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RESEARCH ARTICLE

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Key Points:

- Seismic interpretation of sedimentary architecture and basement structures
- Model of tectonomagmatic evolution for the distal Australian-Antarctic margins
- Multiple detachment systems and complex lithospheric breakup

Supporting Information:

- Readme
- Data set S1
- Data set S2
- Data set S3
- Data set S4
- Data set S5
- Data set S6

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Tectonomagmatic evolution of the final stages of rifting along the deep conjugate Australian-Antarctic magma-poor rifted margins: Constraints from seismic observations

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Abstract The processes related to hyperextension, exhumed mantle domains, lithospheric breakup, and formation of first unequivocal oceanic crust at magma-poor rifted margins are yet poorly understood. In this paper, we try to bring new constraints and new ideas about these latest deformation stages by studying the most distal Australian-Antarctic rifted margins. We propose a new interpretation, linking the sedimentary architectures to the nature and type of basement units, including hyperextended crust, exhumed mantle, embryonic, and steady state oceanic crusts. One major implication of our study is that terms like prerift, synrift, and postrift cannot be used in such polyphase settings, which also invalidates the concept of breakup unconformity. Integration and correlation of all available data, particular seismic and potential field data, allows us to propose a new model to explain the evolution of magma-poor distal rifted margins involving multiple and complex detachment systems. We propose that lithospheric breakup occurs after a phase of proto-oceanic crust formation, associated with a substantial magma supply. First steady state oceanic crust may therefore not have been emplaced before ~53.3 Ma corresponding to magnetic anomaly C24. Observations of magma amount and its distribution along the margins highlight a close magma-fault relationship during the development of these margins.

1. Introduction

The data collected by drilling and refraction/reflection seismic surveys along the Iberia-Newfoundland conjugate margins showed that rifted margins can be formed by large domains of hyperextended continental crust and exhumed mantle [Boillot *et al.*, 1980; Sawyer *et al.*, 1994; Tucholke and Sibuet, 2007; Péron-Pinvidic and Manatschal, 2009]. This discovery resulted in a change in paradigm on the interpretation of how, where, and when lithospheric breakup occurs along rifted margins. However, it is still questioned if the lesson learned from the Iberia-Newfoundland rifted margins can be applied elsewhere and if other margins may have evolved in a similar way. Another, yet poorly understood problem along the Iberia-Newfoundland margins concerns the question of how hyperextended and exhumed domains develop into seafloor spreading. A requisite to answer to this question is to describe the relationships between extensional, sedimentary, and magmatic structures along hyperextended, exhumed, and oceanic domains. It is also yet unclear if the relative importance of tectonic versus magmatic processes changes in a gradual or abrupt way at the transition between exhumed mantle and first unequivocal oceanic crust.

In order to find answers to these questions, we studied the most distal parts of the Australian-Antarctic conjugate rifted margins. In contrast to the Iberia-Newfoundland example, these rifted margins lack drill hole data and refraction seismic data. Only some sparse sonobuoy data are available from the most distal domains. However, the advantages of working at the Australian-Antarctic margins are as follows: (1) the free access to high-quality reflection seismic data imaging the transition into unequivocal oceanic crust and (2) the relative elevated sedimentation rates compared to the extension rates. The latter enables to document the geometrical relationships between deformation and sedimentation and to define deformation phases that can be linked to distinct sedimentary units. The novelty of this paper, compared to previous studies interpreting the same data [Colwell *et al.*, 2006; Close *et al.*, 2007; Direen *et al.*, 2007, 2011, 2012; Espurt *et al.*, 2009, 2012] is that it focuses on the tectonosedimentary and magmatic evolution and that it provides a new explanation for the creation of new basement at the transition between unequivocal continental and oceanic crusts. In contrast to the previous papers, this study concentrates on the most distal domains and

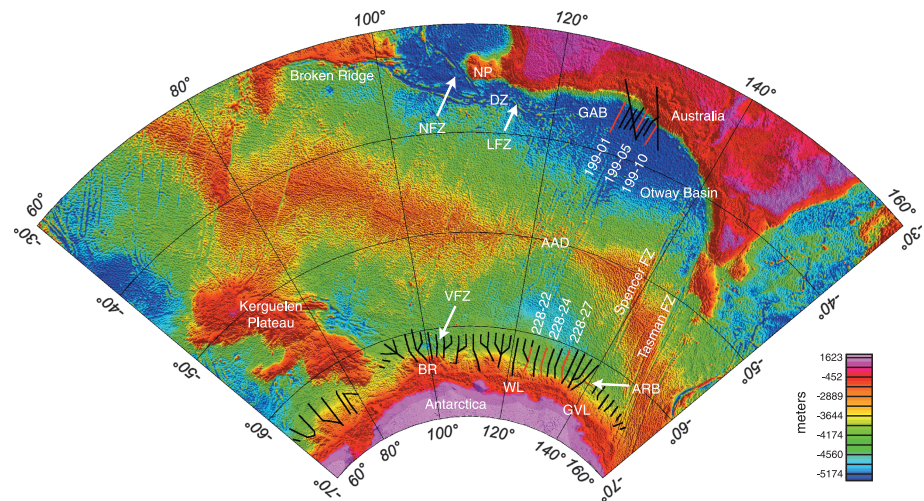


Figure 1. Bathymetric map of the Australian-Antarctic Basin (ETOPO1) [Amante and Eakins, 2009]. GAB: Great Australian Bight; NP: Naturaliste Plateau; DZ: Diamantina Zone; NFZ: Naturaliste Fracture Zone; LFZ: Leeuwin Fracture Zone; VFZ: Vincennes Fracture Zone; BR: Bruce Rise; WL: Wilkes Land; GVL: George V Land; AAD: Australian-Antarctic Discordance; ARB: Adélie Rift Block. Black lines along the two margins correspond to seismic lines of the GA199, GA228, and GA229 surveys. In red: the six lines presented in this paper.

therefore on the final stages of rifting preceding onset of steady state seafloor spreading. The lack of knowledge of the nature of basement in the most distal parts of the margin is at the origin of a debate about the exact location and timing of lithospheric breakup along the Australian-Antarctic margins. Although this study cannot provide absolute age constraints, due to the lack of drill hole data, sediment/basement relationships enable us to describe, map, and discuss the temporal and spatial evolution between unequivocal continental and oceanic crusts. In addition to the regional implications, we believe that our observation-driven approach can be used to describe the link between sediments, magmatic additions, and deformation related to the creation of new basement domains at deep-water rifted margins. The combination of the integrated seismic interpretation including nature of basement and sediment architecture with potential field maps enables to propose and map the lateral extent of different basement domains resulting from different processes, including exhumation and magmatic accretion. Finally, these results are integrated in a model describing the transition from rifting to the first steady state oceanic crust. It is noteworthy that the record of magnetic anomalies by polarity changes of the Earth magnetic field is complex in domains that do not result from simple steady state seafloor spreading. This is particularly true for magnetic anomalies formed over exhumed mantle or magma-starved domains. The nature, age, and significance of these magnetic anomalies are currently highly debated [Sayers et al., 2001; Colwell et al., 2006; Sauter et al., 2008; Bronner et al., 2011, 2013; Direen et al., 2012; Maffione et al., 2014]. Therefore, the implications of the model proposed in this paper for the early kinematic evolution of the Australia-Antarctica margins and, in particular, on the nature and age of the first magnetic anomalies need a careful reexamination and modeling, a point, that is, however, beyond the scope of this study.

2. The Australian-Antarctic Conjugate Rifted Margins

2.1. Geological Setting

The conjugate Australian-Antarctic passive rifted margins laterally extend over a distance of more than 5000 km between Broken Ridge/Kerguelen Plateau to the west and Tasmania/George V Land to the east (Figure 1). The present-day plate boundary between the Australian and Antarctic plates is the Southeast Indian Ridge. These two regions were part of Gondwanaland, and their first phase of rifting probably started during the Triassic-Jurassic [Veevers, 2012]. Three sectors can be differentiated along these margins based on the type of crust and their style of deformation during rifting:

1. To the west, the Broken Ridge/Kerguelen Plateau, which result from the rifting of a magmatic plateau linked to the activity of the Kerguelen hotspot during the Cretaceous (131–97 Ma) [Operto and Charvis, 1995; Rotstein et al., 2001; Borissova et al., 2002; Bénard et al., 2010];

2. In the center, the Great Australian Bight (GAB)/Wilkes Land. Currently, the oceanic domain of this sector is associated with the presence of the Australian Antarctic Discordance (AAD), an area of abnormally deep basement and cold lithosphere interpreted to be linked to the remains of a sinking broken slab [Weissel and Hayes, 1974; Géli et al., 2007; Whittaker et al., 2010];
3. To the east, the Otway Basin/George V Land margins, which result from an oblique continental rift affected by important transform systems [Miller et al., 2002]. This sector contains a major tectonic feature, the Adélie Rift Block, localized at the Antarctic margin, off Terre Adélie. It represents a wide rifted block of highly faulted and hyperextended continental crust [Tanahashi et al., 1997; Colwell et al., 2006; Close et al., 2009].

Thus, the magma-poor Australian-Antarctic rifted margins developed with a magmatic plateau to the west, whereas they seem to overprint an abnormally cold lithosphere in the center, formed as an oblique/transform margin to the east. In this paper, we mainly focus on the central segment, i.e., the Great Australian Bight/Wilkes Land segment.

Rifting between Australia and Antarctica is postulated to have started during Callovian time (around 164 Ma [Totterdell et al., 2000]). Ball et al. [2013] proposed a rift evolution subdivided in two major rift phases:

1. "Rift Phase 1" (165–145 Ma), which corresponds to a first phase resulting in regional extension marked by the development of half grabens and planar normal faults in the upper crust.
2. "Rift Phase 2" (93.5–50 Ma), which represents a second phase of extension, marked by the development of new basement faults in the center of the basin, overprinting older rift structures. These faults affect a hyperextended basement with an average thickness ≤ 7.5 km.

Final rifting and lithospheric breakup occurred within an older rift system indicating that rifting was polyphase along these margins. Moreover, Mutter et al. [1985], Sayers et al. [2001], Stagg et al. [2006], Tikku and Direen [2008], and Ball et al. [2013] proposed that breakup and seafloor spreading propagated from west to east, suggesting a diachronous evolution of deformation along the Australian-Antarctic rift system.

2.2. Problems, Debates, and Open Questions

Deciphering the tectonic history of the Australia-Antarctica rifted margins proved to be difficult because of the poor geological constraints and lack of data for their distal domains. Only few dredges have been made in the Diamantina Zone [Nicholls et al., 1981; Chatin et al., 1998; Beslier et al., 2004]. Drill holes validating the stratigraphic model proposed for the Australian margin [Totterdell et al., 2000] exist only in the proximal parts. The proximal location of the wells makes it difficult to interpolate the sedimentary sequences toward the distal parts of the margin. Therefore, in this study we do not use the stratigraphic model proposed by Totterdell et al. [2000], but we define sedimentary units that are not dated but can be correlated across the distal margins, enabling to define "time lines."

The nature and age of the basement in the ocean-continent transition (OCT) thus remains currently ill defined. Previous studies agree that this basement is either made of extended continental crust associated with magmatic additions and/or serpentinized mantle peridotites [Sayers et al., 2001; Colwell et al., 2006; Direen et al., 2011; Ball et al., 2013]. Particularly, the difficult identification of magnetic anomalies in these ill-defined domains, not corresponding to clearly defined steady state oceanic crust, questioned the classical way of dating the first magmatic oceanic crust in using the oldest magnetic anomaly [Sayers et al., 2001; Colwell et al., 2006]. In this context and without geological data, the localization and dating of the continental and lithospheric breakup appear difficult. This may explain the ongoing debate on the location (Figure 2) and age of the first undisputable oceanic crust within each sector of the Australian-Antarctic margins. Ages proposed for the first oceanic crust range between 93 and 87 Ma in the Diamantina/Labuan sector [Chatin et al., 1998; Beslier et al., 2004; Halpin et al., 2008], 83 and 71 Ma in the Great Australian Bight/Wilkes Land sector [Sayers et al., 2001; Tikku and Direen, 2008; Ball et al., 2013], and 67 and 51 Ma in the Otway/George V Land sector [Krassay et al., 2004; Ball et al., 2013]. These multiple interpretations are at the origin of numerous kinematic reconstructions [Tikku and Cande, 2000; Müller et al., 2006; Whittaker et al., 2007; Tikku and Direen, 2008; Williams et al., 2011; White et al., 2013], most of them leading to geological inconsistencies and/or large overlaps and gaps at the age of assumed breakup. At the western end of the Australia-Antarctica margins we can find three major tectonic structures, identified as the Leeuwin and Naturaliste Fracture Zones at the Australian margin, and as the Vincennes Fracture Zone at the Antarctic margin. The question of which fracture zones can be considered as a conjugate set is currently debated, and the different possibilities

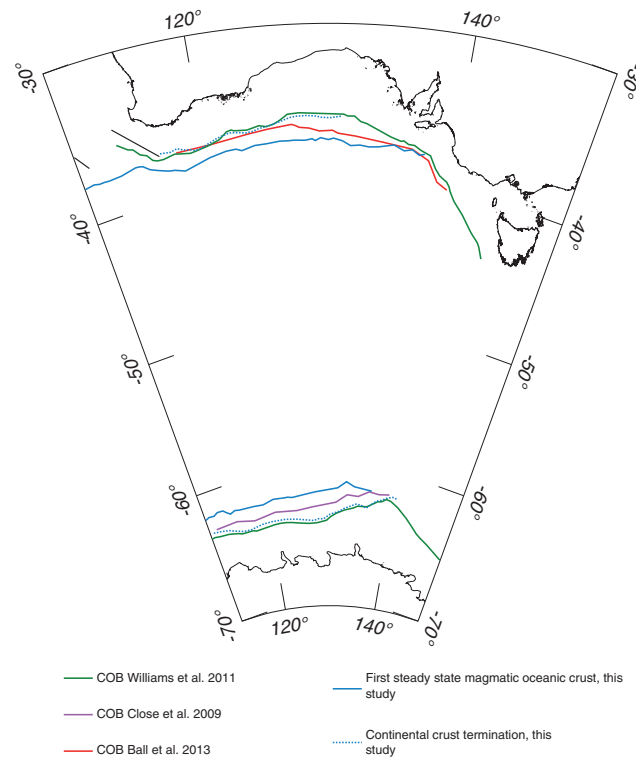


Figure 2. Map showing different interpretations of the limit of first oceanic crust along the Australia-Antarctica margin.

also imply variations in kinematic reconstructions. The different alignments lead to different models for the initial direction of motion between Australia and Antarctica. Two end-member models are generally proposed: one model in which the Leeuwin and Vincennes fracture zones are considered as conjugates [Tikku and Cande, 1999] and one model in which the Naturaliste and Vincennes fracture zones are considered as conjugates [Whittaker et al., 2007; Williams et al., 2011]. Tikku and Cande [1999] and Whittaker et al. [2007] proposed an oblique NW-SE extension between 160 and 83.5 Ma following the trend of the fracture zones and a N-S extension since 83.5 Ma. On the contrary, Williams et al. [2011] suggest that these fracture zones do not represent the motion between both continents and propose a NNE-SSW extension between 136 and 100 Ma, a NW-SE extension between 100 and 50 Ma, and then a NNE-SSE extension since 50 Ma. In addition to these uncertainties, the ill-defined tectonic

structure of the distal margins results in several conflicting models for the evolution of single rift sections, including asymmetric extension accommodated by a single low-angle detachment fault [Espurt et al., 2009, 2012] or symmetric extension by the development of two conjugated upward concave detachment faults [Direen et al., 2011].

The aim of this study is to propose a coherent interpretation of the sediment and basement structures within the OCT and to propose a model to explain the processes leading to lithospheric breakup along the Australian-Antarctic margins.

2.3. Data Set and Processing

This study is based on the description and interpretation of seismic reflection lines and marine magnetic and gravity data. The data discussed here include the AGSO surveys GA199, GA228, and GA229, whose acquisition parameters are described in Table 1. These seismic data have been already previously published and interpreted in several studies [Sayers et al., 2001; Colwell et al., 2006; Close et al., 2007, 2009; Direen et al., 2007, 2011, 2012; Espurt et al., 2009, 2012; Ball et al., 2013]. The aim of this paper is thus to propose new interpretations based on a new approach and method.

Table 1. Acquisition Parameters of the Seismic Surveys GA199, GA228, and GA229

	GA199	GA228	GA229
Area	Great Australian Bight	Australian Antarctic Territory and Southern Ocean	Australian Antarctic Territory and Southern Ocean
Vessel	R/V <i>Rig Seismic</i>	R/V <i>Geo Arctic</i>	R/V <i>Geo Arctic</i>
Date	November 1997	January–April 2001	January–March 2002
Source	49161 cm ³ airguns	59976 cm ³ airguns	59976 cm ³ airguns
Coverage	40 fold	36 fold	36 fold
Shot interval	50 m	50 m	50 m
CDP spacing	12.5 m	12.5 m	12.5 m
Recorded length	16 s	16.384 s	16.384 s

The GA199 survey data have been acquired in 1997 in the deep-water part of the GAB [Symonds *et al.*, 1998]. The survey includes potential field and seismic reflection data that were imaged along 11 lines with a spacing of approximately 70 km and a total length of 3448 km. In addition, 26 sonobuoys were deployed during the course of the survey and their analyses provide velocity constraints for the seismic and gravity interpretation [Sayers *et al.*, 2001]. We added to these results the sonobuoy solutions of Talwani *et al.* [1979].

The GA228 and GA229 survey data have been acquired in 2001 and 2002 over the East Antarctica margin [Stagg and Schiwy, 2002]. The data consist of high-quality geophysical data with a general line spacing of around 90 km. As on the Australian margin, some sonobuoy solutions are available [Stagg *et al.*, 2005].

For the Australian margin, we mainly used the gravity and magnetic grids of Petkovic *et al.* [1999]. As these grids are only available for the Great Australian Bight, we added the free-air gravity grid of Sandwell and Smith [2009] to observe the westward continuity of gravity anomalies. Concerning the magnetic data, we completed the Petkovic *et al.* [1999] grid with the global Quesnel grid [Quesnel *et al.*, 2009]. This grid is not excessively extrapolated and, in consequence, displays large data gaps. We are thus limited to observe the westward continuity of large-scale magnetic features. Major interpretations are thus made from observations based on the more precise and regional grid of Petkovic *et al.* [1999], built mainly from marine data. For the Antarctic margin, we used the gravity grid of Sandwell and Smith [2009] and the magnetic grid of Golynsky *et al.* [2012]. Horizontal gradient processing was applied in several directions on the gravity grids to highlight geological structures. Reduction to the pole of magnetic maps results in minor changes not visible at the regional scale, and thus, it was not undertaken.

2.4. Seismic Observations and Interpretation Approach

Totterdell *et al.* [2000] proposed a subdivision into several stratigraphic sequences for the Australian margin based on the study of seismic data and exploration wells along the Bight Basin. The authors defined different sedimentary supersequences that have been dated using biostratigraphy, serving as reference for most studies along the Australian margin. However, the Totterdell's stratigraphy has been built from data located in the Australian proximal continental shelf. To constrain the evolution of the distal margins, and particularly the emplacement of the first oceanic crust, previous studies [Close *et al.*, 2007, 2009; Espurt *et al.*, 2009, 2012; Ball *et al.*, 2013] correlate this proximal stratigraphy with distal sedimentary units. However, on seismic sections it is difficult, if not impossible, to follow with confidence these sedimentary sequences through the necking zone and further oceanward. Recent studies from hyperextended margins show that such jump correlations, unsupported by drill hole data in the distal part, are often dangerous [Masini *et al.*, 2013]. In this paper we thus define our own sedimentary units that cannot be correlated directly with the stratigraphic levels defined by Totterdell *et al.* [2000] in the proximal margin. Thus, we cannot date the sedimentary units, but since we can correlate the units across the distal margin, we can at least define "time lines" across the OCT. Indeed, thanks to relative high sedimentation rates comparing to extension rates, seismic lines from the deep Australia/Antarctica margins image well the sedimentary architecture and its relation to the underlying basement. In our study, we defined sedimentary units that are associated with a deformation event and/or the formation of a new basement (Figure 3). The main large-scale observation that can be made along these margins is that the successive sedimentary units downlap oceanward directly onto different acoustic basements (Figure 3). This margin-scale downlap geometry may be explained either by (1) onlapping of the sediments onto a former high and subsequent rotation of the sedimentary sequence or (2) by creation of "new" top basement by either tectonic exhumation, magmatic accretion, or a combination of the two. The lack of evidence for a former basement high lead us to favor the formation of "new" basement surfaces that goes in hand with the deposition of new sediments. Linking the emplacement of "new" basement with the deposition of sedimentary units enables to better characterize the age progression of deformation in the distal rifted margins and to link nature of crust to the architecture of sedimentary sequences. The specific architecture of one sedimentary unit is recognizable along the whole central segment (Figure 3). The overall sediment architecture is reminiscent of that of a "sag sequences" described from the South Atlantic rifted margins [Unternehm *et al.*, 2010; Masini *et al.*, 2012]. We notice that each sedimentary unit shows a change from posttectonic, to syntectonic, to finally pretectonic going from proximal to more distal parts of the margin (Figure 3). This sedimentary architecture highlights a migration of the deformation toward the ocean during the latest stages of the margin development and shows that terms such as prerift, synrift, and postrift sediments or the concept of the "breakup" unconformity cannot be applied at the scale of the whole rifted

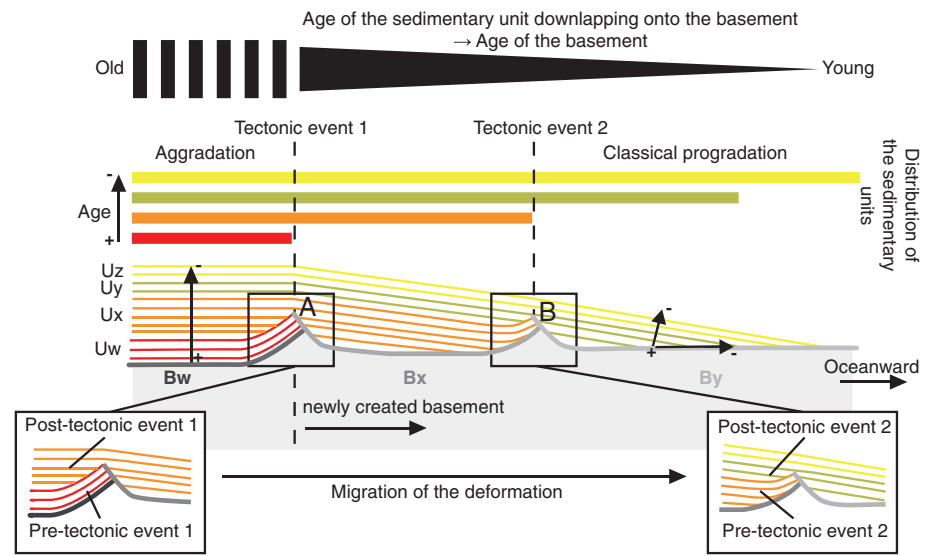


Figure 3. Cartoon illustrating the key seismic observation and interpretation approach proposed in this paper. Uw, Ux, Uy, and Uz represent different sedimentary units of decreasing age. Bw, Bx, and By correspond to different basement units identified in the margin.

margin [e.g., Péron-Pinvidic *et al.*, 2007; Masini *et al.*, 2013]. Moreover, it suggests that the evolution of the margin is marked by “punctual” tectonic events during final stages of deformation. Of major interest is to document if these events are symmetric or asymmetric, stepping or progressive on the scale of the margin, and how far magmatic processes contribute to the formation of “new” basement in the most distal parts of the Australia-Antarctica margins.

2.5. Sedimentary and Basement Units Defined in the Distal Margin

In the following paragraph, sedimentary and basement units are described from the proximal to the more distal parts of the distal margin. As the deformation structures enable to link and define the relative age of the sedimentary units relative to the formation of the “new” basement, we also include their description in this part. The identification of the different units is based on recurrent observations made on several seismic lines of the GA199 and GA228 surveys. Six lines are shown in this paper (Figures 4 and 5). In order to highlight some key observations, we show some detailed interpretations in selected smaller regions documenting the critical observations on which our work is based.

2.5.1. Sedimentary Unit 1 and Basement Unit 1

Sedimentary unit 1 (U1) represents a relatively important unit (around 2 s two-way time (TWT) thick) consisting of flat-lying sediments, deposited in a wide basin extending over about 130 km across the Australian and Antarctic margins. The sediments are well stratified as indicated by high reflectivity, in particular, at the base of the formation (Figure 6). This unit corresponds with the MS4 megasequence of Close *et al.* [2007]. The southern boundary of U1 at the Australian margin is marked by numerous small offset normal faults, some affecting the underlying basement unit 1 (B1). However, they do not create important offsets at the top basement. The distal termination of U1 and B1 shows a specific tectonic feature, as they are both overthrust by a large offset fault (in thick red in Figure 6). Contrary to some previous studies [Colwell *et al.*, 2006; Close *et al.*, 2007; Ball *et al.*, 2013], which proposed the presence of the same sedimentary unit on both sides of the fault, we propose that both sedimentary and basement units B1 and U1 terminate against the continentward side of this fault. Indeed they cannot be recognized oceanward but are present at the Antarctica conjugate margin, which indicates that a new domain opened between Antarctica and Australia after U1 deposition. The large fault thus clearly develops after deposition of U1. At the Antarctic margin, the area with small offset normal faults is wider. Here the termination of U1 and B1 is more progressive. The top of U1 locally shows “toplaps” along the two conjugate margins. This unconformity has already been identified at the Antarctic margin by Eittrheim *et al.* [1985] (horizon K1) and by Colwell *et al.* [2006] (horizon *tur*). Based on the stratigraphic model of Totterdell *et al.* [2000], this horizon was interpreted to be Turonian in age; however, as discussed above, no direct age

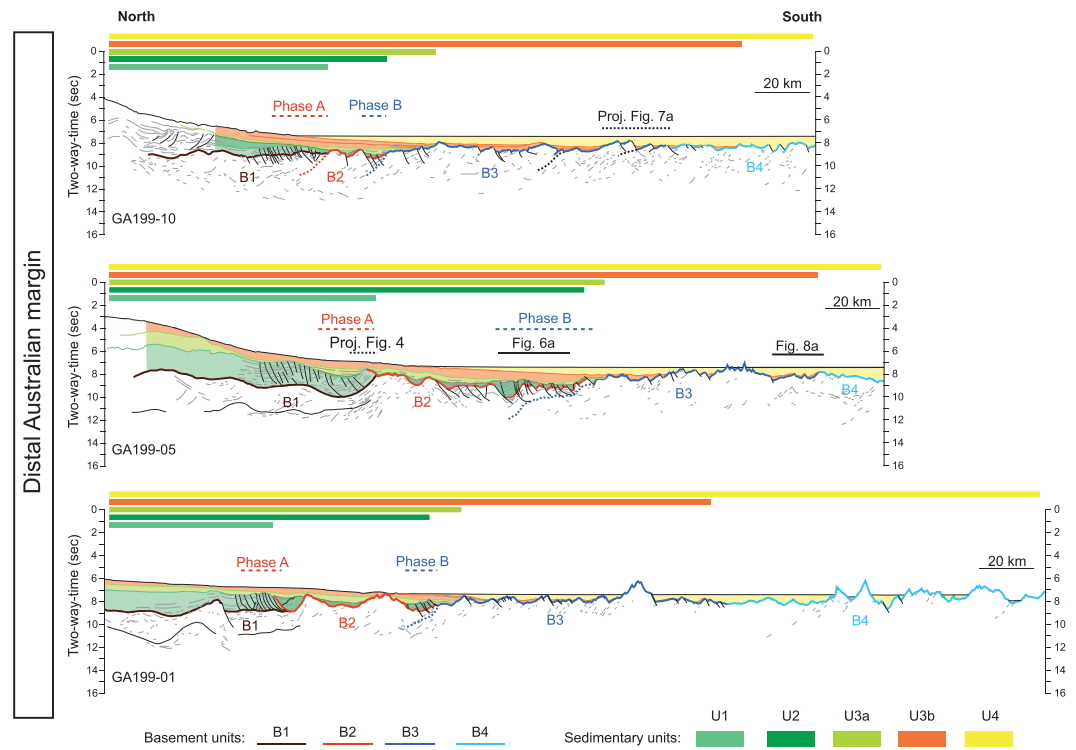


Figure 4. Interpreted seismic lines presented in this paper at the Australian margin: Lines GA199-01, GA199-05, and GA199-10 (for location see Figure 1). Sections showing distribution of the different sedimentary and basement units, as well as the locations of the different zooms (in dashed line if example was taken from a neighboring seismic line and projected). Phases A and B represent the two major systems of deformation identified in the seismic lines.

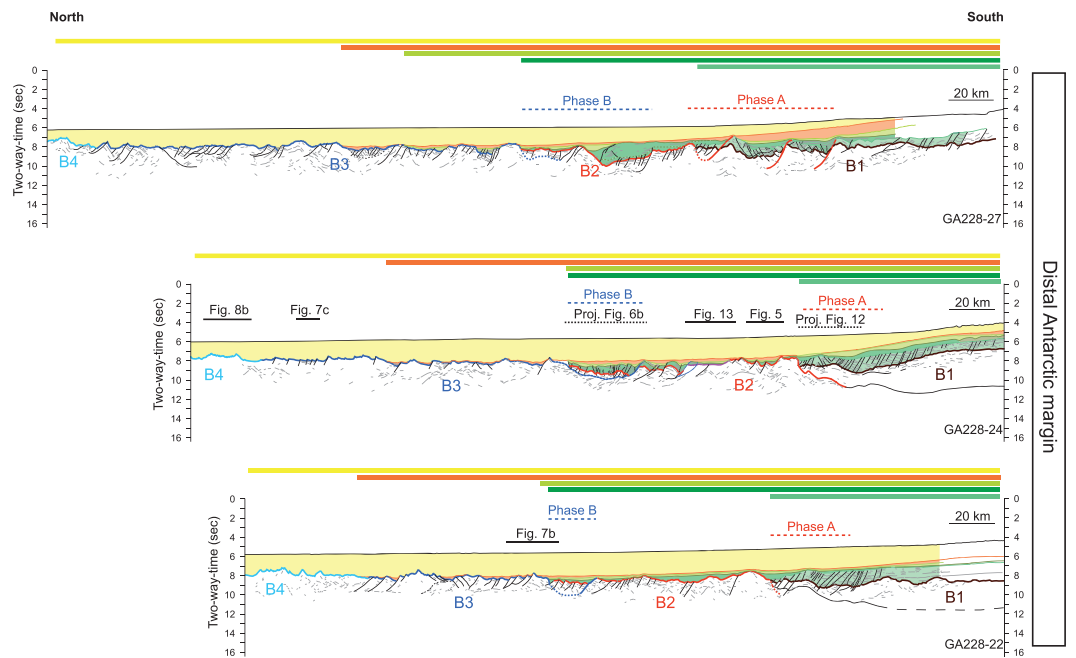


Figure 5. Interpreted seismic lines presented in this paper at the Antarctic margin: Lines GA228-22, GA228-24, and GA228-27 (for location see Figure 1). Sections showing distribution of the different sedimentary and basement units, as well as the locations of the different zooms (in dashed line if example was taken from a neighboring seismic line and projected). Phases A and B represent the two major systems of deformation identified in the seismic lines.

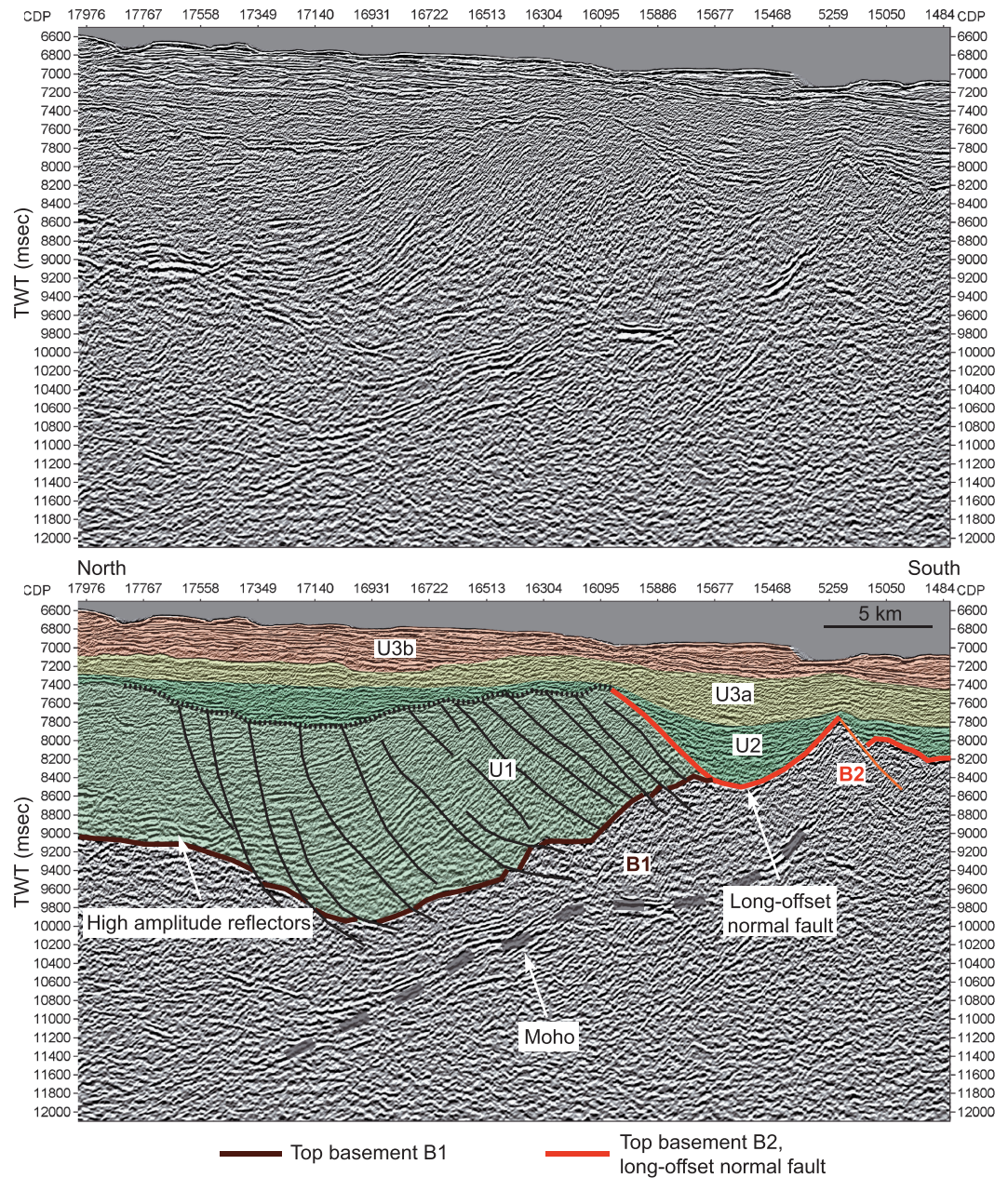


Figure 6. Zoom of seismic line GA199-03 (Australian margin) showing the edge of the thinned back-rotated basement B1 and the overlying faulted sedimentary unit U1. The thick red line shows the occurrence of a major long offset normal fault marking the end of U1. The dashed grey line shows a continentward dipping reflector, interpreted as the Moho. Faults in black affect the basement B1 and the sedimentary unit U1. Faults in orange affect the basement B2 and the sedimentary unit U2. Dotted black line corresponds to a clear stratigraphic contact between U1 and U2. Copyright Commonwealth of Australia (Geoscience Australia).

constraints exist to support this interpretation. At both margins, B1 displays an internally complex structuration and its base is locally marked by a reflector of high amplitude (Figure 6), which could correspond to the Moho. This reflection quickly raises oceanward. The top of B1 is relatively deep (around 8–9 s TWT) and is highly reflective and chaotic, making it generally difficult to distinguish from the overlying unit U1. However, it is punctuated by several basement highs, which are related to large offset normal faults that sometimes affect the reflection interpreted as Moho. Above these highs we can generally observe small perturbations in the sediments: reflectors are slightly deformed and disturbed.

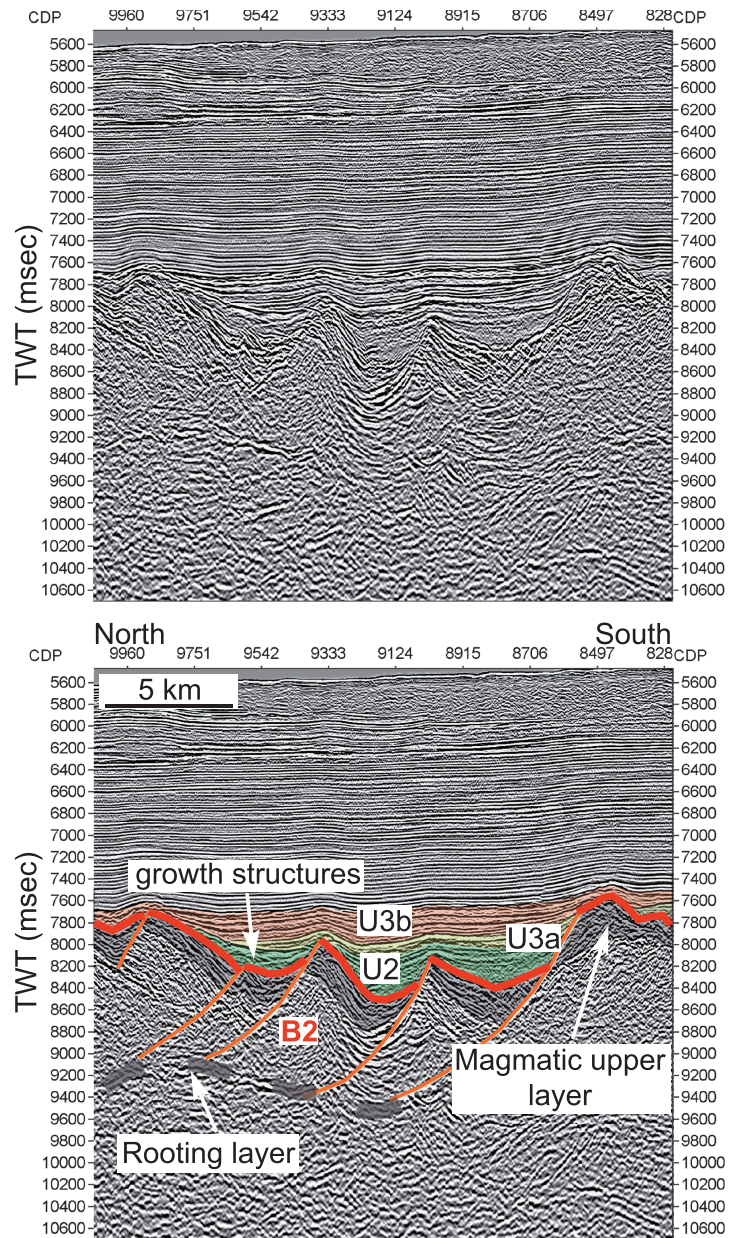


Figure 7. Zoom of seismic line GA228-24 (Antarctic margin), showing the basement B2 affected by normal faults. The thick red line corresponds to the top of the basement B2. The upper reflective layer is clearly visible and imaged in grey. The sedimentary unit U2 displays syn-deformation structures linked to movements along the normal faults (in orange). Copyright Commonwealth of Australia (Geoscience Australia).

2.5.2. Sedimentary Unit 2 and Associated Basement Unit 2

Oceanward of the previously described major long offset normal fault, our proposed stratigraphy varies significantly from previous studies. The footwall of the fault marking the termination of U1 and B1 is well imaged by the lateral onlap of a well-stratified unit (Figure 6). Contrary to *Close et al.* [2007] who proposed the presence of their sequence MS4 (previously corresponding to our unit U1), we propose a younger sedimentary unit 2 (U2), which seals the normal faults and the deformed sediments in U1 on both margins and directly lies on a newly created basement referred to as associated basement unit 2 (B2). The internal structuration of B2 appears complex and chaotic, showing often reflectors of high amplitude. The base is not visible and the top is rough, chaotic, and very reflective. B2 is locally affected by normal faults with large offset, which are syn-deposition or postdeposition of U2 (growth structures

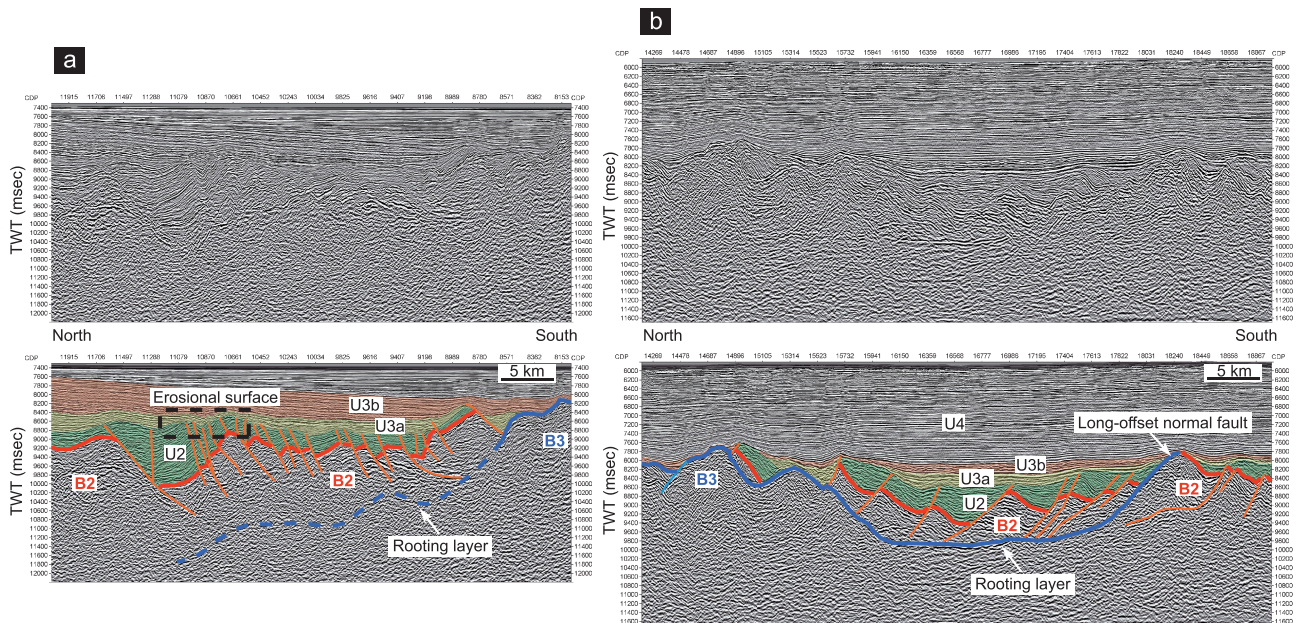


Figure 8. (a) Zoom of seismic line GA199-05 (Australian margin) showing faults affecting the U2 sedimentary unit and the basement B2. These faults seem to root on a deep intrabasement reflector which seems to be related to the long offset normal fault represented in blue. Toplaps are also visible at the top of U2 (dashed box). The sedimentary unit U3 seals this second phase of deformation. (b) Zoom of seismic line GA228-25 (Antarctic margin) showing an isolated and faulted basin. These faults (in orange) affect the basement B2 and the sedimentary unit U2. They root on a deep reflective layer, which appears to be the signature of a long offset normal fault (in thick blue). Copyright Commonwealth of Australia (Geoscience Australia).

can be observed at the Antarctic margin, Figure 7). At the Antarctic margin these faults affect the new basement B2, whose upper layer is composed of continuous and high-amplitude reflectors (in grey, Figure 7). The distal end of the sedimentary unit U2 (and of the associated basement unit B2) is marked by the presence of intense faulting and tilted blocks along both margins (Figures 8a and 8b). These faults clearly affect the whole sedimentary unit U2 and the basement B2, and root on a reflector of high amplitude, which raises oceanward toward the seafloor. This deformation phase thus postdates the deposition of U2.

At the Antarctic margin, this faulted area forms a small isolated basin filled by sedimentary unit 3 (U3) (Figure 8b). The fault on the southern basin border shows overtilted blocks. At the Australian margin, U2 locally shows toplaps (dashed box, Figure 8a), principally above the faulted blocks.

2.5.3. Sedimentary Units 3 and Associated Basement Unit 3

U1 and U2 are overlain by a third younger sedimentary unit, referred to as U3a. In the proximal part of the lines, it seems to partially correspond to the MS2/3 megasequence of *Close et al.* [2007]. At the Australian margin, this unit clearly seals the faults affecting U2 and B2 as well as the deformed sediments in U2. However, on some locations, U3a appears to be syntectonic, forming syndepositional structures (Figure 8). Oceanward of U2, U3a directly overlies a new associated basement unit 3 (B3). This sedimentary unit appears less stratified than U2, with internal reflectors generally of low amplitude that are difficult to follow laterally. The end of this unit is not associated with a clear deformation structure and thus does not mark the termination of the basement B3.

The younger sedimentary unit U3b appears well stratified and shows reflectors of moderate amplitude. The top of this unit presents high-amplitude reflections. U3b is generally not perturbed by deformation. Along the Australian margin we can see that the whole unit is clearly tilted oceanward, downlapping onto the underlying unit U3a and the new basement B3 (Figure 8a). In the most distal part, the seismic facies of U3b changes and the unit appears more transparent. It is tilted above fault-bounded tilted blocks. At the Antarctic margin this architecture is less clear due to an extremely thin unit (Figure 8b). At this margin U3b “onlaps” on a higher basement that we always interpret as B3 due to the similarity of the internal structuration. U3b is no more observed further oceanward (see in Figure 5, lines GA228-24 and

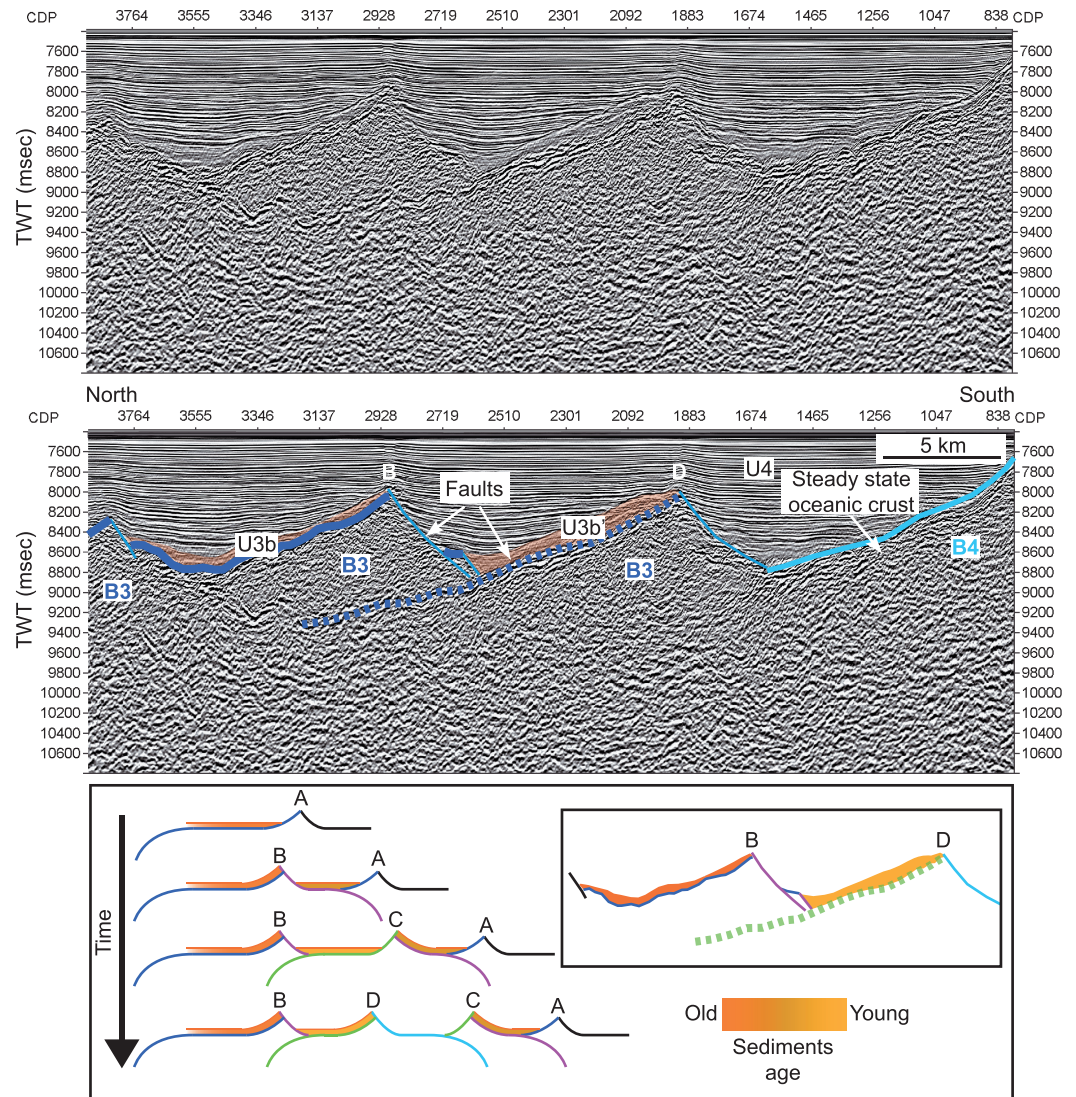


Figure 9. Zoom of seismic line GA199-07 (Australian margin). Complex system of faults in the basement B3, in the eastern GAB, interpreted as flip-flop faults. For comparison see also structures shown in Figure 5 in Sauter et al. [2013]. Copyright Commonwealth of Australia (Geoscience Australia).

GA228-27). The basement B3 appears complex, with lateral variations of morphology along the margins and between the two margins. Indeed, in the western GAB, we can observe large seamounts (e.g., line GA199-01 and GA199-05, Figure 4) with important roughness and normal faults, which do not affect the overlying sediments. On the contrary, in the eastern GAB, B3 has a completely different morphology: there are no seamounts, and we find large and regular tilted blocks (e.g., line GA199-10, Figure 4). These blocks are created by a complex system of faults (Figure 9), which have been previously interpreted as normal faults [Sayers et al., 2001, Figure 8]. However, these faults do not appear to have a typical geometry of normal faults. Indeed, the apparent fault does not root at depth but on another flatter, continentward dipping fault, which constitutes the top of the juxtaposed basement block. This last block could be interpreted as the footwall of the apparent fault but the flat-lying strong reflection suggests that it is the hanging wall of a more recent fault. We thus have two generations of faults with extremely different angles creating these basement blocks, with the top basement corresponding to a fault surface. The distance between two breakaway points (B and D on Figure 9) is approximately 12 km. The sedimentary unit U3b is also affected by this deformation. On the contrary, at the Antarctic margin, B3 generally appears more flat and intensively faulted. It displays a complex internal structuration and a highly reflective top with important variations of

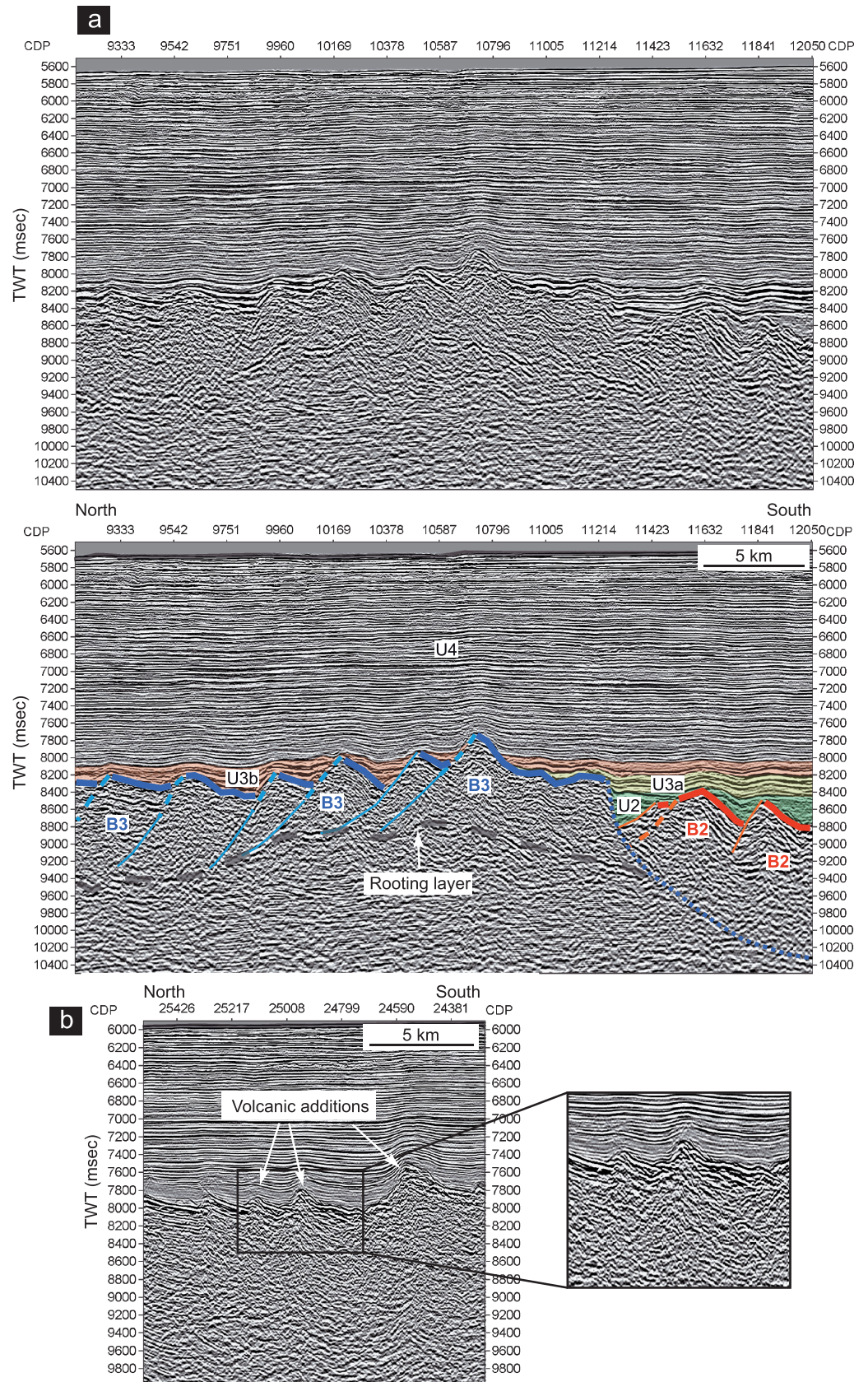


Figure 10

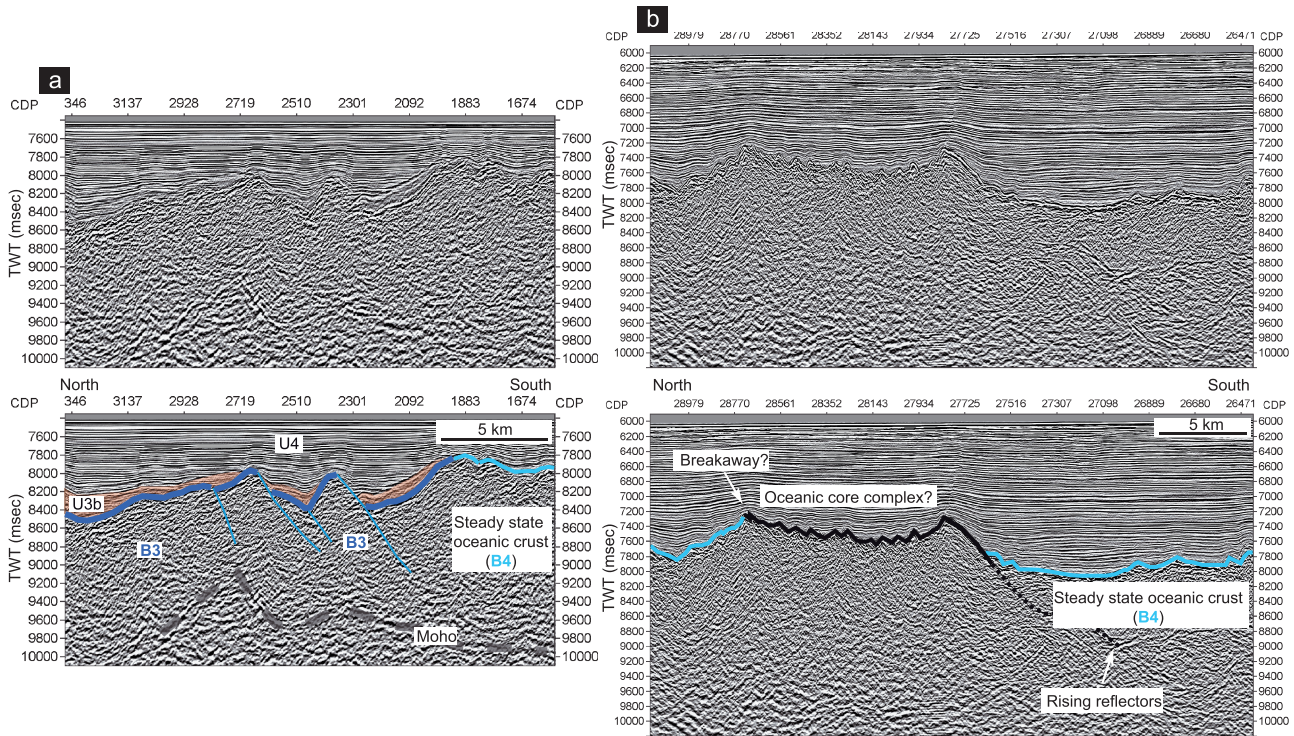


Figure 11. (a) Zoom of seismic line GA199-05 (Australian margin). Termination of basement B3 and onset of basement B4 representing the steady state oceanic crust. The Moho is visible around 10 s (TWT), with depth variations near the basement transition. (b) Zoom of seismic line GA228-24 (Antarctic margin). Rough and high structure in the basement B4, associated with intrabasement reflectors. Copyright Commonwealth of Australia (Geoscience Australia).

the roughness of the top basement. The numerous normal faults all seem to root on a deep reflective layer (Figure 10a), some faults creating important offset and overtilted blocks. In some places, faults are visible at depth but their signature at the basement top is not clear. The offset is more or less visible but blocks are ill defined, and the breakaway seems overprinted by volcanic additions (Figure 10). Instead of being asymmetric, faulted blocks tend to be more symmetric or dome shaped.

2.5.4. Sedimentary Unit 4 and Associated Basement Unit 4

The last sedimentary unit 4 (U4) (corresponding to the MS1 megasequence of *Close et al.* [2007]), lays on a major unconformity surface above U3b. This major unconformity has been interpreted as Eocene in age by *Colwell et al.* [2006]. The unit U4 is not affected by tectonic deformation. It is deposited on the previous units and directly onto the new associated basement unit 4 (B4). At the Australian margin, the transition between B3 and B4 is generally marked by the termination of U3b on a tilted block of B3 (Figure 11a). At the Antarctic side, the boundary between B3 and B4 is less evident as U3b is not as widespread as on the Australian margin, U3b being limited oceanward by the elevation step of basement B3. The boundary between B3 and B4 is in this case localized, thanks to their differences in faulting and intern structuration. Moreover, the top of B4 is highly reflective and irregular. Its base is sometimes visible around 10 s (TWT) (Figure 11a). At the Australian margin, on western lines, B4 is affected by punctual large seamounts, which are not aligned along the margin (e.g., line GA199-01 on Figure 4). At the Antarctic margin we can observe high basement structures with an important roughness associated with basement reflections (Figure 11b). This structure has a width of approximately 11 km and is higher than the surrounding basement of approximately 0.6 s (TWT).

Figure 10. (a) Zoom of seismic line GA228-22 (Antarctic margin). Faults rooting on a deep reflective layer, some creating overtilted blocks. Fault signature disappears near the top basement, the breakaway point seems to be overprinted by volcanic additions. Faults in light blue affect the basement B3 and the sedimentary unit U3. (b) Zoom of seismic line GA228-24 (Antarctic margin). We can see normal faults overprinted by volcanic additions. Copyright Commonwealth of Australia (Geoscience Australia).

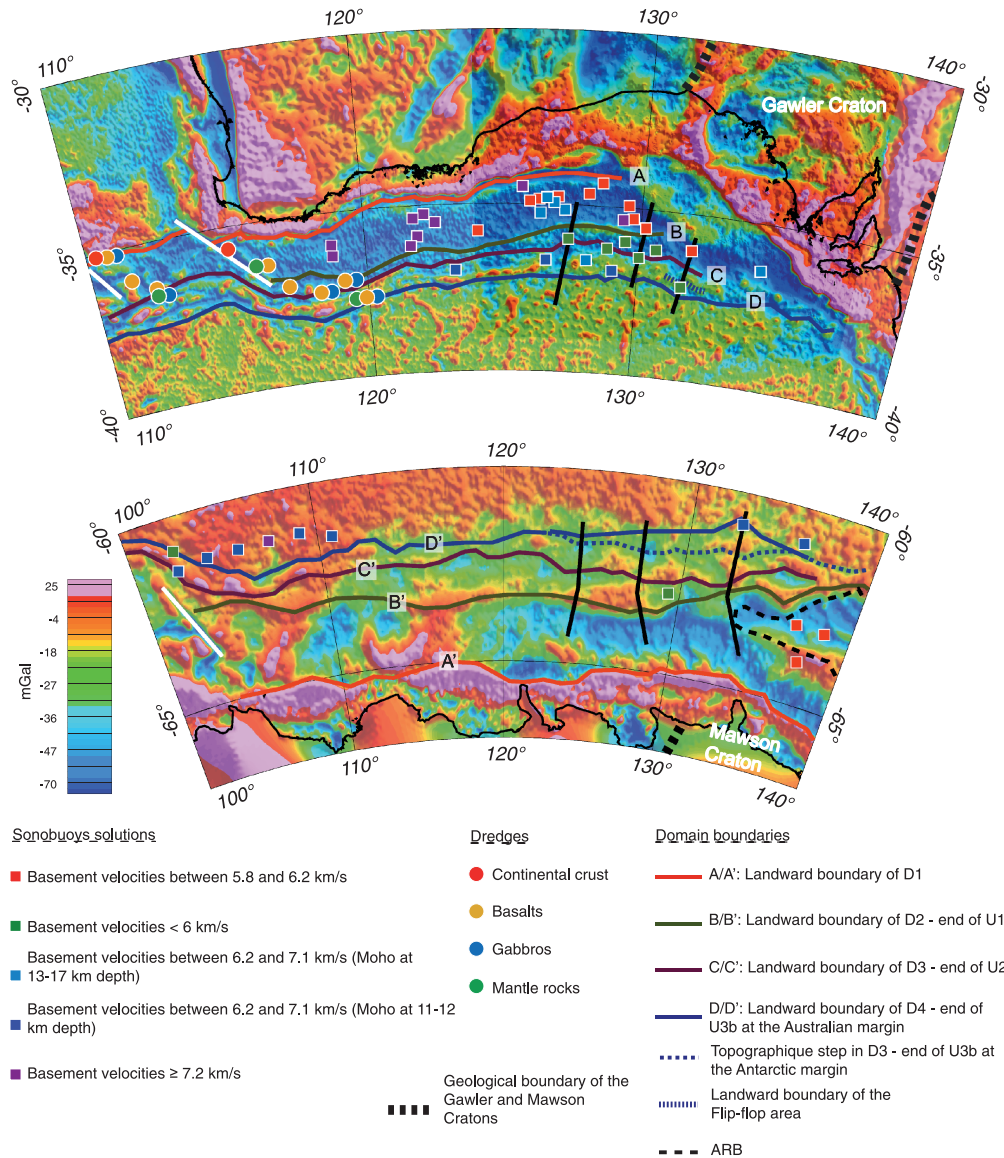


Figure 12. Free-air gravity anomaly map of Sandwell and Smith [2009] and Petkovic et al. [1999]. A, B, C, and D represent the anomalies marking the boundaries of the different domains at the Australian margin. A', B', C', and D' represent the anomalies marking the corresponding boundaries of the same domains at the Antarctic margin. Colored squares represent sonobuoy results and circles represent location of dredges. White lines correspond to the Fracture Zones and black lines correspond to seismic lines imaged in Figures 4 and 5. After comparison with the interpreted seismic lines, it appears that B and B' coincide with the termination of the sedimentary unit U1; C and C' coincide with the termination of the sedimentary unit U2; D more or less coincides with the termination of the sedimentary unit U3b at the Australian margin. At the Antarctic margin, the end of U3b is associated with the topographic step in D3 (dotted blue line). Maps projection: Polar stereographic; Ellipsoid: WGS84.

All these sedimentary units (U1 to U4) can be identified on all the seismic lines interpreted in this study. Particularly, we identified two main systems of deformation, referred to as "Phase A" (corresponding to the U1/B1 termination) and "Phase B" (corresponding to U2/B2 termination) (Figures 4 and 5).

2.6. Domains of the Distal Margin

In the previous section, seismic observations allowed us to define different crustal domains based on the distribution and architecture of sedimentary units. The boundaries between these domains are sharp and can be recognized on all seismic lines along the margins. Each basement boundary coincides with a characteristic

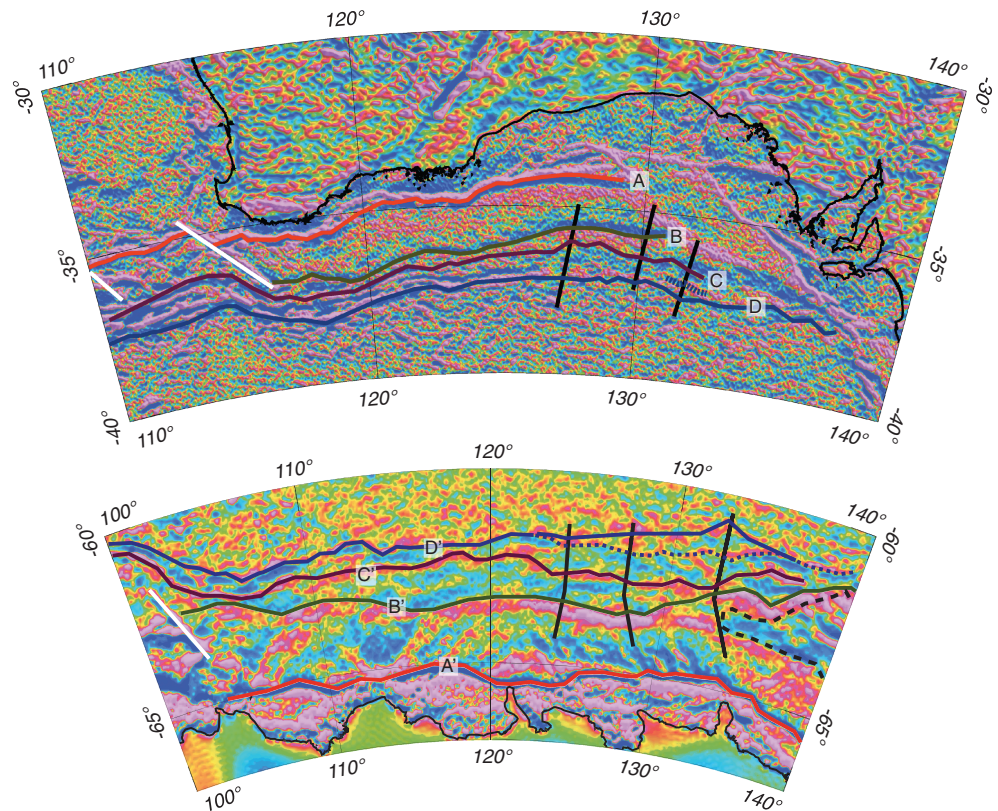


Figure 13. North-south horizontal gradient of free-air gravity anomalies derived from Sandwell and Smith [2009] and Petkovic *et al.* [1999] maps. A, B, C, and D represent the anomalies marking the boundaries of the different domains at the Australian margin. A', B', C', and D' represent the anomalies marking the corresponding boundaries of the same domains at the Antarctic margin. White lines correspond to the Fracture Zones and black lines correspond to seismic lines imaged in Figures 4 and 5. Same legend as for Figure 12.

potential field signal, either with clear and more or less continuous anomalies, or with general changes in the potential field signal. Mapping these seismic boundaries on the potential field maps shows that the related potential field boundaries (A/A', B/B', C/C', and D/D', Figures 12–14) separate areas with characteristic signals, which define laterally continuous domains. These specific signatures of the basement domains allow to interpret their location farther to the west, where very few seismic lines are available. In the following part, we describe the major geophysical characteristics (gravity, magnetic and sonobuoys results) and nature of basement based on dredged rocks to typify the different domains previously defined in seismic reflection sections.

2.6.1. Domain 1

Domain 1 presents a symmetric width between the conjugate margins. It is 140 km wide (N-S direction) on both margins and correlated with a large negative gravity anomaly and a quiet negative magnetic zone. It is delimited continentward and oceanward by two important gravity anomalies (A/A' and B/B', Figures 12 and 13). The A/A' anomaly is relatively continuous along the two margins and is almost parallel to the coastline. In the Diamantina Zone, the A anomaly seems to be cut and shifted in a dextral movement by the Leeuwin Fracture Zone (Figure 12). As already noted by Close *et al.* [2009], the B/B' gravity anomaly is associated with an important and laterally continuous positive magnetic anomaly (Figure 14) interpreted as the anomaly C34 [Tikku and Cande, 1999; Whittaker *et al.*, 2007] (Figure 15b). However, this anomaly appears irregular. We lose the signal of these gravity anomalies near the Leeuwin Fracture Zone (LFZ) at the Australian margin and near the Vincennes Fracture Zone (VFZ) at the Antarctic margin. Even if this domain appears to lie in an area without clear magnetic lineations and previously interpreted as the quiet magnetic zone [Talwani *et al.*, 1979; Cande and Mutter, 1982], the magnetic map shows several positive patches (Figure 14). We cannot see any patterns between these patches, but they are more present in the western part of both margins. Moreover, seismic velocities obtained from the sonobuoys solutions [Talwani *et al.*, 1979; Sayers *et al.*, 2001] show variable

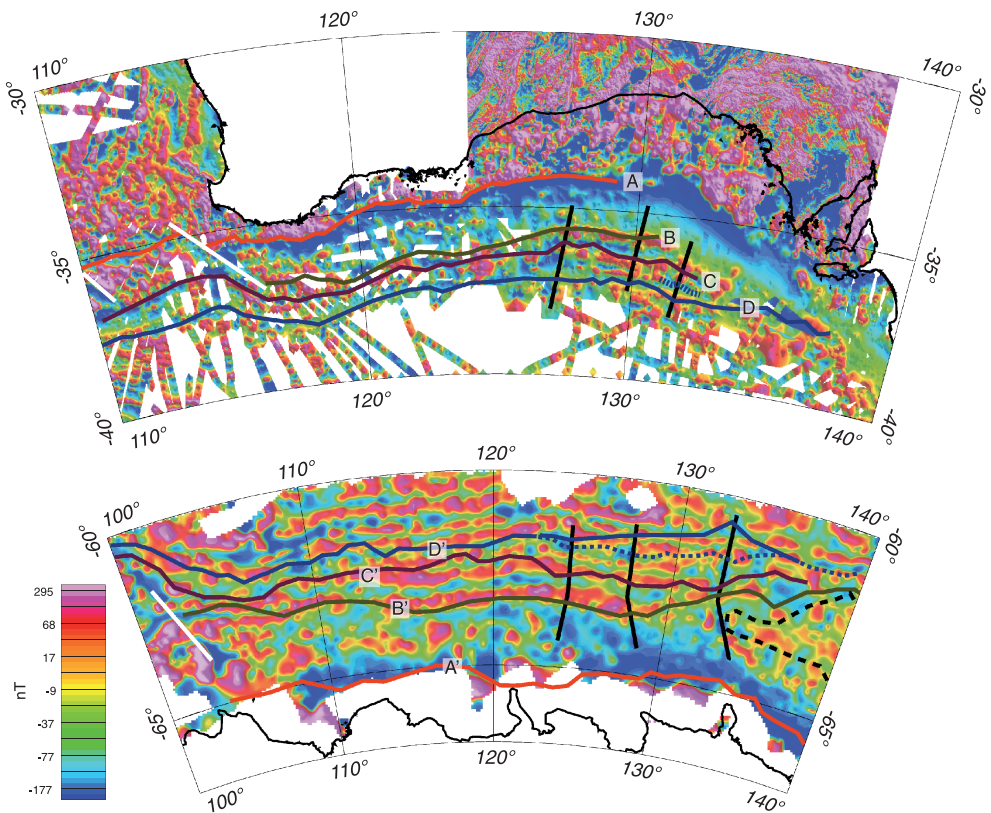


Figure 14. Magnetic anomaly map from Quesnel *et al.* [2009] and Petkovic *et al.* [1999] for Australia and Golynsky *et al.* [2012] for Antarctica. A, B, C, and D represent the anomalies marking the boundaries of the different domains at the Australian margin. A', B', C', and D' represent the anomalies marking the corresponding boundaries of the same domains at the Antarctic margin. White lines correspond to the Fracture Zones and black lines correspond to seismic lines imaged in Figures 4 and 5. Same legend as for Figure 12.

values for this basement. Basement velocities are more elevated (≥ 7.2 km/s) in the western part of the GAB than in the central part (between 5.8 and 7.1 km/s) (Figure 12). This domain coincides with the wide basin observed on the seismic lines, where we find the basement B1 overlain by the sedimentary unit U1. On the seismic lines, A/A' anomaly corresponds to the necking zone (outside the imaged part on the presented lines). The B/B' anomaly is associated with the termination of B1 and U1 and with the first main system of deformation (Phase A).

2.6.2. Domain 2

Domain 2 is bordered by the B/B' gravity anomaly and oceanward by a discontinuous and weak anomaly (C and C') in the central GAB and Wilkes Land, which appears more clearly on the map of the horizontal gradient of gravity (Figure 13). The B/B' boundary represents a slight increase of the gravity signal for Domain 2 compared to Domain 1. Westward of the GAB, C/C' could correspond to a prominent basement ridge visible on some seismic lines (GA187-01 line in Direen *et al.* [2007, Figure 4]) whose signal is clearly visible on the gravity map. In addition to the magnetic anomaly 34y identified by Tikku and Cande [1999] and Whittaker *et al.* [2007], Domain 2 also shows partially the presence of a magnetic lineation. This lineation is interpreted as the 33o magnetic anomaly [Tikku and Cande, 1999; Whittaker *et al.*, 2007] (Figure 15b). Domain 2 corresponds to the basement B2, and the C/C' anomalies coincide with its oceanward termination, with the end of U2 and with the second main system of deformation (Phase B). The available velocity data in this domain display low upper crustal velocities, from 4.5 to 6.65 km/s, with a gradual increase with depth. Moreover, some dredges argue for the presence of basalts and gabbros in the western Australian margin [Beslier *et al.*, 2004] (Figure 12).

2.6.3. Domain 3

Domain 3 displays several prominent gravity anomalies along both margins. These anomalies are only present in the western part of the GAB (west of 125°E) and in the Diamantina Zone at the Australian margin. At the Antarctic margin, they appear west of 110°E. Domain 3 corresponds to the basement B3 and is

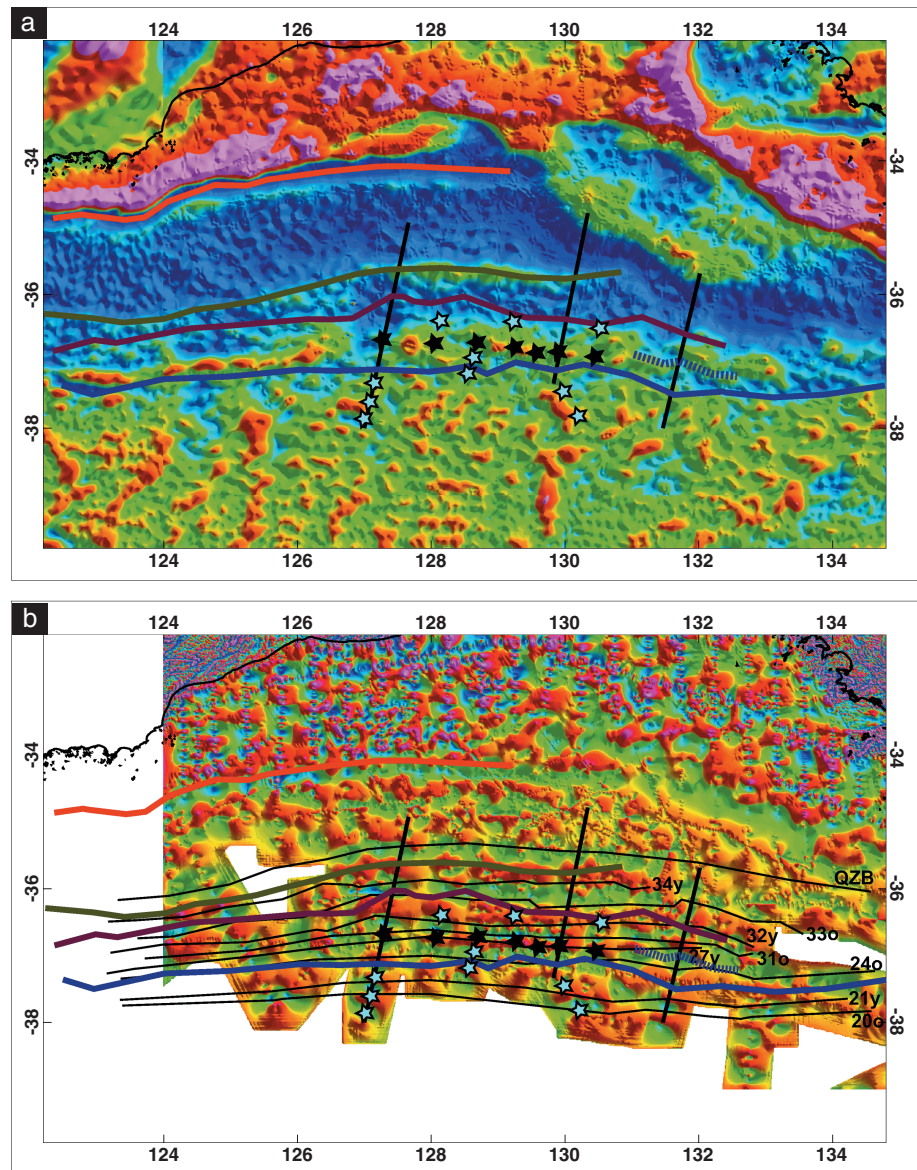


Figure 15. Zoom of the GAB region showing locations of seamounts (stars) identified on seismic sections of the GA199 survey. Black stars: aligned seamounts correlating with a gravity and magnetic anomaly; Light blue stars: seamounts which do not display a clear organization nor a strong correlation with magnetic and gravity anomalies. (a) Free-air gravity map of *Petkovic et al.* [1999]. (b) Magnetic vertical gradient map [*Petkovic et al.* [1999]]. For comparison, the magnetic anomaly interpretations of *Whittaker et al.* [2007] (thin black lines) have been added.

correlated with a change in the gravity and magnetic pattern. Its proximal boundary is the C/C' and its distal boundary is the D/D', which corresponds to the most distal prominent gravity anomaly. In the GAB/Wilkes Land sector, the C/C' boundary is marked by an increase of the gravity oceanward (Figure 15a). At the Antarctic margin, the gravity gradient map highlights another boundary (shown in dashed line in Figure 13), which corresponds with an elevation step in the top basement B3 and to the termination of the U3b unit (Figure 5). Domain 3 also contains magnetic lineations, but the bad data coverage of the Quesnel grid in this area makes them difficult to follow between the GAB and the Diamantina Zone, where no magnetic anomaly younger than C20 has been identified [*Tikku and Cande, 1999*]. This domain displays anomalies interpreted as isochrons 32y to 24o at the Australian margin and 32y up to 20o at the Antarctic margins [*Tikku and Cande, 1999; Whittaker et al., 2007*]. In the GAB, some seamounts observed in the basement B3 (purple stars, Figure 15a) on the seismic lines are aligned and associated with a linear gravity and magnetic

anomaly, which appears in the continuity of the prominent gravity anomalies to the west (Figure 15a). Dredges in this domain have shown the presence of serpentinized peridotites, basalts, and gabbros [Beslier *et al.*, 2004] (Figure 12).

2.6.4. Domain 4

Domain 4 is defined by high gravity anomaly values. D/D' marks the continentward boundary of this domain. Along the Antarctic margin the magnetic signal over this domain presents more regular magnetic lineations, well defined and well shaped. Several sonobuoy solutions show crustal velocities ranging between 6.2 and 7.1 km/s, with a Moho at 11–12 km depth (below sea level) [Talwani *et al.*, 1979]. This domain corresponds to the basement B4. Some seamounts observed on the seismic lines are present in this domain, but they do not display any clear alignment (Figure 15a). Furthermore, no clear gravity anomalies can be observed.

3. Discussion

3.1. Nature of Basement

Seismic observations supported by dredge results and potential field data enable us to describe different basement units and to define different domains in potential field maps. The fact that basement domains and their boundaries can be defined in reflection seismic sections and recognized in potential field maps along the conjugate margins indicates differences in thickness and/or composition of basement units. In the following, we discuss the potential nature of the different basement units forming the distal margins (Figures 16 and 17):

3.1.1. Domain 1: A Hyperextended Continental Crust

In agreement with previous studies [Eittreim *et al.*, 1985; Sayers *et al.*, 2001; Colwell *et al.*, 2006], we propose that the basement B1 represents a hyperextended continental crust, based on the following observations: (1) a visible Moho around 10 s (TWT), (2) upper basement velocities of 6 km/s, and (3) presence of a thick, “sag type,” sedimentary sequence. This basement, belonging to Domain 1, and referred to as “hyperextended continental domain” is less than 7.5 km thick (Beta Factor > 5 , [Kusznr, 2009; Ball *et al.*, 2013]). This extreme thinning and the presence of only few major faults cutting through the whole crust and affecting the Moho (Figure 18) suggest a complex extensional mode. As proposed for the Alps [Müntener and Hermann, 2001], the crust may have deformed by semibrittle deformation processes, with boudinage of the lower crust. Other models that have been proposed to explain the extension in the distal continental crust are depth-dependent stretching models suggesting that extension is not uniformly accommodated with depth leading to a greater thinning of the lower layers compared to the upper brittle crust [Sibuet, 1992; Driscoll and Karner, 1998]. Other authors [Reston, 2005, 2007] proposed that this extreme thinning can be explained by unrecognized faulting of the top basement. At both the Australian-Antarctic margins, arrays of normal faults affecting U1 do not seem to create large basement offset. This observation suggests that these faults are not the main thinning mechanism leading to hyperextended continental crust and that this basement was probably already thinned before the deposition of U1.

The termination of this domain is marked by the development of some major normal faults affecting U1 and B1 (Phase A of deformation). One of them will evolve as a detachment fault exhuming mantle rocks (Figure 6). The small offset normal faults observed in U1 could have formed in response of the detachment system activity. By “detachment system” we understand all recognized and unrecognized extensional faults participating in the development of an exhumed domain. In some Antarctic lines, the deformation of the hyperextended continental crust appears to be controlled by the exhumation process (Figure 18, discussed in next paragraph “Domain 2”), with complex systems of conjugate faults that formed in the hanging wall of the exhumation fault. It thus appears that, when exhumation begins along the detachment fault, it generates new extensive deformation in its hanging wall.

Several observations, including the following: (1) the highly reflective layer at the base of U1, which could represent sills, (2) the magnetic patches, and (3) the high basement velocities to the west (≥ 7.2 km/s) [Talwani *et al.*, 1979, Figure 12], suggest the presence of magmatic additions in this hyperextended domain. Furthermore, the presence of high-amplitude reflections at the base of the continental crust (Figure 6 and 18) may be interpreted as gabbroic underplated bodies or serpentinized mantle [Pérez-Gussinyé *et al.*, 2001]. It is interesting to note that the basement velocities are generally higher in the western part of this domain than in the eastern part. This could be related to a variation in the amount of magmatism along the margin, as already

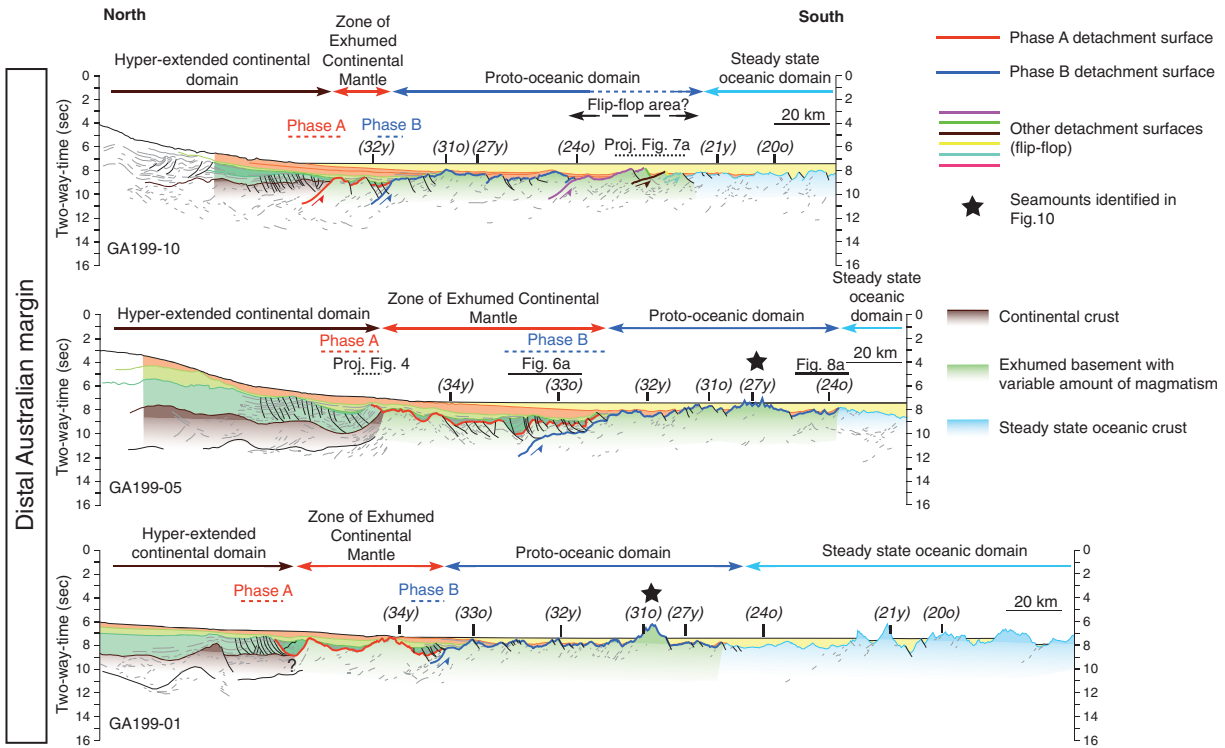


Figure 16. Seismic lines with basement interpretation, Australian margin. The two main deformation phases are clearly visible all along the margin. Magnetic anomaly interpretations from *Whittaker et al.* [2007].

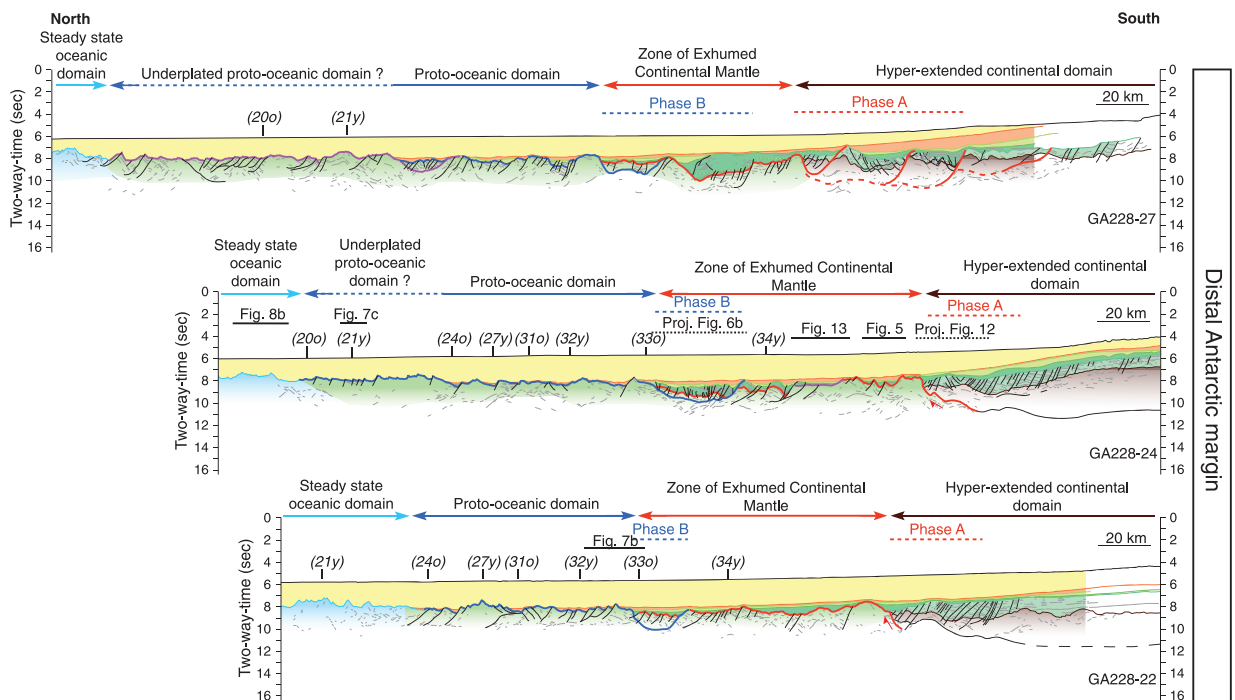


Figure 17. Seismic lines with basement interpretation, Antarctic margin. The two main deformation phases are clearly visible all along the margin. Magnetic anomaly interpretations from *Whittaker et al.* [2007].

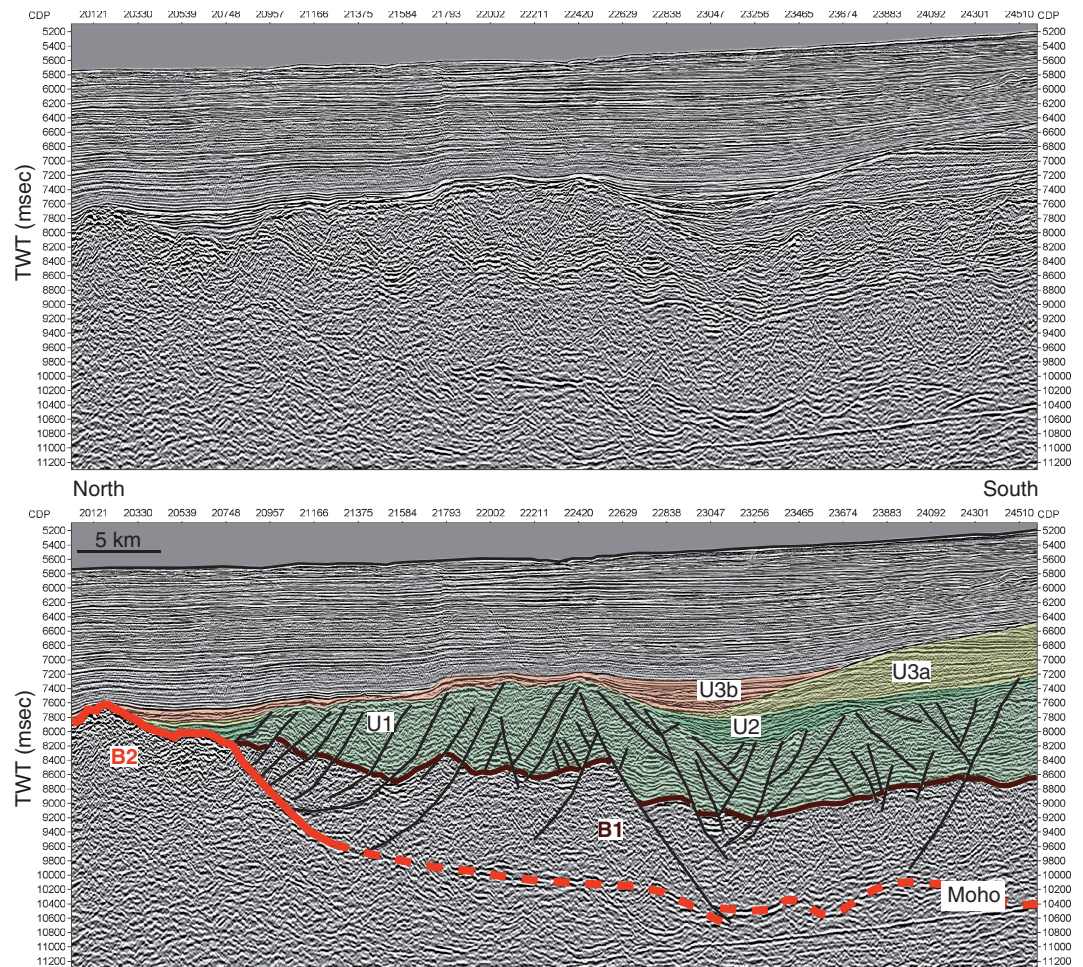


Figure 18. Zoom of seismic line GA228-25 (Antarctic margin) showing the termination of the continental crust and the beginning of the ZECM. The final extension of the hyperextended continental crust appears linked to the mantle exhumation by the “Phase A detachment system” (in thick red). Copyright Commonwealth of Australia (Geoscience Australia).

proposed by *Talwani et al.* [1979]. Moreover, this distribution of basement velocities can be correlated with the presence of the Australian Antarctic Discordance (AAD): indeed, the higher basement velocities are located out of the AAD area. The presence of presumed wedges of depleted mantle, linked to the subduction of a N-S trending Pacific slab until 100 Ma [Gurnis and Muller, 2003; Ritzwoller et al., 2003; Whittaker et al., 2010] could have influenced the distribution of the magmatism during the development of these distal margins.

3.1.2. Domain 2: Zone of Exhumed Continental Mantle

Basement B2 is here interpreted as exhumed serpentinized continental mantle and defines the Domain 2, referred to as “Zone of Exhumed Continental Mantle” (ZECM). This interpretation is coherent with the main observation that the sediments of the U2 unit are downlapping onto B2 (Figure 6). As exhumed mantle is a “newly created basement,” overlying sedimentary units are younger than U1. Indeed, the detachment fault exhuming B2 affects U1 after its complete deposition. In contrast to classical steady state oceanic crust, B2 basement shows the following: (1) no clear Moho reflections, which could indicate progressive decrease in the degree of mantle serpentinization with depth and the absence of mafic lower crustal bodies; (2) lower upper basement velocities (≤ 6 km/s), and (3) the presence of major deformation structures affecting both basement and overlying sediments. The observation that the sediments overlying the crust are deformed, as well as the observed fault heaves and throws observed over this crust are incompatible with the occurrence of a steady state oceanic crust. These observations are more comparable and compatible with observations that can be made along magma-poor rifted margins drilled at several Ocean Drilling Program (ODP) sites in the N-Atlantic [see *Beslier et al.*, 1994].

As the top basement is locally highly reflective, we can suppose the presence of few extrusive magmatic rocks above the exhumed mantle. This hypothesis is supported by the presence of magnetic anomalies in this domain. As shown by *Bronner et al.* [2013], basements formed by serpentinized mantle rocks are unlikely to carry a strong, organized magnetic signal. Observations only based on seismic reflection data cannot lead to a more precise definition of the basement nature, but comparison with other settings where mantle is exhumed (fossil margins exposed in the Alps, drillings along the Iberia-Newfoundland margins, magma-poor ultra-slow spreading ridges) can bring some complementary information. By comparison with the fossil or present-day ZECM's, the magmatic rocks could be dolerites and pillow basalts (e.g., Alpine Tethys margins, [Manatschal et al., 2011]; Newfoundland margin, ODP Site 1277, [Péron-Pinvidic et al., 2007]). Similarly, the top of the serpentinized peridotite could be composed of ophicalcite, overlain by tectonosedimentary breccia of peridotite and by pillow basalts. The serpentinized peridotites found in this domain of exhumed mantle appear to be mainly of subcontinental origin [Piccardo et al., 1990; Trommsdorff et al., 1993; Rampone et al., 1995, 1998; Müntener and Hermann, 1996] and often contain gabbroic intrusions and basaltic dykes [Boillot and Froitzheim, 2001; Desmurs et al., 2001; Müntener and Piccardo, 2003; deMartin et al., 2007]. This is in accordance with the dredged gabbros and basalts recovered in the ZECM at the Australia-Antarctica margins [Beslier et al., 2004]. These observations led to a model where extrusive basalts are emplaced after the crystallization and the exhumation of intruded gabbros [see Desmurs et al., 2001, Figure 16; Manatschal et al., 2011]. However, the timing between gabbro exhumation and basalt extrusion is clearly not constrained. At the Australia-Antarctica margins, the only observation that enables to establish relative ages is based on geometrical relationships. In seismic sections high-angle faults can be observed (Figure 7) that affect both the magmatic upper layer and the underlying serpentinized peridotites, indicating that magma had to be emplaced before the development of these high-angle faults. The sedimentary unit U2 displays syntectonic wedges indicating that U2 was deposited during activity of these faults. Despite the fact that this domain is referred to as the "Zone of Exhumed Continental Mantle," magmatism appears to be present during its formation. Since the normal faults observed in Domain 2 affect exhumed basement (B2), they must belong to a new phase of extension (Phase B) postdating the exhumation. These faults are more numerous at the termination of Domain 2 (Figure 8) where they root onto a reflective layer within the crust. This layer rises oceanward and eventually reaches top basement. As for Phase A, we interpret Phase B as resulting from the initiation of a new detachment system. It develops into basement B2 and leads to the exhumation of basement B3.

3.1.3. Domain 3: A Complex Proto-Oceanic Domain

Basement B3 is interpreted as a complex basement showing a variable morphology along the two margins. Observations suggest that it is composed of exhumed serpentinized mantle with a relatively important but variable amount of magmatism. This is constrained by (1) the sedimentary architecture, with the deposition of the U3a and U3b units onto the basement B3, which suggests that this basement represents a newly created, exhumed basement (Figure 8); (2) the rise of the top basement arguing for an increase of magmatism; (3) the presence of volcanic additions sealing faults (Figure 10) and the occurrence of magmatic seamounts; and (4) the results of dredges in the Diamantina Zone showing that the basement is formed by serpentinized peridotites, basalts, and gabbros. This basement marks the Domain 3, referred to as "proto-oceanic domain." This new domain probably represents the most magmatic part of the distal margin but we do not consider it yet as a steady state oceanic crust. Indeed, we can observe (1) that basement as well as the overlying sediments are deformed (Figures 9 and 11a) showing that the deformation is not yet localized at a stable spreading center; (2) that Moho is not visible but that shallow high-amplitude reflectors can be identified in some places, particularly at the Antarctic margin (Figure 10a); and (3) that in the central sector, the basement morphology between the conjugate margins is variable: at the Antarctica margin the basement seems less magmatic and intensively faulted whereas at the Australia margin a magmatic basement and major seamounts can be observed in the western part of the GAB (Figure 16). These reflections appear as a rooting layer for high-angle faults and have a seismic signature similar to the "S reflector" identified at the Iberian margin and supposed to represent a tectonic feature controlling the final crustal extension. It may correspond to a brittle-ductile transition [de Charpal et al., 1978], a detachment fault [Wernicke and Burchfiel, 1982; Boillot et al., 1988; Winterer et al., 1988; Sibuet, 1992; Reston, 1996, 2009], the crust-mantle boundary [Boillot et al., 1989], or underplating [Whitmarsh et al., 1996]. However, the basement over the S reflector in Iberia is interpreted to be continental, whereas at the Australian-Antarctic margins it is supposed to be ultramafic. The high-angle faults appear to be partially sealed by highly reflective material

that may correspond to volcanic additions. This is comparable to observations made at the Chenaillet Ophiolite [Manatschal *et al.*, 2011]. At this location, faults developed in the previously exhumed serpentinized peridotites and then acted as feeder system for the emplacement of a volcanic sequence. In this context, the shallow high-amplitude reflector could correspond to the top of a gabbroic underplating. Such an underplating could explain the rise of the top basement observed along the Antarctic margin. The nature of the aligned seamounts (Figure 15a) at the Australian margin remains difficult to determine: Are they purely volcanic seamounts or do they correspond to basement highs similar to the serpentinized peridotite highs drilled at ODP Site 637 at the Galicia margin or at ODP Site 1277 along the Newfoundland margin? Moreover, in the eastern part of the GAB/Wilkes Land margins, the proto-oceanic domain displays particular faulted structures (Figure 9), which are laterally continuous with the aligned seamounts (Figure 15a) and that we interpret as “flip-flop detachment faults,” similar to those proposed at the magma-poor Iberian margin [Reston and McDermott, 2011] and observed at magma-poor parts of ultraslow midoceanic ridges [Sauter *et al.*, 2013]. The oceanward end of the proto-oceanic domain thus appears to display variable tectonomagmatic processes.

3.1.4. Domain 4: Steady State Oceanic Crust

Finally, basement B4 is interpreted as an oceanic crust and defines the Domain 4, referred to as “steady state oceanic domain.” This interpretation is based on the following observations: (1) the Moho is more often visible around 10 s (TWT), (2) the overlying sediments of the U4 unit are not deformed, (3) there are generally high gravity signal and well-shaped magnetic lineations, and (4) high basement velocities are observed. However, this basement displays some differences between the two margins: at the Australian margin the oceanic crust displays major seamounts whereas at the Antarctic margin the crust shows the presence of locally high structures with an important roughness (Figure 11b). This structure, which is associated with rising intrabasement reflections, is very similar to that observed by Ranero and Reston [1999] west of the Canary Islands, interpreted as an oceanic core complex created by a detachment fault.

3.2. Tectonomagmatic Processes

There are three ways to create “new” basement at distal rifted margins and oceanic domains: (1) by tectonic exhumation of deep seated continental or mantle rocks along extensional detachment faults, (2) by magmatic accretion, i.e., adiabatic decompression and partial melting of the asthenospheric mantle, or (3) a combination of the two. The different processes result from different conditions and lead to the creation of different types of basements (Table 2):

1. Extensional detachment faults generally occur when magmatic budgets and/or extension rates are low, with low-rigidity rocks forming the crust. Moreover, the formation of low frictional minerals (serpentinite, talk, etc.) is important and facilitates slip along the long offset faults. It leads to the creation of new basement, mainly composed of hydrated crust or mantle, in the latter case made of serpentinized peridotites of either subcontinental (ZECM) or oceanic origin (mature spreading ridge)
2. In contrast, magma-controlled seafloor spreading requests higher magmatic budgets, spreading rates ≥ 2 cm/yr [Cannat *et al.*, 2009] and convection in the enriched underlying asthenospheric mantle. It leads to the creation of a mafic, about 6 to 7 km thick, three layered (basalts, sheeted dykes, and gabbros), also referred to as the “Penrose” crust (Anonymous 1972).
3. These two types of crust are end-member cases and we can find an intermediate case corresponding to the creation of a hybrid crust as the result of a combination of tectonic exhumation and magmatic accretion.

These three different types of basement and processes can be observed at midoceanic ridges corresponding to steady state oceanic spreading. By steady state oceanic spreading, we mean that the creation of new basement, whether magmatic or amagmatic, is installed in a spreading system that is stable and localized in time as well as in space. This means that fast spreading ridges as well as ultraslow spreading ridges are considered as steady state oceanic spreading and lead to the formation of an oceanic crust with variable amount of magmatic additions. On the contrary, a “non steady state” seafloor formation indicates that the spreading center is not yet localized. A key observation in such settings is that the overlying sediments are deformed. This type of “non steady state” oceanic crust, here referred to as “zone of exhumed continental mantle” and “proto-oceanic domain” can be observed at distal parts of magma-poor margins.

Table 2. Characteristics of the Three Types of Crust and Associated Processes

Type of Crust	Characteristics	Processes
Exhumed	<ul style="list-style-type: none"> • Mafic/ultramafic basement composed of hydrated lower crust or serpentinized mantle <ul style="list-style-type: none"> • Few magmatic additions • No visible Moho • Low upper basement velocities (<6 km/s) and gradual increase with depth <ul style="list-style-type: none"> • Low top basement • No clear or patchy magnetic lineations 	<ul style="list-style-type: none"> • Low magmatic budget • Exhumation of deep rocks along extensional detachment faults • Low extension rates
Hybrid	<ul style="list-style-type: none"> • Mafic and ultramafic basement, composed of exhumed serpentinized mantle with large magmatic additions (basalts and gabbros) <ul style="list-style-type: none"> • No Moho visible • Complex intern structuration and complex interaction fault/magma <ul style="list-style-type: none"> • Possible presence of gabbroic underplating • High top basement • Presence of well-defined magnetic lineations 	<ul style="list-style-type: none"> • Combination of tectonic exhumation and magmatic accretion • Exhumation of deep rocks along extensional detachment faults associated to magmatic addition (volcanics, intrusions, underplating)
Magmatic accretion	<ul style="list-style-type: none"> • Mafic basement with a typical three-layer crust (basalts, sheeted dykes, gabbros) <ul style="list-style-type: none"> • Moho visible • Typical thickness of 2 s (7 km) • High basement velocities (6–7 km/s) <ul style="list-style-type: none"> • High top basement • Presence of well-defined magnetic lineations 	<ul style="list-style-type: none"> • High magmatic budget • Adiabatic decompression and partial melting of the asthenospheric mantle • Extension rates ≥ 2 cm/yr

In the case of the Australian-Antarctic margins, Domains 2 and 3, respectively the zone of exhumed continental mantle and the proto-oceanic domain are mainly associated with non steady state seafloor formation. Accordingly, two main deformation phases (Phases A and B), affecting both basement and overlying sediments, punctuate the margin evolution and highlight that the creation of basement is polyphase and associated with a migration of deformation toward the future ocean. This supposes that the deformation is not yet localized, contrary to what we can expect at a mature, steady state oceanic spreading ridge. Both basements B2 and B3 are interpreted to be mainly composed of exhumed serpentinized mantle, but it can be observed that the proportion of magmatic material is probably not negligible, particularly in the proto-oceanic domain. Both seafloor formation processes (mantle exhumation and magmatic accretion) appear to work together in the creation of basement B3 in the proto-oceanic domain, leading to the creation of a hybrid basement. However, magma emplacement varies and is not localized, enabling underplating to occur. High-angle faults and magmatic rocks can overprint previously exhumed mantle, or use existing high-angle faults as feeders to build volcanic bodies or seamounts over existing basement. All these processes are, strictly speaking, not possible over a steady state oceanic crust that is formed along a localized and stable spreading system. However, at the end of the proto-oceanic domain, we observe “flip-flop faults” (Figure 9). As these fault systems are typically observed at magma-poor ultraslow spreading ridges associated with small-scale asymmetric mantle exhumation [Sauter *et al.*, 2013], their occurrence at the most distal part of magma-poor margins (e.g., Iberia-Newfoundland [Reston and McDermott, 2011] and Australia-Antarctica, this study) could represent the onset of steady state seafloor spreading.

As a result and following our interpretations, we propose that the serpentinized peridotites forming the basements B2 and B3 have been exhumed and emplaced at the seafloor by two main detachment systems, whose initiation is marked by two main systems of deformation (Phases A and B), well identifiable in the seismic lines. These systems of deformation are part of the Rift Phase 2 of Ball *et al.* [2013]. They are clearly separated in time and space, showing that the extension along the distal margins was clearly polyphase. The sedimentary units indicate that the detachment system associated to Phase A is postdeposition of U1 but

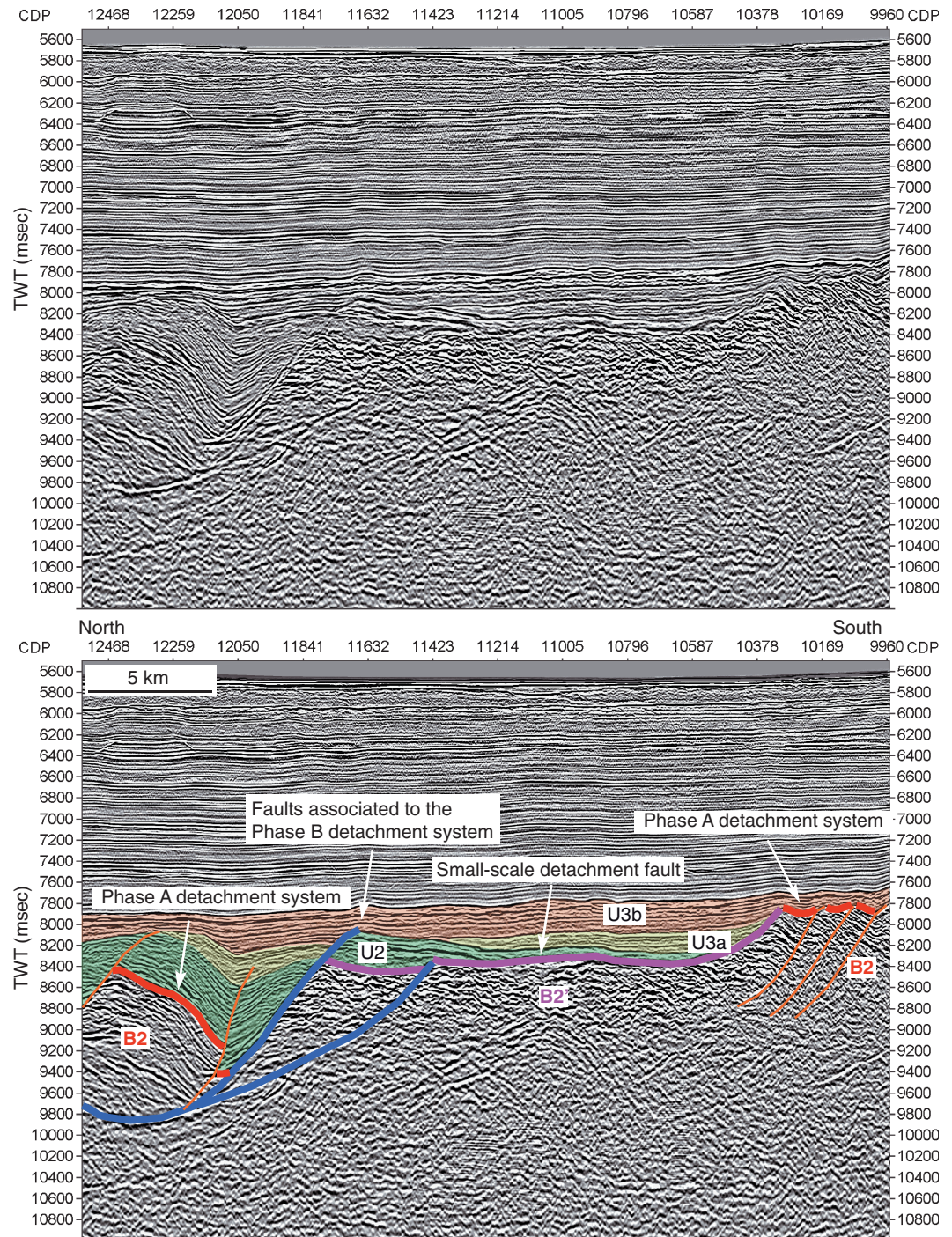


Figure 19. Zoom of seismic line GA228-24 (Antarctic margin) displaying a minor small-scale detachment fault (in thick violet) in the ZECM. Copyright Commonwealth of Australia (Geoscience Australia).

predeposition of U2 and that the detachment system associated to Phase B is postdeposition of U2 and syndeposition or predeposition of U3a. Seismic observations show that the “Phase B detachment system” develops in the center of the basin, cutting through the previously exhumed basement B2. The amount of magma seems to progressively increase with time until the emplacement of the first magmatic steady state oceanic crust (basement B4) or the first amagmatic steady state oceanic basement (represented by flip-flop areas). Along these margins, we do not observe an abrupt boundary between an amagmatic

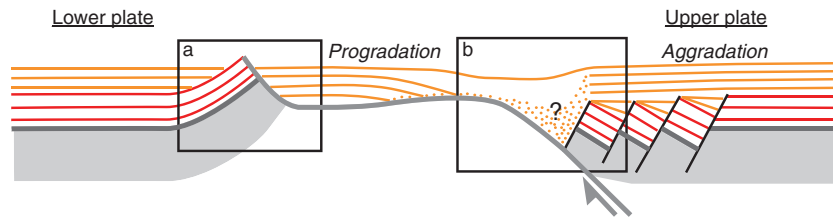


Figure 20. Conceptual model displaying the tectonosedimentary relationships associated with an extensional detachment system. Note that the sedimentary architecture in the footwall (lower plate) and hanging wall (upper plate) are different and can be used to determine the polarity of a detachment system. Note that this figure assumes sedimentation rates that are high relative to the rate of extension. This figure is not oriented.

system and a magmatic oceanic accretion. However, it seems that the different events punctuating the development of these margins are associated with either a change in the deformation mode or the magmatic budget, or a combination of the two.

3.3. Large-Scale Exhumation Systems Versus Small-Scale Structures

As shown in Figures 16 and 17, the two systems of deformation (Phases A and B) appear laterally continuous for the GAB/Wilkes Land segment: (1) they are observed on seismic lines distributed along a distance of more than 400 km, (2) the continuous gravity anomalies B/B' and C/C' (marking the beginning of the two exhumed domains) are relatively linear and continuous along the two margins. We can thus propose the existence of two large-scale mantle exhumation systems along these margins. From west to east, the potential field anomalies, the deformation pattern, and the units affected by the detachment are consistent. This suggests that the exhumation process is stable in time and space over important distances. However, it is likely that these large-scale observations underscores the importance of smaller-scale structures (e.g., “unrecognized faulting” of Reston [2007]). Indeed, detachment system may consist of several detachment faults, either juxtaposed across the domain or along it [Masini et al., 2012]. An alternative possibility is that unrecognized small-scale detachment faults developed as out-of-sequence faults in previously exhumed domains. An example is the fault identified in the ZECM of the Antarctic margin (shown in Figure 19). This small-scale detachment system creates a new basement (B2'), which is younger than the surrounding basement (B2) since U2 is missing and U3a directly overlies this surface.

Based on our observations and interpretations it appears that wide domains of exhumed mantle, parallel to the flow lines, are probably the result of complex, polyphase systems of detachment faults, which cannot be totally resolved on our seismic lines. We can thus conclude that the exhumation processes are, in reality, complex and difficult to describe in detail and to correlate along the two margins. It looks, however, that mantle exhumation along extensional detachment faults represents the main mechanism responsible for the accommodation of extension during the final development of the Australia-Antarctica margins.

From observations based on seismic reflection it thus appears difficult to clearly define the kinematics and polarity of the detachment systems. However, the architecture of the sediments overlaying the exhumed basement can give a first idea of the polarity of large-scale asymmetric fault systems (Figure 20): at the upper plate, sedimentary systems are supposed to show aggradation patterns, while at the lower plate a progradation/downlapping pattern should be observed. In our examples shown in Figures 6, 8 and 18 we can see the following:

1. At the Australian margin, the “Phase A detachment system” emplaced in continental crust (B1), is overthrust toward the continent. U1 is tilted and interrupted, and U2 laterally “onlaps” on the two sides of the fault (Figure 20a). At the Antarctic margin, the extensional structures affecting the continental crust are more distributed and form several small continentward tilted faulted blocks. Here U1 is also interrupted but U2 appears to “drape” the continental crust termination (Figure 20-b). This observation is valid for the lines in the west and the center of GAB/Wilkes Land. For the eastern lines, the configuration seems to be inverted:

overtilted crust is observed at the Antarctic margin and distributed blocks at the Australian margin (Figure 16, line GA199-10 and Figure 17 line GA228-27).

2. At the Australian margin, the "Phase B detachment system" is emplaced in serpentinized peridotite (B2). This deformation phase is distributed over faulted blocks, with faults rooting on rising strong reflectors (Figure 20b). At the Antarctic margin, we can see a small isolated basin with overtilted blocks (Figure 20a).

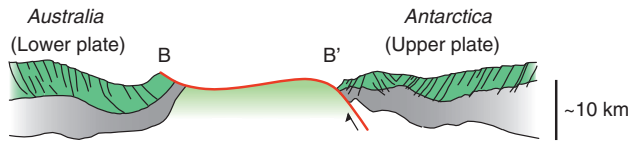
Concerning the "Phase A detachment system", we can thus propose that Australia is the lower plate and Antarctica the upper plate for the west and center GAB/Wilkes Land, whereas it could be inverted for the eastern part. We notice that the dipping direction of the first detachment system can change along the margin, which agrees with a segmented exhumation system. Moreover, the change in the dipping direction occurs when entering the Gawler/Mawson cratons area (see location in Figure 12), which could constitute a rheological boundary [Ball *et al.*, 2013]. Here, the Adélie Rift Block also testifies for a more resistant continental crust. This agrees with our seismic interpretation of the lines GA228-27 (Figure 17), where we can observe that several major normal faults are necessary to sufficiently thin the continental crust and initiate the detachment fault.

3.4. Model for the Evolution of the Distal Australian-Antarctic Margins

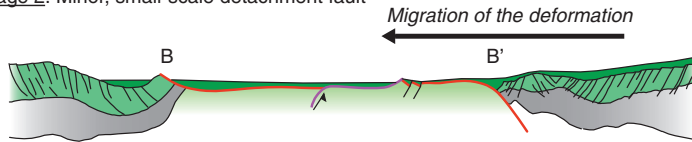
Our observations and interpretations can be summarized in a conceptual model showing the evolution of the distal Australian-Antarctic margins (Figure 21).

- Stage 1: The extreme thinning leads to the embrittlement of the whole crust in the rift center (Phase A), resulting in a hyperextended domain. A first major detachment system initiates, cutting through the whole, previously thinned continental crust and sedimentary unit U1. The latest extension phase of the Antarctic continental crust is probably linked to the onset of the exhumation process. This major tectonic event is marked in seismic lines by the first phase of deformation (Phase A) during the Rift Phase2 defined by Ball *et al.* [2013]. This detachment fault marks the continental crust boundary and the onset of the Zone of Exhumed Continental Mantle. The newly created basement B2 is probably similar to what can be observed in the Platta nappe in the Alps [Desmurs *et al.*, 2001] and in the Iberia-Newfoundland margins [Whitmarsh *et al.*, 2001]. In these examples serpentinized peridotites from subcontinental origin are overlain by ophiolites and tectonosedimentary breccias, while magmatic additions are punctual further inboard and become more widespread and continue further oceanwards. The top of this basement can be locally covered by pillow basalts, small magmatic edifices or flows. Indeed, the extension of the lithosphere is likely accompanied by an adiabatic upwelling of the asthenosphere, resulting in decompression melting. Sediments of the U2 unit begin to deposit on this new basement. In the western and central GAB/Wilkes Land, Australia is the lower plate of this detachment system (configuration displayed in Figure 21). In the eastern part, Australia represents the upper plate.
- Stage 2: The deformation, controlled by small-scale detachment systems, migrates toward more distal parts. U3a sediments begin to be deposited.
- Stage 3: A second phase of deformation (Phase B) leads to the development of a new major detachment system. These new faults cut through the previous exhumed continental mantle and lead to exhumation of new subcontinental mantle. This major tectonic event marks the end of the magma-poor Zone of Exhumed Continental Mantle (B2) and the onset of the proto-oceanic domain (B3). U3b sediments begin to be deposited onto the newly created basement B3.
- Stage 4: Development of the proto-oceanic domain (B3). At the Antarctic margin, the exhumed basement B3 is affected by numerous normal faults rooting on a highly reflective layer, which could correspond to either large intrusive or underplated gabbros. The faults may have served as magma feeders, extruding pillow basalts at the seafloor. This magma-fault interaction can indicate that the old continental lithosphere is massively intruded by magma and that the final lithospheric breakup is close. As a result, B3 displays hybrid features with exhumed serpentinized mantle associated with magmatic material. The Chenaillet Ophiolites could be a fossil analogue for this proto-oceanic domain [Manatschal *et al.*, 2011].

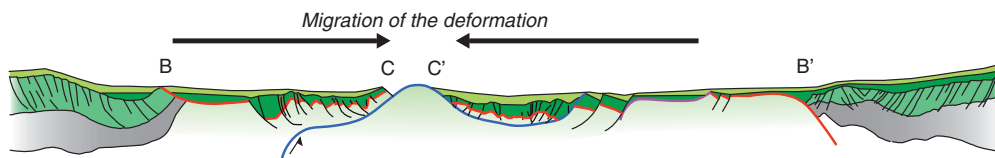
Stage 1: Deformation Phase A, first major detachment fault and continental crust termination



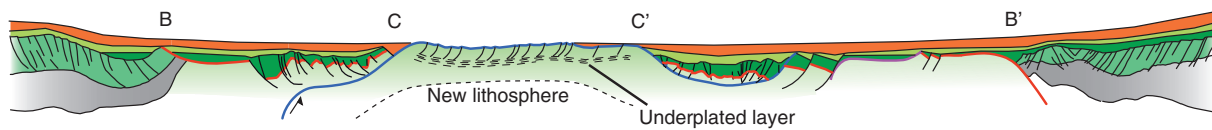
Stage 2: Minor, small-scale detachment fault



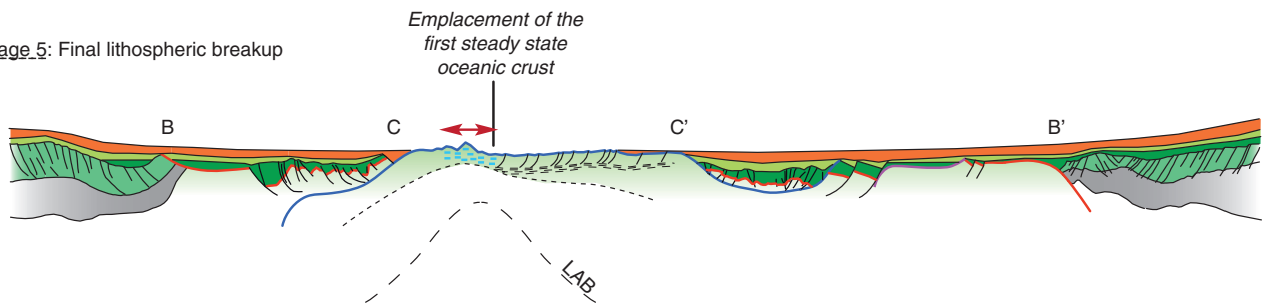
Stage 3: Deformation Phase B, second major detachment fault



Stage 4: Development of the Proto-oceanic domain



Stage 5: Final lithospheric breakup



- Continental crust
- Exhumed continental mantle
- Infiltrated continental mantle
- Phase A detachment system
- Small-scale detachment
- Phase B detachment system
- Top of the new lithosphere
- Zone of lithospheric breakup
- Lithosphere-Asthenosphere Boundary

Figure 21. Evolutionary model for final rift stages and onset of seafloor spreading as observed along the Australian-Antarctic margins. B/B' and C/C' represent the same domain boundaries as in Figure 12.

Stage 5: According to our interpretation, it appears that lithospheric breakup is a progressive process that affects the proto-oceanic domain. The Phase B detachment system progressively exhumes continental lithosphere. The ongoing rise of the asthenosphere increases the thermal gradient and causes massive melt infiltration into the overlying lithospheric mantle. At this point, two different features can be observed: (1) In the west, magmatic pulses create the linear basement highs observed along the margins in the most distal parts of the proto-oceanic domain. (2) In the east, we can rather observe flip-flop detachment systems. We propose that both features testify that lithospheric breakup is on its way to succeed and that a stable spreading center starts to localize. The emplacement of the magmatic seamounts may coincide with a high magmatic budget during spreading center localization, whereas flip-flop detachment systems could indicate a low magmatic budget, not sufficient to directly initiate a magmatic spreading. Such magma-poor systems could result in the localization of a stable spreading center similar to what has been observed at magma-poor ultraslow spreading ridges [Sauter *et al.*, 2013]. Thus, localization and formation of a spreading may not be necessarily linked to a massive volcanic event.

One major implication of our study is that location and age of the first steady state magmatic oceanic crust may be much younger as previously assumed. Indeed, in previous studies, authors proposed an age between 83 and 71 Ma. However, Figure 2 shows that our first steady state oceanic crust is localized clearly more oceanward than continent-ocean boundaries defined by previous studies [e.g., *Weissel and Hayes*, 1972; *Tikku and Cande*, 1999; *O'Brien and Stagg*, 2007; *Close et al.*, 2009; *Williams et al.*, 2011; *Direen et al.*, 2012; *Ball et al.*, 2013]. Comparing our domain locations to interpreted magnetic anomalies [*Tikku and Cande*, 1999; *Whittaker et al.*, 2007] (Figures 16 and 17) we can observe that the first anomaly localized in our steady state oceanic domain varies from the 24o (53.3 Ma, magnetic timescale from *Cande and Kent* [1995]) to the 20o (43.8 Ma). Considering that these anomalies are clearly linked to inversions of the Earth's magnetic field during steady state magmatic seafloor spreading, our first steady state oceanic crust could be dated between 53.3 and 43.8 Ma. This interpretation also implies that mantle exhumation accompanied with sparse magmatic additions could have occurred over 39 Ma and over a distance of as much as 270 km. However, observations on seismic lines and potential field maps at the Australian and Antarctic margins suggest an evolution from west to east for the emplacement of the first steady state oceanic crust. It is noteworthy that the D' boundary at the Antarctic margin crosscuts magnetic lineations (21y and 20o) [*Tikku and Cande*, 1999; *Whittaker et al.*, 2007]. This could be explained if the anomalies are recorded by the magmatic oceanic crust and laterally by the magmatic material in the proto-oceanic domain.

4. Conclusion

In this paper we used a new interpretation approach integrating observations from the basement and overlying sediments, allowing the identification of different deformation phases associated with the creation of "new" basement units. A major outcome of this study is that terms like prerift, synrift, and postrift cannot be used in polyphase rifted margins. We propose that "new" basement units are linked to the development of multiple and complex detachment systems exhuming serpentinized mantle and associated with variable volumes of magma. Boundaries of different types of basement can be defined in the potential field maps, which enables to define different domains for the distal part of the Australian-Antarctic margins. The domains are (1) the Hyperextended Continental Domain, composed of hyperextended continental crust, less than 10 km thick with variable amounts of magmatic additions; (2) the Zone of Exhumed Continental Mantle (ZECM), composed of exhumed serpentinized mantle, with little magmatic additions; (3) the proto-oceanic domain, an area of exhumed subcontinental or oceanic serpentinized mantle, with complex magma-fault relations; and (4) the steady state oceanic domain representing the stable and sustainable oceanic accretion.

Based on seismic interpretation, potential field data, dredges, and sonobuoys data, we propose a new model for the evolution of the most distal parts of the Australia-Antarctica margins. In this model the continental crust boundary is clearly defined and identifiable, whereas the lithospheric breakup is more difficult to localize. Indeed, the magmatic evolution in these margins appears really gradual, and it is likely that the lithospheric breakup represents a gradual process along the Australia-Antarctica margins. We propose that final breakup occurred within a domain of proto-oceanic crust. Depending on the amount of magma, it could

be marked by the presence of magmatic seamounts or flip-flop detachment systems. If final lithospheric breakup was gradual or abrupt and if it was triggered by magmatic and/or mechanic processes is yet unclear.

The emplacement of the first steady state oceanic crust appears to be younger than that proposed by all previous studies. Observation of magmatic additions and of its distribution along the margin highlighted a close magma-fault relation, as proposed for the Chenaillet Ophiolite in the Alps. The timing of magma emplacement as well as the polyphase and out-of-sequence evolution of detachment faults enable us to propose a complex development of the deep margins.

Acknowledgments

Seismic lines of the AGSO surveys GA199, GA228, and GA229 have been provided by Geoscience Australia after personal request and are published with the permission of Geoscience Australia. Gravity grid of *Sandwell and Smith* [2009] is freely available as a .xyz file from the website of the UCSD (topex.ucsd.edu/cgi-bin/get_data.cgi). Magnetic grid of *Quesnel et al.* [2009] is available as a .xyz file from the website <http://projects.gtk.fi/WDMAM/index.html>. Gravity and magnetic grids built by *Petkovic et al.* [1999] are freely available from the Geoscience Australia website (http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_a05f7892-b1ef-7506-e044-00144fdd4fa6/Gravity%2C+Magnetic+and+Bathymetry+Grids+from+Leveled+Data+for+Southwest+Australia+%3A+Great+Australian+Bight). The magnetic grid of the Antarctic margin built by *Golynsky et al.* [2012] has been obtained after personal request to Alexander Golynsky. Processing and map creation have been performed using Oasis Montaj software. We would like to acknowledge the support and kindness of the employees of Geoscience Australia, Alexander Golynsky for providing us the data, and Nick Kusznir for discussions. The authors acknowledge the constructive and helpful reviews of P. Ball, J. Whittaker, and an anonymous reviewer.

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