Structural Architecture of Australia's Southwest Continental Margin and Implications for Early Cretaceous Basin Evolution

L.S. Hall[1], A.D. Gibbons[2], G. Bernardel[1], J.M. Whittaker[3], C. Nicholson[1], N. Rollet[1] & R.D. Müller[2]

Keywords: Plate reconstructions, margin architecture, basin evolution, Perth Basin, Mentelle Basin.

Abstract

The southwest margin of Australia is a complex and relatively poorly studied offshore continental region that includes the Perth and Mentelle basins. Plate reconstruction models, in conjunction with regional seismic and potential field data, demonstrate that the margin comprises three major segments: the normal to oblique Mentelle and southern Perth margins and the Wallaby-Zenith Transform Margin. Margin architecture and overlying basin geometries change markedly across segment boundaries and the patterns of structural reactivation during basin development indicate a strong basement control on margin evolution. Linking plate reconstructions and seismic studies provides new insights into Early Cretaceous basin evolution, including the relative timing of breakup within each sub-basin, the timing of accommodation generation and the distribution of breakup related igneous activity. Active development of the Wallaby-Zenith Transform Margin lasted from the Valanginian to the Aptian and controlled structural activity and the patterns of sediment fill across the northern Perth Basin. Immediately prior to Early Cretaceous breakup, the majority of accommodation-space generation and igneous activity was focused within the Zeewyck and Western Mentelle sub-basins.

1 Energy Division, Geoscience Australia, ACT 2601, Australia; lisa.hall@ga.gov.au

2 EarthByte Group, School of Geosciences, University of Sydney, NSW 2006, Australia

3 Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia

Introduction

The Palaeozoic to Mesozoic southwest Australian margin (Fig. 1) is an under-explored region of the continental margin of Australia and includes the Perth and Mentelle basins, as well as the Naturaliste and Wallaby plateaus. Previous regional-scale studies have shown that margin orientation and geometry vary markedly along strike (Borissova, 2002; Bradshaw et al., 2003; Norvick, 2004). As the architecture of rifted margins exerts a first-order control on basin location and the patterns of sedimentary fill, a better regional understanding of margin evolution is essential for further studies of Perth and Mentelle basin development and petroleum prospectivity.

A series of recently published studies provide fresh insights into the architecture and tectonic evolution of Australia's southwest margin. A regional plate reconstruction model has been developed for all of western Australia (Gibbons et al., 2012) that includes the continental fragments of the Gulden Draak and Batavia knolls (Williams, 2011; Kobler, 2012; Gardner, 2012; Whittaker et al., 2013). In addition, work conducted by Geoscience Australia as part of the Australian Government's Energy Security Program has provided new insights into the evolution and petroleum prospectivity of the Perth and Mentelle basins (Geoscience Australia, 2011). The program included the acquisition of new 2D seismic reflection and potential field data, as well as the re-processing of existing open-file industry seismic data (Foster et al., 2009; Hackney, 2012). These data were then used to underpin a selection of sequence stratigraphy studies in the Mentelle and offshore Perth basins (e.g. Borissova et al., 2010; Jones et al., 2011; Bernardel & Nicholson, 2013; Rollet et al., 2013a, b).

This study compares both new and recently published seismic interpretations from Geoscience Australia with the regional plate reconstruction model of Gibbons et al. (2012). The comparison allows a better characterisation of the along-strike variability of the margin architecture. Integration of a newly-interpreted continent-ocean boundary (red dashed line in Fig. 1) into the plate reconstruction model demonstrates that the margin is highly segmented, similar to other margins around Australia (e.g. Symonds et al., 1998; Blevin & Cathro, 2008; Direen et al., 2008; Totterdell et al., 2012) and elsewhere in the world (e.g. Greenroyd et al., 2008b; Guiraud et al., 2010). In addition, its structural architecture varies significantly along strike according to the relative orientation of the margin with respect to the Early Cretaceous extension direction. Comparison with the seismic data shows that the boundaries between these margin segments are directly linked to the location of major oceanic fracture zones, as well as to the location and geometry of the major Palaeozoic to Mesozoic basins. Furthermore, integration of the plate reconstruction model with recent basin-scale sequence stratigraphic studies provides new insights into Early Cretaceous basin evolution, including the relative timing of breakup within each sub-basin and the distribution of breakup related igneous activity.

Data Sets

Work conducted by Geoscience Australia as part of the Australian Government's Energy Security Program (Geoscience Australia, 2011) included the acquisition of new seismic reflection and potential field data across the southwest margin, as well as the re-processing of existing open-file industry seismic data (Foster et al., 2009) (Fig. 1). Of particular note is the GA 310 survey that acquired 7300 km of new 2D seismic data across sections of the Southern Carnarvon, Perth and Mentelle basins, as well as the Wallaby Plateau. Line spacing is typically between 10–20 km, and the data are 106-fold with a record length of 12 s two-way time. In addition, the marine reconnaissance survey GA-2476 focused on dredge sampling and acquisition of swath bathymetry data across the northern Perth Basin, Southern Carnarvon Basin and Wallaby Plateau (Daniell et al., 2010).

New gravity and magnetic data were acquired with the seismic and swath bathymetry data (Foster et al., 2009; Hackney, 2012). These datasets were merged and levelled with an existing Australia-wide dataset to provide a consistent dataset that covers the whole southwest margin of Australia (106–120°E and 19–37°S) (Hackney, 2012) (Fig. 2). Although ship-track coverage over the northern Perth Basin is reasonably good, large gaps still exist, especially in some of the deeper water areas. Hackney (2012) created additional versions of the datasets where gaps were filled with gravity data from satellite-altimeter-derived measurements (Andersen et al., 2010) and magnetic data from the EMAG2 global compilation (Maus et al., 2009).

Tectonic Setting

The southwest margin of Australia includes the Perth and Mentelle basins, as well as the Wallaby and Naturaliste plateaus (Bradshaw et al., 2003; Norvick, 2004) (Fig. 1). Offshore, the Perth Basin is divided into the following tectonic elements: the Houtman, Zeewyck, Abrolhos and Vlaming sub-basins, as well as the Turtle Dove Ridge (Bradshaw et al., 2003; Nicholson et al., 2008; Jones et al., 2011) (Fig. 1). The Mentelle Basin is divided into eastern and western sub-basins (Bradshaw et al., 2003; Borissova et al., 2010) (Fig. 1). The Perth and Mentelle basins are separated by the structural high of the Yallingup Shelf (Fig. 1).

Basement

Sedimentary basins on the southwest Australian margin are underlain by basement rocks of the Pinjarra Orogen. However, due to limited outcrop and the lack of a well-preserved conjugate margin, the nature and extent of the Pinjarra Orogen is poorly understood (e.g. Dentith et al., 1994; Fitzsimons, 2003; Janssen et al., 2003; Halpin et al., 2008; Cawood and Korsch, 2008; Boger, 2011; Ksienzyk et al., 2012). Basement exposures are restricted to the Northampton and Mullingarra complexes, within the northern Perth Basin, and the Leeuwin Complex, located between the Yallingup Shelf and southern onshore Perth Basin (Fitzsimons, 2003; Janssen et al., 2003) (Fig. 2). To the east of the Pinjarra Orogen and overlying Perth Basin lies the Archean Yilgarn Craton and the Proterozoic Capricorn and Albany Fraser orogens.

The most prominent basement structure of the Pinjarra Orogen is the Darling Fault that separates the Pinjarra Orogen from the Yilgarn Craton to the east (Dentith et al., 1993; Fitzsimons, 2003). This is a major NNW–SSE to N–S trending shear zone, dating back to the Archean (Fitzsimons, 2003; Janssen et al., 2003; Boger, 2011) (Figs 1 & 2). Other significant outcropping basement faults include the Geraldton Fault that marks the southwestern edge of the Northampton Complex, the Urella Fault that forms the western edge of the Mullingarra Complex and the Dunsborough Fault, the eastern boundary of the Leeuwin Complex (e.g. Playford et al., 1970; Byrne & Harris, 1992; Collins, 2003; Janssen et al., 2003; Fitzsimons, 2003).

Limited geochronological data from both outcrop and offshore dredge samples indicate that the Pinjarra Orogen has had a prolonged and complex history that lasted from the Mesoproterozic to the Late Neoproterozoic/Early Cambrian (e.g. Collins, 2003; Fitzsimons, 2003; Halpin et al., 2008; Cawood & Korsch, 2008; Boger, 2011; Ksienzyk et al., 2012).

Initial deposition of both the Northampton and Mullingarra sediments occurred in the Mesoproterozic, between 1150 and 1080 Ma. At around 1090–1000 Ma, during the Pinjarra Orogeny, the Northampton and Mullingarra Complexes were subject to pervasive deformation and granulite to amphibolite facies metamorphism, which was followed by pluton emplacement in the Northampton Complex until around 990 Ma (Bruguier et al., 1999; Cobb et al., 2001; Ksienzyk et al., 2012). This is inferred to mark a Grenville-aged collision

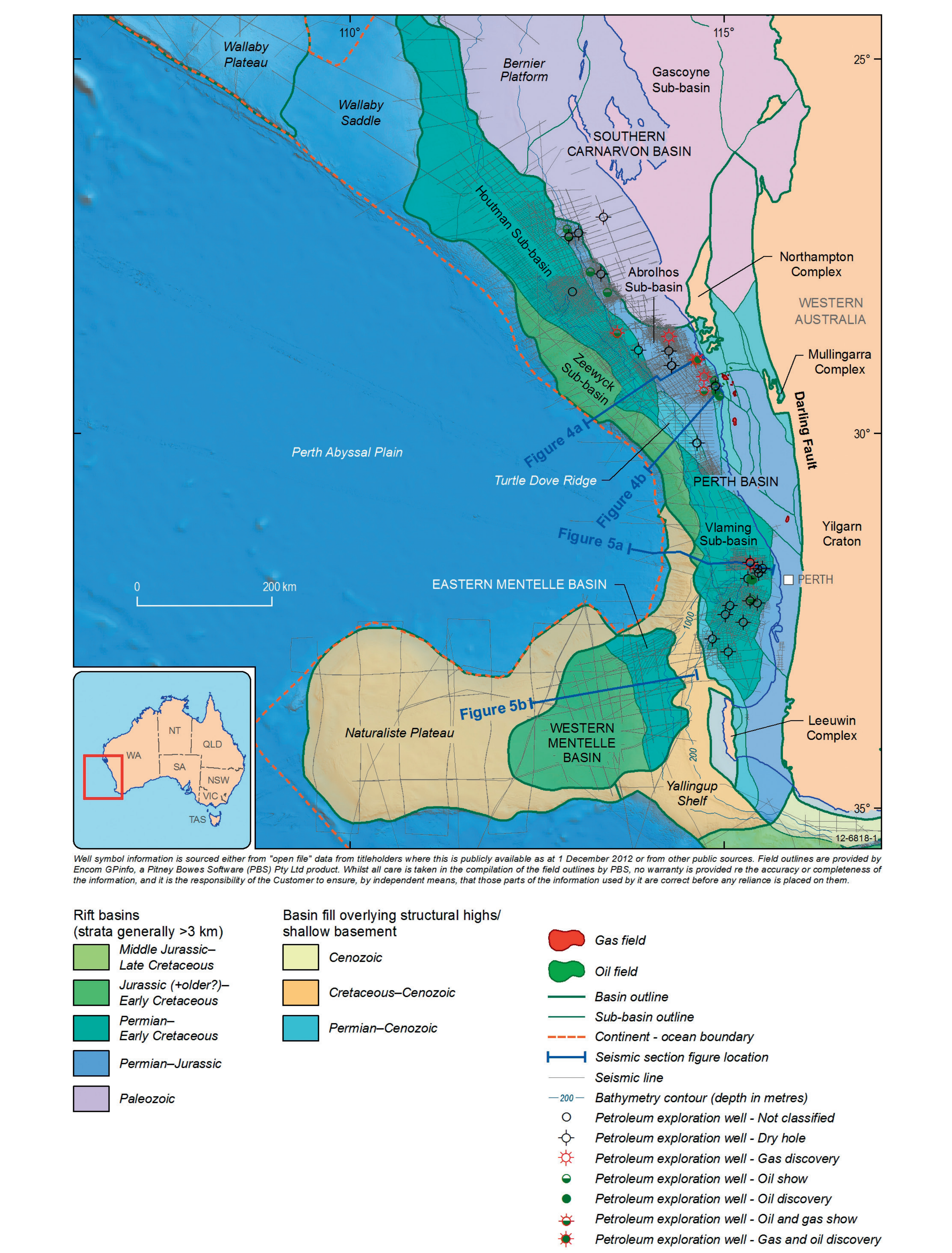

Figure 1. Structural elements of the southwest margin of Australia.

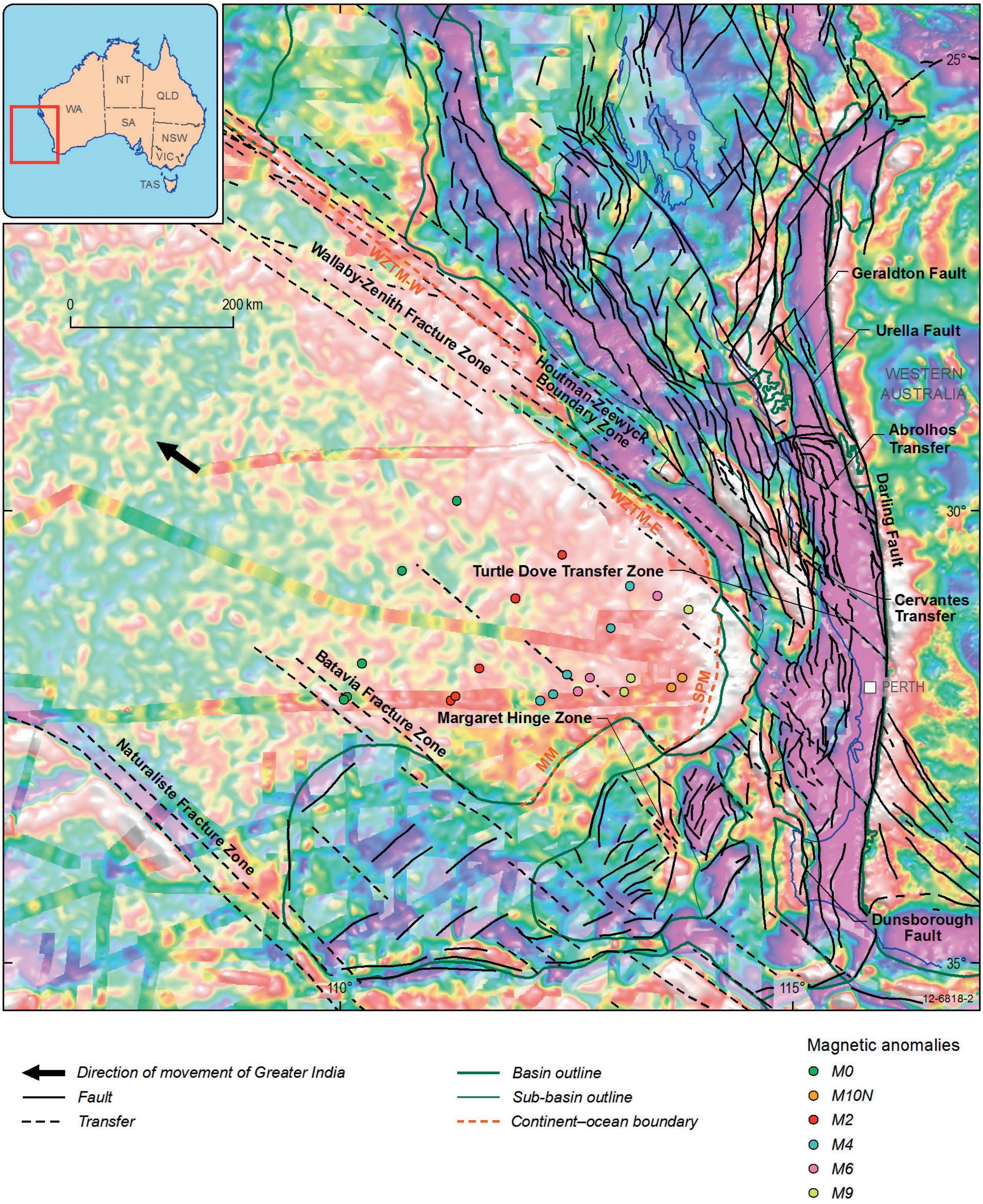

Figure 2. Structural architecture of the southwest margin, showing basin and sub-basin outlines displayed over a residual Bouguer gravity image (Hackney, 2012). The COBs of each margin segment referred to in the text are highlighted by the red dotted lines. WZTM-E: Wallaby Zenith Transform Margin – East; WZTM-W: Wallaby Zenith Transform Margin – West; Southern Perth margin: SPM; Mentelle margin: MM. Seafloor magnetic anomaly picks arc from Gibbons et al. (2012). Major faults are simplified from Mory and Iasky (1996); Hocking et al. (1997); Borissova (2002); Iasky et al. (2003); Norvick (2004); Nicholson et al. (2008); Borissova et al. (2010); Jones et al. (2011) and are supplemented by interpretation of gravity and magnetic datasets (Hackney et al., 2012).

event between the Yilgran Craton and an exotic terrane, the nature of which is still under debate (e.g. Pisarevsky et al., 2003; Collins and Pisarevsky, 2005; Li et al., 2008; Boger, 2011). At around 755–750 Ma, magmatism in the Leeuwin Complex (Collins, 2003) and emplacement of the Mundine Well dyke swarm in the Northampton Complex (Embleton & Schmidt, 1985; Wingate & Giddings, 2000) is interpreted to represent a regional Rodinia breakup event (Collins & Pisarevsky, 2005; Wingate, 2007).

The final phase of basement evolution in the Neoproterozoic-Cambrian was driven by collision between the Indo-Antarctic and Australo-Antarctic plates in part of the Kuunga Orogeny, which marked the final assembly of East Gondwana (Meert, 2003; Boger, 2011). This resulted in high-grade metamorphism of Naturaliste Plateau basement rocks (Halpin et al., 2008) and extensive tectonic activity and metamorphism in the Leeuwin Complex (Collins, 2003). Deformation is also evident further east, including development of greenschist facies shear zones in the Northampton Complex (Embleton & Schmidt, 1985) and possible reactivation of the Darling Fault (Fitzsimons, 2003; Janssen et al., 2003).

Basin Evolution

The Palaeozoic to Mesozoic development of the Perth and Mentelle basins was primarily controlled by multiple phases of tectonic activity acting along the future western margin of Australia, culminating in the Early Cretaceous breakup of Greater India and Australia (Bradshaw et al., 2003; Norvick, 2004). Summary stratigraphic charts for the Mentelle and Perth basins can be found in Borissova et al. (2010) and Rollet et al. (2013a, b).

Pre-rift strata are only evident in the northern part of the Perth Basin and comprise Late Cambrian to Ordovician sediments associated with the Southern Carnarvon Basin (e.g. Hocking et al., 1997; Iasky et al., 2003; Jones et al., 2011).

The first major stage of rifting in the Perth and Mentelle basins was marked by Early- to mid-Permian ENE-oriented intra-cratonic extension, which led to the formation of N to NNW-oriented half-grabens across the region (Mory & Iasky, 1996; Iasky et al., 2003; Bradshaw et al., 2003; Norvick, 2004; Borissova et al., 2010; Jones et al., 2011; Rollet et al., 2013a, b). The lack of well data and poor seismic quality at depth makes it difficult to directly identify any units of this age within the Zeewyck and Western Mentelle sub-basins or the Naturaliste Plateau; however comparison with adjacent sub-basins suggests such units could be present at depth (Borissova, 2002; Borissova et al., 2010). In the northern Perth Basin, the top of the Early- to mid-Permian syn-rift succession is marked by a major angular unconformity which is interpreted to be the result of regional tectonic uplift (Jones et al., 2011; Rollet et al., 2013a).

Initial extension was followed by Late Permian to Middle Jurassic thermal subsidence resulting in the formation of a broad sag basin across the southwest margin (Norvick, 2004). Thermal sag is interpreted to have been punctuated by two local extensional events: an Early Jurassic phase in the onshore Perth Basin (Song & Cawood, 2000; Gorter et al., 2004), followed by an Early–Middle Jurassic phase in the Houtman Sub-basin (Pfahl, 2011; Rollet et al., 2013a). The timing of the offshore extensional event fits with the Early to Late Jurassic NW-SE extensional phase in the Browse Basin to the north and the plate reconstruction models of Gibbons et al. (2012) suggest this could have been drive by NW-SE rifting between the Zenith Plateau and its conjugate margin, western Argoland (Rollet et al., 2013a). Upper Permian–lowermost Triassic volcanics and some intrusives are recorded in the northern Perth Basin (Gorter & Deighton, 2002).

A second regional rifting event, affecting the entire southwest margin, began in the Late Jurassic and culminated in the final separation of the Australia and Greater India in the Early Cretaceous (Larson et al., 1979; Veevers et al., 1991; Bradshaw et al., 2003; Norvick, 2004; Gibbons et al., 2012; Rollet et al., 2013a). NW–SE extension resulted in the further development of the Perth and Mentelle basins (Bradshaw et al., 2003; Norvick, 2004) and is discussed in more detailed below. Breakup between Greater India and Australia began with the formation of the Perth Abyssal Plain in the Valanginian, initiating the development of the Wallaby Zenith Transform Margin (Veevers et al., 1991; Norvick, 2004; Gibbons et al., 2012).

Late-stage fault reactivation and inversion is evident across the southwest region, including the Houtman Sub-basin (Gorter et al., 2004; Rollet et al., 2013a) and the Mentelle Basin (Borissova et al., 2010). This inversion event is interpreted to be the result of Miocene collision between the Australian and Eurasian plates (Rollet et al., 2013a). Minor volcanic activity also occurred in the Houtman Sub-basin during this time (Daniell et al., 2010; Rollet et al., 2013a).

Early Cretaceous Plate Reconstructions and Regional Margin Evolution

Existing Plate Reconstruction Framework

Gibbons et al. (2012) presented a new regional plate reconstruction of the whole of the western Australian margin (Fig. 3). The proposed model includes revised seafloor anomaly picks and crustal ages based on drill and dredge samples. It also accounts for all major tectonic features visible in the marine gravity grid, including volcanic ridges, submerged plateaus/continental rafts, and fracture zones.

The reconstruction of Gibbons et al. (2012) incorporates the newly-discovered continental fragments of the Gulden Draak and Batavia knolls (Williams, 2011; Kobler, 2012; Gardner, 2012; Whittaker et al., 2013). Recent analysis of dredge samples collected from the Batavia Knoll indicates that this is composed of granite and metamorphic basement

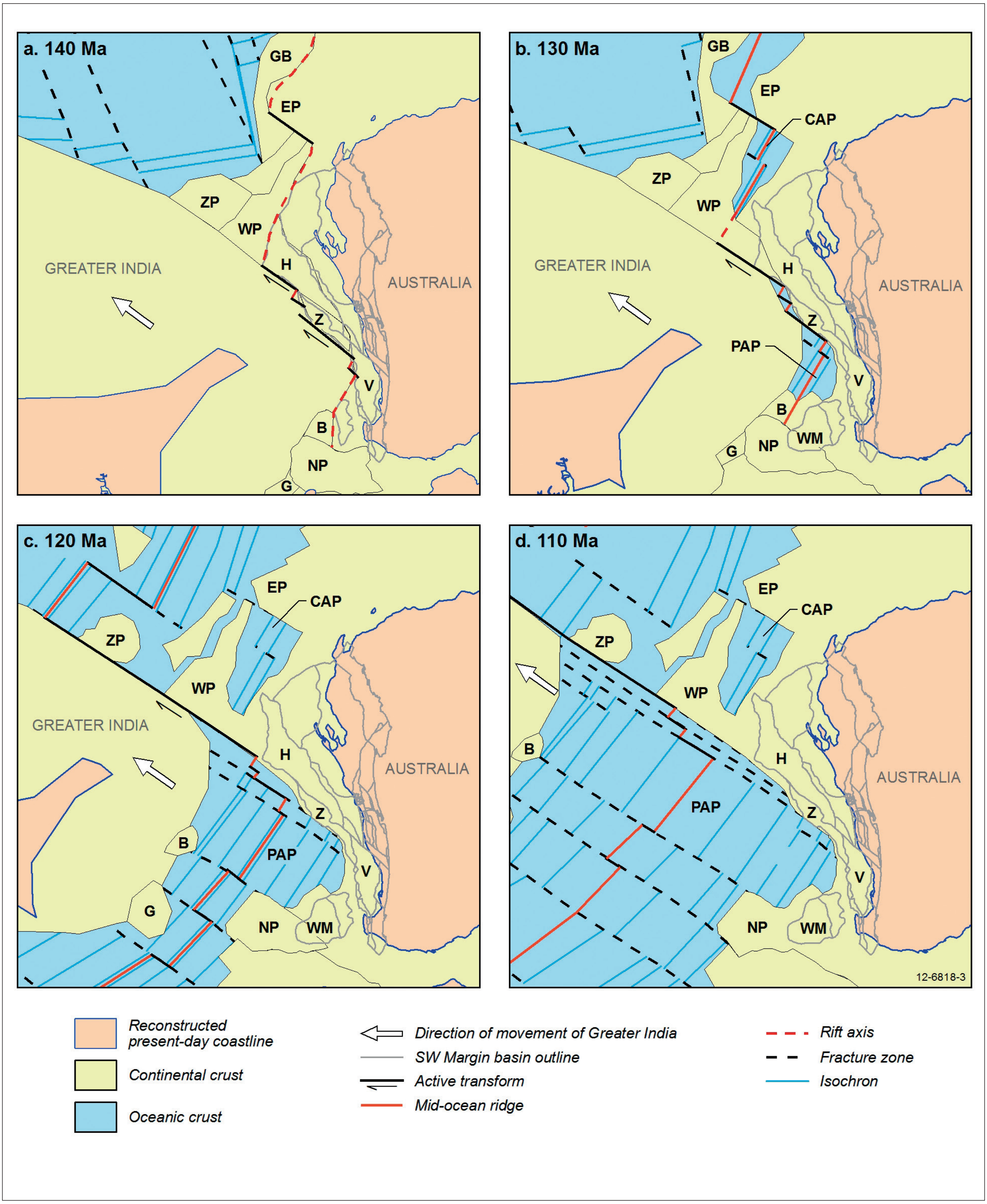

Figure 3. a) Cartoons showing the revised plate reconstruction model of Gibbons et al. (2012) with the modified southwest margin COB at (a) 200 Ma, (b) 150 Ma, (c) 130 Ma and (d) 120 Ma. Models were constructed using GPlates exported geometries with Australia fixed in present-day coordinates. B: Batavia Knoll; CAP: Curvier Abyssal Plain; EP: Exmouth Plateau; G: Gulden Draak Knoll; GB: Gascoyne Block; H: Houtman Sub-basin NP: Naturaliste Plateau; PAP: Perth Abyssal Plain; V: Vlaming Sub-basin; WM: Western Mentelle Sub-basin; WP: Wallaby Plateau; Z: Zeewyck Sub-basin; ZP: Zenith Plateau.

rocks of comparable age and composition to those of the Pinjarra Orogen, beneath the Perth Basin (Kobler, 2012). The reconstruction indicates that prior to breakup, the knolls were located adjacent to the southwest margin. The Batavia Knoll was located to the northeast of the Naturaliste Plateau, forming the conjugate margin to the Mentelle Basin, and the Gulden Draak Knoll was located to the southwest of the Naturaliste Plateau (Whittaker et al., 2013) (Fig. 3). After breakup, the knolls initially moved with the Indian Plate, but at around 108 Ma, they became isolated by a ridge jump triggered by the onset of the northward movement of India with respect to Australia (Gibbons et al., 2012). Other parts of the conjugate margin to Western Australia on the Indian side have subsequently been deformed during India-Asia collision and are now probably located beneath Assam (Kelsey et al., 2008).

Revised Continent-Ocean Boundary

The plate reconstruction model of Gibbons et al. (2012) used the Australia-wide continent-ocean boundary (COB) presented in Brown et al. (2003). However this COB was interpreted at a continent-wide scale and differs significantly outboard of the Perth and Mentelle basins from a detailed southwest margin-specific interpretation by Norvick (2004). To resolve this discrepancy, the COB was reinterpreted for this study using the recently-acquired seismic and potential field data (Figs 1 & 3) and the new results were incorporated back into the plate reconstruction model of Gibbons et al. (2012).

For this study, the COB is mapped as the limit of oceanic crust. In addition, a continent-ocean transition zone (COT) has also been interpreted for key seismic lines, where the COT is considered to be a region of ambiguous composition, somewhere between typical oceanic crust and highly extended continental crust. The COT may represent either significant additional igneous material emplaced at breakup, very highly-extended continental crust with little or no remaining mappable syn-rift section or exhumed mantle.

All available seismic data (Fig. 1) were used to identify the location of the COB and COT on the basis of reflection characteristics of the sea-floor, sedimentary cover, basement reflector characteristics and the presence or absence of coherent signal from the upper crust. These results were then compared with the gravity, magnetic and bathymetry datasets, enabling the COB location to be interpolated between seismic lines.

The new interpretation (Fig. 1) results in only minor changes to the COB along the Wallaby-Zenith Fracture Zone compared with previous studies. However, outboard of the southern Perth and Mentelle basins, the location of newly interpreted COB is much closer to that of Norvick (2004) than Brown et al. (2003). In this region, the COB shows a distinct NW-SE offset at the transition between the Mentelle and Perth basins (Figs 1 & 2), which is not apparent in the Brown et al. (2003) model.

Margin segmentation

The geometry of the revised COB highlights the segmented nature of the southwest margin and, outboard of the Perth and Mentelle basins, three major segments can be defined: the Wallaby-Zenith Transform Margin, the southern Perth margin and the Mentelle margin (Fig. 2).

The Wallaby–Zenith Transform Margin separates the continental crust of the Wallaby Plateau and the Houtman and Zeewyck sub-basins from the oceanic crust of the Perth Abyssal Plain (Sayers et al., 2002; Nelson et al., 2009) (Figs 1 & 2). The margin trends NW-SE and is over 1000 km long. Although the COB is close to parallel with the Early Cretaceous NE-SW extension direction, the Wallaby-Zenith Transform Margin is not completely linear. Based on margin morphology, the COB within the study area can be split into two en-echelon sub-segments, which are offset by about 70 km. The western section (WZTM-W, Fig. 2) sits outboard of the northern Houtman Sub-basin and Wallaby Plateau, while the eastern section (WZTM-E, Fig. 2) lies outboard of the Zeewyck Sub-basin (Figs 1 & 2).

The southern Perth margin lies outboard of the Vlaming Sub-basin and northern Yallingup Shelf and is approximately 200 km long (Figs 1 & 2). The margin gradually changes in orientation along the segment from N–S in the north, then NE-SW in the south. On average it is offset by an angle of 40 to 50 degrees to the sea-floor magnetic anomalies, indicating oblique extension. The 170 km long Mentelle margin lies outboard from the western Mentelle Sub-basin (Figs 1 & 2). It trends approximately NE–SW, parallel to the sea-floor magnetic anomalies (Fig. 2).

The margin segments show a strong connection with the location of major oceanic fracture zones (Fig. 2). The Wallaby-Zenith Transform margin forms the eastern end of the Wallaby-Zenith Fracture Zone (Nelson et al., 2009; Gibbons et al., 2012). The southern end of the Mentelle margin segment ends with the northwest–southeast trending Batavia Fracture Zone, which extends to the west into the oceanic crust of the Perth Abyssal Plain (Norvick, 2004). The exception to the relationship between margin segmentation and fracture zone location is the boundary between the southern Perth and Mentelle margin segments. While this is marked by a northwest–southeast offset of approximately 65 km, both the gravity data and the patterns of sea-floor magnetic anomalies suggest that this offset does not correlate with a significant oceanic fracture zone within the Perth Abyssal Plain (Fig. 2).

Timing of Breakup

A major plate reorganisation occurred along Australia's western margin at around 136–137 Ma (Valanginian) that initiated the separation between Greater India and Australia and the onset of sea-floor spreading along the southwest margin (Gibbons et al., 2012). However, integration of the new COB with the plate reconstruction model of Gibbons et al. (2012) suggests that breakup along each of the southwest margin segments was not synchronous (Fig. 3).

Initial continental breakup and oceanic crust production occurred outboard of the Vlaming Sub-basin and Yallingup Shelf along the southern Perth margin creating an isolated ocean basin (Fig. 3). Whilst the oldest mapped seafloor anomaly is M11 (132 Ma), the full-fit reconstructions with the revised COB indicate that breakup occurred at around 136–137 Ma (Valanginian). This is consistent with biostratigraphic constraints on the timing of the breakup unconformity from within the Vlaming Sub-basin, where sediments immediately overlying the breakup unconformity are determined to be Valanginian in age, also around 136–137 Ma (Crostella & Backhouse, 2000; Jones et al., 2012).

Adjacent to the Houtman and Zeewyck sub-basins, along the Wallaby-Zenith Fracture Zone, dextral transform margin activity initiated at the same time as breakup along the southern Perth margin (Fig. 3). As seafloor spreading continued, the mid-ocean ridge adjacent to the southern Perth margin moved from east to west along the transform and tectonic activity along the margin only ceased once the ridge passed. The reconstructions indicate that active transform motion lasted from about 137 to 123 Ma (Valanginian to early Aptian) outboard of the Zeewyck Sub-basin and may have continued until around 115 Ma (late Aptian) outboard of the northern Houtman Sub-basin (Fig. 3).

From 137 to 128 Ma, the active transform margin connected the newly-formed oceanic basin of the Perth Abyssal Plain with extension in the Wallaby Saddle between the Wallaby Plateau and northern Houtman Sub-basin (Figs 1 & 3). During this time the Wallaby Plateau remained connected to Greater India. At around 128 Ma (Barremian), the ridge within the Cuvier Abyssal Plain jumped further west, transferring the Wallaby Plateau to the Australian Plate. This initiated active transform margin development along the southern margin of the Wallaby Plateau (as Greater India moved away from Australia) and extension between the Wallaby and Zenith plateaus (Gibbons et al., 2012).

Further south, it is likely that the timing of breakup differed also between the southern Perth and Mentelle margins. The offset in the COB between these margin segments does not correlate with a significant oceanic fracture zone and no equivalent offset is observed in the oldest magnetic anomaly picks within the Perth Abyssal Plain (Figs 2 and 3). This suggests that the COB offset was not caused by an en-echelon offset in the mid-ocean ridge, but instead that sea-floor spreading outboard of the Mentelle Basin began at around 132 Ma (Hauterivian), around 3–5 Myr later than further north, outboard from the southern Perth segment.

Margin Architecture and Patterns of Early Cretaceous Basin Fill

A series of recently published studies based on sequence stratigraphy and constraints from well and newly acquired seismic data have provided new insights into the evolution and petroleum prospectively of the Perth and Mentelle basins (Nicholson et al., 2008; Borissova et al., 2010; Geoscience Australian, 2011; Jorgensen et al., 2011; Jones et al., 2011; Bernardel & Nicholson, 2013; Rollet et al., 2013a, b). These data and associated interpretations can be used to show how patterns of margin architecture and basin fill vary along strike and to further investigate the linkage between regional margin evolution and patterns of basin fill. It should be noted that due to the complexity of southwest margin geology and the large amount of available seismic data, much of the discussion that follows is based on regional-scale interpretations only. Significant further work is required to better document the detailed structural architecture within each sub-basin.

Houtman and Zeewyck Sub-basins

Figure 4a shows an interpreted seismic section across the Wallaby-Zenith Transform Margin that extends from the oceanic crust of the Perth Abyssal Plain across the Zeewyck and Houtman sub-basins.

At less than 20 km wide, the continent-ocean transition (COT) zone associated with this section of the Wallaby-Zenith Transform Margin is relatively narrow. In the seismic data it is marked by a prominent basement high that correlates with gravity and magnetic anomalies that have the same trend as the Wallaby-Zenith Fracture Zone (Bradshaw et al., 2003) (Figs 2 & 4a). This morphology is typical of marginal ridges observed at transform margins elsewhere in the world (e.g. Basile et al., 1998; Bird, 2001; Basile & Allemand, 2002; Greenroyd et al., 2007, 2008a, b; Parsiegla et al., 2009). Possible mechanisms of ridge formation include igneous intrusion, as well as uplift due to differential buoyancy forces acting across the transform margin as it develops (e.g. Basile & Allemand, 2002).

The Zeewyck Sub-basin lies inboard of the COT and is interpreted to contain mostly Jurassic to Cenozoic sediments (Bradshaw et al., 2003; Jones et al., 2011, Bernardel & Nicholson, 2013) (Fig. 4a). The sub-basin is bounded to the northeast by a NW-SE trending structural high that marks the boundary with the Houtman Sub-basin (Bradshaw et al., 2003; Jones et al., 2011) (Fig. 4a). This Houtman-Zeewyck boundary fault/hinge zone runs parallel to the COB outboard of the Zeewyck Sub-basin and marks the continuation of the more northerly en-echelon segment of the Wallaby-Zenith Transform Margin to the west. This suggests that during breakup the Zeewyck Sub-basin developed as a major pull-apart basin between the two en-echelon segments of the transform margin (Bradshaw et al., 2003; Norvick, 2004) (Fig. 2).

Although the plate reconstructions and overall basin-geometry strongly suggest that a NW-trending strike-slip fault underlies the Houtman-Zeewyck boundary zone, this is not clearly resolved in the seismic data. The seismic data shows that the geometry of the hinge zone is dominated by a W-dipping fault zone, across which Jurassic strata from the Houtman Sub-basin are downthrown to the SW (Jones et al., 2011) (Fig. 4a).

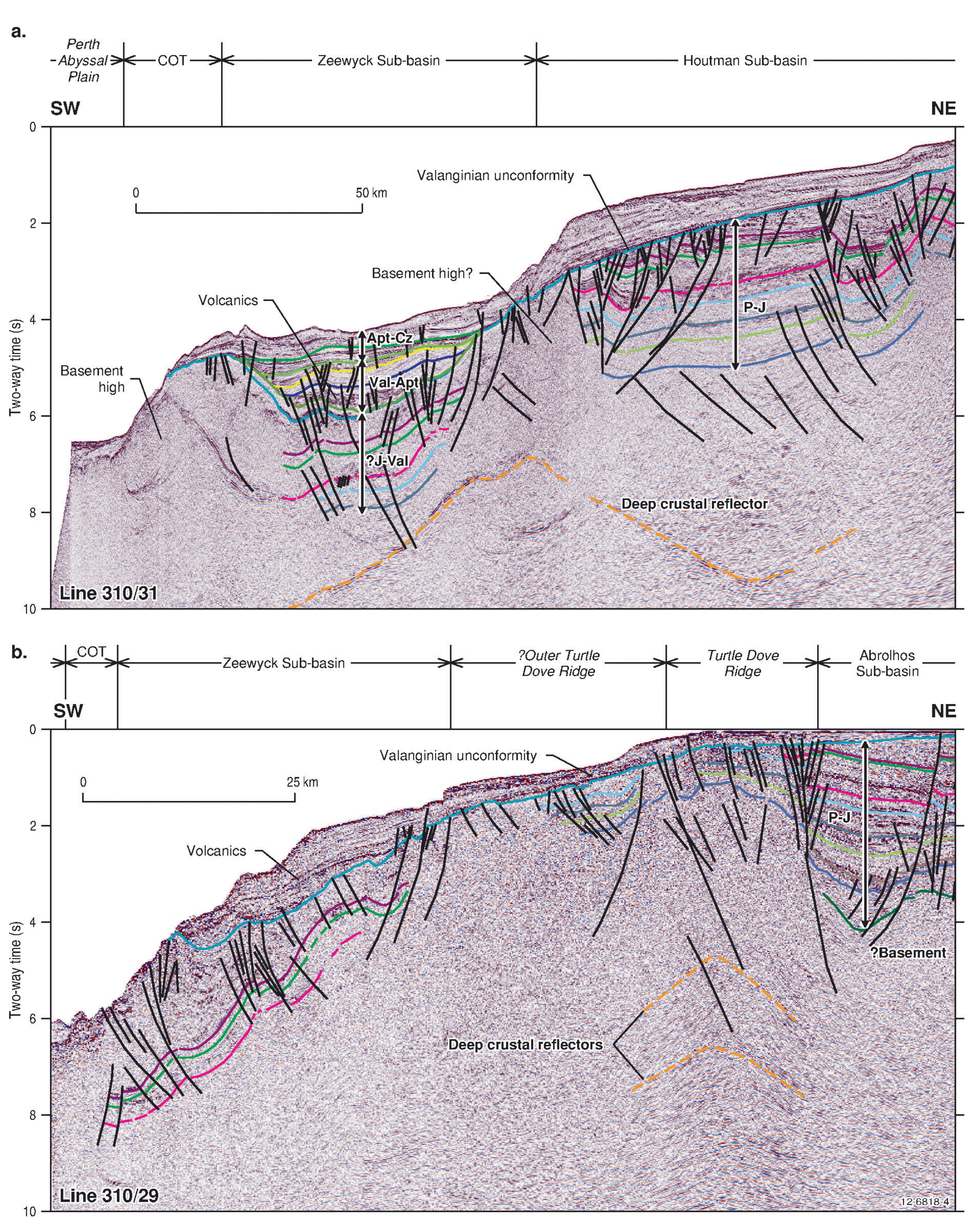

Figure 4. Seismic transects across the Wallaby-Zenith Transform Margin a) through the Zeewyck and Houtman sub-basins and b) through the Turtle Dove Ridge and Abrolhos Sub-basin. Interpretations adapted from Jones et al. (2011). Orange dashed lines marked as deep crustal reflectors are form lines only. Cross-section locations are shown in Figure 1.

This has been interpreted to indicate a transtensional setting rather than one dominated by pure strike-slip motion (Jones et al., 2011; Bernardel and Nicholson, 2013) (Fig. 4a). However comparison with sand box models and other global analogues indicate that such geometries are also consistent with localised transtension within the setting of a pull-apart basin (e.g. McClay & Dooley, 1995; Smit et al., 2008). In addition, the plate reconstruction model suggests an extensional component of motion may also have acted across the transform margin, at the same time as the development of transtensional en-echelon ridges observed within the Wallaby Zenith Fracture Zone (Nelson et al., 2009; Gibbons et al., 2012).

Gravity modelling results show the Zeewyck Sub-basin can be explained by a deep and steep-sided depocentre associated with large variations in Moho depth over short distances (Köther et al., 2013), consistent with typical pull-apart basin geometries (e.g. McClay & Dooley, 1995; Smit et al., 2008). Whilst the gravity models are not well constrained due to poor seismic imaging at depth and the lack of seismic refraction data, they suggest a basement thickness of <10 km beneath the Zeewyck Sub-basin. Assuming an original metamorphic basement thickness of >32 km (determined from the same gravity models) gives a crustal stretching factor of >3 for the Zeewyck Sub-basin.

Within the Zeewyck Sub-basin, new seismic interpretations highlight three major sedimentary packages (Jones et al., 2011; Bernardel & Nicholson, 2013) (Fig. 4a). Whilst no wells penetrate the sub-basin, stratal ages have been inferred through comparison with the regional tectonic events determined from the plate reconstructions and comparison with the adjacent Houtman Sub-basin.

Supersequence 1 (?J-Val) is the lowest resolvable sedimentary package. Although this has no clearly mappable basement horizon, it appears to thicken to the southwest and is interpreted as a Late Jurassic–Valanginian syn-rift sequence, possibly underlain by a Triassic–Early Jurassic sequence (Bernardel & Nicholson, 2013). The lack of well data and poor seismic quality at depth makes it difficult to identify any Permian aged units within the sub-basin. This supersequence is capped by a major unconformity which can be correlated with the Valanginian breakup unconformity within the Houtman Sub-basin to the northeast.

Supersequence 2 (Val-Apt) is represented by a series of sedimentary packages that on-lap onto the surrounding basement highs and are confined to the Zeewyck Sub-basin. Structuring and thickening of sequences indicates that significant tectonic activity continued during this period and so this supersequence is interpreted to represent Valanginian to early Aptian active transform margin development. This is overlain by a second unconformity, interpreted to represent the drift unconformity. As this represents the point at which the mid-ocean ridge moved past the basin and the transform fault became inactive, this unconformity will be progressively younger to the west and a minimum early Aptian age is estimated from the plate reconstructions (Fig. 3).

Supersequence 3 (Apt-Cz) comprises an oceanward-thinning passive margin succession interpreted to be Aptian and younger in age (Bradshaw et al., 2003; Jones et al., 2011, 2012). A third unconformity is also identified within supersequence 3, which may relate to the change in India's plate motion at around 100 Ma, at the end of the Albian.

Breakup in the Zeewyck Sub-basin is likely to have been accompanied by significant magmatism. In addition to possible intrusions forming the marginal ridge along the COT, seismic data suggests the presence of significant intra-basinal volcanics within the sub-basin. The Valanginian breakup unconformity is associated with broken, high amplitude reflectors interpreted to represent volcanic material associated with initial transform margin development (Jones et al., 2011) (Fig. 4a). The area is likely to have experienced further igneous activity as the mid-ocean ridge passed.

The Houtman Sub-basin mostly comprises Permian to Jurassic strata (P-J), equivalent to the onshore Perth Basin, overlain by a Cretaceous and younger passive-margin sequence. Across the basin, a significant unconformity is associated with Valanginian breakup (Bradshaw et al., 2003; Jorgensen et al., 2011; Jones et al., 2011; Pfahl, 2011; Rollet et al., 2013a) (Fig. 4a). The Early Cretaceous rift phase is characterised by a NNW-striking system of closely-spaced, predominantly W-dipping rotated fault blocks (Rollet et al., 2013a). A series of small-scale N- to NNW-striking inversion anticlines and pop-up structures in the Houtman Sub-basin may have formed through transpressional stresses due to local changes in fault geometry during the late stages of extension (Rollet et al., 2013a).

Well data suggest that up to 500 m of Jurassic sediment was removed from the northern Houtman Sub-basin in the Early Cretaceous, between 142 and 137 Ma (Pfahl, 2011; Rollet et al., 2013a). Seismic interpretation shows truncation of progressively older seismic units towards the southeastern part of the sub-basin (Fig. 4a), as well as over the Wittecarra Terrace to the northeast of the seismic section. In the region closest to the Houtman-Zeewyck boundary zone, seismic geometries suggest up to several kilometres of section could have been eroded. There are multiple possible driving mechanisms for this uplift and erosion. These include localised transpression linked to strike-slip motion associated with the transform margin activity and buoyancy effects associated with transform margin development.

Pfahl (2011) used subsidence curves from wells to estimate crustal stretching factors for two of the three rifting events in the Houtman Sub-basin, as follows: Early–Late Jurassic $\beta = 1.45$; Early Cretaceous $\beta = 1.06$ (see also Rollet et al., 2013a). No stretching factor could be determined for the Permian in this area. Gravity modelling also provides a rough estimate of total stretching factor across the Houtman Sub-basin. Although no clear basement or Moho reflectors can be resolved beneath the sub-basin, models were constructed using the deepest resolvable seismic horizon as a proxy for basement and a Moho estimated from the long wavelength components of the observed freeair gravity (Petkovic, 2012). These models estimate basement thickness beneath the Houtman Sub-basin to be around 24 km, and assuming an original thickness of >32 km, this gives a crustal stretching factor of around >1.3. While this value is very poorly constrained, it is consistent with the stretching factors determined from subsidence modelling and is significantly less than those estimated for the Zeewyck Sub-basin.

Breakup in the Houtman Sub-basin was accompanied by significant volcanism, which decreased in amount from west to the east. A seaward dipping reflector sequence visible close to the western boundary of the sub-basin is interpreted to represent flood basalts and shallow sills (Symonds et al., 1998). In addition, abundant sills, cones and dykes can be seen within the sedimentary section throughout the sub-basin ranging from Permian to Early Cretaceous in age (Gorter & Deighton, 2002; Jones et al., 2011). Numerous igneous intrusions have been interpreted within the Yarragadee Sequence in the Houtman sub-basin and numerous volcanoes have been interpreted on the Valanginian unconformity (Jones et al., 2011; Rollet et al., 2013a).

Abrolhos Sub-basin and Turtle Dove Ridge

Figure 4b shows an interpreted seismic line located in the transition zone between the Wallaby-Zenith Transform Margin and the obliquely-oriented southern Perth margin (Fig. 2). The line extends from the COB and the edge of the Zeewyck Sub-basin, across the Turtle Dove Ridge and into the Abrolhos Sub-basin.

The seismic and potential field data show that the COT remains narrow in this region. Inboard of this, the continental shelf rapidly shallows over the outer Turtle Dove Ridge, a N–NW trending structural high within the central Perth Basin. The Turtle Dove Ridge, along with the Turtle Dove transfer zone interpreted onshore to the east (Mory & Iasky, 1996), lies southeast of the termination of the Wallaby-Zenith Transform Margin (Fig. 1; Dentith et al., 1994; Bradshaw et al., 2003; Jones et al., 2011).

The Turtle Dove Ridge is a well-established structural element of the Perth Basin, but its evolution is still poorly understood. Modelling of both gravity and magnetic data indicate this to be a basement high, overlain by around 3 km of sediment (Petkovic, 2012; Johnston & Petkovic, 2012). Although seismic imaging is poor over the Turtle Dove Ridge, the data show that it is highly structured and fault geometries suggest that there was a component of strike-slip motion to fault movement (Quaife et al., 1994; Song & Cawood, 2000; Bradshaw et al., 2003; Bernardel & Nicholson, 2013) (Fig. 4b). Significant uplift occurred along the Turtle Dove Ridge immediately prior to and/or during breakup, resulting in the erosion of up to 3000 m of Triassic and Jurassic strata (Bradshaw et al., 2003; Jones et al., 2011; Rollet et al., 2013a, b).

To the east of the Turtle Dove Ridge lies the Abrolhos Sub-basin, an elongate N–S-oriented depocentre that contains up to 6,000 m of Early Permian to Early Cretaceous sediments, capped by a thin passive margin sequence (Jones et al., 2011; Rollet et al., 2013a, b) (Fig. 4b). The sub-basin also experienced significant uplift and erosion around Valanginian breakup, although to a lesser degree than the Houtman Sub-basin or the Turtle Dove Ridge. Well data suggest that between 200 and 680 m of Jurassic sediment was removed from the Abrolhos Sub-basin in the Early Cretaceous, between 145–137 Ma (Pfahl, 2011).

Pfahl (2011) uses subsidence curves from wells to estimate crustal stretching factors for each rifting phase in the Abrolhos Sub-basin (see also Rollet et al., 2013a). Results are as follows: Permian $\beta = 1.4$; Early-Late Jurassic $\beta = 1.08$; Early Cretaceous $\beta < 1.06$.

Although Early Triassic igneous rocks have been identified at the western end of the Wittecarra Terrance (Gorter & Deighton, 2002), there is no direct evidence of intrabasinal igneous material from well data within the main Abrolhos Sub-basin and Turtle Dove Ridge, either related to Early Cretaceous breakup or older events (Jorgensen et al., 2011). Gorter & Deighton (2002) infer igneous activity in this region on the basis of seismic signatures and maturity profiles, however no extensive igneous bodies have identified in more recent seismic interpretation studies within the Abrolhos Sub-basin (e.g. Jones et al., 2011).

At the southern end of the Zeewyck Sub-basin, high amplitude reflectors interpreted to represent dykes and sills, can be seen in the seismic data between the Valanginian unconformity and the sea-floor (Fig. 4b), strongly suggesting Miocene to recent volcanic activity in this region. It is possible that Early Cretaceous volcanism also occurred here, as observed further west in the sub-basin; however it is hard to distinguish between any Early Cretaceous intrusions and younger igneous activity. The presence of high amplitude reflectors along the COT itself (Fig. 4b) suggests a significant amount of igneous material may have been emplaced here immediately prior to the onset of sea-floor spreading (Norvick, 2004).

Southern Perth Basin

Figure 5a shows an interpreted seismic line running east-west through the central section of the southern Perth margin. It extends from the Perth Abyssal Plain, across the Yallingup Shelf into the Vlaming Sub-basin.

In this region the COT is narrow, at less than 25 km wide and it transitions rapidly into a steep continental slope that shallows onto the northern end of the Yallingup Shelf. Due to the lack of clear seismic reflectors and well intersections, the nature of the Yallingup structural high is even less well understood than the Turtle Dove Ridge. Nevertheless, the seismic data show that this region is highly faulted and the potential field data suggest that these faults are dominantly north-south trending structures that are sub-parallel to the COB and oblique to the northwest-southeast extension direction (Figs 2 & 5a).

East of the Yallingup Shelf, the Vlaming Sub-basin contains more than 12 km of Permian to Cenozoic aged sediment

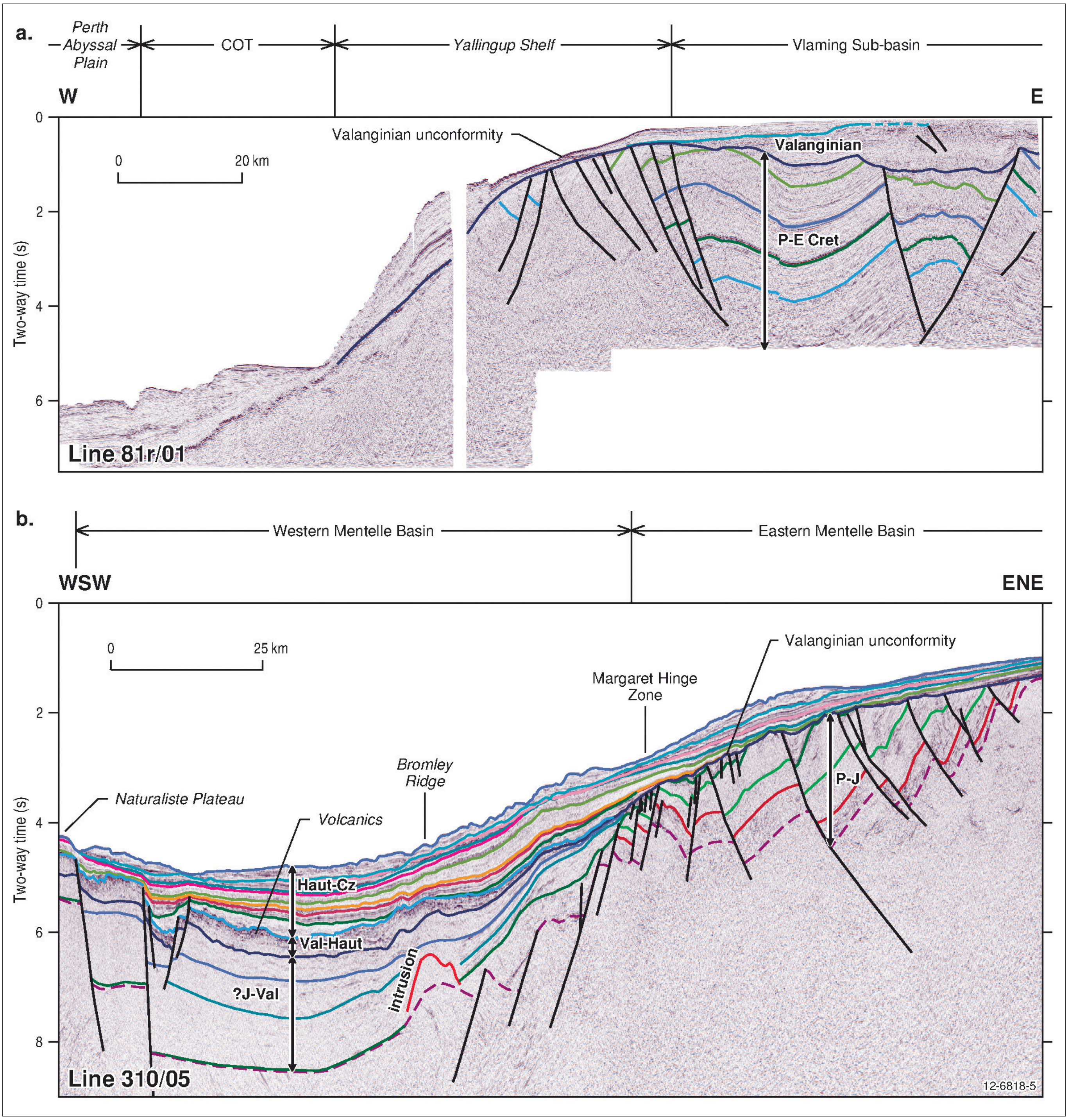

Figure 5. a) Seismic transect across the southern Perth margin across the Yallingup Shelf and Vlaming Sub-basin. b) Seismic transect through the Mentelle Basin (from Borissova et al., 2010). Cross-section locations are shown in Figure 1.

(Nicholson et al., 2008) (Fig. 5a). As observed in the seismic data further north, significant uplift and erosion occurred in association with the Valanginian breakup. Between 250 and 2,000 m of the syn-rift section was removed from the Vlaming Sub-basin, with maximum erosion in the west and northwest towards the Yallingup Shelf (Nicholson et al., 2008).

Volcanism in the southern Perth Basin appears to be primarily restricted to the Bunbury Basalts, which were emplaced in two main phases: Casuarina at ~132 Ma; Gosselin at ~123 Ma (Frey et al., 1996; Coffin et al., 2002). The Casuarina basalts are likely to correlate with Greater India–Australia continental breakup, whilst the Gosselin age basalts may be more closely related to the Kerguelen hotspot activity or Australia-Antarctica rifting (Coffin et al., 2002; Crawford et al., 2006). Most of the Bunbury flows, as identified from aeromagnetic data, lie to the south of Figure 5a (Iasky &

Lockwood, 2004). However, possible igneous intrusions in the northwest Vlaming Sub-basin have also been interpreted on seismic data by Jones et al. (2011).

Along the COT, high amplitude reflectors have been identified from seismic reflection data (Fig. 5a), which correlate with strong gravity and magnetic anomalies. These may represent significant amounts of igneous material emplaced along the future plate boundary immediately prior to the onset of sea-floor spreading (Norvick, 2004).

Mentelle Basin

Figure 5b shows an interpreted seismic line running approximately east-west across the Mentelle Basin to the western edge of the southern Yallingup Shelf (Borissova et al., 2010). Although the COB along the Mentelle margin segment is poorly defined due to limited data, potential field and seismic data suggest that the COT is over 60 km wide. This is in contrast to the narrow COT observed along the southern Perth margin to the north.

Comparison between the seismic lines in Figures 5a and b also highlights how the Mentelle margin architecture and basin morphology differs significantly from the southern Perth margin. The outer section of extended continental crust of the Mentelle margin is dominated by the ~170 km wide Mentelle Basin. The Western Mentelle Sub-basin contains mostly syn-rift Jurassic–Early Cretaceous successions (up to about 9 km thick), while the Eastern Mentelle Sub-basin is interpreted to contain predominantly Permian, Triassic and Lower Jurassic strata (equivalent to the onshore Perth Basin) with only thin Middle Jurassic to Holocene successions (Borissova et al., 2010).

Although crustal structure beneath the basin is poorly constrained, gravity modelling along interpreted seismic lines suggests that the crust beneath the Western Mentelle Sub-basin is very thin, at < 5km thick beneath the central sub-basin (Johnston et al., 2010). In contrast, the crust beneath the eastern sub-basin is > 20 km thick (Johnston et al., 2010). Assuming an original basement thickness of at least 30 km, this gives a total crustal stretching factor of ß > 6 for the Western Mentelle Sub-basin and ß < 1.5 for the eastern sub-basin.

The major sequences in the eastern and western Mentelle sub-basins are described in Borissova et al. (2010). Although data coverage in this area is extremely sparse and sequence ages and lithologies for older strata have been interpreted through indirect correlation with the Vlaming Sub-basin (Borissova et al., 2010), comparison with the regional margin evolution models provides some extra insight into the development of the Mentelle Basin during breakup. Within the Western Mentelle Sub-basin, seismic interpretation has identified a syn-breakup supersequence up to 1 km thick interpreted to be Valanginian to Hauterivian in age (Borissova et al., 2010; Johnston et al., 2010) (Fig. 5b). This supersequence shows evidence of massive syn-depositional volcanism associated with volcanic centres along the Bromley Ridge (Borissova et al., 2010; Johnston et al., 2010) (Fig. 5b). Three main igneous facies have been identified: extrusive flows, cones and sills and dykes, and a strong correlation is observed between the distribution of the thickest volcanic material and the region of greatest crustal thinning (Johnston et al., 2010). This volcanism is interpreted to correlate with the initial phase of Bunbury Basalt emplacement at 132 Ma (Frey et al., 1996; Crostella & Backhouse, 2000; Coffin et al., 2002; Crawford et al., 2006).

The inferred timing of deposition of this syn-breakup supersequence, from approximately 137 to 132 Ma, correlates with the lag time between breakup along the southern Perth and Mentelle segments of the margin suggested by the plate reconstructions. The presence of a newly-developing ocean basin and mid-ocean ridge directly to the north of the Western Mentelle Sub-basin could explain the extensive volcanism and continued high subsidence rates during this period, as well as the high crustal stretching factors.

The Eastern Mentelle Sub-basin is interpreted to contain predominantly Permian, Triassic and Lower Jurassic strata, covered by a thin drape of Late Cretaceous to Holocene sediments (Borissova et al., 2010) (Fig. 5b). Seismic geometries suggest that Permian to Jurassic strata were deformed, faulted and eroded from the eastern Mentelle Basin as a result of Jurassic to Early Cretaceous rifting (Borissova et al., 2010) (Fig. 5b). Further work is required to constrain the magnitude of uplift and erosion across this sub-basin.

Breakup related volcanism is generally restricted to the Western Mentelle Sub-basin and few flows are observed in the eastern area (Johnston et al., 2010).

Discussion

Basement Control on Margin Architecture

The composition and structure of the underlying Pinjarra Orogen basement is likely to have strongly controlled the location of southwest margin basin development throughout the Phanerozoic. The Pinjarra Orogen basement has had a prolonged history involving multiple stages of reactivation from the Mesoproterozoic to the Late Neoproterozoic/ Early Cambrian (e.g. Fitzsimons, 2003; Boger, 2011). In contrast, the Yilgarn Craton to the east has remained largely undeformed since the late Archean (Cassidy et al., 2006 and references therein). This difference in tectonic history suggests that basement rocks of the Pinjarra Orogen are significantly weaker than those of the adjacent Yilgarn Craton. As a result, deformation associated with intra-plate stresses acting across East Gondwana during the Permian and Late Jurassic/ Early Cretaceous extensional events focused within the Pinjarra basement, resulting in basin formation over the Pinjarra Orogen rather than the adjacent craton. This finally resulted in Early Cretaceous continental breakup along the approximate trend of the pre-existing Neoproterozoic to Early Cambrian Kuunga Orogeny suture.

Reactivation of pre-existing basement faults which developed during the Pinjarra and Kuunga Orogenies have influenced basin architecture. The Darling Fault, the boundary between the Pinjarra Orogen and Yilgarn Craton, was reactivated during both Permian and Upper Jurassic–Lower Cretaceous extensional events and now marks the eastern boundary of the Perth Basin (Byrne & Harris, 1992; Cawood & Song, 2000; Bradshaw et al., 2003; Norvick, 2004). Other major basement structures reactivated during the Palaeozoic–Mesozoic include the Urella Fault (Cawood & Song, 2000), Geraldton Fault (Tyler & Hocking, 2001; Jones et al., 2011) and Dunsborough Fault (Bradshaw et al., 2003; Iasky & Lockwood, 2004).

The Darling Fault and other major outcropping basement structures show a change in orientation around the eastern termination of the Wallaby-Zenith Transform Margin and the Turtle Dove Transfer Zone (Byrne & Harris, 1992; Dentith et al., 1994; Song & Cawood, 2000; Hall et al., 2012) (Fig. 2). To the south, basement structures trend predominantly N–S, including the Darling and Dunsborough faults. However, further north, the orientation of many outcropping basement faults (e.g. Urella and Geraldton Faults) shifts to NNW–SSE (Fig. 2). A similar shift in trend can be observed in lineaments generated from both the gravity and magnetic data (Hackney et al., 2012; Hall et al., 2012).

As the shift in basement trend correlates with the transition point between oblique extension along the southern Perth Margin and the Wallaby Zenith Transform Margin, this suggests that the composition and structure of the underlying basement may have influenced the type of margin that developed. South of the inception of the Wallaby-Zenith Transform margin, basement fabric is angled approximately 45° to the extension direction. This means that basement faults may have reactivated as oblique normal or strike-slip faults, permitting the margin to develop under oblique extension. To the north, basement structures are oriented at approximately 30° or less to the extension direction during breakup, so oblique normal reactivation is no longer favoured. Instead, these structures were reactivated as dextral strike-slip faults during Late Jurassic to Early Cretaceous extension, thereby forming the basis for pull-apart basin formation in the Zeewyck Sub-basin and subsequent transform margin development.

Patterns of Early Cretaceous Basin Fill and Mechanisms of Crustal Extension

Figure 6 compares the timing of Early Cretaceous tectonic activity and major basin phases determined from plate reconstructions. The stratigraphy of each offshore sub-basin in Figure 6 is simplified from Nicholson et al. (2008), Borissova et al. (2010), Pfahl (2011) and Jones et al. (2011, 2012).

The Houtman, Vlaming, Abrolhos and Eastern Mentelle sub-basins are all predominantly Permian–Jurassic basins, which were subject to significant uplift and erosion immediately prior to Early Cretaceous breakup (Fig. 6). Within the Houtman Sub-basin, this uplift appears to be partly associated with strike-slip activity on major northwest-southeast trending fault zones that strike nearly parallel to the transform margin. The passing of the mid-ocean ridge may also have resulted in additional temporary uplift during the Valanginian to Aptian. The driving mechanism for uplift within the Turtle Dove Ridge, Abrolhos, Vlaming and Eastern Mentelle sub-basins is less well understood. Although uplift and erosion could have resulted from development of Late Jurassic–Early Cretaceous tilted fault blocks, it is possible that strike-slip activity along major north-south trending reactivated basement structures also influenced patterns of uplift during this time.

Total crustal stretching factors for the Eastern Mentelle, Houtman and Abrolhos sub-basins values are in the order of 1.5. However, the Early Cretaceous stretching factors of $\beta \leq 1.06$ obtained for the Houtman and Abrolhos sub-basins (Pfahl, 2011), further highlights that little extension was accommodated in these sub-basins immediately prior to continental breakup and that the majority of the crustal stretching in these sub-basins is a result of Permian rifting.

Immediately prior to the initiation of breakup in the Early Cretaceous, the majority of accommodation-space generation and sedimentation occurred within the Zeewyck and Western Mentelle sub-basins (Borissova et al., 2010; Pfahl, 2011; Rollet et al., 2013a) (Fig. 6). As discussed in the previous section, while no direct age constraints exist for the syn-rift sequences and associated unconformities identified on seismic profiles within these sub-basins, the regional tectonic framework provides possible explanations for the timing of sequence deposition and helps to infer mechanisms for the generation of accommodation space.

The localisation of strain in the Western Mentelle and Zeewyck sub-basins immediately prior to breakup is reflected in their high total crustal stretching factors. Whilst very poorly constrained, initial estimates suggest that the Western Mentelle Sub-basin may have a β value of up to 6, with the Zeewyck Sub-basin also showing significant crustal stretching of β greater than 3.

The crustal stretching factor for the Western Mentelle Sub-basin value is particularly high, however stretching factors of this order of magnitude have been observed along other extended margins. Perez-Gussinye et al. (2003) report crustal stretching factors up to 5.5 along the West Iberia Margin, where a marked change in the mechanisms of extension is observed as crustal stretching increases. They observe that at rift flanks ($\beta \leq 2$) stretching in the lower and upper crust tends to be uniform, consistent with pure shear. However, at $\beta \geq 3.5$, faults exhume lower crustal rocks and simple shear dominates. Whilst no clear mid/lower crustal detachment surfaces are observed in the seismic data across the Mentelle Basin, the high β value for the Western Mentelle Sub-basin suggests the rift was near the breakup, and that simple shear dominated during the final stage of

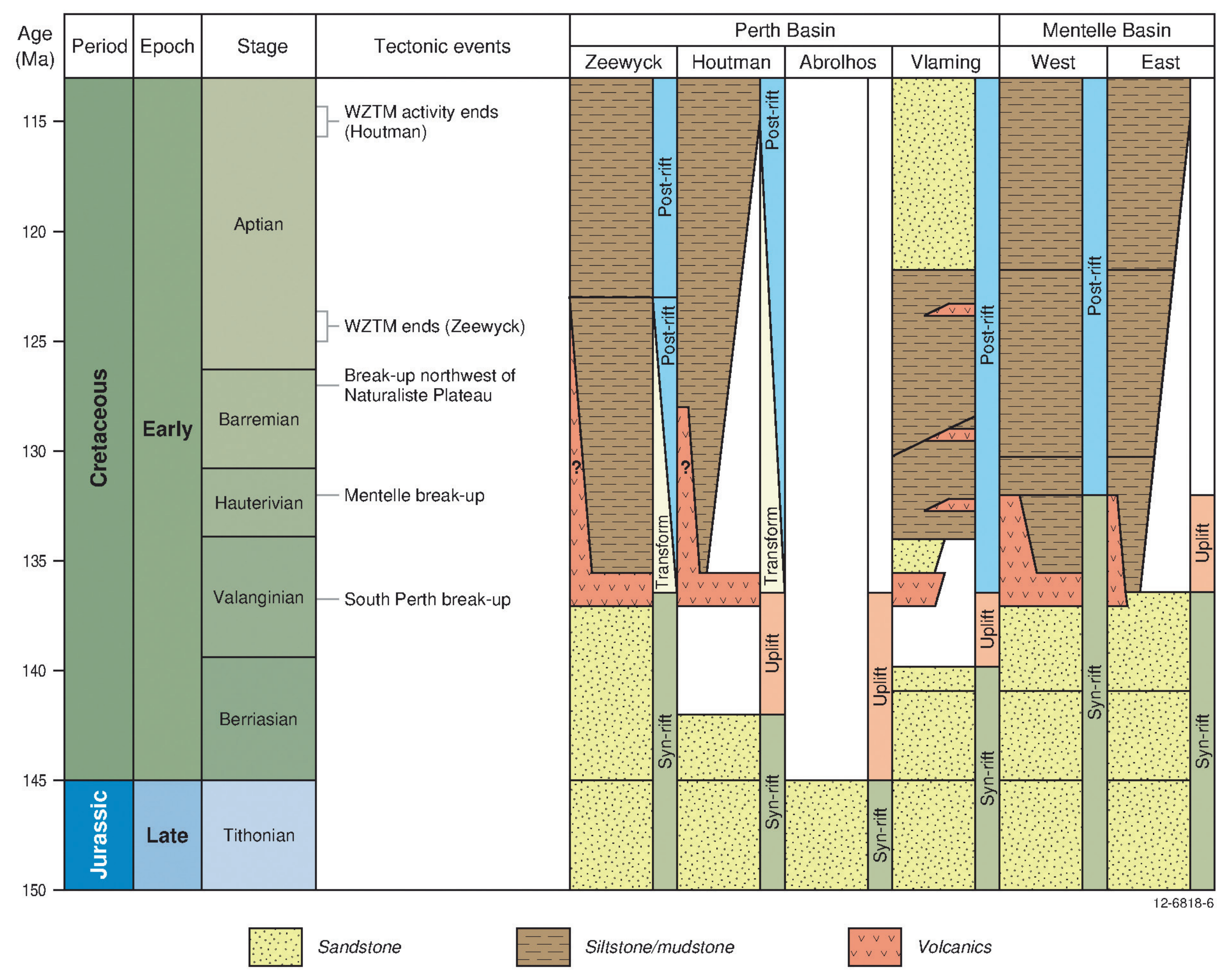

Figure 6. Early Cretaceous basin phase and simplified stratigraphic chart for the Perth and Mentelle Basins, by sub-basin. Simplified stratigraphy has been compiled from Nicholson et al. (2008), Borissova et al. (2010), Jones et al. (2011), Pfahl (2011) and Jones et al. (2012), using the 2012 geological time scale of Gradstein et al. (2012).

basin formation. Collection of seismic refraction data across the margin to better constrain crustal structure would be required to test this further.

Distribution of Early Cretaceous Igneous Activity

The distribution of Early Cretaceous magmatism is highly variable across the southwest region. Extensive igneous activity has been identified in the northwest Houtman Sub-basin, Wallaby Saddle and Wallaby Plateau (Symonds et al., 1998; Sayers et al., 2002), as well as the Zeewyck and Western Mentelle sub-basins (Borissova et al., 2010; Johnston et al., 2010; Jones et al., 2011) and Naturaliste Plateau (Borissova et al., 2002). In contrast, in the Abrolhos, Vlaming and Eastern Mentelle sub-basins and onshore Perth Basin, breakup related igneous activity is more limited and is generally restricted to the Bunbury Basalts and areas close to the continent-ocean transition zone.

In general, within the study area, Early Cretaceous igneous activity is focused in the regions which experienced the highest crustal extension immediately prior to the onset of sea-floor spreading in the Perth Abyssal Plain. Along the southern Perth margin, this is outboard of the Yallingup Shelf, along the COT. Along the Mentelle segment of the margin, this is within the highly extended Western Mentelle Sub-basin and possibly along the COT. Along the Wallaby-Zenith Transform Margin, igneous activity is most prevalent within the Zeewyck Sub-basin and is directly associated with transform margin development and thermal impact of the mid-ocean ridge as it passed.

Further Cretaceous igneous activity in the southern Perth and Mentelle basins, as well as the Naturaliste Plateau, was driven by the impact of the Kerguelen Plume, with peak hotspot activity lasting from 120 to 95 Ma (Borissova et al., 2002; Coffin et al., 2002). However, the full range of factors influencing the variation in igneous activity along the margin remains poorly understood. In particular, the mechanisms driving the transition from a magma rich margin setting in the Wallaby Saddle to a magma poor setting along the southern Perth margin require further investigation.

Conclusions

The regional plate reconstruction model of Gibbons et al. (2012), developed for all of western Australia, is compared with regional seismic and potential field data to better characterise the significant along-strike variability of southwest margin architecture. Integration of a newly-interpreted continent-ocean boundary into the plate reconstruction model highlights the three major margin segments: the normal to oblique Mentelle margin, the southern Perth margin and Wallaby-Zenith Transform Margin. The margin segmentation directly relates to the geometry of the overlying Perth and Mentelle basins. In addition, the location of the major oceanic fracture zones corresponds to major structures controlling margin segmentation. The patterns of structural reactivation during basin development indicate a strong basement control on margin evolution. Intra-plate deformation during Permian and Mesozoic extension was preferentially accommodated in the relatively weak basement of the Pinjarra Orogen, resulting in Early Cretaceous continental breakup along the approximate trend of the Neoproterozoic to Early Cambrian Kuunga Orogeny suture.

Comparison between the new plate reconstruction model, and existing and newly-interpreted seismic data provides new insights into basin development during the Early Cretaceous. It is likely that breakup started along the South Perth margin in the Valanginian and then migrated to the Mentelle region during the Hauterivian. Active development of the Wallaby-Zenith Transform Margin lasted from the Valanginian to the Aptian and controlled tectonic activity and the patterns of sediment fill across the northern Perth Basin. Immediately prior to Early Cretaceous break-up, the majority of accommodation-space generation and igneous activity was focused within the Zeewyck and Western Mentelle sub-basins, and outboard of the Yallingup Shelf. In contrast, the Houtman, Abrolhos, Vlaming and Eastern Mentelle sub-basins predominantly experienced uplift and erosion during this time.

Due to the complexity of southwest margin geology and the large amounts of available seismic data, significant further work should be done to better document the structural architecture within each sub-basin. More detailed seismic interpretation in the central and northern Houtman Sub-basin would provide further insights into the dominant structural styles and patterns of deposition surrounding breakup along the Wallaby Zenith Transform Margin. Reprocessing of available seismic data may help resolve seismic geometries within poorly imaged regions, such as the Turtle Dove Ridge. Finally, collection of seismic refraction data across the margin would provide better constraints on deep-crustal structure and hence crustal stretching factors.

Acknowledgements

Thanks to Ron Hackney, George Gibson, Lynn Pryer and an anonymous reviewer for providing constructive reviews of this manuscript and to Veronika Galinec for drafting the figures. This paper is published with the permission of the CEO, Geoscience Australia. R.D.M was supported by ARC grant FL0992245. A.D.G. and J.M.W. were supported by Statoil.

References

ANDERSEN, O.B., KNUDSEN, P. & BERRY, P., 2010, The DNSC08GRA global marine gravity field from double retracked satellite altimetry, *Journal of Geodesy*, 84, 191–199.

BASILE, C., MASCLE, J., BENKHELIL, J. & BOUILLIN, J.-P., 1998, Geodynamic evolution of the Côte d'Ivoire-Ghana transform margin: an overview of Leg 159 results, in MASCLE, J., LOHMANN, G.P. & MOULLADE, M., (Eds), *Proceedings of the Ocean Drilling Program, Scientific Results*, 159, 101–110.

BASILE, C. & ALLEMAND, P. 2002, Erosion and flexural uplift along transform faults, *Geological Journal International*, 151, 646–653.

BERNARDEL, G. & NICHOLSON, C.J., 2013, Geoscience Australia Seismic Survey 310 – revealing stratigraphy and structure of the outer northern Perth Basin margin, APPEA 2013 Poster Abstract.

BIRD, D., 2001, Shear margins: continent-ocean transform and fracture zone boundaries, *Leading Edge*, 20, 150–159.

BLEVIN, J.E. & CATHRO, D.L., 2008, Australian Southern Margin Synthesis, Project GA707. Client report to Geoscience Australia by FrOGTech Pty Ltd. <https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=68892>

BOGER, S.D., 2011, Antarctica—before and after Gondwana, *Gondwana Research*, 19, 335–371.

BORISSOVA, I., BRADSHAW, B.E., NICHOLSON, C.J., PAYNE, D.S., STRUCKMEYER, H.I.M., 2010, New exploration opportunities on the southwest Australian margin – deep-water frontier Mentelle Basin, *The APPEA Journal*, 50, 1–13.

BORISSOVA, I., 2002, Geological framework of the Naturaliste plateau, *Geoscience Australia Record*, 2002/20, 44 pp.

BRADSHAW, B.E., ROLLET, N., TOTTERDELL, J.M. & BORISSOVA, I., 2003, A revised structural framework for frontier basins on the southern and southwestern Australian continental margin, *Geoscience Australia Record*, 2003/03, 43 pp.

BROWN, B., MÜLLER, R.D., STRUCKMEYER, H. I. M., GAINA, C., STAGG, H. & SYMONDS, P., 2003, Formation and evolution of Australian passive margins: implications for locating the boundary between continental and oceanic crust, in HILLIS, R. R. & MÜLLER, R. D. (eds), *Evolution and Dynamics of the Australian Plate*: Geological Society of Australia Special Publication, 22, 223–243.

BRUGUIER, O., BOSCH, D., PIDGEON, R.T., BYRNE, D.R. & HARRIS, L.B., 1999, U–Pb chronology of the Northampton Complex, Western Australia — evidence for Grenvillian sedimentation, metamorphism and deformation and geodynamic implications, *Contributions to Mineralogy and Petrology*, 136, 258–272.

BYRNE, D.R. & HARRIS, L.B., 1992, Fault patterns during normal and oblique rifting and the influence of basement discontinuities: application to models for the tectonic evolution of the Perth Basin, Western Australia, *Basement Tectonics*, 9, 23–42.

CASSIDY, Y.K.F., CHAMPION, D.C., KRAPEZ, B., BARLEY, M.E., BROWN, S. J.A., BLEWETT, R.S., GROENEWALD, P.B. & TYLER, I.M., 2006, A revised geological framework for the Yilgarn Craton, Western Australia, *Western Australia Geological Survey Record*, 2006/8, 8 pp.

CAWOOD, P.A. & KORSCH. R.J., 2008, Assembling Australia: Proterozoic building of a continent, *Precambrian Research*, 166, 1–38.

COBB, M.M., CAWOOD, P.A., KINNY, P.D. & FITZSIMONS, I.C.W., 2001, SHRIMP U–Pb zircon ages from the Mullingarra Complex, Western Australia: Isotopic evidence for allochthonous blocks in the Pinjarra Orogen and implications for East Gondwana assembly, *Geological Society of Australia Abstracts*, 64, 21–22.

COFFIN, M.F., PRINGLE, M.S., DUNCON, R.A., GLADCZENKO, T.P., STOREY, M., MÜLLER, R.D. & GAHAGAN, L.A., 2002, Kerguelen hotspot magma output since 130 Ma, *Journal of Petrology*, 43, 1121–1139.

COLLINS, A.S., 2003, Structure and age of the northern Leeuwin Complex, Western Australia: constraints from field mapping and U–Pb isotopic analysis, Australian *Journal of Earth Sciences*, 50, 585–599.

COLLINS, A.S. & PISAREVSKY, S.A., 2005, Amalgamating eastern Gondwana: the evolution of the Circum-Indian Orogens, *Earth-Science Reviews*, 71, 229–270.

CRAWFORD, A.J., DIREEN N. G., COFFIN, M., COHEN, B., PAUL, B. & MITROVIC, L., 2006, Extensive basaltic magmatism on the Naturaliste Plateau, offshore SW Australia, *Geochimica et Cosmochimica Acta*, 18, A118.

CROSTELLA, A. & BACKHOUSE, J., 2000, Geology and petroleum exploration of the central and southern Perth Basin, Western Australia, *Western Australia Geological Survey Report*, 57, 85 pp.

DANIELL, J., JORGENSEN, D. C., ANDERSON, T., BORISSOVA, I., BURQ, S., HEAP, A.D., HUGHES, M., MANTLE, D., NELSON, G., NICHOL, S., NICHOLSON, C., PAYNE, D., PRZESLAWSKI, R., RADKE, L., SIWABESSY, J., SMITH, C. & SHIPBOARD PARTY, 2010, Frontier Basins of the West Australian Continental Margin: Post-survey Report of Marine Reconnaissance and Geological Sampling Survey GA2476, *Geoscience Australia, Record*, 2009/38, 229 pp.

DENTITH, M.C., BRUNER, I., LONG, A., MIDDLETON, M.F., & SCOTT, J., 1993, Structure of the eastern margin of the Perth Basin, Western Australia, *Exploration Geophysics*, 24, 455–462.

DENTITH, M.C., LONG, A., SCOTT, J., HARRIS, L.B. & WILDE, S.A., 1994, The influence of basement on faulting within the Perth Basin, Western Australia, in PURCELL, P.G. & PURCELL, R.R. (Eds), *The Sedimentary Basins of Western Australia*: Proceedings of the Petroleum Exploration Society of Australia, Perth, WA, 1994, 791–799.

DIREEN, N.G., STAGG, H.M.J., SYMONDS, P.A. & COLWELL, J.B., 2008, Architecture of volcanic rifted margins: new insights from the Exmouth – Gascoyne margin, Western Australia, *Australian Journal of Earth Sciences*, 55, 341–363.

EMBLETON, B.J.J., & SCHMIDT, P.W., 1985, Age and significance of magnetizations in dolerite dykes from the Northampton Block, Western Australia, *Australian Journal of Earth Sciences*, 32, 279–286.

FITZSIMONS, I.C.W., 2003, Proterozoic basement provinces of southern and southwestern Australia, and their correlation with Antarctica, in YOSHIDA, M., WINDLEY, B.F., DASGUPTA, S. (Eds), *Proterozoic East Gondwana: Supercontinent Assembly and Breakup*, Geological Society of London Special Publication, 206, 93–130.

FOSTER, C., GOLEBY, B., BORISSOVA, I. & HEAP, A., 2009, Southwest margin surveys completed: Surveys investigate basin structure, hydrocarbon potential and marine habitat, *AusGeo News, 94 (June)*, http://www.ga.gov.au/ausgeonews/ausgeonews200906/

FREY, F.A., MCNAUGHTON, N.J., NELSON, D.R., DELAETER, J.R. & DUNCAN, R.A., 1996, Petrogenesis of the Bunbury Basalt, Western Australia: Interaction between the Kerguelen plume and Gondwana lithosphere? *Earth and Planetary Science Letters*, 144, 3–183.

GARDNER, R., 2012, *Characterising rocks dredged from the Gulden Draak microcontinent*, MSc thesis, Macquarie University, Sydney, 90 pp.

GEOSCIENCE AUSTRALIA, 2011, Energy Security Program Achievements—Towards Future Energy Discovery, https://www.ga.gov.au/image_cache/GA19973.pdf

GIBBONS, A.D., BARCKHAUSEN, U., VAN DEN BOGAARD, P., HOERNLE, K., WERNER, R., WHITTAKER, J.M. & MULLER, R.D. 2012, Constraining the Jurassic extent of Greater India: tectonic evolution of the West Australian margin, *Geochemistry Geophysics Geosystems* 13, Q05W13, 25 pp.

GORTER, J.D. & DEIGHTON, I., 2002, Effects of igneous activity in the offshore northern Perth Basin—evidence from petroleum exploration wells, 2D seismic and magnetic surveys, in KEEP, M. & MOSS, S.J. (eds), *The sedimentary basins of Western Australia 3*, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, WA, 875–899.

GORTER, J.D., HEARTY, D.J. & BOND, A.J., 2004, Jurassic petroleum systems in the Houtman Sub-basin, northwestern offshore Perth Basin, Western Australia: A frontier petroleum province on the doorstep? *The APPEA Journal*, 44, 13–57.

GRADSTEIN, F.M., OGG, J.G. SCHMITZ, M.D. & OGG, G. M. (Eds), 2012, *The Geologic Time Scale 2012*: Volumes 1 & 2; Elsevier BV, 1144 pp.

GREENROYD, C J., PEIRCE, C., RODGER, M., WATTS, A.B. & HOBBS, R.W., 2007, Crustal structure of the French Guiana margin, west Equatorial Atlantic, *Geophysical Journal International*, 169, 964–987.

GREENROYD, C.J., PEIRCE, C., RODGER, M., WATTS, A B. & HOBBS, R.W., 2008a, Demerara Plateau – the structure and evolution of a transform passive margin, *Geophysical Journal International*, 172, 549–564.

GREENROYD, C.J., PEIRCE, C., RODGER, M., WATTS, A.B. & HOBBS, R.W., 2008b, Do fracture zones define continental margin segmentation? — Evidence from the French Guiana margin, *Earth and Planetary Science Letters*, 272, 553–566.

HACKNEY, R., 2012, Combined marine and land potential-field datasets for the southwest margin of Australia, *Geoscience Australia Record* 2012/37, 62 pp.

HACKNEY, R.I., HALL, L. & KÖTHER, N., 2012, Potential-field data for structural interpretation in the northern Perth Basin, Australia, *ASEG Extended Abstracts*, 2012, 4 pp.

HALL, L., HACKNEY, R. & JOHNSTON, S., 2012, Understanding Australia's Southwest Margin: Basement Architecture as a Framework for Predictive Basin Analysis, *AusGeo News*, 105.

HALPIN, J.A., CRAWFORD, A.J., DIREEN, N.G., COFFIN, M.F., FORBES, C.J. & BORISSOVA, I., 2008, Naturaliste Plateau, offshore Western Australia: A submarine window into Gondwana assembly and breakup, *Geology*, 36, 807–810.

HOCKING, R.M., MOORS H.T. & VAN DE GRAAFF J.E., 1987, Carnarvon Basin: diagrammatic cross-sections and palaeogeographic reconstructions, *Western Australia Geological Survey Bulletin*, 133, 3 pp.

IASKY, R.P., D'ERCOLE, C., GHORI, K.A.R., MORY, A.J. & LOCKWOOD, A. M., 2003, Structure and petroleum prospectivity of the Gascoyne Platform, Western Australia, *Western Australia Geological Survey Report*, 87, 56 pp.

IASKY, R.P., & LOCKWOOD, A.M., 2004, Gravity and magnetic interpretation of the southern Perth Basin, Western Australia, *Western Australia Geological Survey Record*, 2004/8, 32 pp.

JANSSEN, D.P., COLLINS, A.S. & FITZSIMONS, I.C.W., 2003, Structure and tectonics of the Leeuwin Complex and Darling Fault Zone, southern Pinjarra Orogen, Western Australia — a field guide, *Western Australia Geological Survey Record*, 2003/15, 33 pp.

JOHNSTON, S.W., HACKNEY, R. & NICHOLSON, C., 2010, Distribution of volcanic facies and results from potential field modelling of the Mentelle Basin, southwestern Margin, Australia, *ASEG-PESA 21st Conference and exhibition*, Sydney, 2010, Extended abstracts.

JOHNSTON, S.W. & PETKOVIC, P., 2012, Northern Perth Basin 2D and 3D models of depth to magnetic basement, *Geoscience Australia Record*, 2012/39, 55 pp.

JONES, A.T., KELMAN, A.P., KENNARD, J.M., LE POIDEVIN, S., MANTLE, D. J. & MORY, A.J., 2012, *Offshore Perth Basin Biozonation and Stratigraphy 2011*, Chart 38, Geoscience Australia.

JONES, A.T., KENNARD, J. M, NICHOLSON, C.J., BERNARDEL, G., MANTLE, D., GROSJEAN, E., BOREHAM, C.J., JORGENSEN, D.C, & ROBERSTON, D., 2011, New exploration opportunities in the offshore northern Perth Basin, *The APPEA Journal*, 51, 45–78.

JORGENSEN, D.C., JONES, A.T., KENNARD, J.M., ROBERTSON, D., LECH, M., NELSON, G., MANTLE, D., GROSJEAN, E. & BOREHAM, C.J., 2011, Offshore northern Perth Basin Well Folio, *Geoscience Australia Record*, 2011/09, 72 pp.

KELSEY, D.E., WADE, B.P., COLLINS, A.S., HANDA, M., SEALING, C.R. & NETTING, A. 2008, Discovery of a Neoproterozoic basin in the Prydz belt in East Antarctica and its implications for Gondwana assembly and ultrahigh temperature metamorphism, *Precambrian Research*, 161, 355–388.

KOBLER, M.E., 2012, *Petrographic, geochemical and geochronological characteristation of Batavia Knoll Dredge samples, Perth Abyssal Plain: implications for linkage with Gondwana*, BSc thesis, Macquarie University, Sydney, 110 p.

KÖTHER, N., HACKNEY, R. & JOHNSTON, S.W., in press. Crustal structure of the northern Perth Basin, southwest margin of Australia: insights from three-dimensional gravity models, Geophysical Journal International.

KSIENZYK, A.K., JACOBS, J., BOGER, S.D., KOŠLER, J., SIRCOMBE, K.N. & WHITEHOUSE, M.J., 2012, U-Pb ages of metamorphic monazite and detrital zircon from the Northampton Complex: evidence of two orogenic cycles in Western Australia, *Precambrian Research*, 198-199, 37–50.

LARSON, R.L., MUTTER, J.C., DIEBOLD, J.B., CARPENTER, G.B. & SYMONDS P., 1979, Cuvier Basin: a product of ocean crust formation by Early Cretaceous rifting off Western Australia, E*arth and Planetary Science Letters*, 45, 105–114.

LI, Z.X., BOGDANOVA, S.V., COLLINS, A.S., DAVIDSON, A., DEWAELE, B., ERNST, R.E., FITZSIMONS, I.C.W., FUCK, R.A., GLADKOCHUB, D.P., JACOBS, J., KARLSTROM, K.E., LU, S., NATAPOV, L.M.,

PEASE, V., PISAREVSKY, S.A., THRANE & K., VERNIKOVSKY, V., 2008, Assembly, configuration, and break-up history of Rodinia: a synthesis, *Precambrian Research*, 160, 179–210.

MAUS, S., BARCKHAUSEN, U., BERKENBOSCH, H., BOURNAS, N., BROZENA, J., CHILDERS, V., DOSTALER, F., FAIRHEAD, J.D., FINN, C. & VON FRESE, R.R.B., 2009, EMAG2: A 2–arc min resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne, and marine magnetic measurements, *Geochemistry Geophysics Geosystems*, 10.

MCCLAY, K. & DOOLEY, T., 1995, Analogue models of pull-apart basins, *Geology*, 23, 711–714.

MEERT, J., 2003, A synopsis of events related to the assembly of eastern Gondwana, *Tectonophysics*, 362, 1–40.

MORY, A.J. & IASKY, R.P., 1996, Stratigraphy and structure of the onshore northern Perth Basin, *Geological Survey of Western Australia Report*, 46, 101 pp.

NELSON, G, HUGES, M., PRZESLAWSKI, R., NICHOL, S., LEWIS, B. & RAWSTHORN, K., 2009, Revealing the Wallaby Plateau: Recent survey delivers geophysical, geological and biophysical data, *AusGeo News*, 94, (June).

NICHOLSON, C.J., BORISSOVA, I., KRASSAY, A.A. BOREHAM, C.J. & MONTEIL, E., 2008. New exploration opportunities in the Southern Vlaming Sub-basin, *The APPEA Journal*, 2008, 371–379.

NORVICK, M.S., 2004, Tectonic and stratigraphic history of the Perth Basin, *Geoscience Australia Record*, 2004/16.

PARSIEGLA, N., STANKIEWICZ, J., GOHL, K., RYBERG, T. & UENZELMANN-NEBEN, G., 2009, Southern African continental margin: Dynamic processes of a transform margin, *Geochemistry Geophysics Geosystems*, 10, Q03007,.

PEREZ-GUSSINYE, M., RANERO, C.R., RESTON, T.J. & SAWYER, D., 2003, Mechanisms of extension at non-volcanic margins: Evidence from the Galicia interior basin, west of Iberia, *Journal of Geophysical Research*, 108, 2245–2255.

PETKOVIC, P., 2012, Northern Perth Basin 2D gravity models, Geoscience Australia Record, 2012/44, 24 pp.

PFAHL, M.C., 2011, *Tectonic subsidence, thermal history and petroleum system modelling of the offshore northern Perth Basin, Western Australia*, BSc thesis, Australian National University, 109 p.

PISAREVSKY, S.A., WINGATE, M.T.D., POWELL, C.MCA., JOHNSON, S., & EVANS, D.A.D., 2003, Models of Rodinia assembly and fragmentation, in Proterozoic East Gondwana: supercontinent assembly and breakup, in YOSHIDA M., WINDLEY B.F. & DASGUPTA S., (Eds), *Proterozoic East Gondwana: supercontinent assembly and breakup*: Geological Society of London, Special Publication, 206, 35–55.

PLAYFORD, P.E., HORWITZ, R.C., PEERS, R. & BAXTER, J.L., 1970, Geraldton, W.A. *Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes*, 39 pp.

QUAIFE, R., ROSSER, J. & PAGNOZZI, S., 1994, The structural architecture and stratigraphy of the offshore northern Perth Basin, in PURCELL, P.G. & R.R. (Eds), *The Sedimentary Basins of Western Australia*: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, WA, 1994, 811–822.

ROLLET, N., PFAHL, M., JONES, A., KENNARD J.M., NICHOLSON, C.J., GROSJEAN, E., MANTLE, D., JORGENSEN, D., BERNARDEL, B., KEMPTON, R., LANGHI, L., ZHANG, Y., HALL, L.S., HACKNEY, R.I., JOHNSTON, S., BOREHAM, C.J., ROBERTSON, D., PETKOVIC, P. & LECH, M., 2013a, Northern extension of active petroleum systems in the offshore Perth Basin – an integrated stratigraphic, geochemical, geomechanical and seepage study, this volume.

ROLLET, N., NICHOLSON, C., JONES, A., GROSJEAN, E. & BERNARDEL, G., 2013 b, New exploration opportunities in the Houtman and Abrolhos sub-basin, northern Perth Basin, *The APPEA Journal*, 53.

SAYERS, J., BORISSOVA, I., RAMSAY, D. & SYMONDS, P.A., 2002, Geologic Framework of the Wallaby Plateau and adjacent areas, *Geoscience Australia Record*, 2002/21, 133 pp.

SMIT, J., BRUN, J.-P., CLOETINGH, S. & BEN-AVRAHAM, Z., 2008, Pull-apart basin formation and development in narrow transform zones with application to the Dead Sea Basin. *Tectonics*, 27, TC6018.

SONG, T. & CAWOOD, P.A., 2000, Structural styles in the Perth Basin associated with the Mesozoic break-up of Greater India and Australia, *Tectonophysics*, 317, 55–72.

SYMONDS, P.A., PLANKE, S., FREY, O. & SKOGSEID, J., 1998, Volcanic evolution of the Western Australian continental margin and its implications for basin development, in PURCELL, P.G. & R.R. (Eds), *The Sedimentary Basins of Western Australia 2*: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1998, 33–54.

TOTTERDELL, J.M, GIBSON, G.M., STACEY, A.R., MITCHELL, C.H., MORSE, M.P., NAYAK, G.K. & KUSZNIR, N.J., 2012, The structure of Australia's southern rifted margin: basement architecture, rifting processes and basin development, *Proceedings of the 34th International Geological Congress 2012, Brisbane, Australia*, Poster and Abstract 2346.

TYLER, I.M. & HOCKING, R.M., 2001, Tectonic units of Western Australia (scale 1:2, 500,000), Western Australia Geological Survey.

VEEVERS, J.J., POWELL, C.MCA. & ROOTS, S. R., 1991, Review of seafloor spreading around Australia. I. Synthesis of the patterns of spreading, *Australian Journal of Earth Sciences*, 38, 373–389.

WHITTAKER, J.M., HALPIN, J., WILLIAMS, S., HALL, L.S., GARDNER, R., KOBLER, M., DACZKO, N., & MÜLLER, R.D., 2013, Tectonic evolution and continental fragmentation of the Southern West Australian Margin, this volume.

WILLIAMS, S.E., 2011, RV Southern Surveyor SS2011/06 Voyage Summary, report, Marine National Facility, Hobart, Tasmania, Australia. http://www.marine.csiro.au/nationalfacility/voyagedocs/2011/index.htm

WINGATE, M.T.D. & GIDDINGS, J.W., 2000, Age and palaeomagnetism of the Mundine Well dyke swarm, Western Australia: implications for an Australia–Laurentia connection at 755 Ma, *Precambrian Research*, 100, 335–357.

WINGATE, M.T.D., 2007, Proterozoic mafic dykes in the Yilgarn Craton, in BIERLEIN, F.P. & KNOX-ROBINSON, C.M. (Eds), Proceedings of Geoconferences (WA) Inc. Kalgoorlie '07 Conference, *Geoscience Australia Record*, 2007/14, 80–83.

Biographies

Lisa Hall is a senior research scientist in Geoscience Australia's Basin Resources Group. Her current research is focused on unconventional hydrocarbon resource assessments and petroleum systems modelling in a variety of Australian basins. Lisa holds an MSc in Geology and Geophysics from Cambridge University (1999) and a DPhil in structural geology and neotectonics from Oxford University (2003). Member: PESA.

Ana Gibbons joined the University of Sydney's School of Geosciences in 2008 where she undertook a PhD, with supervision from Prof Dietmar Müller and Dr Joanne Whittaker. Her thesis, titled 'Tectonic evolution of the Indian Ocean', helped revise the break-up of East Gondwana, initially focusing on the abyssal plains off western Australia before expanding to incorporate seafloor spreading between Antarctica, India, Madagascar and Sri Lanka. This was achieved by plotting freely available pre-existing magnetic data (from GEODAS), as well as new data from a two month research cruise Ana joined in the NE Indian Ocean (CHRISP 2008, with IFM-Geomar), which were matched to a synthetic model (Modmag) to derive poles of rotations for fit reconstructions in an iterative fashion using a freely available plate tectonic software (GPlates). Ana then completed a one-year post-doc position as part of a government-funded Australian-Indian collaborative initiative (AISRF, Australia-India Strategic Research Fund). Ana is currently based at Statoil (Oslo, Norway). She holds a BSc Hons degree in Marine Biology and Coastal Management from the University of Newcastle Upon Tyne (UK) in 1997.

George Bernardel is a geoscientist in Geoscience Australia's Basin Resources Group. He has a B.Sc (Hons) and B.Eng. After a short period at Bridge Oil N.L. he has worked at Geoscience Australia since 1988. In the last few years he has been undertaking research into the architecture and evolution of Australia's Southwest Margin. Member: PESA and EAGE.

Jo Whittaker joined the Institute for Marine and Antarctic Science (IMAS) at the University of Tasmania in January 2013. Her research interests are predominantly in plate tectonics, marine geophysics and geodynamics. Jo completed a combine science/commerce undergraduate degree with Honours in Geophysics from the University of Sydney in 2003, followed by a Masters in Geophysics from Victoria University, Wellington, New Zealand. She received her PhD, on the tectonic consequences of mid-ocean ridge formation, evolution and subduction, from the University of Sydney in 2008. Following graduation she worked both for industry (GETECH in the UK) and academia (post-doc, University of Sydney).

Chris Nicholson is a geoscientist in Geoscience Australia's Basin Resources Group. He graduated from the Australian National University with a B.Sc (Hons) 2000. Chris's research focus has been studying the hydrocarbon prospectivity of frontier basins on Australia's continental margin. Recently, Chris worked with a multidisciplinary team to re-assess the hydrocarbon prospectivity of the offshore northern Perth Basin. Previously, he has undertaken similar research on the Mentelle, Vlaming and Bremer basins. Chris is leading a regional integrated assessment of petroleum prospectivity and CO2 storage potential in the Browse Basin. Member: PESA and EAGE.

Biographies

Nadege Rollet is a research scientist in Geoscience Australia's Basin Resources Group. Nadege graduated from the University of Paris – Pierre et Marie Curie, France where she obtained a MSc (1995) and a PhD (1999) in geology and geophysics. Her studies focused on geodynamic reconstructions around the South Tasman Rise and structural framework of the Ligurian Sea in the Western Mediterranean. Since joining Geoscience Australia in 2000, she has contributed to geodynamic reconstructions, structural framework, and seepage studies for Australia's continental margins and assessment of the petroleum prospectivity in the Remote Eastern Frontiers and in the offshore northern Perth Basin. Nadege is currently working on a project investigating CO_2 storage and petroleum prospectivity in the Browse Basin. Member: PESA.

Dietmar Müller is Professor of Geophysics at the University of Sydney, Australia. He obtained his PhD in Earth Science from the Scripps Institution of Oceanography in 1993 and his undergraduate degree at the University of Kiel, Germany. After joining the University of Sydney in 1993, he established the University of Sydney Institute for Marine Science and the EarthByte e-research group (www.earthbyte.org), pursuing collaborative development of open-source software and community digital data sets. One of the fundamental aims of his research is geodata and model synthesis through space and time, assimilating the wealth of disparate geological and geophysical data into a four-dimensional Earth model. His achievements have been acknowledged by winning the year 2000 Fresh Science Prize, awarded by the British Council and 'ScienceNow!', followed by the Carey Medal in 2004 for his contributions to the understanding of global tectonics. In 2009 he was awarded a 5-year Australian Laureate Fellowship to build a Virtual Geological Observatory.