narrow east–west oriented region near coastal basement outcrops, in Paleocene–Eocene times. They interpret the reactivation and inversion to be the result of transpressional stress conceivably related to the azimuth and rate change in the Australia–Antarctic spreading regime in the Eocene (De Santis et al. 2010). We agree that this is the most likely interpretation, and suggest that the same event has also affected parts of the Wilkes Land margin. The event is probably contemporaneous with the bends in Australian–Antarctic fracture zones interpreted by Whittaker et al. (2007) to reflect a global plate reorganisation 53–50 Ma.

Reconstructions of key horizons on five conjugate profile pairs, including the basement and Moho modelled from refraction and sonobuoy data (Whittaker *et al.* 2012) (Figure 3), illustrate the following points:

- The East Antarctic crust is thicker than the Australian crust on most profiles, with the exception of profiles 199-01/228-24, where the Australian crust is anomalously thick.
- The East Antarctic basement is more elevated than the Australian basement, with the exception of profiles 199-01/228-24, on which the Australian side is anomalous shallow, due to the relatively thick crust there. This profile pair is also located closest to the Australian-Antarctic Discordance (AAD) corridor, which exhibits various anomalies (Whittaker et al. 2010).
- Syn-rift sediments are substantially thicker on the Australian side.
- The Paleocene–Eocene sediments deposited roughly between 65 and 48 Ma on the Antarctic side are somewhat thicker than on the Australian side, and generally thicken from west to east.

On the GAB margin syn-rift sediment thicknesses are locally in excess of 10 km on profile 199/05, decreasing both to the east and west to a maximum of about 5–6 km. On the Antarctic margin, the maximum syn-rift sediment thickness merely reaches ~4 km; therefore syn-rift sedimentation along the Antarctic margin is significantly less substantial.

The post-rift sequence on the Australian margin shows more irregularity than the syn-rift sequence (Figure 2a). The direction of thinning is to the southwest, consistent with the progradation of the Hammerhead Supersequence. The GAB post-rift Hammerhead Supersequence corresponds to a large Cretaceous delta (Krassay & Totterdell 2003). The large amount of sediment associated with the Hammerhead delta is responsible for the thick post-rift sediment accumulation. A maximum thickness of 5000 m occurs in the middle parts of the delta, decreasing to less than 500 m in the distal parts.

The sediments deposited in this delta system were likely derived from uplift to the north and northeast. This uplift started in the Cenomanian, when subduction east of Australia had ceased and the Eromanga and Surat basins rebounded after being drawn down by Australia's Early Cretaceous eastward motion over a subducting slab in the mantle (Matthews *et al.* 2011).

On the Wilkes Land side, the thickest Paleocene–Eocene post-rift sedimentary section occurs on lines 228/26 and 27. The variation in thickness along the margin suggests a major sediment source to be located between 130° and 135°. The Wilkes Subglacial Basin {Ferraccioli, 2003 #283} lies almost directly inboard of this region. It has been suggested that at least the younger portion of the Wilkes Subglacial Basin may be due to uplift of the Trans-Antarctic Mountains (Ferraccioli & Bozzo 2003), but it is unclear whether this potential connection is related to the variation of Paleocene–Eocene sediment thicknesses we observe along the Wilkes Land margin.

It also needs to be kept in mind that the presence of ice on the Antarctic margins is a key constraining factor on our interpretation. The extent of the ice sheet limits how far landward the seismic profiles extend and secondly, the presence of sea ice reduces the data quality. As a consequence, only the more distal units along the Wilkes Land margin were imaged, and one must keep in mind that the seismic character in more proximal units may be significantly different. The maximum sediment thickness of the Wilkes Land margin sequences may therefore have been underestimated. The spacing of the seismic profiles along the Wilkes Land margin also proves to be a constraining factor. While each line extends well onto ocean crust, line spacing was on average, 90 kilometres without tie-lines or exploration wells available to consolidate the interpretation.

Conclusions

We present a sequence stratigraphic framework for the Wilkes Land margin that allows, for the first time, correlation with the stratigraphy of the conjugate GAB margin previously established by Totterdell et al. (2000). Our interpretation of the Wilkes Land margin has identified nine sequences based on seismic character. The overall syn-rift stratigraphy of the two margins is remarkably similar, although syn-rift sediments are substantially thicker on the Australian side. The character and thickness of the post-rift sediments on each margin is a product of differing sedimentary environments, notably the influx of deltaic sediments to the GAB margin during the Late Cretaceous, and glacial sediments to the Wilkes Land margin since the Oligocene. Regional mapping of juxtaposed sequences shows substantial differences in the thickness of the post-breakup sediments, indicating different sediment sources for the two margins. The Paleocene–Eocene sediments deposited roughly between 65 and 48 Ma on the Antarctic side are thicker than on the Australian side, generally thickening from west to east. This may be related to the location of the eastern profiles more proximal to the Wilkes Subglacial Basin, which in turn may have been affected by increased sediment flux due the onset of uplift of the Transantarctic Mountains. Post-rift reverse fault reactivation of syn-rift faults on the Wilkes Land margin has affected the Emperor and Pinquo units. We relate this reactivation to the bends in Australian-Antarctic fracture zones interpreted by Whittaker et al. (2007) to reflect a global plate reorganization 53–50 Ma. This structural reactivation is likely related to a contemporaneous transpressional event observed by De Santis et al. (2010) on the George V Land margin. Our combined conjugate margin sequence stratigraphy will provide a basis for future studies of passive margin formation and evolution.

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References

Cannat M. 1993. Emplacement of mantle rocks in the seafloor at mid ocean ridges. *Journal of Geophysical Research* **98**, 4163–4172.

Bradshaw, B.E., Rollet, N., Totterdell, J.M., & Borissova, I., 2003, —A revised Structural Framework for Frontier Basins on the Southern and Southwestern Australian Continental Margin. *Geoscience Australia Record* **2003/03**.

Close D. I., Stagg H. M. J. & O'Brien P. E. 2007. Seismic stratigraphy and sediment distribution on the Wilkes Land and Terre Adelie margins, East Antarctica. *Marine Geology* **239**, 33–57.

Colwell J. B., Stagg H. M. J., Direen N. G., Bernardel G. & Borissova I. 2006. The structure of the continental margin off Wilkes Land and Terre Adélie, East Antarctica. *In:* Fütterer D. K., Damaske D., Kleinschmidt G., Miller H. & Tessensohn F. eds., *Antarctica: Contributions to Global Earth Sciences*, pp 327–340, Springer Verlag, Berlin.

De Santis L., Brancolini G., Donda F. & O'Brien P. 2010. Cenozoic deformation in the George V Land continental margin (East Antarctica). *Marine Geology* **269**, 1–17.

Direen N. G., Stagg H. M. J., Symonds P. A. & Colwell J. B. 2011. Dominant symmetry of a conjugate southern Australian and East Antarctic magma-poor rifted margin segment. *Geochemistry Geophysics Geosystems* **12**, Q02006.

Ferraccioli F. & Bozzo E. 2003. Cenozoic strike-slip faulting from the eastern margin of the Wilkes Subglacial Basin to the western margin of the Ross Sea Rift: an aeromagnetic connection. *Geological Society, London, Special Publications* **210**, 109–133.

Gibson G. M., Totterdell J. M., Morse M. P., Goncharov A., Mitchell C. H. & Stacey A. R. 2012. Basement structure and its influence on the patttern and geometry of continental rifting and breakup along Australia's southern rift margin. Geoscience Australia Record 2012/47.

Krassay A. A. & Totterdell J. M. 2003. Seismic stratigraphy of a large, Cretaceous shelf-margin delta complex, offshore southern Australia. *AAPG Bulletin* **87**, 935–963.

Matthews K. J., Hale A. J., Gurnis M., Müller R. D. & DiCaprio L. 2011. Dynamic subsidence of Eastern Australia during the Cretaceous. *Gondwana Research* **19**, 372–383.

Sayers J., Bernardel G. & Parums R. 2003. Geological Framework of the central Great Australian Bight. *Geoscience Australia Record* **2003/12**.

Sayers J., Symonds P. A., Direen N. G. & Bernadel G. 2001. Nature of the continent-ocean transition on the non-volcanic rifted margin in the central Great Australian Bight. *In:* Wilson R. C. L., Whitmarsh R. B., Taylor B. & Froitzheim N. eds., *Non-volcanic rifting of continental margins: a comparison of evidence from land and sea*, Vol. Special Publication, pp 51–76, Geological Society of London.

Totterdell J. & Bradshaw B. 2004. The structural framework and tectonic evolution of the Bight Basin. *Eastern Australasian Basins Symposium II, Adelaide*, pp. 41–61. PESA.

Totterdell J. M., Belvin J. E., Struckmeyer H. I. M., Bradshaw B. E., Colwell J. B. & Kennard J. M. 2000. A new sequence framework for the Great Australian Bight: Starting with a clean slate. *Australian Petroleum Production and Exploration Association Journal* **40**, 95–117.

Whittaker J. M., Goncharov A., Williams S. E. & Müller R. D. 2012. Crustal velocity and sediment thickness asymmetries along and between the conjugate Australian-Antarctic margins. *In*: Mares, T. (Ed), 2012. *Eastern Australasian Basins Symposium IV*. Petroleum Exploration Society of Australia, Special Publication, CD-ROM.

Whittaker, J. M., R. D. Müller, and M. Gurnis (2010), Development of the Australian-Antarctic depth anomaly, *Geochemistry Geophysics Geosystems*, 11, Q11006, doi:10.1029/2010GC003276.

Whittaker J. M., Muller R. D., Leitchenkov G., Stagg H., Sdrolias M., Gaina C. & Goncharov A. 2007. Major Australian-Antarctic Plate reorganisation at Hawaiian-Emperor bend time. *Science* **318**, 83–86.

Williams S. E., Whittaker J. M. & Müller R. D. 2011. Full-fit, palinspastic reconstruction of the conjugate Australian-Antarctic margins. *Tectonics* **30**, 1–21.