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Australian-Antarctic break up and seafloor spreading: balancing geological and geophysical constraints

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Abstract

The motion of diverging tectonic plates is typically constrained by geophysical data from preserved ocean crust. However, constraining plate motions during continental rifting and the breakup process relies on balancing evidence from a diverse range of geological and geophysical observations, often subject to differing interpretations. Reconstructing the evolution of rifting and breakup between Australia and Antarctica epitomizes the challenges involved in creating detailed models of Pangea breakup. In this example, differing degrees of emphasis on and alternative interpretations of offshore geophysical data, in particular magnetic anomalies and seismic reflection profiles, and onshore geological data, lead to starkly contrasting views of how the continents were configured at the onset of Mesozoic rifting. Here, we critically review reconstructions of rifting and breakup in the light of all available geological and geophysical data, including magnetic anomalies, fracture zones, conjugate crustal domains, amounts of continental extension, continental geology, plate boundary locations, break-up ages and stratigraphy. We identify the most viable plate tectonic reconstructions both with and without the input of the oldest, more controversial, magnetic anomaly interpretations, and discuss implications for reconstructions of other margin pairs. Our analysis highlights key discrepancies between reconstructions based solely on geological piercing points, and those based on a range of constraints. These insights provide a powerful framework for reducing the range of viable models for Australian-Antarctic rifting, and provide key lessons for future efforts aimed at constraining pre- and syn-rift plate tectonic reconstructions.

Introduction

The Southern Australian and conjugate East Antarctic margin pair (Fig. 1) is among the best example of the challenges in reconstructing plate motions during Pangea breakup. Whereas more recent plate motions are well-constrained by magnetic anomalies and fracture zones in oceanic crust, the motion history is increasingly ill-constrained and controversial further back in time, during early seafloor spreading, continental breakup, and initial rifting.

Many competing models have been proposed for Australian-Antarctic plate motion history, from the onset of rifting at ~160 Ma (Totterdell et al., 2000) until the mid-Eocene, ~46 Ma (Fig. 2). In particular, the configurations of Australia and Antarctica through continental rifting into early seafloor spreading from the Late Jurassic to the Early Cenozoic have been extensively studied in recent years (Williams et al., 2011, 2012; Whittaker et al., 2007; 2013; White et al., 2013; Aitken et al., 2014; Jacob et al., 2014), yet, the disparities between these reconstruction scenarios are greater than ever before.

The controversies in reconstructing the plate kinematic history arise largely through different weighting of the available lines of evidence, namely geology versus geophysics, onshore versus offshore, and consideration of geodynamic plausibility, to address a series of unresolved questions:

(1) What is the nature of the Continent-Ocean Transition (COT)? What is the extent of stretched continental crust within the margins? Is exhumed mantle material present? Are there linear magnetic anomalies in the COT? If so, how did they form? What defines the onset of 'true' seafloor spreading? When did this commence?

(2) What was the rate of motion during rifting and early seafloor spreading? How well can we quantify the amount and timing of continental extension during rifting? Can we consider magnetic anomalies in the COT as isochrons that constrain relative plate motions? If not, how else can we constrain the rate of motion?

(3) *What was the direction of relative plate motion during rifting and breakup? Did the direction of relative motion change through time? How can we constrain the direction of motion when fracture zones are absent or unclear?*
(4) *How well constrained are correlations of Palaeozoic and older basement features onshore Australia and Antarctica? Are these correlations reliable constraints for Mesozoic reconstructions of Australia and Antarctica prior to continental rifting?*

Questions around the evolution of the Australian-Antarctic conjugate margins are generic to many conjugate margin pairs, where there remain significant uncertainties regarding the timing and kinematics from the onset of continental rifting throughout the transition to 'normal' seafloor spreading processes.

Here, we review the geophysical and geological observations available to address these questions in the Australian-Antarctic conjugate margin context, and the uncertainties in these observations and their interpretation. We begin by reviewing the arguments for and against the use of magnetic anomalies adjacent to the Australian and Antarctic margins as constraints on seafloor spreading rates and plate tectonic reconstructions. We then consider what other observations are available to constrain plate configurations during early Australia-Antarctica divergence - these include information from tectonostratigraphic studies of marginal sedimentary basins, large igneous provinces, onshore geology correlations, and consideration of whether modelled plate motions are geodynamic plausible. Using a suite of tests, we directly compare published plate tectonic reconstructions of the Australian-Antarctic plate pair. We illustrate that consideration of all the available geological and geophysical data, and the uncertainties inherent within their interpretation, allows us to identify the range of viable reconstructions. Our analysis highlights how reconstructions that do well in reconciling single lines of evidence appear less feasible once all relevant observations are considered.

Background

The first reconstructions for Australia-Antarctica (Le Pichon and Heirtzler, 1968; Le Pichon, 1968) inferred Early Eocene (~C18) continental breakup. The first quantitative pre-rift Australian-Antarctic reconstructions used the geometrical fit of bathymetric contours (Sproll and Dietz, 1969; Smith and Hallam 1970), and the fit of the submerged oceanic plateaus Broken Ridge and Kerguelen Plateau (McKenzie and Sclater, 1971).

Subsequently, alternative interpretations for the oldest magnetic anomaly lineation (Fig 3.), and thus the onset of seafloor spreading in the Australian-Antarctic basin, were proposed 1) Chron 22, ~49 Ma (Weissel and Hayes, 1972), 2) C34, ~83.5 Ma (Cande and Mutter, 1982); and 3) 95 ± 5 Ma based on an edge effect at the continent-ocean boundary, corresponding to breakup (Veevers, 1986). The latter interpretation was reflected in reconstructions for the rifting and early spreading history (Veevers and Eittreim, 1988; Powell et al. 1988). NNE-SSW directed continental rifting was proposed from 160 to 95 Ma, based primarily on estimates of continental extension from seismic profiles from the Bass and Gippsland Basins. Royer and Sandwell (1989) used Geosat data to interpret fracture zones, which combined with magnetic anomaly identifications, generated well-constrained reconstructions for the Eastern Indian Ocean from the onset of rifting at C34 to the present-day.

Later generations of models grappled with reconciling constraints from across the Australian-Antarctic system. Reconstructing the transition from rifting to seafloor spreading, Royer and Rollet (1997) achieved good fits between the South Tasman Rise and Cape Adare, but generated misfits the Bight Basin, and between the Broken Ridge and Kerguelen Plateau. Tikku and Cande (1999) produced a better fit between Broken Ridge and Kerguelen, but which instead resulted in large overlaps between Tasmania and Cape Adare, requiring significant, undocumented, Late Cretaceous strike-slip motion between Tasmania and Australia (Tikku and Cande, 2000). Whittaker et al. (2007) invoked a major change in

Australia-Antarctica relative motions from NW-SE to N-S between C21-24 (~47-53 Ma), resulting in a model with tectonically improbable episodes of extension and compression between Broken Ridge and Kerguelen (Tikku and Direen, 2008; Whittaker et al., 2008). Williams et al. (2011) generated a pre-rift reconstruction of Australia-Antarctica by restoring the continental extension constrained using crustal thickness. Whittaker et al. (2013) focussed on the early seafloor spreading phase of Australian-Antarctic motions (C34-C20) resolving the Broken Ridge - Kerguelen issues, maintaining the change in direction and the fits further east, and incorporating the preferred pre-rift reconstruction of Williams et al. (2011). Jacob et al. (2014) reconstructed Australian-Antarctica motions (38-84 Ma; <C20 to C34) as part of a three-plate system involving India, using scarce constraints from the later deformed Wharton Basin and Southwest Indian Ridge. Their solution yielded reconstructions statistically indistinguishable from Whittaker et al. (2013) for C21-C32, but that significantly deviate for C33 and 34. Their pre-rift reconstruction used the Bullard et al. (1965) bathymetric contour method and added independent Tasmania motion, resulting in ~350 km of undocumented compression in the Wilkes Land/Transantarctic Mountains.

Others have focussed on onshore geological constraints. Alternative, conflicting interpretations of the pre-rift alignment between onshore geological terranes within Australia and Antarctica have been proposed (Goodge and Fanning, 2010; Gibson et al., 2011; 2013; Veevers, 2012). White et al. (2013) proposed a full-fit reconstruction based on the geological correlations proposed by Gibson et al. (2011, 2013), resulting in a model with a significantly looser fit at the beginning of rifting (~165 Ma) than any other proposed reconstruction. Aitken et al. (2014) re-evaluated correlations of geological units between Antarctica and Australia using lithospheric boundaries beneath the East Antarctic Ice Sheet mapped from new Antarctic geophysical data. They preferred the Leeuwin full-fit reconstruction of Williams et al. (2011), which provided a better match to their new observations than other reconstructions.

The various reconstructions are summarised in Table 1, which lists the time span covered and main observational constraints used in each case. Table 1 also defines the abbreviations used here to refer to different reconstruction models.

Defining the Continent-Ocean Transition

Plate tectonic reconstructions of breakup and seafloor spreading are dependent on constraints from the separating conjugate margins. This is relatively straightforward for seafloor spreading, where magnetic anomaly lineations and fracture zones can be used. For continental rifting, markers are more enigmatic. Continental rifting and breakup is a complex and diverse process (e.g. Reston and Pérez-Gussinyé, 2007; Peron-Pinvidic et al, 2013; Dean et al., 2015), resulting in regions where the nature of the crust is often ambiguous from geophysical observations, commonly referred to as the Continent Ocean Transition (COT). As recognised previously, the concept of a distinct continent-ocean boundary is problematic though sometimes necessary (Direen et al, 2007; Heine et al, 2013; Brune et al, 2016). Direen et al. (2007) defined the COT for the Australian-Antarctic margin pair as, "*the region between unequivocal oceanic crust and unequivocal attenuated continental crust, containing variable amounts of sedimentary and magmatic components*", while Gillard et al (2015) proposed a detailed evolutionary model for the phases of breakup from rifting to hyperextension, mantle exhumation and seafloor spreading.

For the Australian-Antarctic conjugate margins, the thickness of the continental crust (Fig. 4) decreases dramatically around the location of the present-day bathymetric shelf edge (e.g. Mutter et al., 1985; Veevers and Eittreim, 1988; Willcox and Stagg, 1990; Sayers et al., 2001; Stagg et al., 2005; Direen et al., 2007; Kusznir, 2009; Espurt et al., 2009; Close et al., 2009; Whittaker et al., 2012; Ball et al., 2013). Crustal thickness maps produced by Kusznir (2009; Fig. 4) delineate strong gradients in present-day crustal thickness from > 30 km thickness on the landward side to crust < 10 km thick on the oceanward side of this gradient (thinning factor >0.7). The transition between continental and oceanic crust is interpreted to lie somewhere within the thinner crust, typically several hundred kilometres oceanward of the bathymetric shelf edge.

Seismic reflection signatures of the COT

Due to the difficulty in directly sampling the deep, sedimented Australian-Antarctic margins, geophysical data is typically interpreted to constrain the transition from unequivocal continental crust to the transitional crust to unequivocal oceanic crust. Over the last decade, contrasting interpretations have been made for where the continental domain ends and the oceanic domain begins, based largely on seismic profiles (e.g., Colwell et al., 2006; Leitchenkov et al., 2007; Close et al., 2009; Czarnota et al., 2013; Ball et al, 2013; Gillard et al., 2015).

Alternative seismic reflection interpretations of the distribution of oceanic and continental crust across the conjugate Australian-Antarctic margins show consistency in some regions, for example in the Otway Basin – Terra Adélie sector. However, disagreements occur further west, in the conjugate Bremer Basin and western Wilkes Land sectors (Fig. 4), where there is up to 150 km difference between the most inboard and most outboard interpretation of oceanic crust from seismic reflection profiles. On the Australian margin, Blevin and Cathro (2008) interpreted the COT to extend fairly linearly westwards from the eastern Bight Basin into the distal section of the Bremer Basin. By contrast, Czarnota et al. (2013) interpreted 'bona fide' oceanic crust to lie 150-200 km further landward using the same seismic data. The interpretation of Czarnota et al. (2013) suggests that oceanic crust formed during the so-called 'magnetic quiet zone', in contrast to the Bight Basin to the east where all studies interpret the laterally equivalent basement to be thinned continental crust. Gillard et al. (2015) interpreted a very wide COT, comprising exhumed continental mantle and a 'proto-oceanic' domain. The innermost boundary interpreted by Gillard et al. (2015) between extended continental crust and the COT broadly aligns with that of Blevin and Cathro (2008), but their interpreted onset of oceanic crust is significantly further outboard. Some caution needs to be used when comparing the Gillard et al. (2015) interpretation with the other available interpretations, as they did not set out to interpret an explicit boundary between the continental and oceanic crust. As noted by the authors, both their 'exhumed mantle' and 'proto-oceanic' domains can be considered as seafloor spreading processes, albeit in a non-steady state.

On the Wilkes Land margin, the largest uncertainties in the crustal architecture occur in the Sabrina coast sector, which is broadly conjugate to the Bremer Basin (Fig. 4). Colwell et al. (2006) and Close et al. (2009) both interpreted geophysical data collected by Geoscience Australia, and arrived at similar interpretations for the COT east of 125°E. However, west of 125°E, Colwell et al. (2006) tentatively interpreted the outboard limit of unequivocal oceanic crust to lie up to 150 km oceanward compared with the interpretations of Close et al. (2009) from the same data. Interpretations by Leitchenkov et al. (2007), which used Russian seismic profiles from the same region, are remarkably similar to those of Close et al. (2009). The interpretations of Gillard et al. (2015), using both Australian and Russian data, are closest to those of Colwell et al. (2006), although the former interprets a wider overall COT and a more outboard location for unequivocal ocean crust. Figure 5 shows one of the seismic profiles where the interpretations of COT are most divergent; innermost COT - Close et al. (2009), Leitchenkov et al. (2007); outermost COT - Colwell et al. (2006). However, the most oceanward interpretation of continental crust extent of Colwell et al. (2006) should be treated with caution, as the authors themselves noted. Their tentative preference for the more oceanward interpretation was based on the seismic reflection character and because reconstructions that treated magnetic lineations in this area as seafloor spreading anomalies (Tikku and Cande, 1999) result in unreasonable overlap between Tasmania and Cape Adare. The ability of seismic data to image the crust in the region is limited by thick and highly reflective post-rift sediments (Close et al., 2009) and reconstructions presented by Royer and Rollet (1997) or Whittaker et al. (2007, 2013) arguably resolve the Tasmania-Cape Adare overlap objection.

Potential field constraints on the COT

In summary, interpretations of seismic reflection data result in large (in some cases >100 km) uncertainties in COT locations. To discriminate between these interpretations, it is logical to evaluate whether the continuity of the COT is compatible with other geophysical data. Maps of gravity and magnetic anomalies provide a powerful constraint on first-order crustal structure along each margin (Williams et al, 2011). Additionally, we can evaluate both conjugate margins together, and ensure that observations from both sides have been interpreted self-consistently. For example, we expect that each magnetic anomaly related to seafloor spreading forms as a conjugate pair observed with a similar distribution along both margins.

Viewed in this framework, some seismic reflection interpretations make more sense than others. The COT interpretations of Leitchenkov et al. (2007) and Close et al. (2009) provide self-consistent explanations for a range of geophysical observations, including seismic reflection data and stratigraphy as well as gravity and magnetic anomalies. Significantly, in these interpretations COT boundaries do not cross-cut any linear magnetic anomalies, and are also consistent with the interpretation of Blevin and Cathro (2008) for the Australian margin - together yielding a consistent pattern of conjugate magnetic anomalies recorded in the crust of the western Bight Basin and western Wilkes Land margins.

Alternative COT interpretations fit less well into a self-consistent framework. The inboard oceanic crust interpretation on the Australian margin by Czarnota et al. (2013) is inconsistent with all published models for the Antarctic margin. The interpretation of Colwell et al. (2006) implies that some magnetic anomalies continue across boundaries between oceanic crust and regions of COT. In this case, we would expect that truncations of magnetic anomalies older than C21o on the Wilkes Land margin would be mirrored by similar truncations on the Australian side. No such truncations are observed - instead, the magnetic compilation of

Golynsky et al. (2012) compellingly illustrates how the series of parallel magnetic signatures persist for >1000 km along the Antarctic margin. Gillard et al. (2015) interpret domains of different types of crust crossing magnetic anomaly lineations, that are not symmetric between the conjugate margins. How one margin transitions between basement types before the other, without an observed discontinuity in the linear magnetic anomalies, as implied by this interpretation, remains unresolved. Alternatively, interpretations where crustal boundaries cross-cut magnetic lineations (e.g. Colwell et al. 2006; Gillard et al., 2015) may imply that some or all of these magnetic anomalies must result from other, more unusual, mechanisms.

Geological Origin of COT Geophysical Signatures

Defining the transition from continental to oceanic crust is fundamental to the understanding the geodynamic evolution of rifted margins. In particular, the nature of the crust, and how magnetic lineations form, dictates if and how magnetic lineations may be used to constrain early plate motions. Many studies have used linear magnetic anomalies as old as C34 (~83 Ma) as constraints on reconstructions (Royer and Sandwell, 1989; Royer and Rollet, 1997; Tikku and Cande, 2000; Whittaker et al., 2007, 2013; Jacob et al., 2014). However, the validity of the oldest anomalies as constraints on past plate motions has been questioned on the basis that these anomalies do not result from 'true' seafloor spreading (Tikku and Direen, 2008; Direen et al, 2012; White et al, 2013).

One mechanism proposed to explain the Australian-Antarctic magnetic anomalies (Direen et al., 2007), is that they originate from thick, magnetised basalt piles overlying stretched continental crust. An alternative possibility is that they originate from linear underplating and intrusion into previously exhumed mantle during a pulse of magmatism (e.g. Bronner et al., 2011). This mechanism is a plausible, albeit controversial (Tucholke and Sibuet, 2012; Bronner et al., 2012) proposal to explain one anomaly pair within the Iberia-Newfoundland case.

However, both mechanisms in the Australian-Antarctic context are problematic. A single volcanic or magmatic pulse during breakup could potentially explain the existence of a single magnetic anomaly in the conjugate margins, but it is very difficult to envisage a series of pulses resulting in the observed series of parallel, linear magnetic anomalies on the Australian-Antarctic margins. Further, in the underplating and intrusion case, the amplitude and width of the Iberian-Newfoundland J-anomaly decreases northwards (Bronner et al. 2011), interpreted to reflect the northward propagation of magma (Reston and Phipps Morgan, 2004). However, the anomalies formed during Australian-Antarctic divergence show consistent amplitudes and widths over distances >1,000 km, and the amplitudes are consistent with unequivocal spreading anomalies in adjacent, younger crust.

Another mechanism proposed to explain the presence of linear Iberian-Newfoundland magnetic anomalies, exposed mantle rocks and a block faulted basement is mantle exhumation and serpentinisation (leading to magnetisation) in thinned continental lithosphere (Sibuet et al. 2007). This mechanism has also been proposed for the origin of linear magnetic anomalies in the Australian-Antarctic COTs (Veevers, 1986; Sayers et al., 2001; Direen et al., 2007). However, results from the currently active Southwest Indian Ridge indicate that in slow spreading systems with observed mantle exhumation (Sauter et al., 2008, 2013) it is the volcanic sections that record seafloor spreading anomalies (Bronner et al., 2014), whereas the exhumed mantle regions display weak and highly variable magnetic patterns. In this example, non-steady state seafloor spreading results in clearly identifiable linear magnetic anomalies.

Given the above observations, it remains unclear how exhumed mantle material could be responsible for the observed proximal high amplitude, linear magnetic anomalies of the conjugate Australian-Antarctic margins. Rather, it is more plausible that the linear magnetic anomalies originate from volcanic/magmatic sections that may be interspersed with exhumed mantle and that the process operates similarly to that interpreted at the Southwest Indian Ridge. Supporting this inference, magnetic and dredge data have led some researchers to propose that at least some of the Australian COT is deformed oceanic and/or exhumed mantle (e.g. Beslier et al., 2004; Mutter and Cande, 1983; Royer and Sandwell, 1989; Munschy et al., 1992; Munschy, 1998). All dredges within the Australian and Antarctic COTs have recovered volcanic or exhumed mantle rocks, which strongly supports the interpretation that most to all of the lithosphere formed due to ultra-slow plate motions between Australia and Antarctica from ~83 to ~50 Ma result in magnetic anomalies that can be used in plate tectonic reconstructions.

In summary, arguably the simplest explanation to explain the origin of linear anomalies adjacent to the Australian and Antarctica COTs is that they are formed by seafloor spreading processes, where seafloor spreading processes encompass 'non-steady state' processes (e.g. Gillard et al., 2015).

Geological Constraints on Australia-Antarctica breakup

Despite our relative confidence in using the linear magnetic anomalies of the conjugate Australian and Antarctic margins, and in view of the conflicting interpretations of geophysical data, we can nonetheless ask the question: what data can constrain plate configurations if we exclude magnetic anomalies? Alternative ways to constrain the relative positions of the Australian and Antarctic plates during Cretaceous separation, that are distinct from magnetic anomaly constraints include:

A. Constraints on the timing of rifting and breakup from geological sampling and stratigraphic studies.

B. Geological plausibility of implied magnitudes and rates of continental rifting.

C. Geological consistency along the entire Australian-Antarctic plate boundary, including the Kerguelen-Broken Ridge large igneous province in the west, and the Tasmania-Cape

Adare sector in the east.

D. Geodynamic consistency of plate motions, such that plate motions and plate motion changes are relatively smooth and can be linked to changes in plate driving forces.

E. Alignment of continental terranes and geological structures (‘piercing points’).

We present a series of tests to illustrate how well alternative published reconstructions agree with these criteria.

A) Geological constraints on rifting and breakup timing

The evidence for Mesozoic rifting between Australia and Antarctica has been extensively described in previous studies (e.g. Blevin and Cathro, 2008; Totterdell and Bradshaw, 2004; Norvick and Smith, 2001; Stacey et al, 2013; and references therein). These syntheses of observations from the Australian margin including onshore geology, offshore drill holes, and seismic stratigraphic analysis, reveal a first episode of rifting in the Late Jurassic, with only minor extension recorded through much of the Early Cretaceous in the Bremer, Bight and Otway basins. The sediments within these basins record predominantly fluvio-lacustrine depositional environments in the Jurassic and Early Cretaceous (Blevin and Cathro, 2008), with the Late Cretaceous witnessing clear episodes of crustal extension and subsidence (e.g. Totterdell and Bradshaw, 2004; Espurt et al, 2012; Stacey et al, 2013), increasingly coastal and marine depositional environments, and the development of the Ceduna Delta (Totterdell and Bradshaw, 2004; Norvick and Smith, 2001).

The age of breakup within different parts of the rift system is constrained by geological evidence (summarised by Direen, 2012), which reinforce the view that Australia and Antarctica broke up progressively from west to east (e.g. Royer and Sandwell, 1989). As with magnetic anomalies, these constraints come with inherent uncertainties and ambiguities, and our purpose here is to compare previous interpretations objectively to alternative reconstruction models. Exhumed mantle rocks dredged from the Diamantina

Zone display low-temperature deformation fabrics dated at 90-87 Ma (Beslier et al., 2004), and which according to Direen (2012) records the approximate age of breakup between here and the Bruce Rise. Blevin and Cathro (2008) report a 83-85 Ma age for basalt dredged from the Bremer Basin, and interpret breakup to coincide with a Turonian unconformity. Breakup is inferred as 83-71 Ma in the Bight Basin-Wilkes Land Sector, 68-63 Ma in the Otway Basin-Terre Adelie sector, and 58-49 Ma in the Sorell Basin, mainly on the basis of stratigraphy (Direen, 2012). The final link to be broken between Australia and Antarctica was across the South Tasman Rise, where separation occurred around 35-32 Ma (Hill and Exon, 2004; Scher et al., 2015); by this stage, the breakup history is well-constrained by reconstructions of magnetic anomalies and fracture zones formed at the southeast Indian ridge to the west of Tasmania.

To test alternative tectonic reconstructions, we combine reconstruction models with alternative COT interpretations and examine predictions of the age of breakup with the observed ages. To account for the complex and protracted nature of breakup (see Peron-Pinvidic et al, 2013), we use the classification of Gillard et al. (2015) to subdivide the crust within each margin into regions formed during different stages of breakup (Fig. 6a). These regions represent the (variably extended) continental domain (red), the mantle exhumation domain (green), and the oceanic domain (blue), the latter being further subdivided into proto-oceanic and steady state oceanic domains. For each reconstruction, , at each point along the reconstructed conjugate pairs, we calculate the latest time that overlap exists with the different crustal domains interpreted by Gillard et al. (2015) on the Australian and Antarctic margins (in other words, the time at which a gap begins to appear between the conjugate domains, implying onset of the next phase of the breakup process). Figure 6 compares the timing of inferred breakup between the conjugate rifting/spreading domains for different reconstructions. Each reconstruction is further compared with breakup timing constraints summarized by Direen (2012) and detailed in the figure caption. Within this comparison, most reconstructions place the breakup ages at times where the corresponding section of the rift system was undergoing the late stages of the extension phase, or within the mantle exhumation phase, according to the scheme of Gillard et al. (2015). The model of White et al. (2013) predicts onset of proto-oceanic crust significantly earlier than other reconstructions and the breakup ages compiled by Direen (2012).

B) Geological consistency of implied amounts and rates of continental rifting

Continental crust is thinned and extended during continental rifting and breakup. In studies of the crustal extension process (Huismans and Beaumont, 2011; Brune et al., 2012; Brune, 2014), a typical assumption is that the crust in the future rift zone has a fairly uniform thickness before rifting begins. Extension of this crust results in a pair of thinned and extended margins whose combined width will exceed the original width of the crust by an amount equivalent to the amount of extension. The amount of extension and the resulting margin width depends on factors including the physical properties of the crust and mantle, and the influence of sediment loads (Buck et al, 1991; Bialas and Buck, 2009). Observations from passive margins elsewhere in the world reveal individual margin widths ranging from 50 to over 400 km; the width of individual rifted margins is correlated with their total crustal extension, typically between 50 and 200 km (Crosby et al, 2011). This suggests typical values for total extension within rift systems that proceed to breakup between 100 and 400 km, though larger values may be observed where the pre-rift crustal thickness is thicker than average (e.g. western North America).

Because of this crustal stretching, 'full-fit' reconstructions typically show large overlaps between the present-day extent of continental crust of the reconstructed plates, which provides a simple way to visualise the amount of continental extension implied by different reconstructions. The amount of overlap is a proxy for the amount of continental extension that occurred before the plates broke apart (Dunbar and Sawyer, 1989; Torsvik et al., 2001; Moulin et al., 2010). Overlaps can be directly compared to estimates of extension predicted, for example, from crustal balancing constrained by seismic refraction experiments and/or gravity modelling.

An alternative, more quantitative approach to constrain the relative configuration of continents prior to rifting involves estimating and restoring extension within each margin, then fitting the restored margins back together (Dunbar and Sawyer, 1987; Srivastava and Verhoef, 1992; Veevers, 2009; Kneller et al., 2012; Louden et al., 2012).

A number of studies have estimated total continental extension across the Australian-Antarctic conjugate margins using a variety of methods: 296-360 km of continental extension from seismic and gravity data (Veevers and Eittrem, 1988); ~300 km from crustal balancing of cross-sections constrained by seismic data (Veevers 2012); 473 km of total extension from sequential restoration of faulting interpreted from seismic profiles across the Bight Basin and Wilkes Land margin (Espurt et al., 2009; 2012); ~330-620 km of continental extension along the whole conjugate margin system, using grids of crustal thickness generated from gravity inversion (Williams et al., 2011). Together, these results indicate that Australian-Antarctic full-fit reconstructions that produce an overlap of between 290 - 620 km of present-day COTs, can be considered reasonable.

We compare alternative full-fit reconstructions by plotting the amount of continental overlap using present-day outermost COT boundaries (Fig. 7). We would expect a large amount of overlap (i.e. 290 - 620 km), representing the amount of continental extension preceding breakup. The amount of overlap predicted (Fig. 7) shows that most reconstructions reproduce continental extension consistent with this expectation. The exception is White et al. (2013) which does not reconstruct any total continental margin extension in the Bight Basin and therefore does not appear to be a viable full-fit reconstruction. The reason is that the geological piercing points that form the primary basis for the White et al. (2013) reconstruction are only useful for constraining the lateral alignment of the two plates, akin to reconstructing ocean basins using fractures zones, but not magnetic anomalies. For full-fit reconstructions, restored COBs are to analogous to magnetic anomalies in constraining the fit in the direction of extension, and reconstructions where these constraints were considered (e.g. Veevers and Eittreim, 1988; Williams et al, 2011; Veevers, 2012) show that a much tighter fit is required.

C) Reconciling the entire Australia-Antarctica plate boundary in the Late Cretaceous

During much of the Cretaceous, the western end of the plate boundary between Australia and Antarctica connected with the India-Australian-Antarctic triple junction, in an area now heavily overprinted by the volcanic Kerguelen Plateau. In the east, the Cretaceous plate boundary ran between Tasmania and Cape Adare. Plate tectonic reconstructions need to simultaneously reconcile observations from this entire length of plate boundary.

Reconciling observations from Kerguelen and Broken Ridge

The significance of the fit between the bathymetric plateaus of Broken Ridge (BR) and the Kerguelen Plateau (KP), formed due to voluminous outpourings of magma between ~90–130 Ma, related to the Kerguelen hotspot (Coffin et al., 2002), was recognised by McKenzie and Sclater (1971). Broken Ridge and the Central Kerguelen Plateau formed together, then separated during the time of the plate motions we are trying to constrain. The importance of reconciling observations from this sector has been a focus of several previous studies (Royer and Coffin, 1988; Tikku and Cande, 1999; 2000; Tikku and Direen, 2008; Whittaker et al., 2013).

Assessing the fit of Kerguelen and Broken Ridge, Tikku and Cande (2000) argued that their reconstruction (Fig. 8) was able to honour constraints on the extent of the plateau from 83 Ma onwards; and further, that previous reconstructions (e.g. Royer and Rollet, 1997) produced an unreasonable overlap between 83-53 Ma. Following this line of argument, other reconstructions also produce problematic overlaps of varying amounts (e.g. Fig. 8).

Instead of problematic overlap, the reconstruction of Whittaker et al. (2007) results in a significant gap between Broken Ridge and Central Kerguelen Plateau (Fig. 8), implying unlikely compression between the plateaus during the Late Cretaceous (Tikku and Direen, 2008). A revised reconstruction resolves this gap and reconciles the likely evolution of the Kerguelen and Broken Ridge plateaus throughout the Late Cretaceous (Whittaker et al. 2013). The reconstruction of Whittaker et al. (2013) differs from that of Tikku and Cande (2000) by implying c. 200 km of right-lateral strike-slip motion along a plate boundary running through Kerguelen and Broken Ridge prior to their separation.

Reconciling observations from Tasmania and Cape Adare

The Sorell Basin, along the western margin of Tasmania, developed in a setting of sinistral transtension and continental shearing, beginning in the latest Jurassic and continuing through the Cretaceous (Hill et al., 1997; Hill and Exon, 2004; Exon et al., 2004). The western section of the South Tasman Rise (Ninene Basin) records similar wrench tectonics in the late Cretaceous (Hill et al. 2001). Fewer data are available over the offshore area in the conjugate George V Land section of the Antarctic margin. However, seismic profiles from the George V Basin (De Santis et al., 2010) show evidence for two phases of deformation, with the development of (likely Cretaceous) extensional grabens followed by a phase of transpressional/strike-slip deformation, of Palaeocene or Eocene age.

Reconciling observations from both ends of the system

Some Australian-Antarctic reconstructions model an overlap of the Tasmania and Cape Adare region COTs (Fig. 8) at the expense of a good fit between Broken Ridge and the Kerguelen Plateau. Tikku and Cande (1999, 2000) model a good fit between Broken Ridge and Central Kerguelen Plateau at ~83 Ma but a large (~350 km) overlap between Tasmania and Cape Adare (Fig. 8). A similar overlap (~350 km) is produced by the model of Jacob et al. (2014). Other reconstructions produce much smaller overlaps, typically ~50 km of overlap measured between the present-day COT edges, consistent with moderate amounts of extension/transtension during the final stages of rifting prior to Cenozoic breakup in this region.

Reconstructions with larger overlaps between Tasmania and Cape Adare have been used to invoke significant intraplate deformation within Australia and/or Antarctica since 83 Ma. Tikku and Cande (1999, 2000) suggested ~85 km of dextral motion between mainland Australia and Tasmania within the Bass Strait (along the Colac-Rosedale fault), or Late Cretaceous-Cenozoic extension within the Wilkes Land Basin. Jacob and Dyment (2014) proposed significant motion of the Tasmanian and Polda (eastern Bight basin) blocks relative to Australia, as well as significant compression within Wilkes Land, during the Cretaceous. However, geological and geophysical evidence supporting significant deformation in these proposed areas is lacking.

Geophysical data across the Bass Strait and adjacent onshore regions, including dense seismic surveys and aeromagnetic data, have been extensively studied (Young et al., 1991; Power et al., 2001; Cayley et al., 2002; Cummings et al., 2004; Blevin et al., 2005; Bernecker et al., 2006; Cayley, 2011), discounting any evidence for dextral motion between Tasmania and SE Australia since the Late Cretaceous.

The onshore Wilkes Land Basin (Fig. 1) is covered by ice, and so quantifying the timing and magnitude of any deformation within this region is difficult. Based on available geological and geophysical data, the Wilkes Land Basin has an average sediment thickness of 1.1–1.6 km (Frederick et al. 2016), although Ferraccioli et al. (2009) estimate that some parts of the basin may contain up to 3 km of sediments, likely deposited before the Mesozoic, and localised post-Jurassic depocentres with a maximum thickness of 6 km may exist in the central part of the basin (Ferraccioli et al., 2009; Frederick et al. 2016). The Rennick Graben within Cape Adare (Fig. 1) is interpreted as a tectonic depression formed within a regional dextral strike-slip setting during Cenozoic times (40-50 Ma, Rossetti et al., 2003). Cenozoic strike-slip deformation within the Cape Adare region (Rossetti et al., 2003) could influence the fit between Australia and Antarctica for earlier times (Storti et al., 2007). The amount of motion is poorly quantified - however, if the shear sense of Cenozoic motions is dextral as interpreted, then restoring this motion would tend to increase problematic overlaps between Cape Adare and Tasmania. In summary, current estimates of Late Cretaceous extension in the Wilkes Land Basin do not support the 350 km of post-83 Ma extension required by the reconstructions of Tikku and Cande (1999, 2000), nor is there strong evidence for major Cretaceous compression in this region as proposed by Jacob et al. (2014).

D) Smoothness of plate motions

In this section, we consider the evidence for changes in plate motion proposed in different reconstructions. Changes in spreading rate are more frequent for models that use magnetic anomalies as constraints (Fig. 9a). For the 79-53 Ma period, magnetically derived reconstructions yield relatively stable divergence rates of 5-10 km/Myr. The reconstruction of Powell et al. (1988), not based on magnetic anomalies, yields a similar rate of spreading in the Bight Basin, while the reconstruction of White et al. (2013) yields a lower rate (Fig 9b).

A notable spike in spreading rates is observed for a number of models that used magnetic anomalies between 79-83 Ma (C33-C34). These anomalously high rates may be taken as evidence that the C34 interpretation is not a true isochron (Veevers, 1986), or an example of noise in reconstructions derived by statistical fitting of magnetic picks and which can be removed by temporal smoothing of finite rotations (Iaffaldano et al., 2012). Global plate motion compilations (e.g. Müller et al., 2016) only contain finite rotations at 5-10 Myr intervals and are less likely to contain geodynamically implausible plate motion changes (black curve in Fig. 9a). A further observation from Figure 9 is that the range of plate divergence rates from alternative reconstruction models is similar in magnitude during the post-45 Ma phase of divergence (during which the interpretation of seafloor spreading magnetic anomalies is uncontroversial) to the range of rates in the earlier phases of rifting.

Constraints on rates of continental extension from subsidence curves (Totterdell et al., 2000) and sequential restoration of structural cross-sections (Espurt et al., 2009; 2012) suggest that initiation of rifting in the Late Jurassic was followed by an acceleration in extension and subsidence in the late Early Cretaceous (thick grey line, Fig. 9a and 9b). Espurt et al. (2009; 2012) interpreted an initial phase of rifting at 9.4 km/Myr (165-145(?) Ma) followed by a slower rate of 3.2 km/Myr (145(?)-93.5 Ma), then an acceleration to 17 km/Myr. Espurt et al. (2012) also suggest that their estimates of crustal stretching represent minimum values, since the profiles are oblique to the direction of motion. Reconstructions that cover the Early Cretaceous phase all yield low extension rates, broadly comparable with the estimates of Espurt et al. (2012). Many reconstructions also show an increase in extension rates during the Late Cretaceous phase compatible with geological observations.

Some differences between models also occur in the direction of implied plate motion. The models of Tikku and Cande (1999) and Jacob et al. (2014) produce sinuous directions of motion, implying a series of significant changes in plate motions on the timescales of a few million years. Such motions are at the limit of what could be considered geodynamically plausible, although Jacob et al. (2014) point out that much smoother motions could be accommodated within the 95% confidence regions of their poles of rotation. Directions of motion for most models allow for some phase of NW-SE motion during the rift phase in the Bight Basin, as proposed by previous observational studies (e.g. Willcox and Stagg, 1990; Totterdell and Bradshaw, 2004). An exception is the reconstruction of White et al. (2013), in which no phases of NW-SE extension are apparent.

E) Constraints from geological piercing points

Correlating geological terranes and boundaries can provide important first-order constraints for the Proterozoic reconstructions (e.g., Karlstrom et al., 1999; Goodge et al., 2008; Ernst and Bleeker, 2010). A shared history between parts of proto- Australia and Antarctica extends back to the formation of Gondwana (Collins and Pisarevsky, 2005), the preceding Proterozoic supercontinents Rodinia (Li et al., 2008; Merdith et al., 2016) and Nuna (Zhang et al., 2012; Pisarevsky et al., 2014), and potentially even within the Archean Rae family of cratons (Pehrsson et al., 2013; Halpin and Reid, 2016), inviting correlation of a variety of terranes and structures across the conjugate margin (e.g., Stump et al., 1986; Foster and Gleadow, 1992; Fitzsimons, 2003; Goodge and Fanning, 2010; Boger, 2011; Cayley, 2011; Gibson et al., 2011, 2013; Veevers, 2012; Aitken et al., 2014, 2016).

However, geological correlations across the conjugate Australian-Antarctic margins in a Gondwana context are complicated by a number of factors. First, correlations of geological units may be non-unique, and suffer from the problem of variable preservation across the conjugate margins, an aspect exacerbated in the Antarctic case due to limited (<1%) bedrock exposure (Burton-Johnson et al., 2016). Further, large differences between the age of formation of a proposed geological correlation and the onset of breakup can cause significant ambiguity. Some workers have speculated that lateral motion may have occurred between Australia and Antarctica prior to Gondwana breakup (e.g. Flottman and Oliver, 1994; Veevers 2000; Cayley, 2011; Tikku and Direen 2008). Any net shift during the Palaeozoic means that the pre-rift Jurassic configuration may not honour the continuity of terranes or structures formed hundreds or thousands of million years earlier. The effects of post-rift Cenozoic intraplate deformation in Australia and Antarctica may also be important to consider.

Which Piercing Points to use?

Geological features used to align continents ("piercing points") should ideally comprise precisely-dated, near-vertical, planar features, such as dykes, shear zones or faults, that are oriented at a high angle to the conjugate margins and can be uniquely correlated. Piercing points formed just prior to or during the initial stages of rifting are preferred.

Numerous faults and shear zones penetrate the southern margin of Australia, and attempts to link to these structures across into the Antarctic continent could provide valuable piercing points. In Australia, the modern Darling Fault (Fig. 10) extends for over 1000 km along the western margin of the Archean Yilgarn Craton, and forms the eastern boundary of the Phanerozoic Perth Basin. The Darling Fault is considered to be a major crustal discontinuity (Dentith et al., 1993) with a long reactivation history (Wilde, 1999).have been e.g., Correlation of the Darling Fault (Western Australia) with structure(s) interpreted to lie beneath the Denman-Scott glaciers (Antarctica) has been used as a key piercing point by many workers (e.g., Harris, 19954; Fitzsimons, 2003; Boger, 2011; White et al., 2013). However, recent geological work has identified Proterozoic reworking of Archean rocks in the Bunger Hills that are genetically related to those in the Obruchev Hills (Tucker et al., 2017), together forming part of the Proterozoic Albany-Fraser-Wilkes Orogen (Fig. 10). Furthermore, rocks of interpreted Australo-Antarctic affinity have been identified in the Obruchev Hills and immediately to the west of the Denman Glacier (Daczko et al., 2018) casting doubt on any major basement terrane discontinuities beneath the Denman and/or Scott glaciers. Based on recently acquired airborne geophysics in Wilkes Land, Aitken et al. (2014, 2016) map lithospheric domains and their bounding faults interpreted through correlation across the conjugate margin. These workers link: (1) the unexposed eastern boundary of the Albany-Fraser Orogen in Australia (Rodona Shear Zone) with an equivalent structure beneath the Antarctic Totten Glacier (Totten Fault) and (2) the Darling Fault with the newly identified Conger Fault to the east of the Bunger Hills forming the eastern boundary to the Knox Rift (Fig. 10). Maritati et al. (2016) suggest the Knox Rift contains a SW-trending sedimentary basin (Knox Subglacial Sedimentary Basin) that is the conjugate to the Perth/entirely offshore Mentelle basins (Fig. 10). If, as this interpretation suggests, the Knox Rift does contain a Phanerozoic sedimentary basin formed during the extension and breakup of East Gondwana (Maritati et al., 2016), its bounding faults become attractive new piercing points (Gardner et al., 2015).

Further east, Archean-Paleoproterozoic rocks of the Gawler Craton in South Australia have been correlated with outcrops along the Antarctic coastline of Terre Adélie and George V Land, commonly called the Terre Adélie Craton (Fig. 11; Oliver and Fanning, 1997; Peucat et al., 1999; 2002; Goodge et al., 2001; Ménot et al., 2005). Together they comprise the nucleus of the Mawson Continent (e.g., Payne et al., 2009). The Mertz Shear Zone is a major crustal structure separating late Archean-early Paleoproterozoic Terre Adélie Craton rocks from early Paleozoic rocks of the Ross Orogen to the east (Talarico and Kleinschmidt, 2003; Di Vincenzo et al., 2007). However, a likely correlate in Australia is controversial. Depending on how terrane boundaries are defined, the Paleoproterozoic Kalinjala Shear Zone is considered to either fall within, or define the eastern boundary to, the Gawler Craton. In either case, most workers correlate this structure with the Mertz Shear Zone (e.g., Goodge and Fanning, 2010; Boger, 2011; Aitken et al., 2014). By contrast, Gibson et al. (2013) argued that a better match for the Mertz Shear Zone is the Coorong Shear Zone, a Palaeozoic structure >300 km long mapped principally from geophysical data. A chain of magnetic Cambrian-Ordovician granites intruded along the Coorong Shear Zone are also imaged across the conjugate margin in the Ross Orogen and mirror the geometry of the Gawler/Terre Adelie Craton margin (Aitken et al., 2016).

The geology of southeast Australia, Tasmania and Northern Victoria Land records a complex history of Palaeozoic events along the eastern margin of Gondwana, interpreted to include accretionary orogenesis, oroclinal bending and major strike-slip deformation (e.g. Direen and Crawford, 2003; Glen, 2005; Musgrave and Rawlinson, 2010; Cayley, 2011; Greenfield et al., 2011; Aitchison and Buckman, 2012; Moore et al., 2016; Mulder et al., 2016). Several authors consider Cambrian arc-related rocks in Northern Victoria Land (Wilson and Bowers Zones) to be counterparts of similar units in Victoria (Glenelg and Grampians-Stavely Zones; Finn et al., 1999; Gibson et al., 2011; Cayley, 2011). How these units extend into offshore areas is less certain. Gibson et al. (2011) propose that correlatives of the Grampians-Stavely Zone can be mapped into the Otway and Sorell Basins and the South Tasman Rise. Aspects of this interpretation, notably the continuity of the Avoca Fault interpreted from geophysical data, have been questioned (Moore et al., 2013; Pilia et al., 2014). Dredging of the South Tasman Rise has recovered various Proterozoic rocks (Fioretti et al., 2005; Berry et al., 2008), which do not correlate well with either mainland Australia or the conjugate region of Antarctica (Cayley, 2011).

Alignment of Piercing Points within candidate reconstructions

Our earlier comparisons (e.g. Fig. 2c) illustrate that the range of full-fit reconstructions can be broadly classified into three groups, for which the piercing point connections are plotted in Figs. 10-12. Models proposed by Sproll and Dietz (1969) and Smith and Hallam (1970) are similar to more recent reconstructions that benefited from a wider range of data constraints (e.g. Williams et al., 2011; Veevers, 2012). A second group places Australia further west relative to Antarctica in the Jurassic (Veevers and Eittreim, 1988; Powell et al., 1988), though the distance between the reconstructed continents is similar to the first group. Differences between various piercing points are significant and it is not possible to derive any reconstruction that satisfies them all. The reconstruction of White et al. (2013) places Australia too far away from Antarctica at the beginning of rifting by several hundred kilometres to satisfy constraints from syn-rift extension estimates; therefore, we focus on three viable alternatives for the pre-rift configuration (based on Powell et al., 1988; Williams et al., 2011; and Aitken et al., 2014, Figs. 10-12).

In the western sector (Fig. 10), the reconstruction of Powell et al. (1988) aligns the Darling Fault with Denman Glacier. Alternative models, most consistent with estimates of syn-rift extension, reconstruct the Darling Fault to the east of the Denman Glacier (Fig. 10, top and middle panels), favouring alignment with the Conger Fault proposed by Aitken et al. (2014). Between the Eyre Peninsula and eastern Wilkes Land (Fig. 11), models based on restoration of syn-rift extension produce a close juxtaposition of the Mertz Shear Zone with the Kalinjala Shear Zone (Figs. 11, top and middle panels), and satisfy additional connections proposed by Veevers (2012). The reconstruction of Powell et al. (1988) places Australia further to the west and does not align these proposed connections, instead aligning the proposed Coorong Shear Zone closely with the Mertz Shear Zone (Fig. 11, bottom panel).

In the sector linking Eastern Australia to Northern Victoria Land (Fig. 12), each of the reconstructions produce an alignment that is consistent with proposed continuity of Palaeozoic terranes across this region prior to breakup. Models directly constrained by syn-rift extension estimates (Williams et al. 2011) indicate some bending of the terrane boundaries towards the area of Mesozoic rifting (Figs. 12, top and middle panels), consistent with the arcuate trends of magnetic anomalies that define these terranes from mapped areas onshore into submerged margin regions (Williams et al, 2012). In addition to geological constraints, these reconstructions produce a good match of reconstructed geophysical data sets across all sectors of the conjugate margins (Aitken et al., 2014).

Discussion

A fundamental part of recreating past plate motions is assessing the goodness of fit between the reconstructions and the data used to constrain them (e.g. Wessel and Müller, 2007). Such methods are well-developed for reconstructions of seafloor spreading constrained by well-defined magnetic anomalies and fracture zones (Hellinger, 1981; Stock and Molnar, 1983; Kirkwood et al., 1999). Using these methods, we can rigorously quantify uncertainties in calculated plate motions (e.g. Cande and Stock, 2004), infer additional motions across diffuse plate boundaries (Gordon, 1998), and assess whether the inferred changes in plate motions are consistent with the rules of geodynamics (Iaffaldano et al., 2012).

However, assessing the quality of a reconstruction becomes progressively more difficult moving back through time from motions forming oceanic crust to those forming the COT and extended continental crust; data constraints become sparser and more diverse, and are increasingly subjective. The goodness of fit between geometrical constraints, whilst useful, does not necessarily tell us about systematic errors in our initial assumptions (e.g. if the magnetic lineations were really isochrons, or if the piercing point correlation was sound). In the following discussion, we consider the extent to which the goodness of fit for any reconstruction can be assessed for different criteria.

We have considered a range of criteria that may be used to reconstruct plate motions during continental rifting and breakup and have assessed alternative plate tectonic reconstructions on the basis of how well they satisfy these criteria. The criteria are all, to greater or lesser degrees, subjective, and some are controversial - for example, whether or not a reconstruction fits isochrons is irrelevant if the isochrons are incorrectly interpreted. Nonetheless, a reconstruction that satisfies many criteria should be considered more reliable than a reconstruction that satisfies few. In Table 2, we summarise how each alternative reconstruction fares against the various criteria available to assess them.

Relative plate motions in the Early Cretaceous are difficult to constrain. There are a group of viable full-fit reconstructions (Table 2) by Sproll and Dietz (1969), Smith and Hallam (1970), McKenzie and Sclater (1971) and Williams et al. (2011), that vary in their E-W alignment by up to ~380 km. These reconstructions are all consistent with alignment of the Naturaliste Plateau and Bruce Rise with their bounding fracture zones. Alternative piercing points would require that reconstructions place Australia further west (e.g. Powell et al., 1988), though with revisions necessary to account for quantitative estimates of continental extension. Coupled with the most likely scenarios for Late Cretaceous kinematics, these full-fit configurations suggest a net NE-SW motion of Australia relative to Antarctica during the Early Cretaceous.

Orthogonal to the strike of the margin, all models place Australia a similar distance away from Antarctica at full-fit (Fig. 7), except the model of White et al. (2013; Fig. 2c, pink outline; Fig. 7d), which places Australia up to 700 km further away from Antarctica than any other reconstruction. This reconstruction is faithful to certain piercing point interpretations but is unsuccessful in explaining other key observations including breakup ages, subsidence histories, tectonostratigraphy of the margins, and is inconsistent with the well-established concept that hyperextended continental margins are formed by crustal extension. Although there are a number of viable full-fit reconstructions, we prefer models based on the analysis of Williams et al. (2011) as they incorporate diverse offshore geophysical constraints while satisfying onshore geological relationships (Figs 10–12). Further constraints on the geology of East Antarctica (e.g., Maritati et al., 2016; Daczko et al., 2018) allow for full-fit reconstructions to be further refined in a way that remains consistent with estimates of continental extension during Mesozoic rifting.

For post-breakup (Late Cretaceous) plate reconstructions, the models by Royer and Sandwell (1989) and Whittaker et al. (2013) provide the best agreement with the constraints considered. Based on the currently available observations, these models incorporate a change in relative plate motion direction in the early Eocene, prior to the well-constrained N-S spreading observed from the mid-Eocene to present-day. Such a change in plate motion is required to both explain the observed breakup ages whilst avoiding problematic overlaps between Tasmania and Cape Adare. Powell et al.'s (1988) reconstruction yields a larger overlap between Kerguelen and Broken Ridge in the Late Cretaceous but may also be viable. Relative plate motions within each of these models follow NW-SE to NNW-SSE flowlines during the Late Cretaceous-Early Eocene. The Whittaker et al. (2013) model is preferred here, over the Royer and Sandwell (1989) model because it incorporates a greater range of geophysical constraints and fits with the Williams et al (2011) model to create a consistent set of plate tectonic motions from full-fit through to the Eocene. While the validity of controversial magnetic anomaly interpretations to constrain plate motions remains an important unresolved question, a key outcome of our review is that multiple independent datasets point to a qualitatively similar history of plate motions. More detailed studies of the tectonostratigraphic architecture across both the Australian and Antarctic margins (Espurt et al., 2012; Gillard et al., 2015) hold the key to further refining quantitative reconstructions of Australia-Antarctica rifting.

Conclusions

A well-established framework exists for plate tectonic reconstructions of ocean crust, making use of the complementary geometric constraints of fracture zones and magnetic anomalies, but for periods of continental rifting that predate the onset of seafloor spreading an equivalent methodology is yet to be formalised. A diverse range of geophysical and geological observations hold clues to the history of rifting and breakup, with each individual approach containing inherent uncertainties which are much larger than the uncertainties associated with reconstructions of plate motions recorded by well-defined seafloor spreading. Due to these large uncertainties, reconstructions that may appear to best-fit individual lines of evidence, can be shown as problematic when the evidence is viewed in totality. We show that by considering multiple lines of evidence together it is possible to narrow the range of possible plate motion histories considerably. Crucially, we demonstrate that full-fit reconstructions must incorporate constraints on both the lateral alignment of the plates (e.g. piercing points based on geophysical and/or geological data) and how close together they were prior to the beginning of rifting (e.g. estimates of crustal extension). Our approach lays the foundation for devising a future methodology to quantitatively compute uncertainties in syn-rift reconstructions.

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Table 1: Summary of alternative quantitative reconstructions for Australia-Antarctica configurations considered in this study

	Abbreviation	*Time span covered*	*Oldest Magnetic Anomaly considered*	*Other constraints used*
Sproll and Dietz (1969)	SD1969	Full-fit only	N/A	N/A
Smith and Hallam (1970)	SH1970	Full-fit only	N/A	N/A
McKenzie & Sclater (1971)	MS1971	N/A	N/A	N/A
Powell et al (1988); Veevers and Eittreim (1988)	PVE1988	c21y-c34y	c20	Used observations from rift basins along southern Australian margin
Royer and Sandwell (1989)	RS1989	Full-fit to present-day	c34	First to use Geosat data defining seafloor fabric
Royer and Rollet (1997)	RR1997	c13o to 'Quiet Zone Boundary'	c34	Focus on data from around South Tasman Rise
Tikku and Cande (1999, 2000)	TC1999 TC2000	c20o to 'Quiet Zone Boundary'	c34	Kerguelen-Broken Ridge fit
Whittaker et al (2007)	W2007	c20o to c34y	c34	Repicking of fracture zone correlations
Williams et al (2011)	W2011H (Hybrid Fit) W2011L (Leeuwin Fit)	c34y to Full-fit (Williams et al, 2011)	c34	Quantitative full-fit reconstruction using estimates of continental extension.
Whittaker et al (2013)	W2013	Full-fit to c20o	c34	Constraints from Kerguelen-Broken Ridge and Tasmania-Cape Adare sectors
White et al (2013)	WGL2013	Full-fit to 45 Ma	c21	Piercing Points

Jacob et al (2014)	JD2014	Full-fit to c21y	c34	Gravity Anomaly fitting

Table 2: Summary of agreement between alternative Australia-Antarctica reconstructions tested in this study and different lines of geological evidence.

	Criteria for Kinematics during Rifting and Breakup				**Criteria for Full-fit**	
	Magnetic Anomalies	***Breakup Ages***	***Kerguelen-Broken Ridge Fit***	***Fit of Cape Adare-Tasmania Fit***	***Crustal Extension***	***Piercing Points***
Sproll and Dietz (1969)					**Good Agreement**	Matches some interpretations
Smith and Hallam (1970)					**Good Agreement**	Matches some interpretations
McKenzie & Sclater (1971)					**Good Agreement**	Matches some interpretations
Powell et al (1988); Veevers and Eittreim (1988)	Not used as constraint; Fair Agreement to 83 Ma	**Good Agreement**	Poor agreement - too much overlap	**Good Agreement**	Used as constraint; Reasonable agreement, overestimate in east	Matches some interpretations
Royer and Sandwell (1989)	Used as constraint; Matches for times <83 Ma	**Good Agreement**	**Good Agreement**	**Good Agreement**	Poor Agreement - overestimates total extension	Matches some interpretations
Royer and Rollet (1997)	Used as constraint; Matches for times <83 Ma	**Good Agreement**	Poor agreement - too much overlap	**Good Agreement**		
Tikku and Cande (1999,	Used as constraint;	**Good Agreement**	**Good Agreement**	Poor Agreement		

2000)	Matches for times <83 Ma					
Whittaker et al (2007)	Used as constraint; Matches for times <83 Ma	**Good Agreement**	Poor agreement - too large a gap	**Good Agreement**		
Williams et al (2011)					**Good Agreement**	Matches some interpretations
Whittaker et al (2013)	Used as constraint; Matches for times <83 Ma	**Good Agreement**	**Good Agreement**	**Good Agreement**		
White et al (2013)	Not used as constraint; Matches for times <45 Ma	Poor Agreement	Poor agreement - too much overlap	**Good Agreement**	Poor Agreement - underestimates total extension	Matches some interpretations
Jacob et al (2013)	Used as constraint; Matches for times <83 Ma	**Good Agreement**	**Good Agreement**	Poor Agreement		

Figure Captions

Figure 1: Free-air satellite gravity (Sandwell et al., 2014) map illustrating major tectonic features of the Australian-Antarctic region. Abbreviations: Ba, Bass Basin; BK, Batavia Knoll; BR, Broken Ridge; Br, Bremer Basin; CKP, Central Kerguelen Plateau; EB, Elan Bank; En, Enderby Basin; GAB, Great Australian Bight Basin; GDK, Gulden Draak Knoll; Gi, Gippsland Basin; GVL, George V Land; NKP, North Kerguelen Plateau; Ot, Otway Basin; PAP, Perth Abyssal Plain; SKP, South Kerguelen Plateau; So, Sorell Basin; TA, Terre Adélie.

Figure 2: Alternative reconstructions of Australia and Antarctica at 45 Ma, 83 Ma, and 160 Ma in an Antarctica fixed reference frame, so that differences between figures are purely a function of the different relative motions. Present-day coastlines of Australia and Antarctica are plotted - Greater India and Zealandia are omitted. Reconstructions are relatively well constrained at 45 Ma, but the data available to constrain older reconstructions has been interpreted differently. Model abbreviations: SH1970 - Smith and Hallam (1970); PVE1988 - Powell et al. (1988); RS1989 - Royer and Sandwell (1989); RR1997 - Royer and Rollet (1987); TC2000 - Tikku and Cande (1999, 2000); W2007 – Whittaker et al. (2007); W2011H - Williams et al. (2011) hybrid model; W2011L – Williams et al. (2011) Leeuwin model; WGL2013 - White et al. (2013); JD2014 – Jacob and Dyment (2014).

Figure 3: Reconstruction at 40.1 Ma showing total magnetic intensity anomaly grids for Australia (adapted from Maus et al., 2009) and Antarctica (Golynsky et al., 2012). Shiptrack data, from which these grids are derived, is denser and more consistent on the Antarctic margin, leading to better definition of the anomalies. The anomaly field over the deep ocean areas is characterised by linear magnetic anomalies, persistent for >1,000 km, within crust <7km thick. Linear anomaly trends cross-cut the more oceanward outer-COT boundary of Colwell et al. (2006) – grey lines.

Figure 4: Reconstruction at 40.1 Ma, showing coverage of available geophysical data for the conjugate Australian-Antarctic margins, overlain on total crustal thickness (Kusznir, 2009). Australian alternative COT (green dashed line) from Czarnota et al. (2013), Antarctic alternative COT from Colwell et al. (2006). The greyscale illumination effect superimposed on the crustal thickness map is based on the spatial gradient of the bathymetry. The reconstruction is plotted using fixed Antarctic coordinates in a polar stereographic projection.

Figure 5: Representative seismic section across the COT in the Wilkes Land margin, transecting the region with the largest discrepancies between interpretations of COT versus 'true' oceanic crust. Crust between the 'innermost COB' and the 'outermost COB' locations corresponds with the hatched region in Fig. 4. Reproduced with permission © *Commonwealth of Australia (Geoscience Australia) 2015. With the exception of the Commonwealth Coat of Arms and where otherwise noted, this product is provided under a Creative Commons Attribution 3.0 Australia Licence.* *http://creativecommons.org/licenses/by/3.0/au/deed.en*

Figure 6: a) Reconstructions showing possible spatio-temporal evolution of crustal domains following the classification of Gillard et al. (2015), with coloured regions representing the (variably extended) continental domain (red), the mantle exhumation domain (green), and the oceanic domain (blue; further subdivided into proto-oceanic and steady state oceanic domains). In the example shown, the rift system is characterised by continental extension in the Early Cretaceous; by the Late Cretaceous, western segments of the rift system were undergoing mantle exhumation mantle and by Early Paleocene proto-oceanic spreading was widespread, though continental extension continued between Tasmania and Cape Adare. b) depicts the temporal transition between the different rift phases as a function of distance along the rift system from west to east for alternative reconstructions, and integrates breakup ages compiled by Direen (2012). These geological constraints on the timing of breakup are: DZ = Exhumation fabrics from the Diamantina Zone south of Naturaliste Plateau (Beslier et

al., 2004)

Br = Breakup volcanics from Bremer Basin (Blevin and Cathro, 2008)

Bi = Breakup in Bight Basin from seismic data and magnetic anomalies (Sayers et al., 2001) and seismic stratigraphy (Totterdell et al., 2000)

Ot = Breakup in Otway Basin from seismic stratigraphy (Krassay et al., 2004)

Figure 7: Comparison of full-fit reconstructions for Australia and Antarctica, prior to onset of Jurassic rifting (~165 Ma). Polygons defining the present-day extent of continental crust within each margin, based on the outermost COT location (see Figure 4). Dark grey areas show amount of overlap between the present-day extended margins, which can be used as a simple proxy for the amount of extension implied by a given model.

Figure 8: Comparison of alternative reconstructions at 83 Ma of (top row), the fit of Cape Adare and Tasmania, and (bottom row) the western end of the Australian-Antarctic plate boundary system, showing the configuration of the Kerguelen Plateau-Broken Ridge large igneous province (based on their present-day outlines). Light grey regions indicate areas of submerged (and mostly stretched) continental crust, with darker grey regions showing the reconstructed overlap between these regions when stretching is not accounted for. Shades of red illustrate the same concept for the igneous crust of Broken Ridge and Kerguelen. Brown regions fall within present-day coastlines, shown for visual reference. Abbreviations: BR, Broken Ridge; CKP, Central Kerguelen Plateau; SKP, South Kerguelen Plateau; Tas, Tasmania; WLB, Wilkes Land Basin.

Figure 9: Spreading rates for (a) models that used magnetic anomalies, and (b) those that did not use anomalies older than chron 21. Rates computed for a seed point located on Australia (present day coordinates 130E, 36S) relative to fixed Antarctica. The black line illustrates the plate motions used in the global compilation of Müller et al (2016), which is based on the models of Whittaker et al (2013) and Williams el al (2011) but only uses

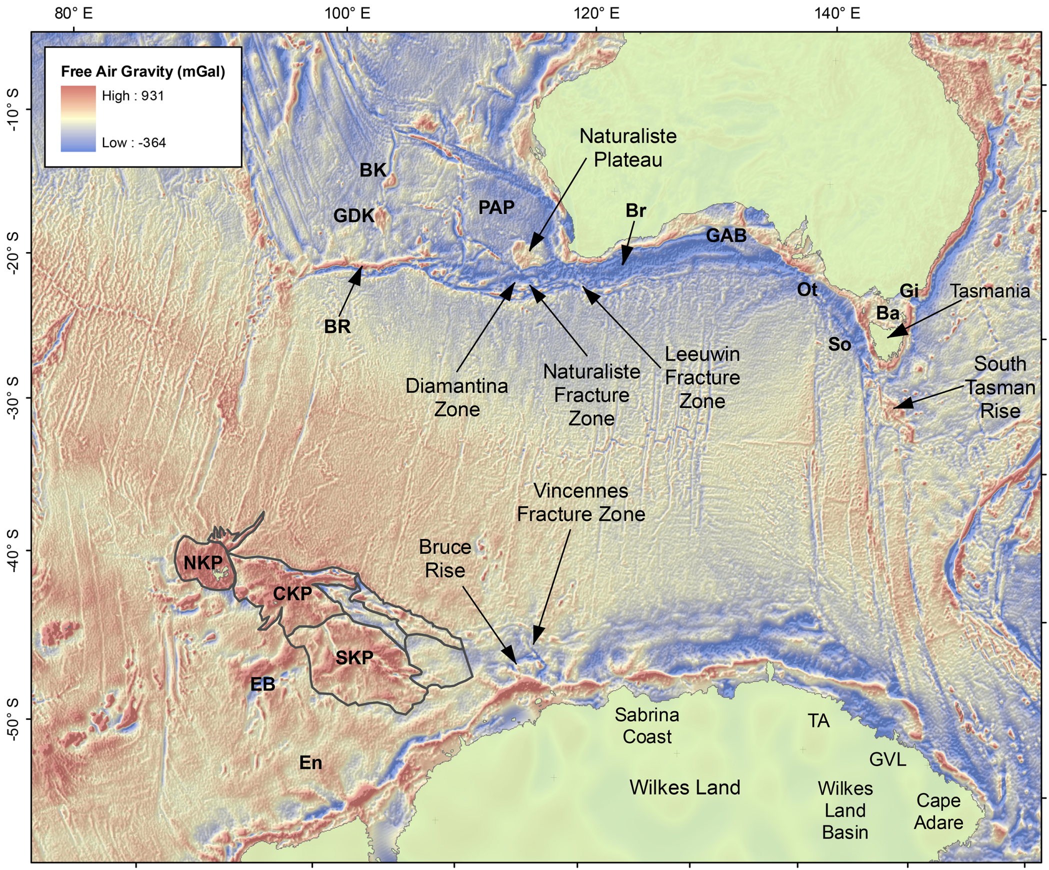
selected isochrons to lessen the influence of possibly spurious short-term rate changes. The thick grey line shows the cumulative extension estimates of Espurt et al. (2012), derived from structural restoration of cross-sections. Extension rates for the reconstructions are computed in the direction of plate motion, so models with significant obliquity would be expected to yield higher divergence rates than inferred from margin-orthogonal seismic profiles.

Figure 10: Juxtaposition of geological provinces and structures between southern Western Australia and western Wilkes Land, according to three different reconstructions for the Australia and Antarctica prior to Mesozoic rifting. (a) Williams et al. (2011) Hybrid model (b) Williams et al. (2011) Leeuwin model; (c) Powell et al. (1988) model. Geological provinces and naming conventions adapted from Fitzsimons (2003), Boger (2011), Aitken et al. (2014), lineaments (grey) based on Aitken et al. (2014) and Maritati et al (2016). Black arrows denote approximate coastal locations of Denman (D) and Scott (S) glaciers. Abbreviations: GZ – Glenelg Zone (see Fig. 12).

Figure 11: Juxtaposition of geological provinces and structures between the Eyre Peninsula and Eastern Wilkes Land, according to three different reconstructions for the Australia and Antarctica prior to Mesozoic rifting. (a) Williams et al. (2011) Hybrid model (b) Williams et al. (2011) Leeuwin model; (c) Powell et al. (1988) model. Geological provinces and naming conventions adapted from Fitzsimons (2003), Goodge and Fanning (2010), Gibson et al. (2011), lineaments (grey) based on Aitken et al. (2014)

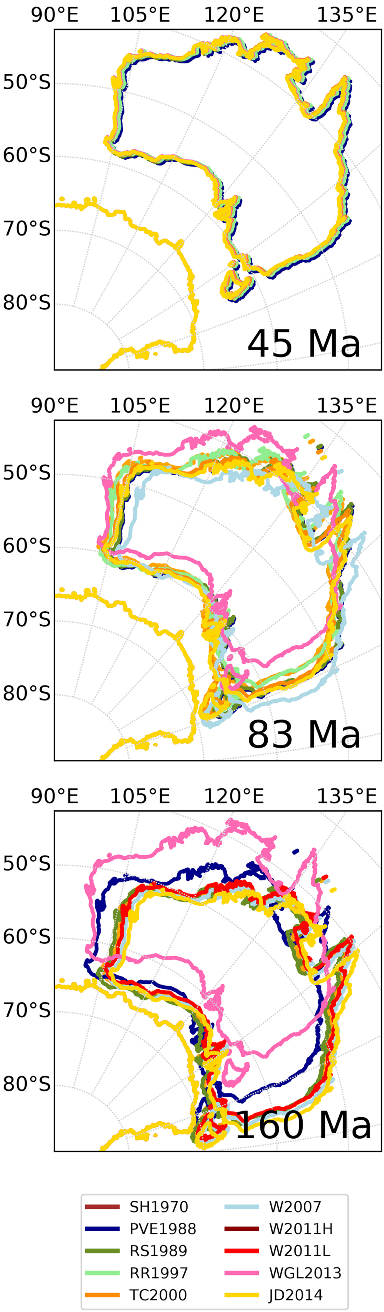
Figure 12: Juxtaposition of geological provinces and structures between eastern Australia and George V Land-Cape Adare, according to three different reconstructions for the Australia and Antarctica prior to Mesozoic rifting. (a) Williams et al. (2011) Hybrid model (b) Williams et al. (2011) Leeuwin model; (c) Powell et al. (1988) model. Geological provinces and naming conventions based on Gibson et al. (2011), Cayley (2011), Moore et al. (2013).

Abbreviations: GZ – Glenelg Zone; GSZ – Grampians-Stavely Zone; SZ – Stawell Zone; BZ – Bendigo Zone; MZ – Melbourne Zone; Etas – East Tasmania; WTas –West Tasmania; RCB – Rocky Cape Block; WT – Wilson Terrane; BT – Bowers Terrane; RBT – Robertson Bay Terrane.



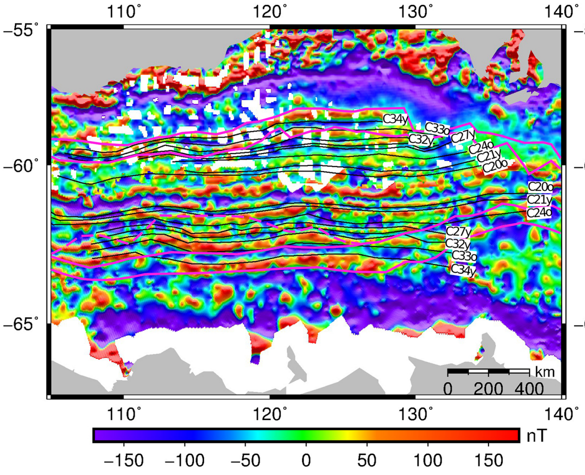
Free Air Gravity (mGal)
High : 931
Low : -364
80° E
100° E
120° E
140° E
40° E
60° E
80° E
100° E
120° E
140° E
160° E
180°
-10° S
-20° S
-30° S
-40° S
-50° S
-20° S
-30° S
-40° S
-50° S
-60° S
-70° S
BK
GDK
PAP
Naturaliste Plateau
Br
GAB
BR
Ot
Gi
Tasmania
Ba
So
Diamantina Zone
Naturaliste Fracture Zone
Leeuwin Fracture Zone
South Tasman Rise
Vincennes Fracture Zone
Bruce Rise
NKP
CKP
SKP
EB
En
Sabrina Coast
TA
GVL
Wilkes Land
Wilkes Land Basin
Cape Adare

Figure 1



90°E
105°E
120°E
135°E
50°S
60°S
70°S
80°S
45 Ma
90°E
105°E
120°E
135°E
50°S
60°S
70°S
80°S
83 Ma
90°E
105°E
120°E
135°E
50°S
60°S
70°S
80°S
160 Ma
SH1970
PVE1988
RS1989
RR1997
TC2000
W2007
W2011H
W2011L
WGL2013
JD2014

Figure 2



110°
120°
130°
140°
−55°
−60°
−65°
C34y
C33o
C32y
C27y
C24o
C21y
C20o
C20o
C21y
C24o
C27y
C32y
C33o
C34y
km
0 200 400
−150 −100 −50 0 50 100 150
nT

Figure 3

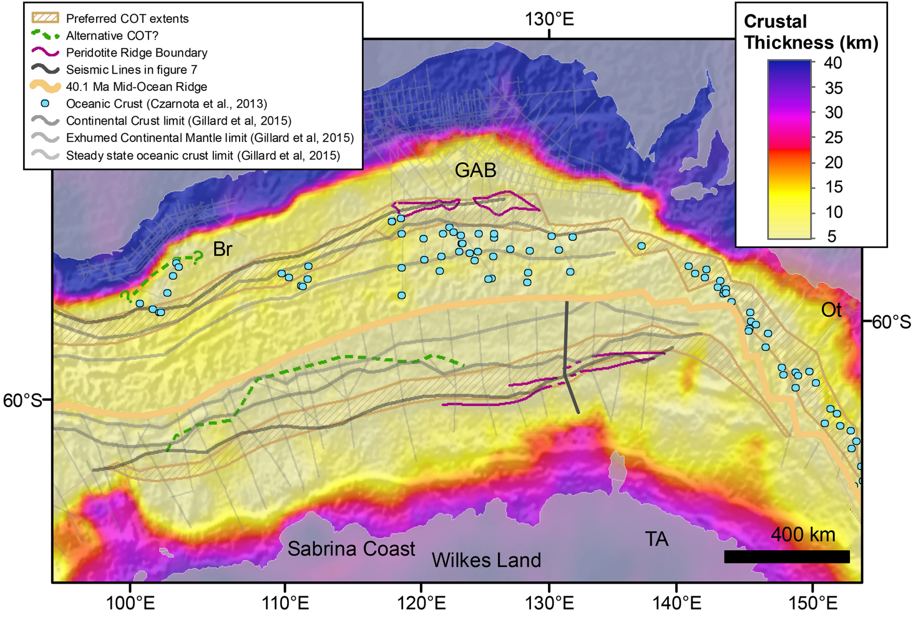
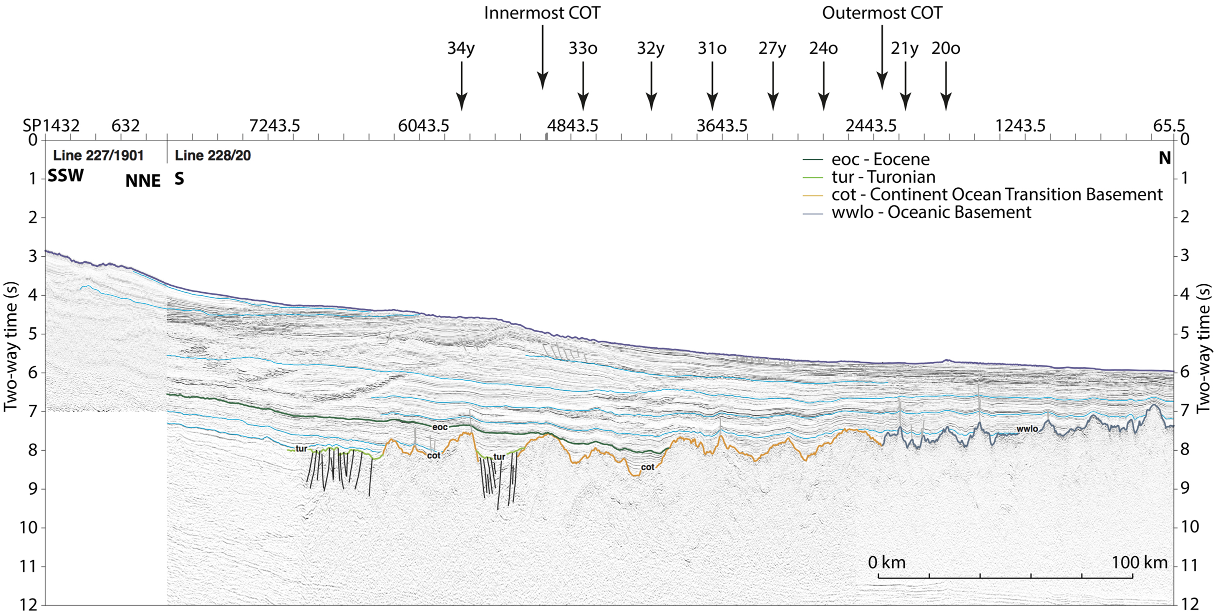

Preferred COT extents
Alternative COT?
Peridotite Ridge Boundary
Seismic Lines in figure 7
40.1 Ma Mid-Ocean Ridge
Oceanic Crust (Czarnota et al., 2013)
Continental Crust limit (Gillard et al, 2015)
Exhumed Continental Mantle limit (Gillard et al, 2015)
Steady state oceanic crust limit (Gillard et al, 2015)
Crustal Thickness (km)
40
35
30
25
20
15
10
5
130°E
GAB
Br
Ot
60°S
60°S
Sabrina Coast
Wilkes Land
TA
400 km
100°E
110°E
120°E
130°E
140°E
150°E

Figure 4



Innermost COT
Outermost COT
34y
33o
32y
31o
27y
24o
21y
20o
SP1432
632
7243.5
6043.5
4843.5
3643.5
2443.5
1243.5
65.5
Line 227/1901
Line 228/20
SSW
NNE
S
N
eoc - Eocene
tur - Turonian
cot - Continent Ocean Transition Basement
wwlo - Oceanic Basement
Two-way time (s)
eoc
tur
cot
wwlo
0 km
100 km

Figure 5

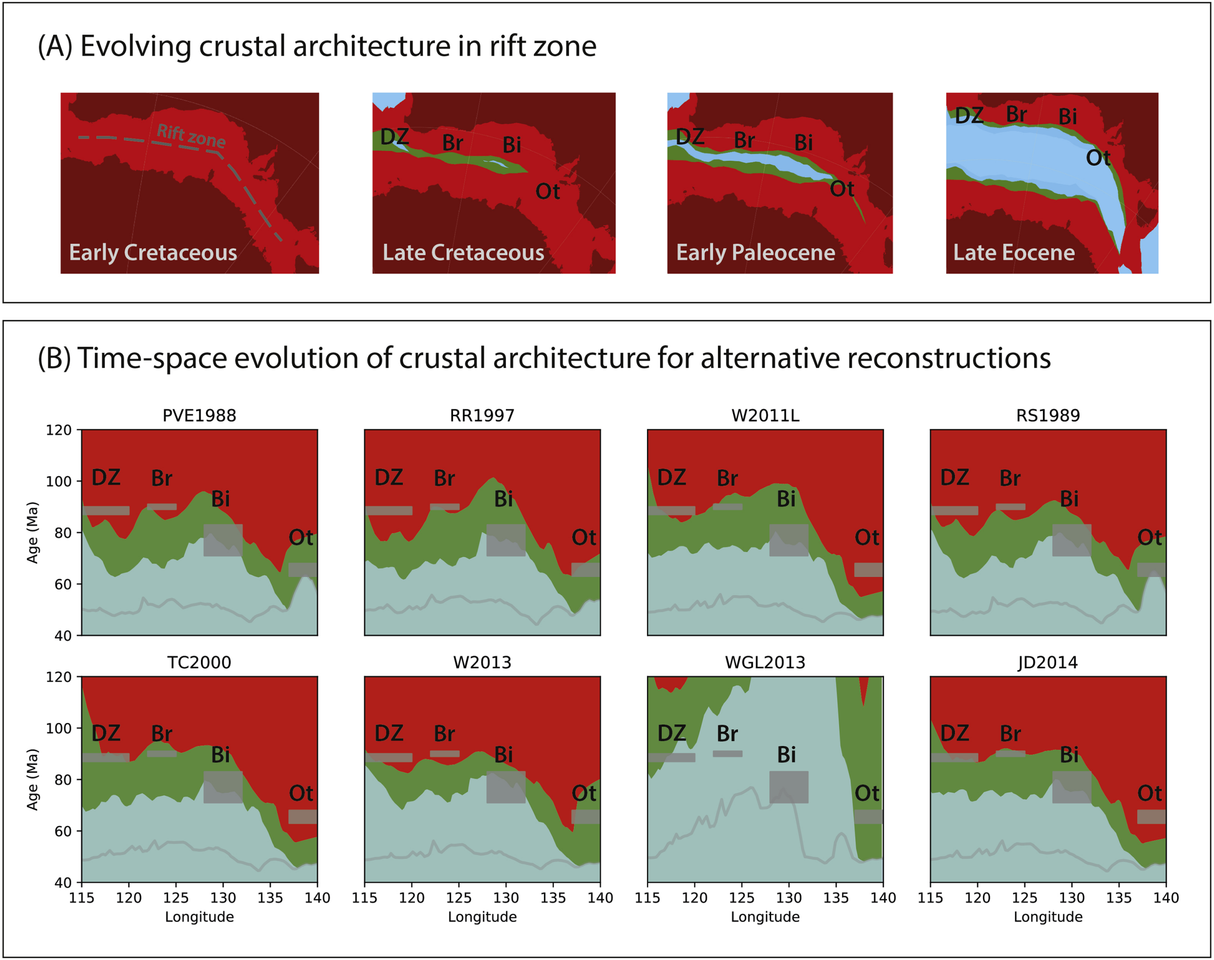
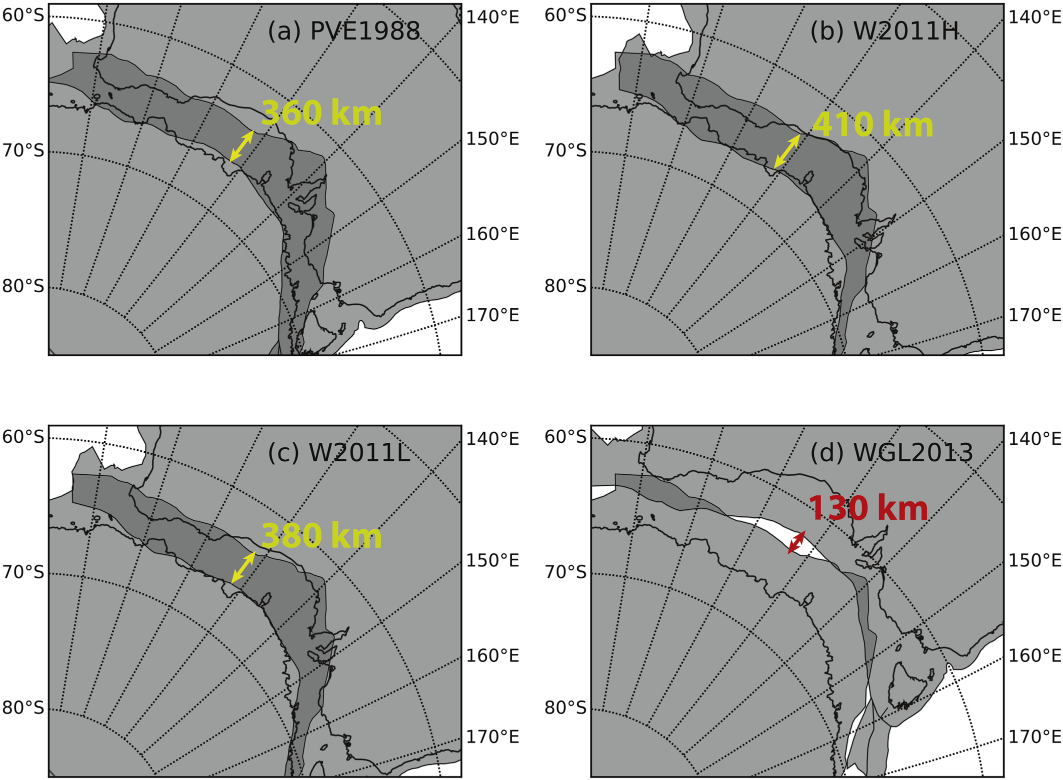
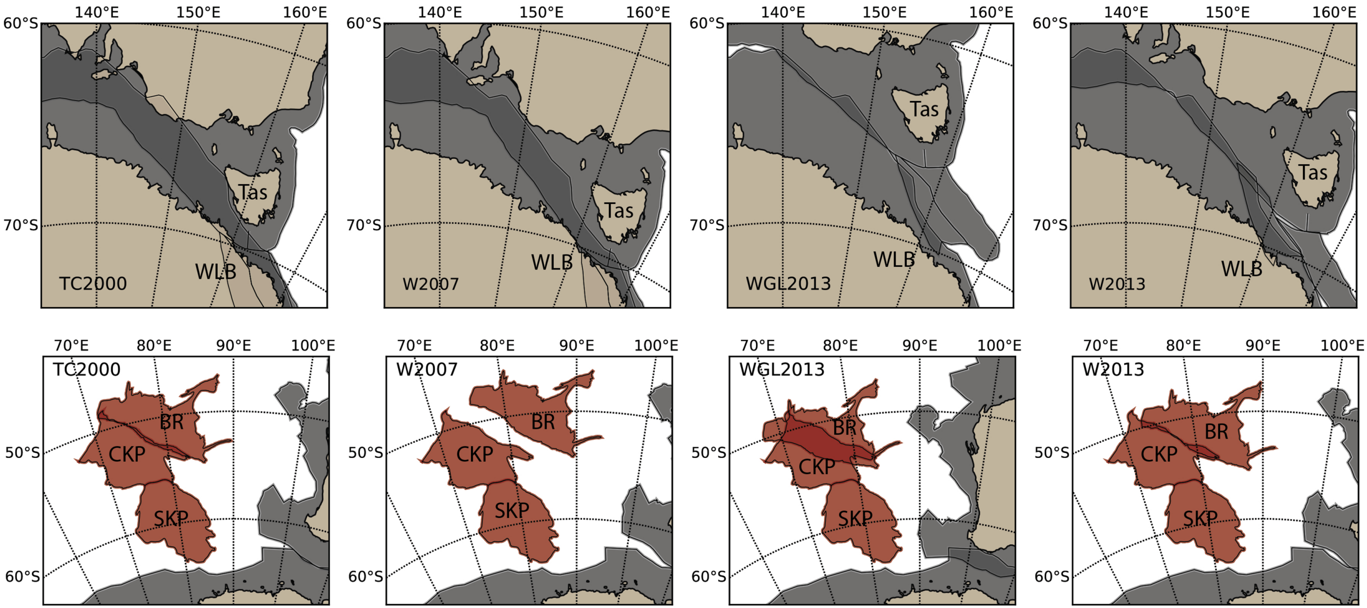

(A) Evolving crustal architecture in rift zone
Rift zone
Early Cretaceous
DZ
Br
Bi
Ot
Late Cretaceous
DZ
Br
Bi
Ot
Early Paleocene
DZ
Br
Bi
Ot
Late Eocene
(B) Time-space evolution of crustal architecture for alternative reconstructions
PVE1988
RR1997
W2011L
RS1989
TC2000
W2013
WGL2013
JD2014
Age (Ma)
120
100
80
60
40
115
120
125
130
135
140
Longitude
DZ
Br
Bi
Ot

Figure 6



(a) PVE1988
360 km
(b) W2011H
410 km
(c) W2011L
380 km
(d) WGL2013
130 km
60°S
70°S
80°S
140°E
150°E
160°E
170°E

Figure 7



140°E
150°E
160°E
60°S
70°S
Tas
WLB
TC2000
W2007
WGL2013
W2013
70°E
80°E
90°E
100°E
50°S
60°S
BR
CKP
SKP

Figure 8

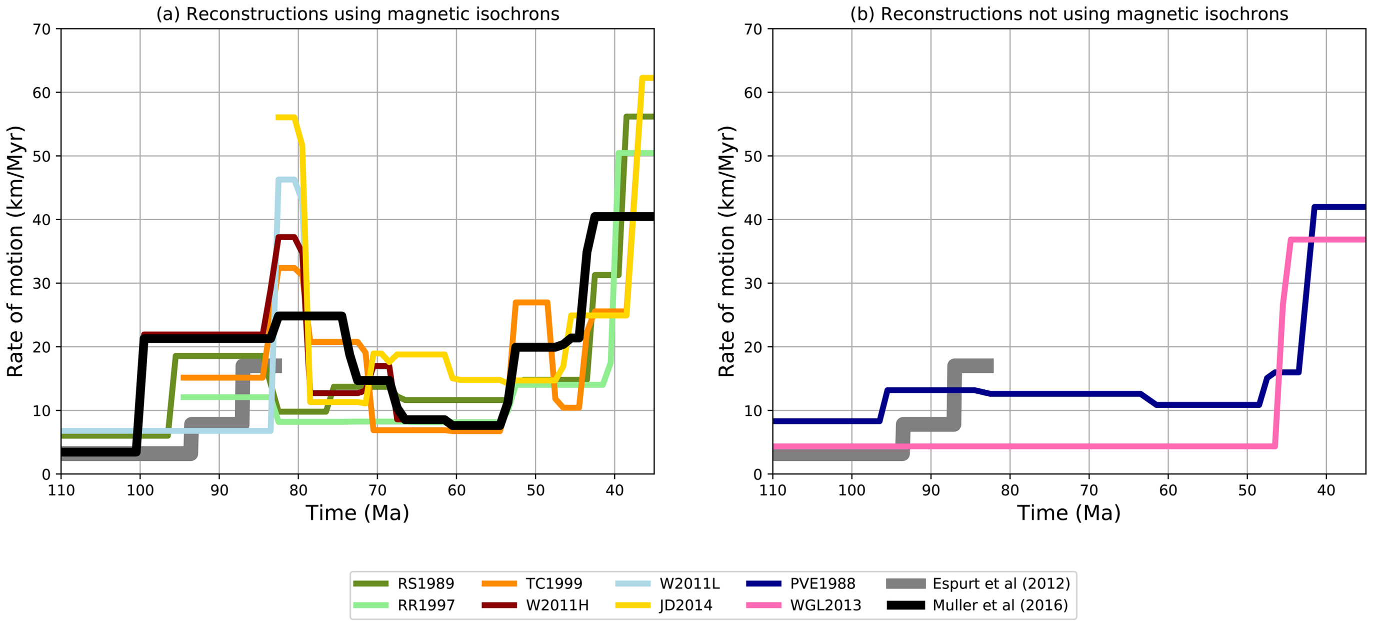
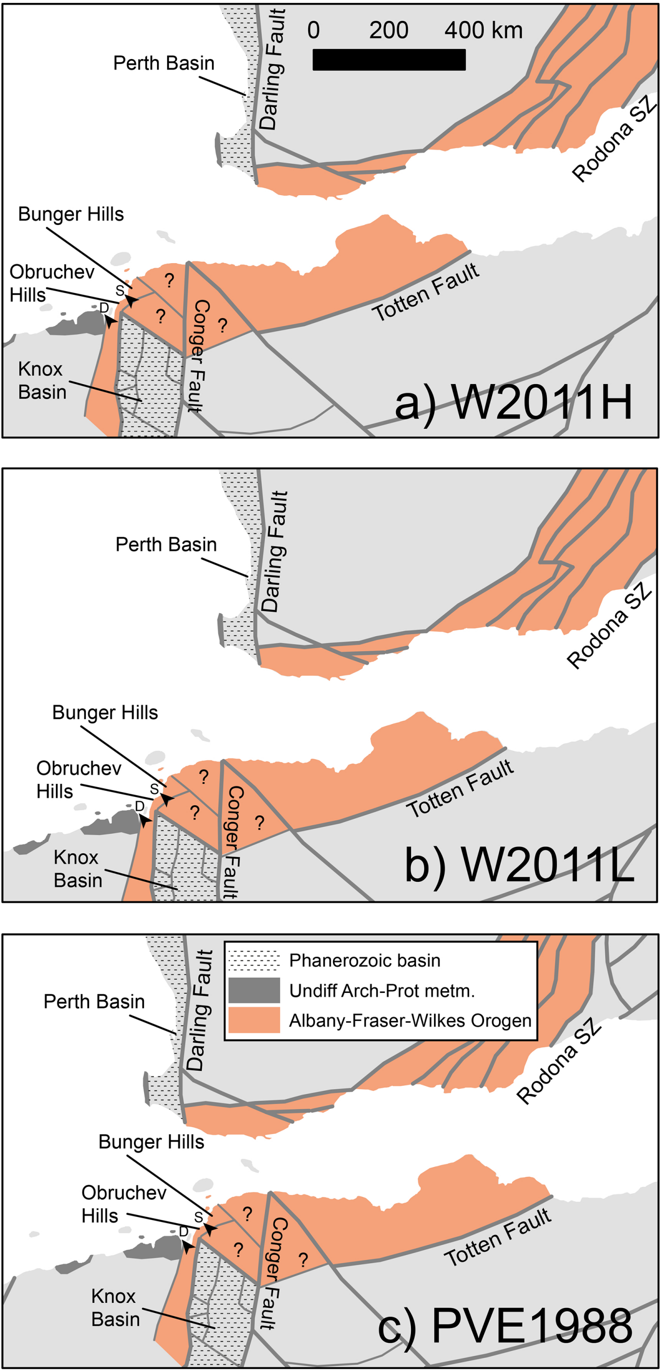
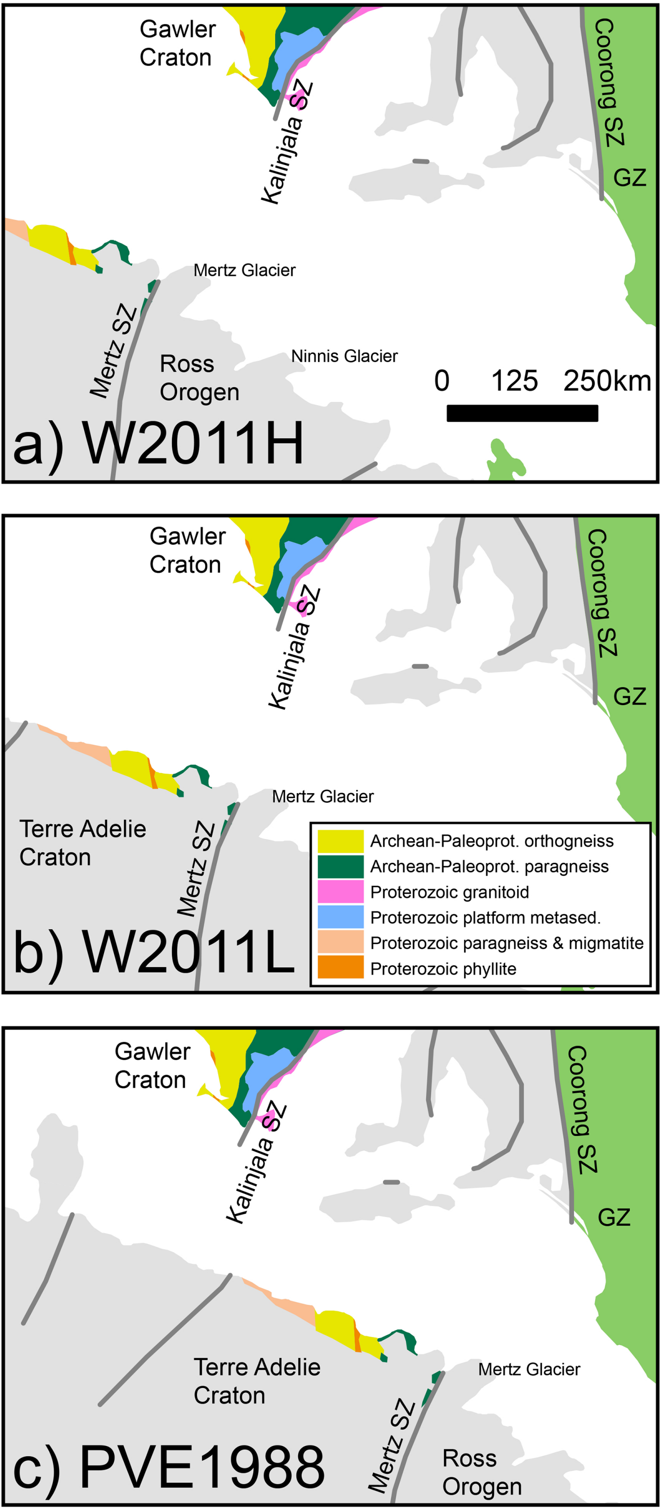

(a) Reconstructions using magnetic isochrons
(b) Reconstructions not using magnetic isochrons
Rate of motion (km/Myr)
Time (Ma)
0
10
20
30
40
50
60
70
110
100
90
80
70
60
50
40
RS1989
RR1997
TC1999
W2011H
W2011L
JD2014
PVE1988
WGL2013
Espurt et al (2012)
Muller et al (2016)

Figure 9



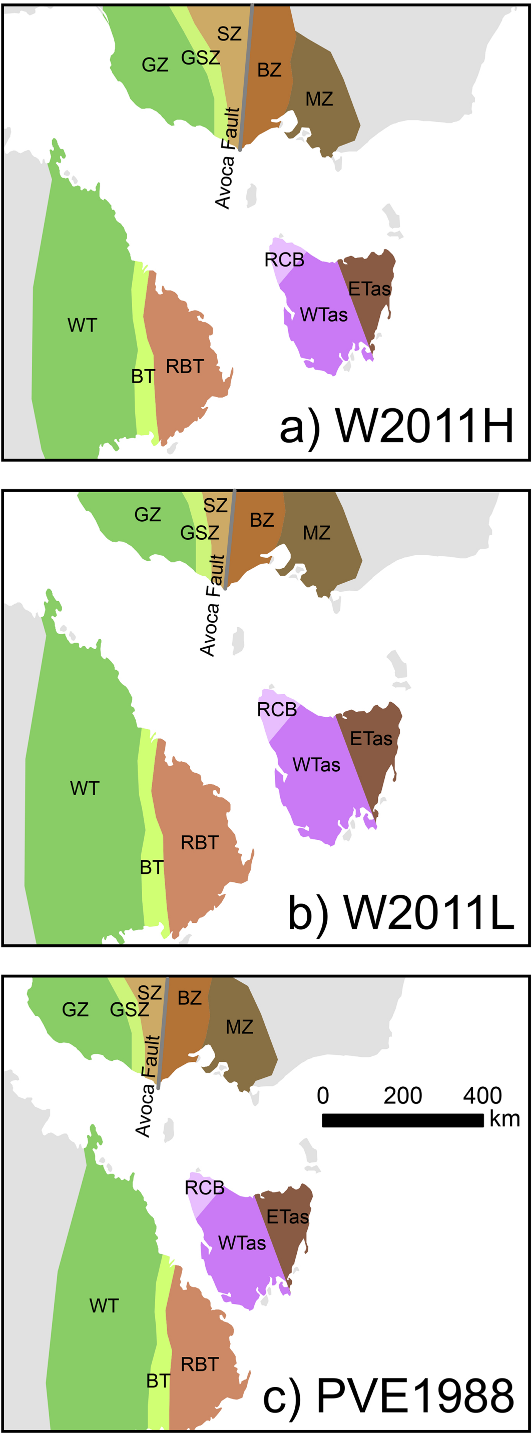
Perth Basin
Darling Fault
0
200
400 km
Rodona SZ
Bunger Hills
Obruchev Hills
S
D
?
Conger Fault
Totten Fault
Knox Basin
a) W2011H
b) W2011L
c) PVE1988
Phanerozoic basin
Undiff Arch-Prot metm.
Albany-Fraser-Wilkes Orogen

Figure 10



Gawler Craton
Kalinjala SZ
Coorong SZ
GZ
Mertz Glacier
Mertz SZ
Ross Orogen
Ninnis Glacier
0 125 250km
a) W2011H
Gawler Craton
Kalinjala SZ
Coorong SZ
GZ
Mertz Glacier
Terre Adelie Craton
Mertz SZ
b) W2011L
Archean-Paleoprot. orthogneiss
Archean-Paleoprot. paragneiss
Proterozoic granitoid
Proterozoic platform metased.
Proterozoic paragneiss & migmatite
Proterozoic phyllite
Gawler Craton
Kalinjala SZ
Coorong SZ
GZ
Terre Adelie Craton
Mertz Glacier
Mertz SZ
Ross Orogen
c) PVE1988

Figure 11



GZ
GSZ
SZ
BZ
MZ
Avoca Fault
WT
BT
RBT
RCB
ETas
WTas
a) W2011H
GZ
GSZ
SZ
BZ
MZ
Avoca Fault
WT
BT
RBT
RCB
ETas
WTas
b) W2011L
GZ
GSZ
SZ
BZ
MZ
Avoca Fault
0
200
400
km
WT
BT
RBT
RCB
ETas
WTas
c) PVE1988

Figure 12