



Government of **Western Australia**
Department of **Mines and Petroleum**

RECORD 2014/14

THE TECTONIC FRAMEWORK OF THE PERTH BASIN: CURRENT UNDERSTANDING

by
CM Thomas



Geological Survey of Western Australia



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Perth 2014



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The tectonic framework of the Perth Basin: current understanding

by

CM Thomas

Abstract

Due to the burgeoning of 3D seismic surveys and the advent of more sophisticated physical and numerical modelling techniques, concepts of rift basin evolution have advanced considerably over the last two decades. Therefore, a need was recognized to review the structure and tectonic evolution of the Perth Basin, especially as there are conflicting interpretations of the duration of tectonic phases, and the nature and ages of important structures within the basin.

Different interpretations of rift phase timing or structure formation are partly due to the inconsistent application of stratigraphic nomenclature. At present, there is no consistently used stratigraphic framework that allows reliable regional correlation of strata for the entire, >1000 km-long, Perth Basin. The most widely used nomenclature is lithostratigraphic, which introduces the possibility of the same stratigraphic unit name being applied to similar facies of significantly different ages. Alternatively, different stratigraphic names may be applied to age- and facies-equivalent rocks identified in different studies, even within the same basin. The correlation of lithologically similar but diachronous packages has obscured patterns of uplift and subsidence in the Perth Basin, preventing a thorough understanding of its tectonic evolution. To rectify this problem, it is recommended that more detailed biostratigraphic sampling be undertaken across the basin, particularly for Mesozoic units that, until recently, have received considerably less attention than the Permian section, which was considered more prospective for petroleum. Integration of biostratigraphic ages with seismic, thermal maturity, and provenance studies, should provide a more complete picture of the tectonic evolution of the basin.

The interpretation of long transfer faults subperpendicular to larger rift faults to explain apparent lateral ‘jumps’ of the latter in map view is entrenched in the literature, but evidence for their existence remains weak and there is little appreciation of the model-driven nature of these interpretations. It is likely that these ‘transfer faults’ are accommodation zones, as most cannot be identified as discrete structures in seismic data. This reinterpretation can also explain the apparent truncations or strike-slip displacement of normal faults related to the rift margin without the need to invoke strike-slip faults.

KEYWORDS: growth faults, Phanerozoic, rift basins, seismic interpretation, stratigraphic mapping, stratigraphy, tectonics

Introduction

The Perth Basin forms part of the continental margin of southwestern Australia, and is the result of a long history of rifting that eventually led to the breakup of Gondwana and the formation of the Indian Ocean. It is bounded by the Archean Yilgarn Craton to the east, the Southern Carnarvon Basin to the north, the Bight Basin to the southeast, and oceanic crust of the Indian and Southern oceans to the west and south, respectively (Fig. 1). The basin contains up to 15 km of mid-Carboniferous to Lower Cretaceous sedimentary rocks, which record a long-lived, mostly nonmarine depositional environment with occasional marine incursions (Playford et al., 1976). These rocks are truncated by a breakup unconformity of Valanginian (Early Cretaceous) age, they are overlain by a thinner veneer of post-rift sediments, and are interpreted to be underlain by igneous and metamorphic rocks of the

Meso- to Neoproterozoic Pinjarra Orogeny, which are exposed in the Leeuwin, Mullingar, and Northampton Inliers. Interest in the Perth Basin has been renewed due to its gas and geothermal resources, potential for CO₂ sequestration, and proximity to markets and existing infrastructure.

At present, uncertainties remain in the history of subsidence and uplift, internal geometry, and paleogeography of the Perth Basin. This is demonstrated by very different interpretations in the literature of the timing, kinematics and history of tectonic events that shaped the basin. Part of the reason for these disagreements is the lack of consistency in stratigraphic nomenclature. Past stratigraphic correlations have been based primarily on lithostratigraphy. As a result, key formations have been defined differently. The inconsistent application of formation definitions, even within a single

study, renders well correlations and subsequent seismic interpretations unreliable, and this hinders a thorough evaluation of the basin's tectonic history. The aim of this Record is to assess previous literature on the structural framework and tectonic history of the Perth Basin, and to identify the gaps in understanding that warrant future investigation.

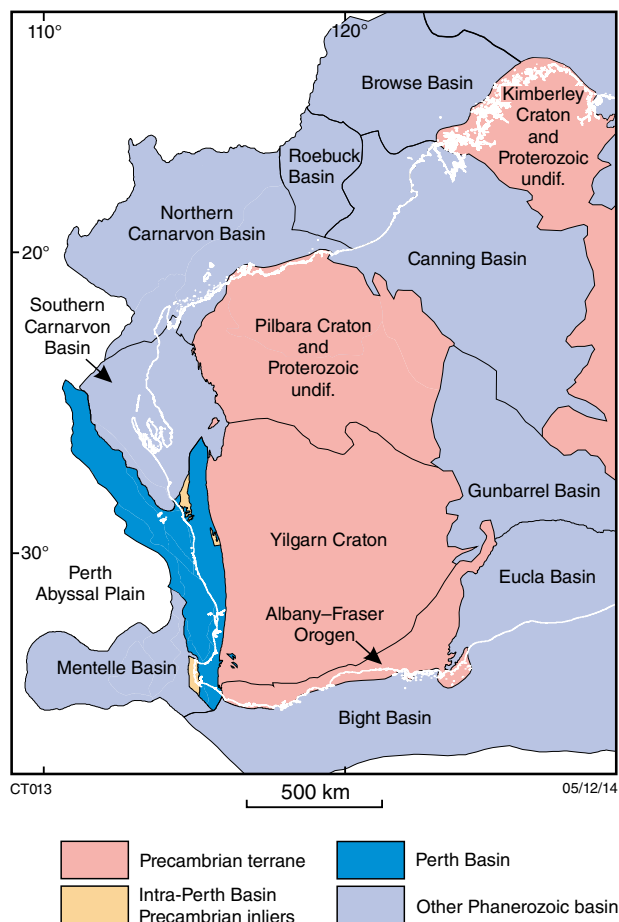


Figure 1. Location of Perth Basin at the western margin of the Archean Yilgarn Craton

Structural framework

The broad architecture of the Perth Basin was initially revealed by the first regional gravity survey, between Geraldton and Cape Leeuwin, the results of which were described by Thyer and Everingham (1956). They showed that the onshore basin comprises two north-south trending, westward-shallowing depocentres west of the Darling Fault — which they named the Dandaragan and Bunbury Troughs — separated by an east-west trending 'saddle' to the southwest of Pinjarra, now called the Harvey Ridge. Subsequent offshore seismic, gravity and magnetic surveys have allowed additional major depocentres to be delineated within the Perth Basin (namely the Abrolhos, Houtman, and Vlaming Sub-basins; Jones and Pearson, 1972; Playford, 1971; Symonds and Cameron, 1977).

The Bunbury and Dandaragan Troughs have since been further subdivided into discrete tectonic units (Fig. 2), especially in the onshore north of the basin, which has received greater attention from researchers due to the greater number of petroleum exploration wells and denser seismic coverage. In the onshore basin, a series of north to north-northwesterly trending normal faults have been mapped (Figs 3 and 4), and are interrupted by what have previously been interpreted as northwest-, northeast-, and east-west striking transfer (strike-slip) faults (e.g. Hall and Kneale, 1992; Marshall et al., 1993; Mory and Iasky, 1996; Crostella and Backhouse, 2000; Iasky and Lockwood, 2004; Fig. 5). Where tectonic units are delineated by mapped normal faults, their boundaries in map view (Figs 3 and 4) are the positions of the faults at their shallowest level; in other words, it is the position of the fault at the breakup unconformity (mapped from seismic), or, where the breakup unconformity has been

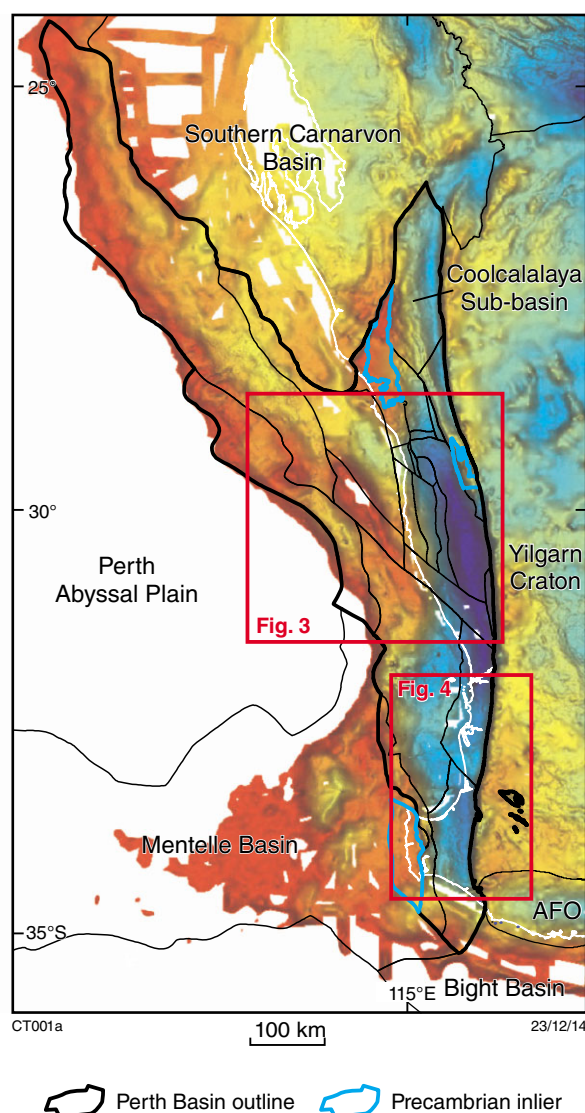


Figure 2. Outline of the Perth Basin and principal subdivisions (after Geological Survey of Western Australia, 2007) superimposed on a Bouguer gravity anomaly image (modified from Hackney, 2012). See Figures 3 and 4 for details of basin subdivisions. AFO – Albany-Fraser Orogen

further eroded, at the shallow subsurface (pre-Cenozoic; mapped from seismic) or surface (mapped from outcrop) levels. Therefore, it cannot be assumed that these tectonic units existed throughout the history of the basin.

Middleton (1991) recognized that major fault azimuths in the southern and central Perth Basin are restricted to a narrow envelope around due north, whereas those in the northern portion of the basin have orientations that range across a broader north-northwesterly envelope (Fig. 5). This variance may reflect the orientation of basement discontinuities, as many studies have suggested a strong control of major structures either directly by underlying basement shear zones (e.g. Byrne and Harris, 1992; Dentith et al., 1994b; Harris et al., 1994), or by contrasts in basement rheology (Dentith et al., 1994b). The following descriptions of each tectonic unit (in their approximate north to south order), as recognized in Geological Survey of Western Australia (2007), includes discussions of the robustness of their definitions. It should be noted that, although reference is given to the authors who originally named the tectonic unit, the present tectonic unit definitions are likely to be very different from the original definitions, which were often nebulous due to the lack of geophysical data. Figures 3 and 4 show the confidence placed on each tectonic unit boundary based on whether a structure is evident on seismic profiles only, or in outcrop.

Coolcalalaya Sub-basin

The Coolcalalaya Sub-basin (formerly the 'Coolcalalaya Basin' of Condon, 1965; Fig. 2) is an elongate sub-basin generally accepted as the northernmost extent of the Perth Basin (Playford et al., 1976; Hocking, 1994). Mory and Haig (2011) judged it as 'transitional' between the Perth and Southern Carnarvon Basins, as its stratigraphy has similarities with both basins. Its northern boundary with the Byro Sub-basin of the Southern Carnarvon Basin was considered by Hocking (1994) to be a putative strike-slip fault, which was inferred only from poor potential-field data of the day. However, Mory et al. (1998) found no justification for the location of this boundary, from outcrop and more modern potential-field datasets. Its southern boundary with the Irwin Terrace is at present arbitrarily defined, because it is now unclear if there are stratigraphic thickness changes between the two tectonic units as previously thought (Mory et al., 1998). The sub-basin is bounded to the east by the Darling Fault, and is separated from the Northampton Inlier to the west by the easterly dipping Yandi Fault. Several splays from the Darling Fault extend into the Coolcalalaya Sub-basin, and some of these evidence little activity after the Permian (Hocking et al., 1982).

Very little is known about this sub-basin due to the sparseness of deep subsurface data and rarity of pre-Cenozoic outcrops, apart from near the Darling Fault and along Murchison River. Shallow coal exploration holes and water bores have intersected mid-Carboniferous to lower Permian, Lower Cretaceous, and Cenozoic strata (Green, 1982; Backhouse, 1998) that are estimated to be up to 8.5 km thick (Mory et al., 1998).

Irwin Terrace

The Irwin Terrace (1 – Figs 3 and 7; Iasky and Mory, 1993; formerly the 'Irwin Basin' of Clarke et al., 1951) is a narrow, easterly tilted half-graben bounded to the east and west by the Darling and Urella Faults, respectively. This tectonic unit contains the most extensive exposures of lower Permian (Cisuralian) rocks in the basin, and these strata form the bulk of outcrop within it. Overall, the oldest known outcrops in the terrace have been variously assigned to the Ordovician–Silurian Tumblagooda Sandstone (Playford et al., 1971) and Devonian (Hocking, 1991), but were not systematically differentiated by Mory et al. (1998). The only record of Mesozoic rocks is within a small, fault-bound sliver along the terrace's western margin (containing Kockatea Shale, Cattamarra Coal Measures, and Cadda Formation; Coleman and Skwarko, 1967; Mory and Iasky, 1995) within the Urella Fault system.

The Irwin Terrace is traversed by northwest and north-northwesterly striking normal faults, which Le Blanc Smith and Mory (1995) interpreted as resulting from sinistral strike-slip movement along the Darling and Urella Faults sometime after deposition of lower to middle Permian strata. Le Blanc Smith and Mory (1995) also reported northerly trending folds in Permian strata abutting the Darling Fault, which they attributed to hangingwall inversion during this same strike-slip movement. Whether or not the Darling and Urella Faults were also active during deposition of the lower Permian succession remains uncertain. Mory and Iasky (1996) interpreted the Nangetty Formation and Holmwood Shale to thicken eastward towards the Urella Fault, but it is not known if the equivalent sequence (now mostly eroded) in the footwall of the Urella Fault originally exhibited the same eastward-thickening trend.

Vitrinite reflectance (R_o) results obtained from Irwin River Coal Measures samples at ~146 m depth averaged 0.45%, indicating that this unit was previously buried at much greater depths (Le Blanc Smith and Mory, 1995). However, palynomorphs within the Kockatea Shale in the small, western fault sliver are well preserved (Coleman and Skwarko, 1967), consistent with less overburden removal of this succession compared with the underlying Permian succession. Together, these lines of evidence imply that the middle–late Permian was a period of major uplift and erosion on the Irwin Terrace, with either a break between the Kockatea Shale and underlying Permian strata, or between the Wagina Formation and underlying strata.

Wicherina Terrace

The Wicherina Terrace (2 – Figs 3 and 7; Tyler and Hocking, 2002), previously included within the Allanooka High of Crostella (1995), is a narrow half-graben bounded by the westerly dipping Urella and Wicherina Faults, and terminating at the Allanooka Fault to the south. No petroleum wells have been drilled in this tectonic unit to date but the Bookara Shelf seismic survey shows thickening of Permian and possibly older strata into the Urella Fault, although it is unclear if this is due to syndepositional movement.

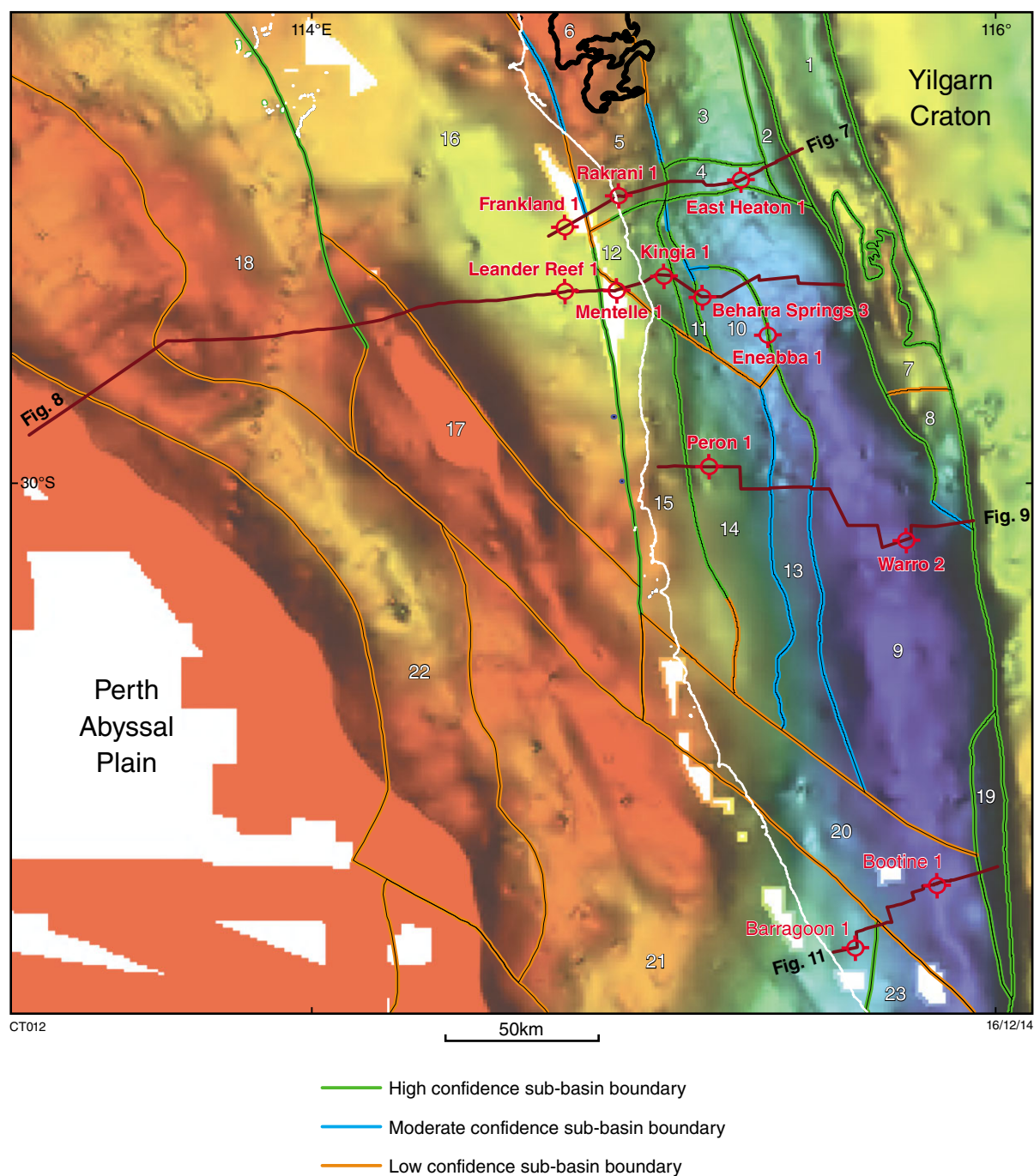


Figure 3. a) Tectonic elements of the northern Perth Basin superimposed on a Bouguer gravity image (modified from Hackney, 2012): 1 – Irwin Terrace, 2 – Wicherina Terrace, 3 – Bookara Shelf, 4 – Allanooka Terrace, 5 – Greenough Shelf, 6 – Northampton Inlier (Precambrian), 7 – Mullingar Inlier (Precambrian), 8 – Yarra Yarra Terrace, 9 – Dandaragan Trough, 10 – Donkey Creek Terrace, 11 – Beharra Springs Terrace, 12 – Dongara Terrace, 13 – Coomallo Trough, 14 – Cadda Terrace, 15 – Beagle Ridge, 16 – Abrolhos Sub-basin, 17 – Turtle Dove Ridge, 18 – Houtman Sub-basin, 19 – Barberton Terrace, 20 – Beermullah Trough, 21 – Vlaming Sub-basin, 22 – Zeewyck Sub-basin, 23 – Mandurah Terrace. Sub-basin boundaries are categorized as: 1) high confidence boundary – boundary corresponds with a well-defined fault or fault zone clearly imaged in seismic or recognized in outcrop; 2) moderate confidence boundary – sub-basin boundary corresponds with a low-offset fault or flexure, such that it is difficult to justify a boundary at this location, or boundary is inferred only from poor or sparse data, thus a significant fault or fault zone is likely to exist, but its location is uncertain; 3) low confidence boundary – sub-basin boundary not adequately covered by seismic surveys, or boundary does not correspond with any structure on seismic.

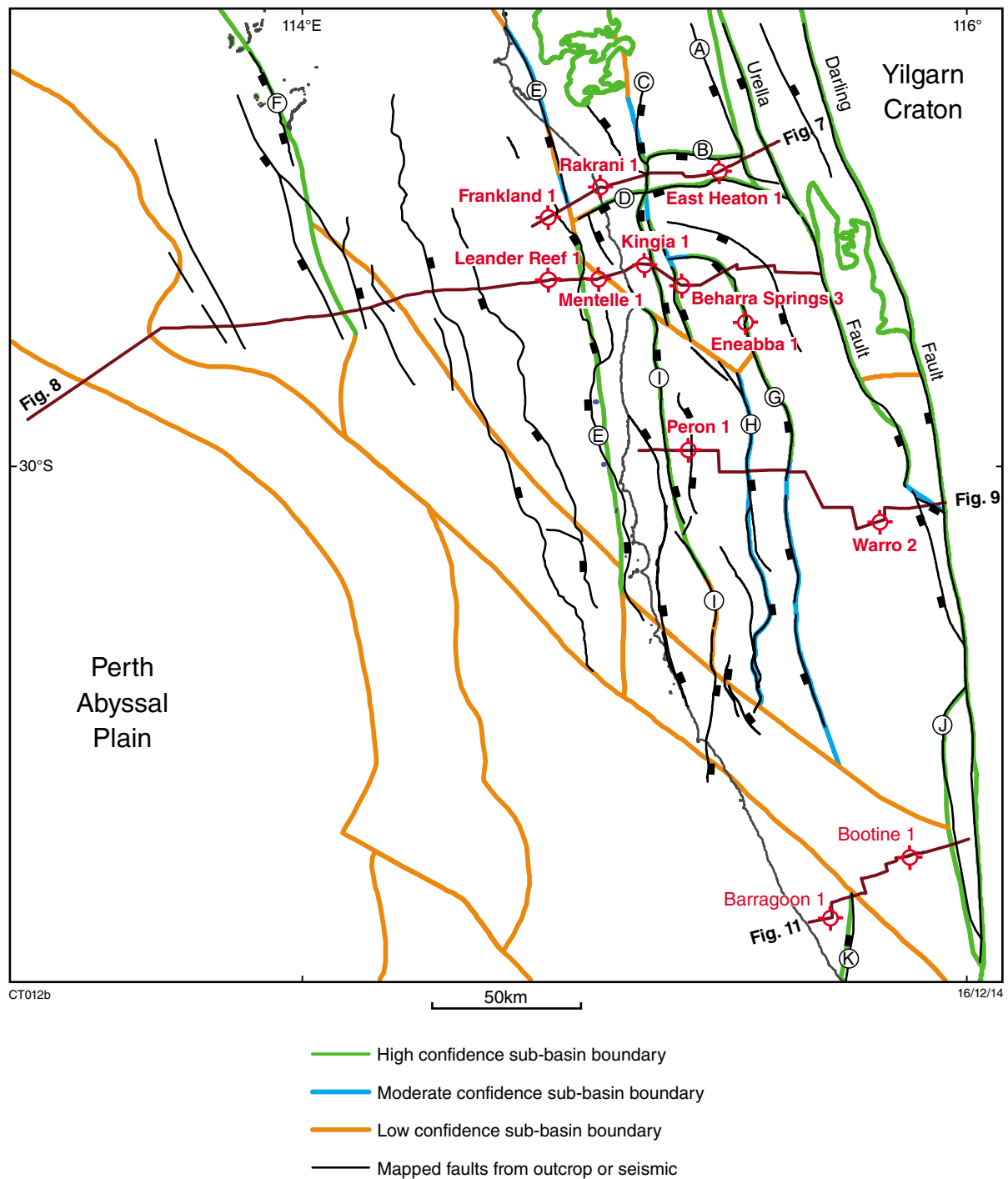


Figure 3. b) Selected faults mapped directly from seismic or outcrop superimposed on tectonic elements of the northern Perth Basin. Onshore faults are at pre-Cenozoic level (from plate 10 of Mory and Iasky, 1996), and offshore faults are at Permian level (from Jones et al., 2011). This figure shows the coincidence (or lack thereof) of sub-basin boundaries and mapped structures: A – Wicherina Fault, B – Bookara Fault, C – Mountain Bridge Fault, D – Allanooka Fault, E – Geraldton Fault, F – Houtman Fault (System), G – Coomallo Fault, H – Eneabba Fault, I – Beagle Fault (System), J – Muchea Fault, K – Badaminna Fault (System)

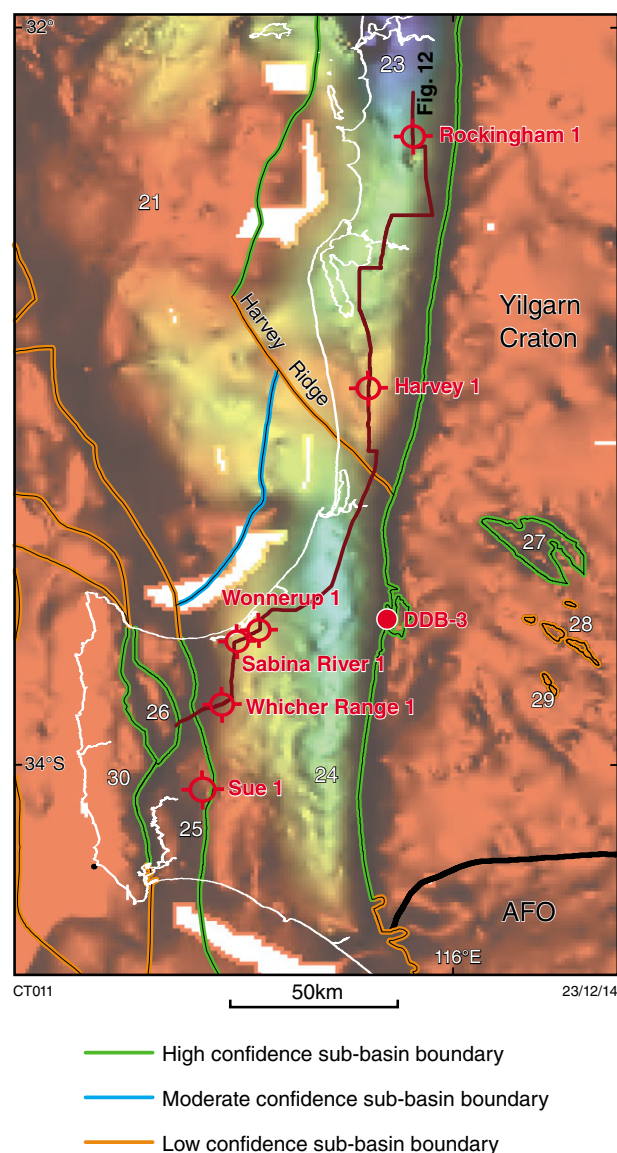


Figure 4. a) Tectonic elements of the southern Perth Basin superimposed on a Bouguer gravity image (modified from Hackney, 2012): 21 – Vlaming Sub-basin, 23 – Mandurah Terrace, 24 – Bunbury Trough, 25 – Vasse Shelf, 26 – Treeton Terrace, 27 – Collie Sub-basin, 28 – Wilga Sub-basin, 29 – Boyup Sub-basin, 30 – Leeuwin Inlier (Precambrian). Tectonic element boundaries are characterized as in Figure 3a.

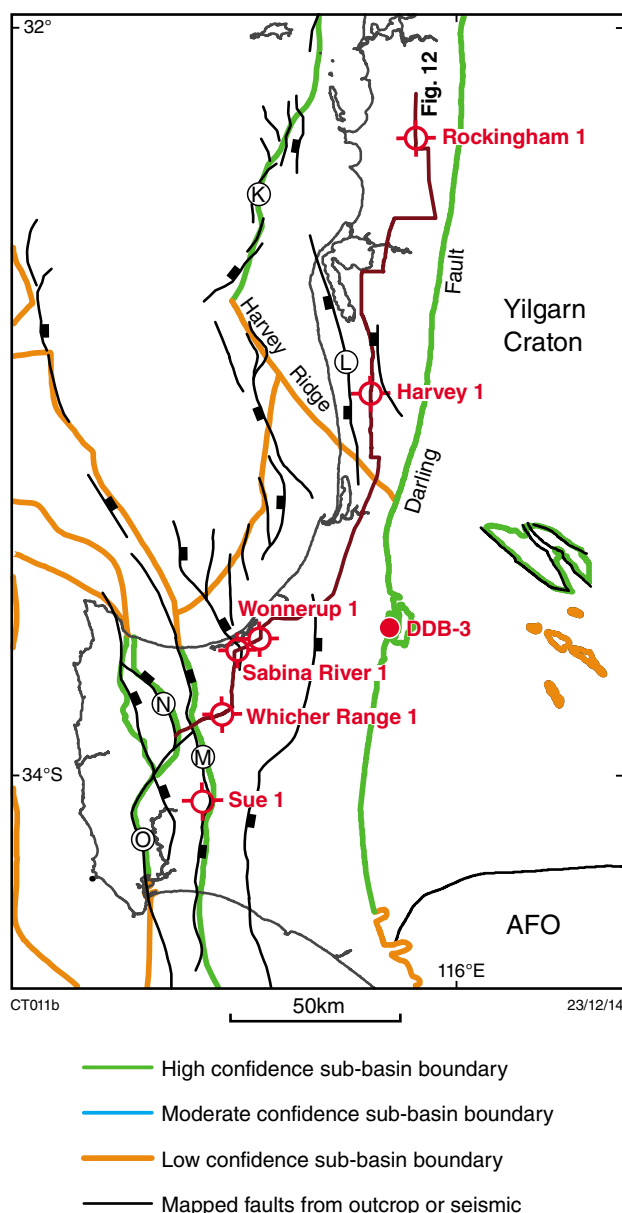


Figure 4. b) Selected faults mapped directly from seismic or outcrop superimposed on tectonic elements of the southern Perth Basin. Onshore faults are at Jurassic level (from Iasky, 1993 and Zhan, 2014), and offshore faults are from an unspecified level (from Nicholson et al., 2008). This figure shows the coincidence (or lack thereof) between tectonic element boundaries and mapped structures: K – Badaminna Fault (System), L – ‘F2’ and ‘F3’ fault of Zhan (2014), M – Busselton Fault, N – Wirring Fault, O – Dunsborough Fault

Bookara Shelf

The Bookara Shelf (3 – Fig. 3; Tyler and Hocking, 2002) is between the Northampton Inlier and Wicherina Terrace. Its southern margin is defined by the east–west striking Bookara Fault, and the eastern boundary by the Wicherina Fault, both of which are clearly imaged in seismic data. The western margin is the eastern edge of the Northampton Inlier, bounded by the easterly dipping Mountain Bridge Fault, which is mapped from limited seismic data south of Jurassic outcrop adjoining the inlier.

Allanooka Terrace

The Allanooka Terrace (4 – Figs 3 and 7; Tyler and Hocking, 2002; formerly the ‘Allanooka High’ of Crostella, 1995) is bounded by the east–west striking Allanooka Fault to the south, the Bookara Fault to the north, the northern section of the Mountain Bridge Fault to the west, and the Wicherina Fault to the east. Seismic and petroleum-well data show that Permian strata within the terrace thicken eastwards towards the Wicherina Fault.

Greenough Shelf

The Greenough Shelf (5 – Figs 3 and 7; Crostella, 1995; Mory and Iasky, 1996) is defined as an area of shallow basement bounded by the Allanooka Fault to the south and the Mountain Bridge Fault to the east. Permian and younger strata progressively onlap the Northampton Inlier northwards (Playford et al., 1970). The Greenough Shelf lies immediately east of the Abrolhos Sub-basin; however, although the boundary is represented in published maps (Crostella, 1995; Mory and Iasky, 1996; Geological Survey of Western Australia, 2007) to be contiguous with the westerly dipping Geraldton Fault, it is clear from the interpreted section (Fig. 7) and published fault interpretations (Fig. 4b; 5) that the Geraldton Fault is not as continuous as previously thought. This makes the boundary between the two tectonic units difficult to place in some areas, and the definition of the Greenough Shelf as an area of ‘shallow basement’ difficult to reconcile with its current outline.

Yarra Yarra Terrace

The Yarra Yarra Terrace (8 – Mory and Iasky, 1996) is a half-graben between the Urella and Darling Faults, and is separated from the Irwin Terrace further north by outcropping Precambrian metamorphic and sedimentary rocks of the Mullingar Inlier (7). It differs from the Irwin Terrace in containing a Mesozoic section deepening to the south (Mory and Iasky, 1996).

Dandaragan Trough

The north–south trending Dandaragan Trough (9 – Figs 3, 8 and 9; Thyer and Everingham, 1956) is a half-graben with up to 12 km of Permian and younger strata (Mory and

Iasky, 1996), and is the deepest onshore depocentre of the Perth Basin. Using apatite fission track analysis (AFTA) data, Green and Duddy (2013) suggested there has been little uplift and exhumation of the Dandaragan Trough. The tectonic unit is associated with a marked gravity low (Fig. 2). Hackney et al. (2012) were able to achieve a best-fit model of this gravity signature by invoking a deeper Moho under this part of the basin. The oldest outcropping rocks in the trough belong to the Middle–Upper Jurassic Yarragadee Formation.

The trough is bounded by the Urella, Darling, and Muchea Faults to the east, and the Eneabba Fault System to the west (Crostella, 1995; Mory and Iasky, 1996). Although the southern boundary was originally placed at the abrupt shallowing of strata onto the Harvey Ridge, Crostella and Backhouse (2000) did not consider the Dandaragan Trough to extend that far south, and instead designated the Cervantes Transfer Fault (Fig. 5) as the southern boundary with the Beermullah Trough. Even though this interpreted transfer fault was neither clearly defined nor recognized in seismic data, Crostella and Backhouse’s (2000) amendment to the Dandaragan Trough was adopted by Geological Survey of Western Australia (2007). The Cervantes Transfer Fault is discussed in more detail in the ‘Transfer faults’ section under Timing and nature of major structures.

The Dandaragan Trough shallows northwards towards the east–west striking Allanooka Fault, and the general deepening of strata towards the east suggests that the Urella, Muchea, and Darling Faults were the primary controls on accommodation space. Mory and Iasky (1996) reported southward thinning of Permian strata from the Allanooka and Wicherina Terraces towards the Dandaragan Trough, and further postulated that Permian strata could be absent in some parts of the trough. However, this interpretation was based on a seismic line oriented roughly perpendicular to the Urella Fault, and in this Record I suggest that the apparent thinning or absence of Permian strata in the northern Dandaragan may be reflective of eastward thickening, rather than southward thinning, *per se*.

The Dandaragan Trough contains short-wavelength, northwest-trending anticlines in the hangingwalls of the Darling Fault System, such as the Warro and Gingin Anticlines. Song and Cawood (2000) interpreted these features to have formed from localized compression at restraining bends along the major north–northwest-trending faults as a consequence of oblique extension during the final rifting phase.

Donkey Creek Terrace

The Donkey Creek Terrace (10 – Figs 3 and 8; Crostella, 1995) is an asymmetric graben bounded by the Eneabba Fault to the east and north, and by the interpreted Abrolhos Transfer Fault to the south. Vitrinite reflectance studies of samples from Redback 1 and Donkey Creek 1 (Cook, 1979b; CoreLab, 2013) suggest that the Donkey Creek Terrace is unlikely to have undergone significant uplift and erosion after the early Permian.

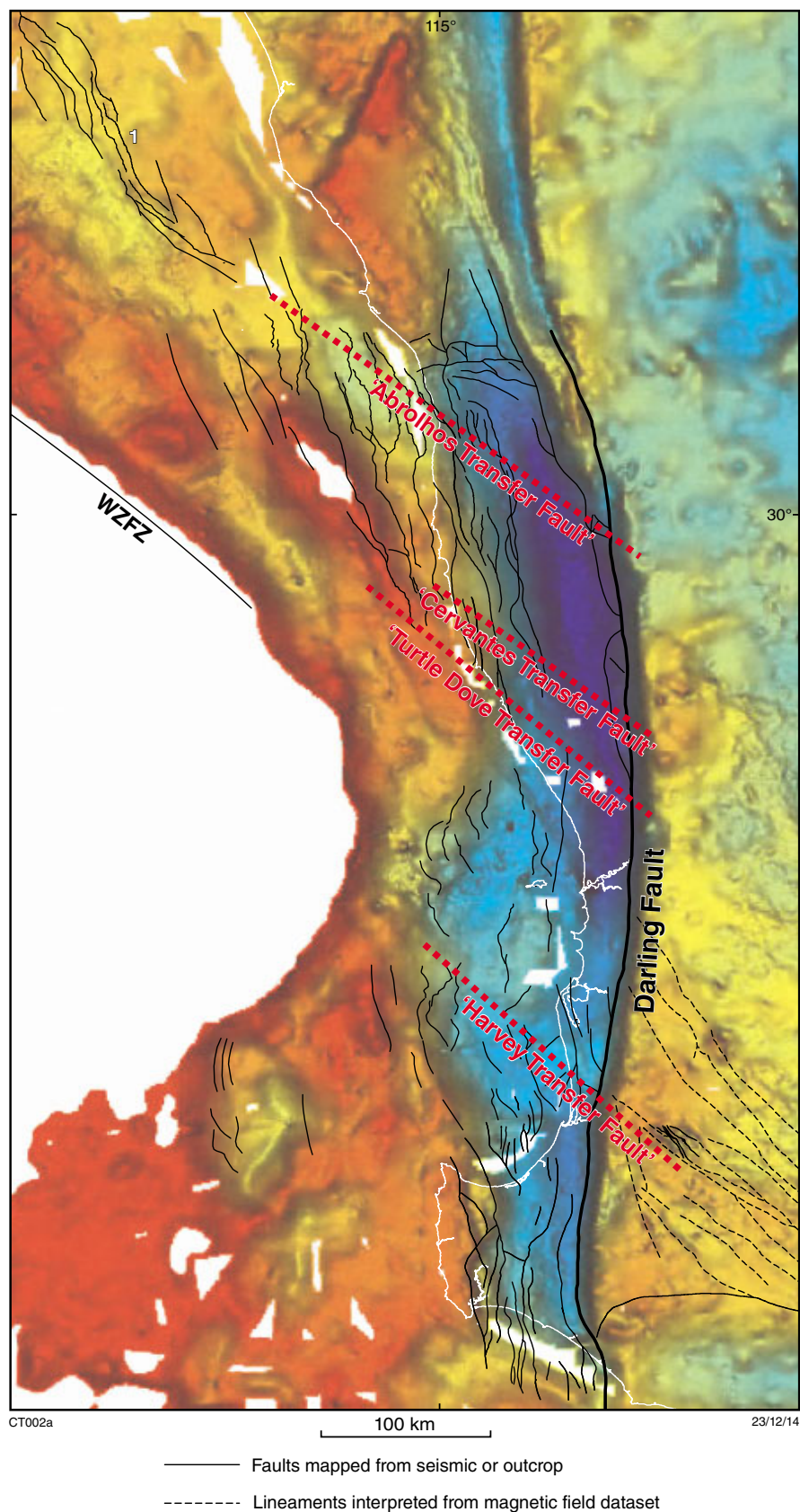


Figure 5. Bouguer gravity anomaly image of the Perth Basin (modified from Hackney, 2012), proposed locations of 'transfer faults', and near top Permian fault centrelines mapped from seismic data (modified from Iasky, 1993; Mory and Iasky, 1996; Crostella and Backhouse, 2000; Nicholson et al., 2009; Jones et al., 2011; Zhan, 2014). Lineaments on Yilgarn Craton are from Martin et al. (2014). WZFF – Wallaby-Zenith Fracture Zone.

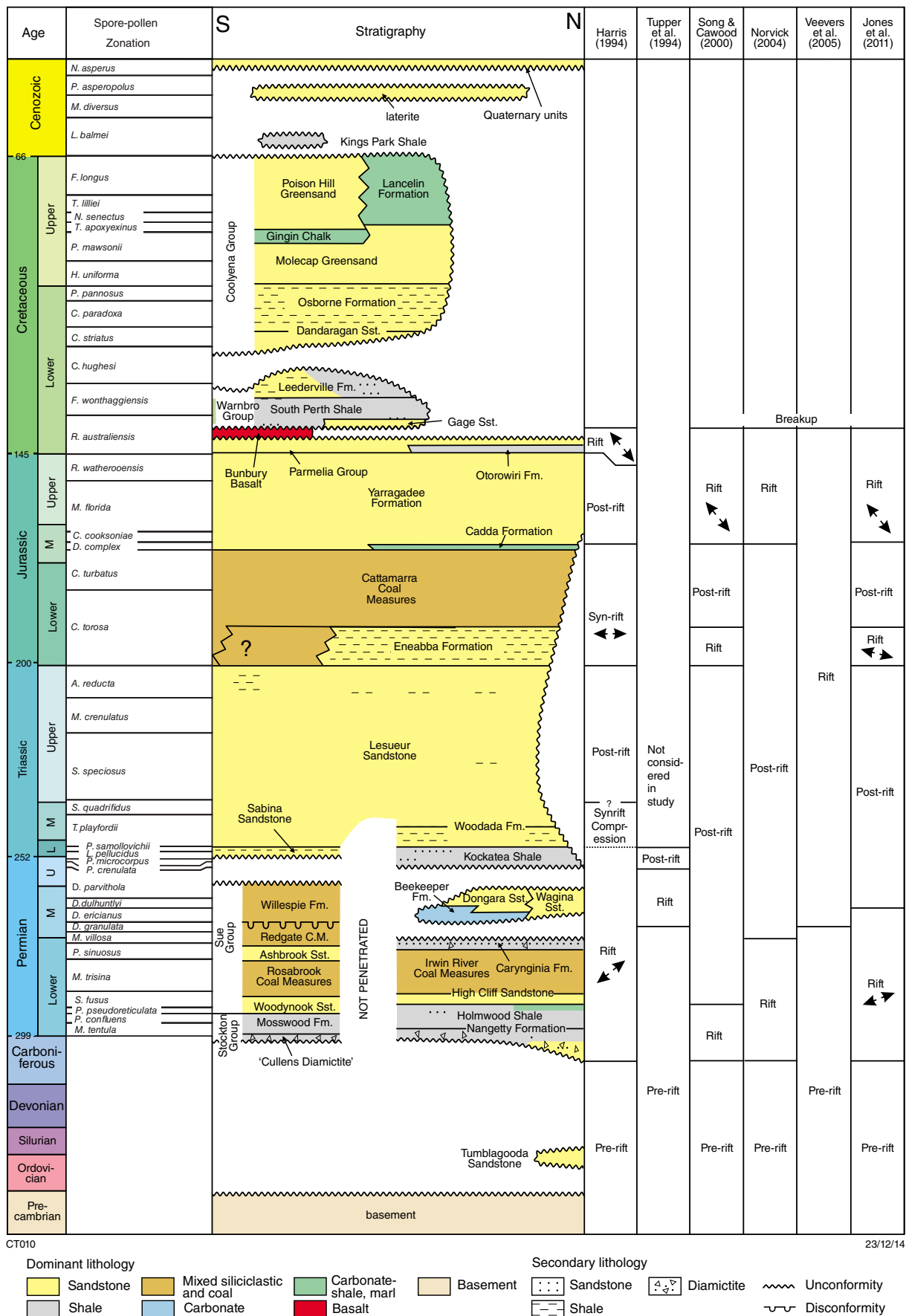


Figure 6. Stratigraphy of the Perth Basin and comparison of tectonic regimes proposed to have driven basin development through time. Spore–pollen zonation boundaries taken from Mory et al. (2013)

Beharra Springs Terrace

The term Beharra Springs Terrace (11 – Figs 3 and 8) was introduced by Crostella (1995), who defined it as an ‘intermediate’ terrace between the structurally higher Dongara Terrace to the west, and the structurally lower Donkey Creek Terrace and Dandaragan Trough to the east. The eastern boundary is formed by an en echelon set of low-displacement normal faults subparallel and synthetic to the Mountain Bridge Fault (‘Beharra Springs – Mondarra – Yardarino Trend’; Mory and Iasky, 1996); therefore, the eastern boundary is poorly defined in some places, such as at relay ramps between en echelon faults. The central portion of the Beharra Springs Terrace forms part of a broad dome in the hangingwall of the Mountain Bridge Fault.

Dongara Terrace

The Dongara Terrace (12 – Figs 3 and 8; Mory and Iasky, 1996; formerly the ‘Dongara Saddle’ of Jones and Pearson, 1972) is shown in Tyler and Hocking (2002) as a horst block bounded by the Mountain Bridge Fault to the east and the northern extension of the Geraldton Fault to the west. However, the Geraldton Fault peters out around the central part of the Dongara Terrace, and the northern half of the terrace’s western boundary is imprecisely defined. At the western boundary, the faults predominantly dip eastwards, but strata rise steadily eastwards. The north–south trending Beagle Fault continues northwards into the terrace, and effectively bisects it (Fig. 3b). Towards the south of the Dongara Terrace, Song and Cawood (2000) and Song et al. (2001) interpreted a large, roughly northwest-trending anticline within Lower Jurassic and older strata in the hangingwall of the Beagle Fault, located where this fault makes a distinct change in strike to the northwest. These authors suggested the anticline resulted from strike-slip movement at a restraining bend on the Beagle Fault, which, given the fault’s geometry, implies a component of right-lateral movement. In their interpreted seismic section (Song and Cawood, 2000), the anticline is truncated by the breakup unconformity, and no thickness changes are observable in strata in its vicinity, implying that the anticline formed just before, or during, breakup. This timing is consistent with dextral reactivation during the final northwest–southeast rifting phase.

Based on apatite fission track analysis of a sample from Dongara 1, on the footwall of the Mountain Bridge Fault in the east of the terrace, Green and Duddy (2013) suggested there had been ~1 km of uplift and erosion on the Dongara Terrace during breakup.

Coomallo Trough

The Coomallo Trough (13 – Figs 3 and 9; Crostella, 1995) is a graben bounded by the Coomallo Fault to the west and the Eneabba Fault to the east. Seismic data quality

degrades sharply near the interpreted fault boundary with the Cadda Terrace, which is likely due to the fault zone itself. This tectonic unit coincides with an elongated magnetic anomaly, which Hall et al. (2012) interpreted to be related to basement lithology. The Yarragadee Formation is the oldest outcropping unit within the tectonic unit.

To date, only seven petroleum wells have been drilled in the Coomallo Trough, all of which tested the Cattamarra Coal Measures but did not extend into deeper units. Vitrinite reflectance measurements of Cattamarra Coal Measures intersected at depths of ~3 km suggest these rocks are presently at their maximum burial depth, and thus have experienced very little uplift and sediment removal since at least mid-Jurassic times. The higher vitrinite reflectance gradient seen in the Cattamarra Coal Measures in Walyering 2 indicates proximity to a localized heat source (Discovery Petroleum, 1993), although igneous material has not been described in cuttings or cores either in this well or in nearby wells.

Cadda Terrace

The Cadda Terrace (14 – Figs 3 and 9; Hocking, 1994; formerly the ‘Cadda Shelf’ of Thomas, 1979) is bounded to the west by the Beagle Fault System and to the east by the Eneabba Fault System. Vitrinite reflectance values from measurements of subsurface Permian and Lower Triassic strata in this sub-basin are high given present-day depths, suggesting significant uplift and erosion sometime after the Early Triassic along the length of the Cadda Terrace. Vitrinite reflectance values between 1.5 and 4.6% have been recorded in the lower Permian Irwin River Coal Measures and Carynginia Formation at depths of 1500–2700 m in Gairdner 1 and Woolmulla 1 (Cook, 1979b; AWE Ltd, 2011). The sharp increase in thermal maturity of Permian – earliest Triassic rocks compared to younger rocks in these wells, as indicated by both vitrinite reflectance and palynomorph colour, may be due to hydrothermal alteration, which has been noted in Woolmulla 1 (Pudovskis, 1963), as intrusive rocks are not present in either of these wells nor elsewhere within the terrace, and burial alone is insufficient to explain them.

Beagle Ridge

The Beagle Ridge (15 – Figs 3, 8 and 9; Playford and Willmott, 1958) is a prominent north-northwesterly to south-southeasterly trending horst bounded to the east by the Beagle Fault System — a system of en echelon, north-northwesterly striking, easterly dipping normal faults — and to the west by the putative southward continuation of the Geraldton Fault. The northern boundary of the ridge is taken to be the Abrolhos Transfer Fault (‘Abrolhos transfer’ of Mory and Iasky, 1996), and the Cervantes Transfer Fault defines the southern boundary (Crostella and Backhouse, 2000).

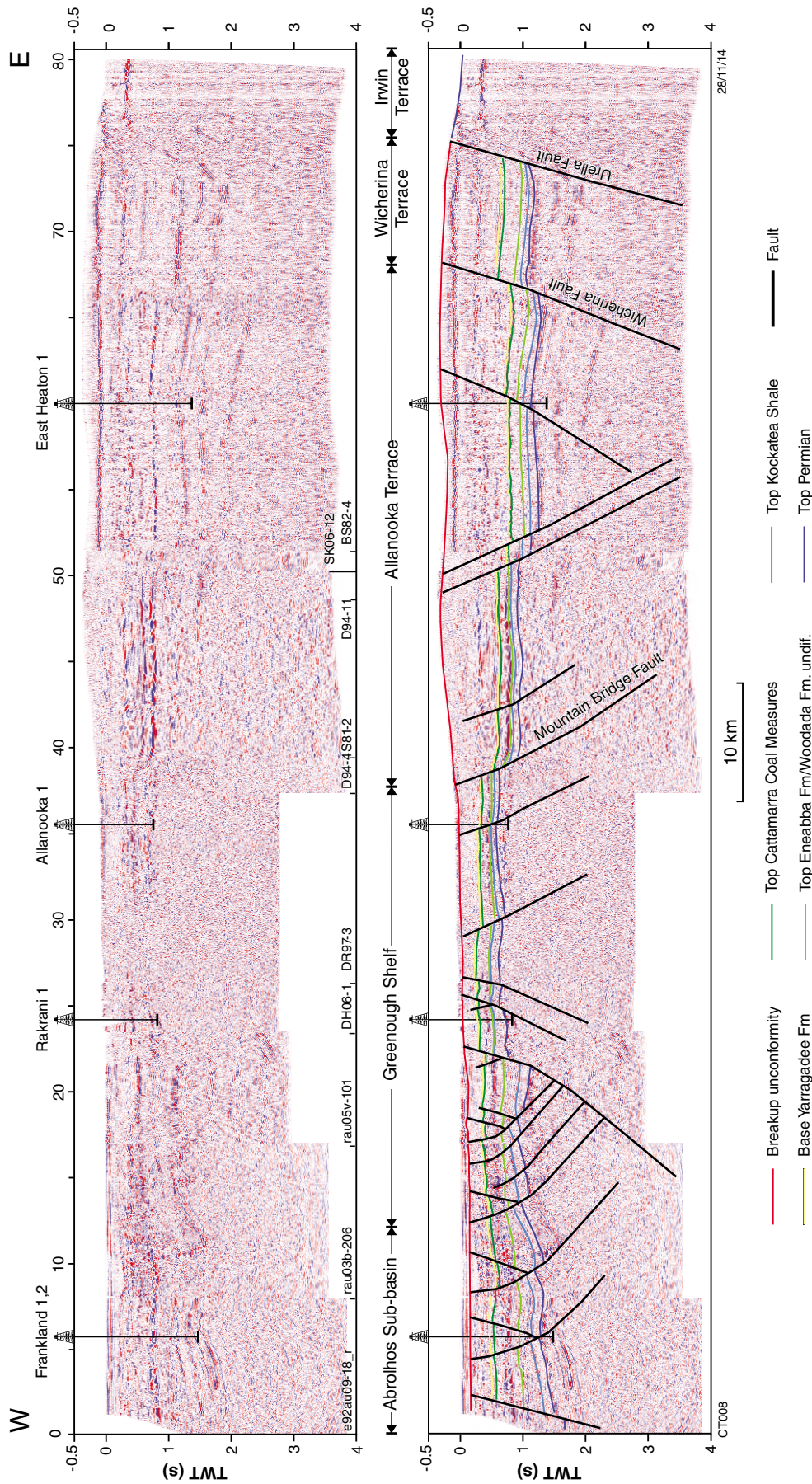


Figure 7. West to east composite seismic section from the Arolhos Sub-basin to the Irwin Terrace (location marked on Fig. 3)

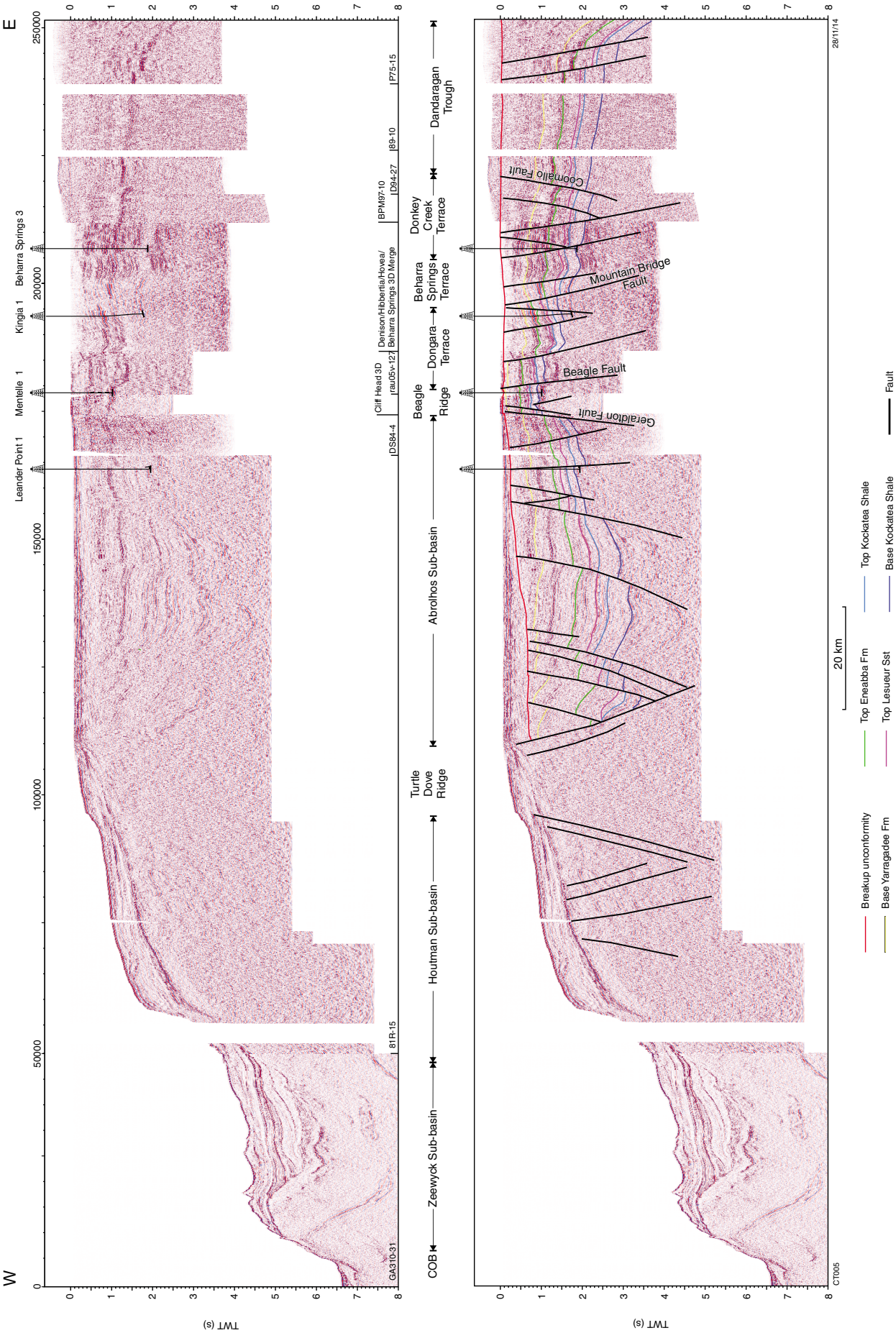


Figure 8. West to east composite seismic section from the continent-ocean boundary to the Dandaragan Trough (location marked on Fig. 3)

The Beagle Ridge is a basement high, where gneisses and ?granites, presumably belonging to the Proterozoic Pinjarra Orogen, have been intersected at depths ranging from 1013–1726 m below sea level in Freshwater 1, Jurien 1, Leafcutter 1, Mentelle 1, BMR 10A Dongara, and Cliff Head 1, 3 and 4. Westward thinning and onlap of the lower Permian succession onto basement suggests that the Beagle Ridge was a positive feature throughout this epoch (Jones and Hall, 2002).

Vitrinite reflectance values and spore-pollen maturity indexes determined from samples from petroleum wells of the Cattamarra Coal Measures, Kockatea Shale, and lower Permian strata indicate that the Beagle Ridge underwent significant uplift and erosion during breakup (Cook, 1979b; Watson, 1983; Wood, 2003; Geotech, 2004; AWE Ltd, 2011). Between 400 and 450 m of overburden is estimated to have been removed at Cliff Head oilfield in the western Beagle Ridge (Roc Oil Pty Ltd, 2004).

From aeromagnetic field data onshore, Mory (1994) and Mory and Iasky (1996) interpreted a series of short northwest-striking strike-slip faults that offset a major northerly striking fault part of the Beagle Fault System. This interpretation was in agreement with Heath et al. (1993), who had interpreted northwest-striking dextral strike-slip faults in magnetic data offshore. The onshore lineaments are closely spaced (1 – 2.5 km), and some faults display left-lateral displacement, whereas others display right-lateral displacements, which is difficult to explain if they formed at the same time. With more recent reprocessing of magnetic data, these northwest-trending lineaments are more noticeable (Fig. 10), although lateral offsets along these lineaments, if any, remain uncertain. In addition, many of these northwest-trending lineaments correspond more closely with Cenozoic heavy mineral sand strandlines and ferricrete bodies within coastal-plain sedimentary rocks and limestone (Miller, 2003, 2004; Fig. 10) — an association confirmed by drilling. Heavy mineral sand strandlines have a strong magnetic response in many areas of the Swan Coastal Plain, and in the Jurien to Gingin area are typically distinctly linear bodies that trend northwest to north for up to 40 km, and may also have subtle topographic expressions. However, it is still possible that the strandlines and ferricrete bodies formed in response to tectonism or non-tectonic vertical movements spatially coinciding with underlying faults (for example, due to differential compaction). Unfortunately, there is no reflection seismic coverage over the interpreted strike-slip faults, and their existence remains inconclusive.

Abrolhos Sub-basin

The Abrolhos Sub-basin (16 – Figs 3, 7, and 8; Playford, 1971) is located almost entirely offshore, directly west of the Greenough Shelf, Dongara Terrace, and Beagle Ridge. Hocking (1994) interpreted the sub-basin's southern faulted boundary with the Turtle Dove Ridge to have formed as a result of sinistral transtension; however, Jones et al. (2011) found no evidence of strike-slip movement along this fault. Therefore, the sub-basin's southern margin is imprecisely defined and, as currently shown by Geological Survey of Western Australia (2007), does

not follow the mapped structures of Jones et al. (2011) or correspond with any gravity anomalies.

The sub-basin consists of a central, narrow, north-northwesterly trending graben, and a northwesterly trending major horst block (the Geelvink High of Jones et al., 2011). The sub-basin narrows drastically to the northwest, forming an elongate, structurally intermediate block (Wittecarra Terrace) between the Houtman Sub-basin to the southwest and the Gascoyne Platform of the Southern Carnarvon Basin to the northeast. The boundary between the two basins follows the Geelvink Fault System (Fig. 5; Iasky et al., 2003).

The Abrolhos Sub-basin was a major early Permian to Early Jurassic depocentre (Jones et al., 2011), and contains up to 12 km of sedimentary fill (Petkovic, 2012). The oldest unit is the Tumblagooda Sandstone, which has been interpreted in petroleum wells on the Wittecarra Terrace and the Geelvink High based on lithology only (Crostella, 2001; Jorgensen et al., 2011).

Although the Abrolhos Sub-basin has good seismic coverage, relatively few wells have been drilled (16) within its boundaries.

Turtle Dove Ridge

The offshore Turtle Dove Ridge (17 – Figs 3 and 8; Jones and Pearson, 1972) is a narrow, north-northwesterly trending horst between the Abrolhos, Houtman, Vlaming, and Zeewyck Sub-basins. The trend and boundaries of this tectonic unit as shown in Geological Survey of Western Australia (2007) differ from that of Jones et al. (2011), whose interpretations were based on more recent and more detailed seismic mapping. Basement in this region is shallow, reaching ~3 km below the sea floor at its deepest (Petkovic, 2012).

Houtman Sub-basin

The offshore Houtman Sub-basin (18 – Figs 3 and 8; Symonds and Cameron, 1977) is an elongate, northwest-trending depocentre, which differs from all tectonic units to the south and east in having predominantly northwest-striking normal faults, as opposed to more northerly to north-northwesterly trending faults (Jones et al., 2011; Bradshaw et al., 2003; Fig. 5). The proximity of the sub-basin to the northwesterly trending Wallaby–Zenith Fracture Zone may explain the dominant fault strike. Johnston and Petkovic (2012) interpreted up to 12 km of sedimentary fill in this sub-basin, which Jones et al. (2011) show as largely Triassic to Middle Jurassic in age.

The northern boundary of the Houtman Sub-Basin is defined as a thinning of strata caused by Valanginian (Early Cretaceous) uplift and erosion. Bradshaw et al. (2003) considered the western sub-basin boundary to be a volcanic rifted margin, based on the interpretation of Valanginian seaward-dipping reflectors (Colwell et al., 1994; Symonds et al., 1998) and possible flood basalts and sills. Using seismic data, Gorter (2009) interpreted a set of recent volcanic sea mounts close to the basin's southern

boundary, and although this interpretation has not been tested, basalts were dredged along this boundary in 2008. Their age has yet to be determined (Daniell et al., 2009).

Despite relatively dense seismic coverage, especially towards the south, only three wells have been drilled within the sub-basin, limiting the available control on seismic data.

Barberton Terrace

The Barberton Terrace (19 – Figs 3 and 11; Mory and Iasky, 1996) is interpreted as an elongate half-graben bounded completely by the Darling and Muchea Faults. Data from Barberton 1 (the only petroleum well drilled to date in the terrace) and a set of water bores confirm that the terrace's thick succession of pre-breakup Triassic–Jurassic strata is at very shallow depths (Sanders, 1967; Backhouse, 1992b).

Beermullah Trough

Crostella and Backhouse (2000) considered the Beermullah Trough (20 – Figs 3 and 11) to be an unconnected depocentre to the Dandaragan Trough. The Beermullah Trough's eastern boundary is defined as the combined Darling and Muchea Faults, and the western boundary with the Turtle Dove Ridge is poorly defined. The southern and northern boundaries are interpreted to be the Turtle Dove Transfer Fault and the Cervantes Transfer Fault, respectively. However, the orientation and continuity of both the Turtle Dove and Cervantes Transfer Faults are poorly defined, at best, and the current quality and distribution of seismic data cannot help constrain these boundaries. This uncertainty calls into question the existence of these faults, and means that the definition of the Beermullah Trough may itself need to be reconsidered. The Turtle Dove and Cervantes Transfer Faults are discussed further below (see the 'Transfer faults' section under 'Timing and nature of major structures').

Crostella and Backhouse (2000) interpreted the Beermullah Trough to be structurally lower than the Mandurah Terrace to the south, as they interpreted the Mesozoic section in Mandurah Terrace wells to sit higher than those in the Beermullah Trough. Major normal faults in this tectonic unit strike north-northwest, and faults with less offset strike northwest. The trough also contains large-scale anticlines, which Crostella and Backhouse (2000) interpreted as compressional structures related to the 'convergence' of the two transfer faults, although it is unclear exactly what they meant by this. Some of these anticlines are in the hangingwalls of major north-northwesterly striking faults, and so it is possible that wrenching along these faults formed these anticlines at jogs, which is consistent with the mechanism postulated by Song et al. (2001) for other anticlines throughout the basin.

Vlaming Sub-basin

The mostly offshore Vlaming Sub-basin (21 – Figs 3, 4 and 11; Jones and Pearson, 1972) lies west of both the Mandurah Terrace and Bunbury Trough, and is delineated from these sub-basins by the westerly dipping Badaminna Fault System. Iasky and Lockwood (2004) identified an elongate residual gravity anomaly straddling the interpreted Vlaming Sub-basin – Mandurah Terrace boundary, which they interpreted as a shallowing of basement.

The Zeewyck Sub-basin, Mentelle Basin, and the interpreted offshore extension of the Vasse Shelf all lie to the west of the Vlaming Sub-basin, and their boundary with the Vlaming Sub-basin is the offshore extension of the Busselton Fault. However, Nicholson et al. (2008) considered part of the western boundary of the Vlaming Sub-basin to lie further west, and so incorporated part of the offshore Vasse Shelf into the Vlaming Sub-basin.

The Vlaming Sub-basin has more than 12 km of sedimentary fill (Nicholson et al., 2008). The oldest known basin-fill rocks were dredged from the deeply incised submarine Perth Canyon, and are of late Permian age (Seggie, 1990). The sub-basin is interpreted to have been a major depocentre during Jurassic times, and is deepest centrally, outboard of Rottnest Island (Nicholson et al., 2008).

Seventeen wells have been drilled to date within this sub-basin, most of which are in the southern half of the sub-basin and tested sizeable structural highs, such as tilted half-grabens (e.g. the Roe High). Other drilled highs have been interpreted by Marshall et al. (1993) as wrench anticlines associated with interpreted northwest-striking transfer faults that formed during the last phase of rifting (e.g. the Peel, Koombana, and Sugarloaf Arches). Alternatively, Bradshaw et al. (2003) interpreted the Peel Arch to be an inverted graben.

Zeewyck Sub-basin

The Zeewyck Sub-basin (22 – Figs 3 and 9; Bradshaw et al., 2003) is a narrow, north- to northwest-trending sub-basin bounded by Indian Ocean crust to the west, the Vlaming Sub-basin and Turtle Dove Ridge to the east, and by the Houtman Sub-basin to the north and northeast. The northwest-trending portion of the sub-basin in the north is interpreted as a pull-apart basin (Bradshaw et al., 2003), and lies along strike of the Wallaby–Zenith Fracture Zone (Fig. 5) in the Perth Abyssal Plain. Despite its narrowness, the sub-basin is very deep (up to 13.5 km; Johnston and Petkovic, 2012), consistent with it being a pull-apart basin. The age of sedimentary fill is uncertain as there are no wells drilled within its boundaries, and correlation from wells in adjoining tectonic units using seismic data is difficult due to uncertainty in matching seismic signatures across major faults.

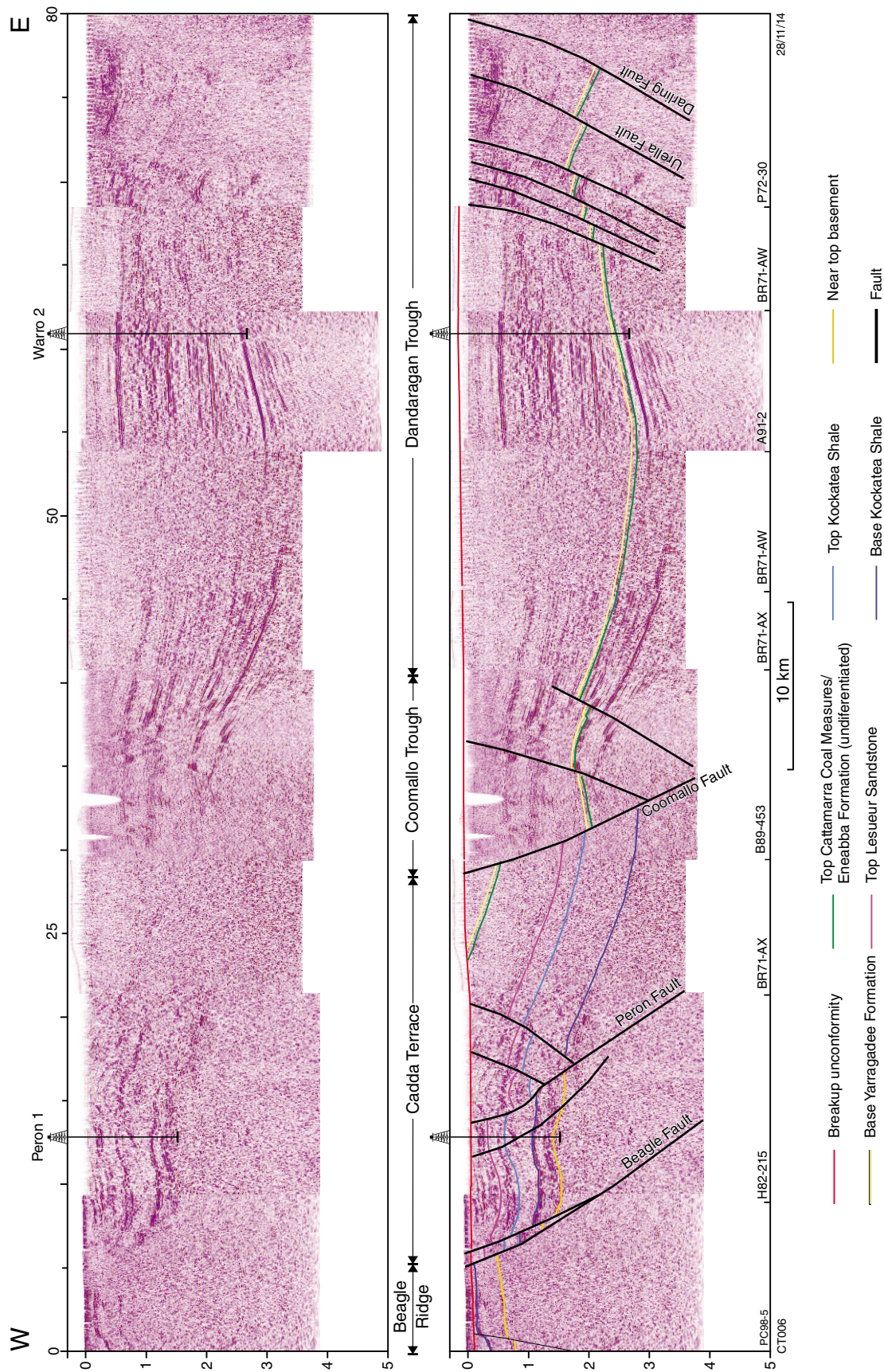


Figure 9. West to east composite seismic section from the Beagle Ridge to the Darling Fault (location marked on Fig. 3)

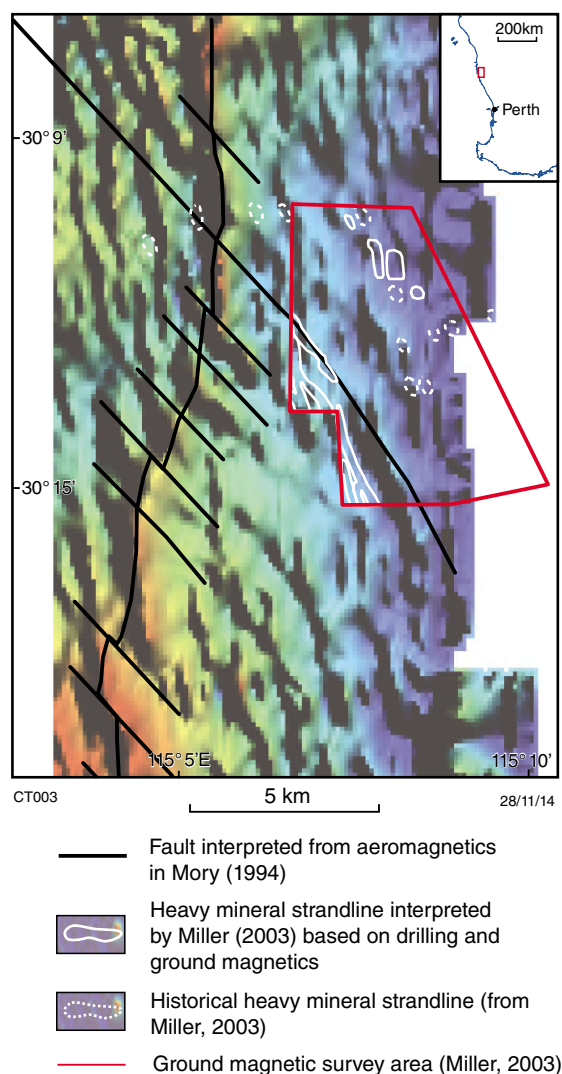


Figure 10. Aeromagnetic anomaly image over part of southern Beagle Ridge, and two different interpretations of the northwesterly trending lineaments

Mandurah Terrace

The Mandurah Terrace (23 – Figs 4 and 12; Crostella and Backhouse, 2000) is defined as a structurally intermediate fault block between the Yilgarn Craton to the east, and the Vlaming Sub-basin to the west, bounded by the Darling Fault and Badaminna Fault System, respectively.

The northern boundary is designated as the Turtle Dove Transfer Fault, which is vaguely defined. The terrace's relationship with the Beermullah Trough to the north is uncertain, especially because there are few deep wells in the northern half of the Mandurah Terrace. Pre-breakup strata become shallower towards the south, culminating in the Harvey Ridge (see subsection 'Harvey Ridge').

Wilkes et al. (2011) interpreted a pervasive set of predominantly northwesterly and northerly striking normal faults in the central Mandurah Terrace (Perth metropolitan area) to explain present-day topographic ridges or depressions and river-bends. The present-day land surface around Perth is dominated by a set of parallel, northerly trending ridges within the eolian Pleistocene Tamala Limestone, and the modern redistribution of sediments by wind-blown dunes mainly along the coast, implying an age of faulting at least younger than Pleistocene. However, it seems more probable that the northerly trending topographic ridges and depressions reflect the crests of the linear, lithified dunes and former interdunal lagoons comprising the Spearwood Dune System (part of the Tamala Limestone; Gozzard, 2007), rather than being the direct result of faulting. Furthermore, it is unlikely that northwesterly and northerly striking faults would be reactivated as normal faults, given that the present-day maximum horizontal compressive stress in the Perth Basin is oriented east–west, although good quality data to ascertain the in situ stress field in the immediate Perth metropolitan area is lacking (Reynolds and Hillis, 2000). Further, Wilkes et al. (2011) conceded they were uncertain about which side of their interpreted faults was the hangingwall. Patterns of Pleistocene to Recent sedimentation might still have been influenced by underlying faults, if those faults had an effect on sedimentary processes such as differential compaction.

Harvey Ridge

The Harvey Ridge (referred to as the 'Preston Ridge' in some early reports; e.g. Lehmann, 1966) is a broad, roughly east–west to southeast–northwest oriented basement high seen in seismic sections and associated with a higher gravity anomaly than adjacent areas (Sealy, 1969). Interpretations of its origin, orientation, geometry and westward (offshore) extent vary in the literature. It has been described variously as: a basement ridge as a result of normal faulting (e.g. 'Harvey Fault' of Hawkins et al., 1965); a fold with intrusions that formed during regional compression (Iasky, 1993); an extensional accommodation zone (Dentith et al., 1994a,b); or as an 'uplift' that formed in response to strike-slip movement along a transfer fault (Marshall et al., 1993; Song and Cawood, 2000). Rocks equivalent in age to the Yarragadee and Cadda Formations appear to be absent on the ridge, but whether this is due to erosion or lack of deposition, is unclear. Crostella and Backhouse (2000) suggested that the Yarragadee Formation had been eroded from the ridge, although the basis for this interpretation is unclear. Vitrinite reflectance values of Mesozoic strata in Pinjarra 1 and Lake Preston 1 were used as evidence that some overburden had been removed (Kantsler and Cook, 1979), presumably during breakup. Langhi et al. (2013) estimated ~1500 m of sediment removal above the Permian section, but how this compares with areas directly adjacent to the ridge is uncertain.

Iasky (1993) argued that the Harvey Ridge is the result of uplift during the late Permian, based on an abrupt

change in the gradient of vitrinite reflectance values seen between upper Permian and Upper Triassic strata in Lake Preston 1. It is likely that the ridge was a topographic high sometime during the Mesozoic, as Mesozoic strata thicken southwards from the ridge (Fig. 12). Although Crostella and Backhouse (2000) interpreted this thickening as mainly within the Lesueur Sandstone, they used a lithostratigraphic framework based on northern Perth Basin strata to define formation tops and did not consider biostratigraphic or seismic data tied to wells; therefore, this thickening could have been later in the Mesozoic. Based on more recent seismic horizon mapping (Zhan, 2014; this Record), potentially significant thickening can be interpreted for the Eneabba Formation or younger strata (Fig. 12). However, there are few deep petroleum exploration wells directly south of the Harvey Ridge (where the seismic interpretation is constrained by shallower water bores), and hence there is presently little control on the correlation between GSWA Harvey 1 and Wonnerup 1 (Figs 4, 12). The sparse distribution and poor quality of seismic lines directly south of the ridge make correlation extremely difficult, which in turn has hampered a thorough understanding of this enigmatic structure. This problem has been exacerbated by the difficulties in identifying time-equivalent units in wells and water bores throughout the southern Perth Basin. In the Harvey Ridge region, rock samples are typically heavily oxidized, and yield few (if any) palynomorphs, reducing the resolution of spore-pollen biostratigraphy. Furthermore, many previous studies correlated wells and water bores using lithostratigraphy only, with no attention paid to seismic or fossil data.

The Bouguer gravity anomaly map (Fig. 4a) shows that onshore the Harvey Ridge broadly comprises two adjacent regions with different gravity responses (Zhan, 2014, figure 20). The change in gravity response broadly coincides with a major north-striking normal fault downthrown to the west (Fault 'L'; Fig. 4b). This gravity response, where the footwall of a major normal fault is associated with a lower gravity anomaly than the hangingwall, is unexpected, and the cause is presently unknown; it may be related to the presence of deep intrusions, as proposed by Iasky (1993), or to differences in basement lithology. Recent and historical 2D seismic horizon mapping indicates that the ridge is traversed by northwest- and north-striking normal faults (Hearty, 1991; Schlumberger Carbon Services, 2011; Zhan, 2014), of which the northwest-striking faults represent splays off the Darling Fault and other large north-striking faults. There is no clear evidence of synrift wedge-geometries or significant hangingwall strata thickening against any of the normal faults. Therefore, it is likely that these faults formed, or were mainly active, after deposition of the Eneabba Formation (as interpreted by Zhan, 2014), but before the Valanginian breakup unconformity. Hearty (1991) noted the minor, north-striking normal faults across the Harvey Ridge that offset the base of the Lesueur Sandstone and lower strata, but do not reach the Yalgorup Member ('upper Lesueur Sandstone'). Unfortunately, the seismic quality is poor at these depths, and these faults

have negligible throws and cannot be traced far below the Wonnerup Member ('lower Lesueur Sandstone'). Therefore, these faults are either syndepositional with this member, or are blind faults contemporaneous with the younger faults.

The Harvey Ridge not only corresponds to the area with the greatest throw and footwall uplift along the major north-south striking fault about 17 km west of the Darling Fault (Fault 'L' in Fig 4b), but peculiarly, also corresponds to the shallowest part along its hangingwall (see figure 19 of Zhan, 2014). Together, these features suggest low-amplitude folding orthogonal to both the north-south fault and Darling Fault. Given the predominance of north- and northwest-striking faults in the area, it is feasible that the ridge sits within a restraining bend formed during dextral strike-slip reactivation of the major north-striking faults, consistent with northwest-southeast extension during the final rifting phase, although much more work is needed to confirm this. This interpretation does not invoke strike-slip movement along a transfer fault, and similar structures of this age have been interpreted elsewhere in the basin, albeit on a much smaller scale (e.g. along the Beagle Fault; Song et al., 2001). Although based on sparse 2D seismic data, existing interpretations indicate a complex fault-pattern that should be better delineated by the 2014 Harvey 3D seismic survey.

Bunbury Trough

Like the Dandaragan Trough, the Bunbury Trough (24 – Figs 4 and 12; Thyer and Everingham, 1956) is a major graben in the hangingwall of the Darling Fault, associated with a marked gravity low. To the west, it is bounded by the north-striking, easterly dipping Busselton Fault, which shows much less normal dip-slip movement than the opposing Darling Fault. The Harvey Ridge and Vlaming Sub-basin lie to the north, and the Bight Basin lies to the south. Permian and Mesozoic strata in the Bunbury Trough are mostly structurally higher than in the adjacent Vlaming Sub-basin. Iasky (1993) interpreted up to ~11 km of Permian and younger strata within the trough, which overall thin towards the south. Subsidence modelling based on vitrinite reflectance values obtained from Permian and younger rocks in Whicher Range 1 (Iasky, 1993) indicates little uplift and erosion within at least that part of the Bunbury Trough throughout its history.

A series of large anticlines in the hangingwall of the Busselton Fault host gas accumulations, such as at Whicher Range (Owad-Jones and Ellis, 2000). These folds are truncated by the Valanginian breakup unconformity, and were interpreted to have resulted from strike-slip reactivation during the final rift phase in the Late Jurassic – Cretaceous (Iasky, 1993; Crostella and Backhouse, 2000). Conversely, these structures have also been interpreted as rollover anticlines (WA:ERA, 2012), an interpretation supported by more recent seismic mapping that indicates that the Busselton Fault is listric at depth (Amity Oil N.L., 2000).

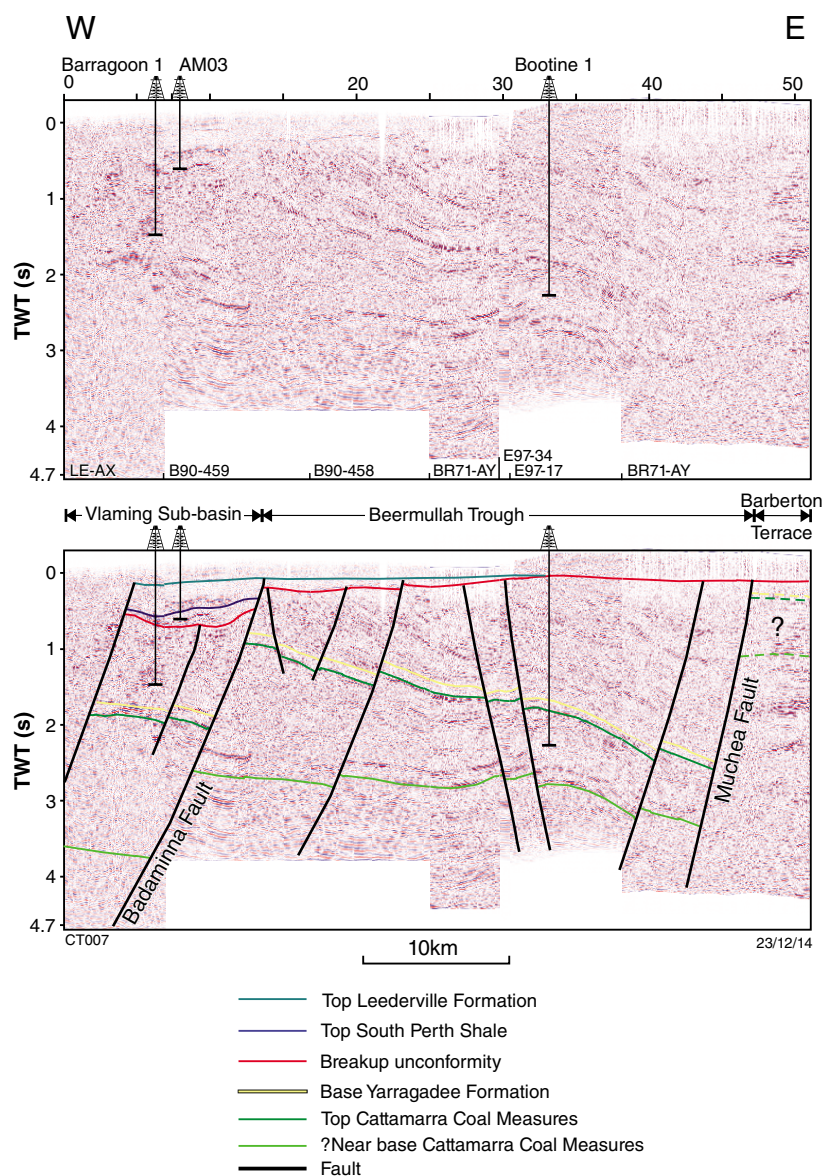


Figure 11. West to east composite seismic section from the easternmost Vlaming Sub-basin to the Barberton Terrace (location marked on Fig. 3)

Vasse Shelf and Treeton Terrace

The Vasse Shelf (25 – Playford and Willmott, 1958), including the Treeton Terrace (26) to the west (Fig. 4; Hocking, 1994), is a shallow basement fault block on which up to 2000 m of Permian strata were deposited (Crostell and Backhouse, 2000), overlain by up to 1000 m of thinner Triassic and younger Mesozoic strata. Jurassic strata are mostly absent, except in the hangingwalls of some faults where a small number of coal drillholes intersected thin sections of the Yarragadee Formation (e.g. Watts, 1984; Ellis, 1985). Iasky and Lockwood (2004) postulated that basement rocks of the Leeuwin Inlier (30) continue under the Vasse Shelf based on potential-field data only, although earlier Fletcher and Libby (1993) suggested that a different basement terrane underlies the shelf based on Sm–Nd model ages.

To the west, the Treeton Terrace and southern Vasse Shelf are both bounded by the Dunsborough Fault, which separates them from the Mentelle Basin and Precambrian Leeuwin Inlier (30). It is bounded to the east by the Busselton Fault, which separates it from both the deeper Bunbury Trough and the offshore Vlaming Sub-basin. Towards the south, the Dunsborough Fault increases in throw and Vasse Shelf strata deepen (Iasky and Lockwood, 2004).

The Treeton Terrace is shown in Geological Survey of Western Australia (2007) as the sliver of the Vasse Shelf between the Dunsborough and Wurring Faults. Basement is shallower here than in the rest of the southern Perth Basin (Iasky and Lockwood, 2004), and Permian coal seams are also at shallower depths (<500 m in the Treeton Terrace compared to <800 m in northern Vasse Shelf). This has attracted substantial coal exploration since the 1960s. High

vitrinite reflectance values (up to 0.8%; Millar, 1989; Park, 1989) obtained from these coal seams indicate up to ~3 km uplift and removal of overburden from the Treeton Terrace.

Within the remainder of the Vasse Shelf, a lateral variation in vitrinite reflectance values from Permian coals was interpreted by Le Blanc Smith and Kristensen (1998) to be the result of lateral variation in basement lithology or undulating basement topography at the time of deposition, or both, which would have caused variable crustal heat flow across the shelf. Iasky (1993) suggested uplift and erosion during the late Permian and again in the Late Jurassic based on vitrinite reflectance data from Sue 1 in the southern Vasse Shelf. However, evidence for the postulated late Permian uplift event is weak, because vitrinite reflectance measurements on lower Permian samples from Sue 1 are scattered (Cook, 1979a), and Iasky's (1993) interpretation of a change of reflectance gradient is based on one outlier, which came from a cuttings sample. Furthermore, the well encountered a dolerite intrusion within the lower Permian succession (Williams and Nicholls, 1966), but its possible effect on vitrinite reflectance values was not discussed by Iasky (1993). The age of the dolerite has not yet been established. Given that vitrinite reflectance within the lower Permian samples are 0.6 – 0.8% (excluding the outlier), and that Sue 1 reached 3074 m, it is possible that there has been very little uplift in this area, and therefore across the southern part of the Vasse Shelf. Sue 1 offers the most expanded and complete section of lower Permian strata in this part of the basin, and a thorough evaluation of its burial history should be included in future work, as it has implications for the timing of structures including the Darling Fault. In contrast to Iasky's (1993) postulated late Permian uplift, Late Jurassic uplift better explains the reworked Permian palynomorphs in the Yarragadee Formation in the Bunbury Trough (Wharton, 1982).

Iasky (1993) interpreted extensive sinistral strike-slip movement along the Dunsborough Fault, to explain the Wurring Fault and other minor faults within the Vasse Shelf and Treeton Terrace. Furthermore, he considered the Wurring Fault and other minor faults to have formed at releasing and restraining bends where the Dunsborough Fault abruptly changed strike. However, this interpretation was based on very sparse, poor-quality 2D seismic in the area immediately adjacent to the Dunsborough Fault, and Iasky (1993) did not show any seismic that would be consistent with that interpretation.

Collie, Wilga and Boyup Sub-basins

The Collie Sub-basin (27 – Fig. 4) is an outlier within the southwestern Yilgarn Craton, and contains up to 1400 m of lower to middle Permian strata unconformably overlain by up to 20 m of the Lower Cretaceous Nakina Formation (Millar et al., 2011). Its southwestern and northeastern boundaries are along steep, northwest-striking normal faults, whereas the Permian strata unconformably onlap basement on its northern and southern boundaries.

The sub-basin lies along northwest–southeast trending lineaments of uncertain origin and age, which traverse the Yilgarn Craton and appear to laterally displace the Darling Fault and structures of the Albany–Fraser Orogen (Dentith et al., 1994a). The sub-basin comprises two northwest-trending half-grabens, which Le Blanc Smith (1993) interpreted as pull-apart basins resulting from dextral strike-slip reactivation of the enigmatic lineaments.

The Wilga and Boyup Sub-basins (28, 29 – Fig. 4) also contain lower to earliest middle Permian strata, and were regarded by Le Blanc Smith (1990) to be northwesterly trending half-grabens. These sub-basins have not been investigated as thoroughly as the Collie Sub-basin, so the nature and extent of their boundaries are poorly known.

All three sub-basins were once considered part of a basin separate to and distinct from the Perth Basin ('Collie Basin', including Wilga and Boyup 'Outliers'), but were later designated by Tyler and Hocking (2002) as sub-basins of the Perth Basin. There are strong similarities between the Permian stratigraphy of the Collie, Wilga and Boyup Sub-basins, and the rest of the Perth Basin, particularly the Vasse Shelf, based on lithology and palynology (Le Blanc Smith, 1990; Backhouse, 1993). Therefore, the Permian strata of these sub-basins are now regarded to have once formed part of an extensive sheet of sediments that extended from the larger Perth Basin across the Darling Fault and over at least part of the Yilgarn Craton, and to have been preserved by normal faulting sometime between the mid-Permian and Early Cretaceous (Millar et al., 2011). Le Blanc Smith (1993) argued that the normal faults bounding the Collie Basin must have occurred after early mid-Permian, given that the early mid-Permian strata show no hangingwall thickening within the sub-basin. Millar et al. (2011), who noted that faults in the Permian strata of the Collie Sub-basin post-date lithification, suggested that faulting took place during the latest Jurassic – earliest Cretaceous. The original thickness of Permian and younger strata over the Yilgarn Craton, is currently uncertain. Also uncertain is whether Permian strata were originally deposited more thinly over the Yilgarn Craton than in the Dandaragan and Bunbury Troughs, perhaps due to an active Darling Fault. This point is discussed further in the Darling Fault System section (under 'Timing and nature of major structures').

Basement

There have been relatively few intersections of basement rocks in wells or drillholes in the Perth Basin, and most of those intersections were in wells drilled on basement highs, such as the Beagle Ridge, Cadda Terrace, Dongara Terrace, Greenough Shelf and Vasse Shelf. However, igneous and metamorphic basement rocks outcrop in the adjacent Leeuwin Inlier (30), Northampton Inlier (6) and Mullingar Inlier (7), all of which are now interpreted as discrete terranes assembled during multiple orogenic events in the Proterozoic (Janssen et al., 2003; Johnson, 2013 and references therein). These terranes are also interpreted to underlie much of the sedimentary succession in the surrounding Perth Basin (Hall et al., 2012; Iasky and Lockwood, 2004).

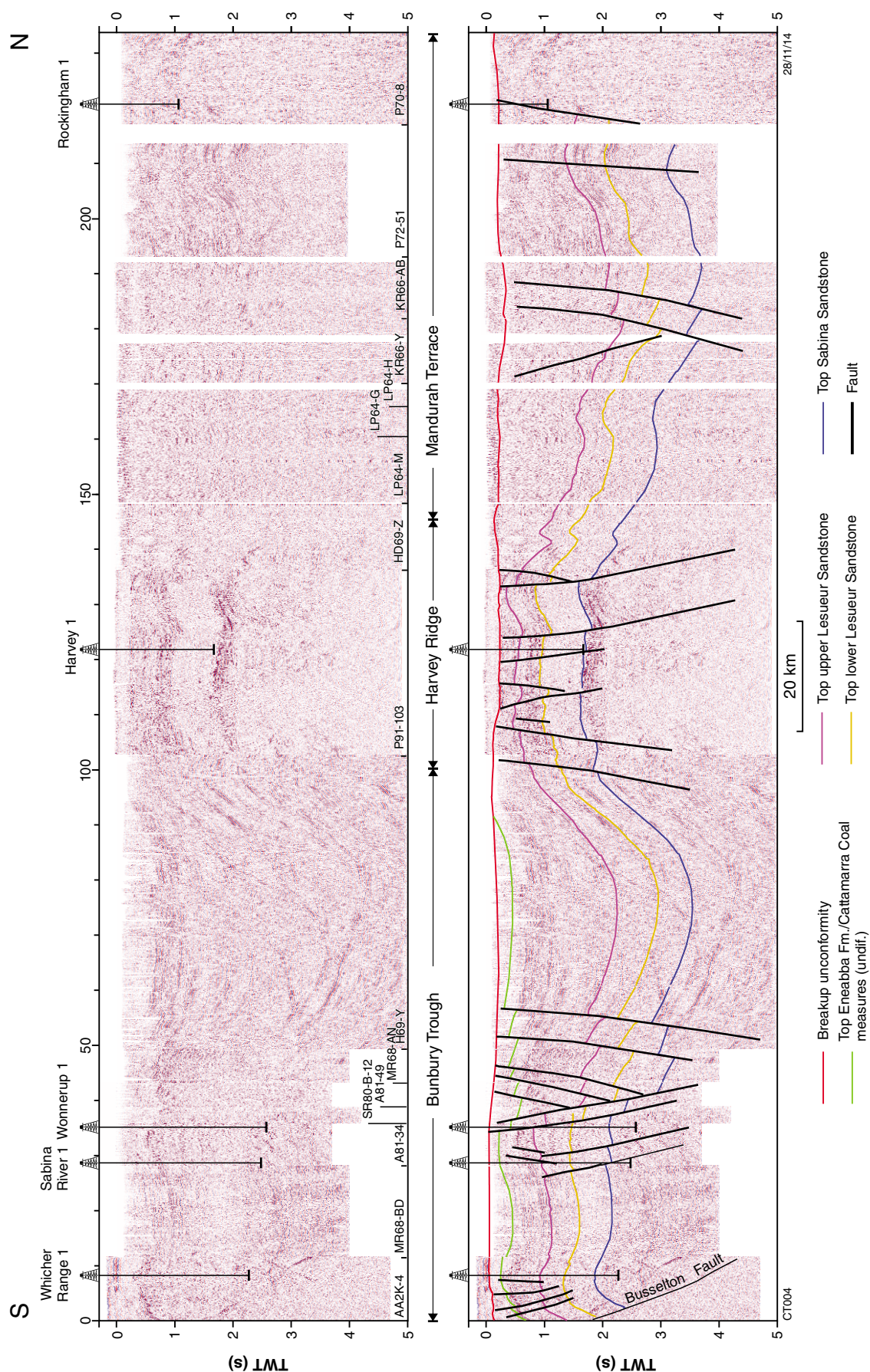


Figure 12. South to north composite seismic section from the Bunbury Trough to the Mandurah Terrace (location marked on Fig. 4)

Stratigraphy and tectonic events

Figure 6 outlines the stratigraphy of the Perth Basin, and summarizes the tectonic events recognized in the most recent studies. For detailed lithological descriptions, age controls, or interpretations of depositional environments, refer to Playford et al. (1976), Mory and Iasky (1996), or Crostella and Backhouse (2000).

The mid-Carboniferous to middle Permian succession records a period of glaciation and subsequent deglaciation in a mainly marine-influenced depositional setting, within which marine influence decreases southwards. This succession is truncated by a mid-Permian unconformity that is angular in the north of the basin (Cockbain and Lehmann, 1971; Quafe et al., 1994). The exact age attributed to this unconformity varies between studies of different areas within the basin although this may be due to a genuine diachronism across the basin. For the most part, the unconformity is interpreted to lie between the Carynginia Formation and the overlying Beekeeper Formation – Wagina Sandstone – Dongara Sandstone (e.g. Hall, 1989; Quafe et al., 1994; Mory and Iasky, 1996; Norvick, 2004). The break between the Carynginia Formation and overlying units is indicated by the apparent absence or scarcity of the *Dulhuntyispora granulata* spore-pollen zone in wells north of the Beermullah Trough (Backhouse, 1993), as well as in the offshore Abrolhos Sub-basin and northwards (Jorgensen et al., 2011). However, Jones et al. (2011) and Jorgensen et al. (2011) interpreted the angular unconformity to correspond to the *D. dulhuntyi* spore-pollen zone, which is also apparently absent across the basin (Backhouse, 1993), thereby placing it between what they defined as the Beekeeper Sequence below and Dongara Sequence above. In contrast, Mory and Backhouse (1997) did not recognize the *D. dulhuntyi* zone in the Southern Carnarvon Basin, and did not consider it relevant in that basin, so it is possible that the *D. dulhuntyi* zone is similarly not relevant in the upper Permian stratigraphy of the northern Perth Basin. The definitions for, and interpretations of coevality of, the middle to upper Permian Wagina Sandstone, Dongara Sandstone and Beekeeper Formation also differ between research studies and industry reports (e.g. Tupper et al., 1994; Mory and Iasky, 1996; Laker, 2000). This confusion is partly due to the typically poor spore-pollen yield from this interval in the Perth Basin (e.g. Backhouse, 1992a; Purcell, 1994), the lack of other biostratigraphically useful paleontological data in the siliciclastic Wagina and Dongara Sandstones, and the difficulties in correlating between different biostratigraphic schemes. Therefore, the low biostratigraphic resolution of this interval has meant that units were assigned largely on the basis of lithology, even though it is clear that these lithostratigraphic units are at least partly contemporaneous.

The uppermost Permian – lowermost Cretaceous units record mainly fluvial to lacustrine deposition punctuated by briefer episodes of shallow-marine deposition extending until breakup (Cockbain and Lehmann, 1971; Playford et al., 1976; Crostella and Backhouse, 2000). Due to their similar continental, mostly fluvial, depositional

environments, it can be difficult to distinguish between the Lesueur Sandstone, Eneabba Formation, Yarragadee Formation, and even the Cattamarra Coal Measures in outcrop or core, unless seen in context with the more easily recognized shallow-marine Kockatea Shale or Cadda Formation, or if confirmed by biostratigraphy or other biomarkers. Unfortunately, the marine incursions responsible for the Kockatea Shale and Cadda Formation did not extend into the southern Perth Basin where their southern lateral equivalents are fluvial in origin, thereby introducing considerable difficulties in differentiating pre-breakup Triassic – lowermost Cretaceous units without biostratigraphic data.

Given the predominance of continental facies prior to the Valanginian and the length of the basin, lateral facies changes are likely, such that features considered characteristic for a unit in one part of the basin may not be evident elsewhere. An example of this is the widely used definition of the Eneabba Formation, which includes the ‘multicoloured’ mudstone in its type section in Eneabba 1 and most wells in the northern onshore part of the basin. However, such red-bed lithologies — produced by penecontemporaneous or post-depositional subaerial exposure and oxidation — have also been encountered in the Lesueur Sandstone or its equivalents in the Abrolhos Sub-basin and possibly the Mandurah Terrace (Watt, 2009; Millar and Reeve, 2014). Within the Bunbury Trough, sections considered equivalent to the Eneabba Formation based on palynology, but which lack multicoloured mudstone, were assigned by Crostella and Backhouse (2000) to the Cattamarra Coal Measures, thereby implying that the formation is highly diachronous across the basin. These issues demonstrate the shortcomings of relying heavily on lithostratigraphy for determining the history of subsidence and uplift across the basin. Recognition of palynological zones — the most applicable form of biostratigraphy for these continental successions, especially in the more mud-prone sections of these units — offers the best chance of making meaningful regional well correlations. However, facies suitable for palynology are rare in the Perth Basin due to pervasive oxidation. Furthermore, the prevalence of low-diversity assemblages in the Late Triassic – Early Jurassic hinder the identification of spore-pollen biozones.

Subsurface correlations for the upper Permian – Lower Cretaceous are also hindered by poor, commonly oxidized, outcrop. In addition, well-preserved exposures tend to be associated with faults and so are of limited stratigraphic extent. Therefore, a large dataset including seismic, wells and shallow boreholes is required to fully understand these units, although oxidation and faulting are still a problem.

Early to mid-Paleozoic intracratonic sag/?rifting

The oldest recorded sedimentary rocks in the Perth Basin belong to the Tumblagooda Sandstone of probable Ordovician – earliest Silurian age (Hocking, 1991; Mory and Hocking, 2008). It is not known if the ?Cambrian–Ordovician unit identified by Iasky et al.

(2003) underlying the Tumblagooda Sandstone in the Southern Carnarvon Basin extends into the Perth Basin. Within the Perth Basin, the Tumblagooda Sandstone is only recorded as far south as 28°45'S on the Greenough Shelf, along the western margin of the Bookara Shelf and in Coolcalalaya Terrace, but is far more extensive within the Southern Carnarvon Basin. This suggests that the Southern Carnarvon and northernmost Perth Basins were effectively one depocentre at this time, and so it cannot be expected that the present-day geographical extent of the Perth Basin bears any relation to the Paleozoic depocentre. Therefore, this raises the possibility that the Tumblagooda Sandstone in the northern Perth Basin would be better assigned to the Southern Carnarvon Basin, and that the Perth Basin is wholly comprised of uppermost Carboniferous and younger successions that in the north were deposited upon older rocks of the Southern Carnarvon Basin. The concept of overlapping or superimposed basins is discussed in some detail in Hocking (1994). Hocking (1991) described the 'Perth Basin' during deposition of the Tumblagooda Sandstone as a 'fault-bounded, northward-opening trough', with its eastern boundary along the Darling Fault, and interpreted the Darling Fault as active during the early Paleozoic. Playford et al. (1976) also considered extensional faulting to be contemporaneous with deposition of the Tumblagooda Sandstone. The southern boundary of this unit is defined by a shallowing of basement, which implies that the restriction of the Tumblagooda Sandstone to the northern Perth Basin was due to onlap onto the basement of the northern Perth Basin margin and hence nondeposition farther south, rather than erosion. Southward onlap of the Tumblagooda Sandstone onto the Northampton Inlier as seen in outcrop also suggests a southward shallowing of basement in the early Paleozoic; however, the absence of paleocurrent readings that could be inferred to show deflection around topographic highs, and the scarcity of garnet in the sandstone (although garnet is common in the inlier), indicates that the inlier was not emergent at this time (Hocking, 1991). The north-south trend of the basin during deposition of the Tumblagooda Sandstone is inferred only from the present-day strike of the Darling Fault (System), and is not indicated by facies distributions (Hocking, 1991). Most studies (summarized in Fig. 6) consider that deposition of the unit took place in an intracratonic sag.

Late Paleozoic rifting

Permian synrift deposits are easily identifiable on seismic data throughout the Perth Basin where strata thicken towards the major northerly and north-northwesterly striking faults that bound and define the some tectonic units. Synrift strata in the Abrolhos Sub-basin (Jones et al., 2011), and in the Vlaming Sub-basin (Nicholson et al., 2008), are truncated by an angular unconformity of middle-late Permian age (Quaife et al., 1994), and show significant thickening against the Beagle and Turtle Dove Ridges. During this rifting event, the Beagle Ridge and Northampton Inlier were emergent (Hall, 1989), with clear evidence of Permian onlap (Hocking, 1994; Jones and Hall, 2002).

Easterly striking faults of suspected Permian age that appear to span the entire Beharra Springs Terrace were identified by Powell (2002) in 3D seismic data, although the exact timing was not specified. However, these faults are relatively minor compared to the larger north-striking Mountain Bridge and Beharra Springs Faults, and they may be breached relays.

Duration and timing

The duration of this rifting phase is interpreted differently in different studies, although, like the sedimentary records, this may indicate genuine diachronism across the basin. Despite this, most studies agree that the onset of rifting is marked by the start of deposition of the mid-Carboniferous – lower Permian Nangetty Formation (e.g. Song and Cawood, 2000; Norvick, 2004; Jones et al., 2011).

Harris (1994) interpreted this rifting event as continuing until the Middle Triassic, whereas Marshall et al. (1989a) and Tupper et al. (1994) considered the middle to upper Permian Wagina Sandstone only to be a synrift deposit. In contrast, most other studies have concluded that the prominent unconformity above the Carynginia Formation or older lower Permian strata seen in the northern Perth Basin marks the end of the rifting phase (e.g. Mory and Iasky, 1996; Norvick, 2004). This mid-Permian unconformity is markedly angular in the Abrolhos and Houtman Sub-basins and possibly in some parts of the onshore northern Perth Basin, although interpretations of its age vary.

In many studies, biostratigraphic evidence (summarized above) was used to place the unconformity between the Carynginia Formation and the Beekeeper Formation, or its lateral equivalents, the Wagina and Dongara Sandstones. Other biostratigraphic interpretations placed it between the Beekeeper Formation and Dongara Sandstone.

At the top of the Redgate Coal Measures, which is considered age-correlative with the Carynginia Formation (le Blanc Smith and Kristensen, 1998), no angular unconformity was discernible in seismic data from the southern Perth Basin (Iasky, 1993). Furthermore, Crostella and Backhouse (2000) interpreted a conformable relationship between the Redgate Coal Measures and the overlying Willespie Formation, which is a correlative of the Dongara and Wagina Sandstones.

Kinematics and stress regime

Markedly different stress regimes have been proposed for this rifting event in different parts of the basin. Harris (1994) inferred regional extension direction in the range northeast-southwest to east-northeast – west-southwest based on: north-northwesterly and northwesterly striking normal faults in the (northern) Perth Basin; northwest-striking normal faults bounding the Collie Sub-basin; and a series of northwest-trending dykes interpreted to be Carboniferous and Triassic intruding Proterozoic metamorphic rocks in the Yilgarn Craton and Albany-Fraser Orogen, respectively, based on paleomagnetic

data only (Harris and Li, 1995). Furthermore, Harris (1994) had argued that this extension initiated a sinistral transtensional tectonic regime, with a sinistral strike-slip component inferred for the major northerly to north-northwesterly striking normal faults, and dextral component inferred for east-striking normal faults. However, there is presently no evidence for strike-slip movement along any of these faults at those times.

The inferred Carboniferous age for the Yilgarn Craton dykes was refuted by subsequent direct U–Pb dating of the dykes (Rasmussen and Fletcher, 2004), which yielded a c. 1218 Ma (Proterozoic) age. This weakens the case made by Harris (1994) for northwest–southeast extension during the late Paleozoic to early Mesozoic, and so this cannot be used to support that interpretation.

Phanerozoic secondary magnetization has previously been reported in Precambrian dykes in the Yilgarn Craton (e.g. Halls and Wingate, 2001), and may also have been an influence in the interpretation of Harris and Li (1995). The northwest strike of faults bounding the Collie Sub-basin is not sufficient evidence to confidently infer northeast–southwest extension, because the tectonic fabric of sheared basement rocks exposed along these faults has a similar strike to the faults, suggesting they are reactivated older structures (Le Blanc Smith, 1993). Furthermore, latest movement on these faults appears to post-date lithification of Permian strata (Millar et al., 2011).

Mory and Iasky (1996) also interpreted northeast–southwest Permian extension for the northern Perth Basin, based on a comprehensive compilation of fault azimuths mapped from seismic data, although they found the predominant normal-fault strike to be north-northwesterly. Furthermore, it is not clear if there was Permian growth on these faults. Stress tensor analyses of small-scale basement faults along the Darling Fault Zone by Beeson (1992; summarized in Dentith et al., 1994a) indicate northeast–southwest extension sometime between the Precambrian and Middle Jurassic. Beeson (1992) proposed that this event may have initiated basin formation. East-northeasterly extension was also proposed by Jones et al. (2011) for the offshore Abrolhos and Houtman Sub-basins, based on the predominance of north-northwesterly striking normal faults at the Permian level.

In contrast, Iasky (1993) suggested regional northwesterly extension for the southern Perth Basin, although his study did not extend north of 32°30'S. Iasky's (1993) interpretation was based on an assumption that the Harvey Ridge is a northwest-trending fold initiated in the late Permian. This is despite finding that almost all normal faults in this area strike north–south, and that the age of the Harvey Ridge is still uncertain (see 'Transfer faults' section under Timing and nature of major structures). Northwesterly extension implies a dextral strike-slip component on the major north-striking normal faults, which is in contrast to the sinistral component of north-striking faults implied by Harris (1994).

Late Triassic – Early Jurassic rifting

The earliest recognition of mid-Mesozoic rifting was by Hall and Kneale (1992), who interpreted Early Jurassic movement on the Mountain Bridge, Allanooka, Darling, Urella, and Muchea Faults. Gorter et al. (2004) suggested that thickening of the Eneabba Formation in the Abrolhos Sub-basin was caused by rifting at this time. Similarly, Song and Cawood (1999) and Mory and Iasky (1996) also interpreted syndepositional thickening of the Eneabba Formation towards both the Mountain Bridge and Beharra Springs Faults. Elsewhere in the Perth Basin, the absence of the Lesueur Sandstone or Eneabba Formation, or both, north of the Allanooka Fault (Mory and Iasky, 1996), due to erosion or nondeposition, is potentially the result of rift-generated topography. Although Mory and Iasky (1996) indicated conformable relationships between the Eneabba Formation and the underlying Lesueur Sandstone in the onshore Perth Basin, Quaife et al. (1994) and Jones et al. (2011) interpreted an angular unconformity at the base of the Eneabba Formation in the Abrolhos Sub-basin, which Jones et al. (2011) attributed to rift-related uplift.

Quaife et al. (1994) considered rifting in the offshore northern Perth Basin to be continuous from the Late Triassic (sometime during deposition of Lesueur Sandstone) to breakup in the Valanginian. Syndepositional faulting and thickening of the base Eneabba Formation up to the time of breakup in the western Houtman Sub-basin (Gorter et al., 2004) lends credence to the idea of continuous rifting at this time. Alternatively, Harris (1994) interpreted two separate rifting events during this time, designating the Eneabba Formation and Cattamarra Coal Measures as synrift deposits of one rift episode, and the Parmelia Formation as a synrift deposit in the next rift phase, with the intervening Yarragadee Formation designated as a post-rift deposit (Fig. 6). In contrast, Song and Cawood (2000) considered rifting to have ended before deposition of the Cattamarra Coal Measures, as they interpreted a uniform thickness for this unit across the (onshore) northern Perth Basin. However, minor growth on normal faults based on thickening of the lower part of the Cattamarra Coal Measures has been noted in the Beermullah Trough (IKODA Pty Ltd, 1998; Warris, 2012). Inconsistencies in stratigraphic nomenclature by Crostella and Backhouse (2000) — it is unclear if they included sections that are equivalent to the Eneabba Formation in the Cattamarra Coal Measures in the Bunbury Trough — make their claim of thickening of the latter unit towards the Darling Fault difficult to relate to other parts of the basin. In the southern part of the basin, the timing of rift onset in the Triassic–Jurassic is poorly constrained due to the lack of palynomorphs or other biostratigraphically useful organisms in the dominantly sand-prone, continental facies. The long time range of the Middle Triassic to Middle Jurassic spore-pollen zones also presents a problem, and it may be that the resolution of current biostratigraphic schemes is not sufficient to provide a more precise date.

Kinematics and stress regime

Various orientations have been proposed for regional extension in the Late Triassic and Early Jurassic, including east–west (Hall and Kneale, 1992; Harris, 1994; Mory and Iasky, 1996), west–northwest to east–southeast (Harris, 1994; Jones et al., 2011), and northeast–southwest (Iasky et al., 1991; Iasky, 1993). Of these, Harris' (1994) deduction of east–west extension was based on three earlier interpretations: dextral movement along northwest–striking transfer faults (Marshall et al., 1989a); a claim by Iasky et al. (1991) that Jurassic rifting was 'orthogonal'; and Early Jurassic initiation of north– to north–northwest–striking normal faults in the Cadda Terrace and Coomallo Trough (Hall and Kneale, 1992). In fact, Marshall et al. (1989a) interpreted northwest–southeast extension based on the similar extension vectors in the North West Shelf. Although they also interpreted dextral movement from positive flower-structures associated with north–northwesterly to northwesterly striking faults in the offshore Perth Basin, dextral movement was inferred assuming northwest–southeast extension, which resulted in a circular argument by Harris (1994)! More recent work in the offshore Abrolhos and Houtman Sub-basins by Geoscience Australia (Jones et al., 2011) did not agree with previous reports of strike-slip movement in the offshore Abrolhos and Houtman Sub-basins.

Although Iasky et al. (1991) indicated 'orthogonal rifting' in the Jurassic, they considered extension to be northeast–southwest, based on the predominance of Jurassic northwest–southeast striking normal faults that they interpreted in the southern Vlaming Sub-basin. From this they further deduced that north–south striking normal faults would have had oblique-slip displacement (Iasky et al., 1991; Iasky, 1993). Interestingly, the pattern of northwest–southeast striking faults illustrated in Iasky et al. (1991) is very different to that in Marshall et al. (1993), who interpreted a series of normal faults striking north–northeast. Subsequent interpretation by Nicholson et al. (2008) was closer to that of Iasky et al. (1991) in terms of normal-fault orientations, although Nicholson et al. (2008) did not specify the timing of fault movement.

Thickening of the Eneabba Formation has been interpreted as coinciding with growth on north–northwesterly striking faults in the Woodada gasfield (Cadda Terrace; Bulley, 2003), with no growth seen within older units. This supports the claim that Early Jurassic extension was oriented roughly east–west as advocated by Hall and Kneale (1992) and Harris (1994). Hall and Kneale (1992) also suggested that major normal displacement on the Darling Fault occurred at this time, based on what they considered to be the growth of Lower Jurassic sections in its hangingwall. Mory and Iasky (1996) interpreted the north–northwesterly striking normal faults to have been active in the Permian and also inferred east–west extension in the northern Perth Basin based on growth seen in Lower Jurassic units across these faults. Therefore, Jurassic growth on north–northwesterly striking normal faults could reflect reactivation of older faults, rather than the regional stress regime. Oblique-slip or strike-slip fault reactivation has been shown to require less force than the initiation of new normal dip-slip faults (Brune et al., 2012).

Middle Jurassic – Early Cretaceous rifting and continental breakup

This rift phase is particularly significant in the geological history of Western Australian basins, as it includes the separation of Greater India from Australia, the closure of the Neotethys Ocean, and the birth of the Indian Ocean (Gibbons et al., 2012). In the Perth Basin, significant synrift growth of the Yarragadee and Parmelia Formations can be seen in the hangingwalls of many major faults, such as the Urella, Muchea, and Darling Faults, and normal reactivation of north and northwesterly striking faults has also been interpreted within the Beagle Ridge (Jones and Hall, 2002; Roc Oil Pty Ltd, 2004). Iasky (1993) and Mory and Iasky (1996) interpreted a significant period of uplift and cooling during the Late Jurassic (extending into the earliest Cretaceous in the northern Perth Basin), based on burial reconstruction histories of onshore wells using vitrinite reflectance measurements. This history is likely due to footwall uplift along major faults during rifting. Conversely, Green and Duddy (2013) interpreted cooling to have commenced at or after breakup, based on fission track studies of selected well samples in the northern Perth Basin, although they also suggested that cooling may have commenced earlier on the Beagle Ridge sometime between the Early Jurassic and earliest Cretaceous.

Overall, this rifting phase has mostly been interpreted as beginning in the Middle Jurassic with the deposition of the Yarragadee Formation (e.g. Mory and Iasky, 1996; Song and Cawood, 2000; Norvick, 2004; Jones et al., 2011). The end of continental rifting — or a transition to sea floor spreading — is constrained by the oldest sea floor magnetic isochron recognized in the Perth Abyssal Plain, dated at 131 Ma (Gibbons et al., 2012), although plate modelling by these same authors suggested breakup began at c. 136 Ma. Breakup was accompanied by basaltic volcanism (Bunbury Basalt) in the southern Perth Basin.

Kinematics and stress regime

Northwest–southeast regional extension is reliably inferred from northeast-trending magnetic polarity reversal isochrons and northwest-trending fracture zones in the Perth Abyssal Plain (Gibbons et al., 2012). Extension in this direction would have set up a transtensional regime, with a dextral strike-slip component for reactivated north to north–northwesterly striking normal faults (Byrne and Harris, 1992; Harris, 1994; Mory and Iasky, 1996). Song and Cawood (2000) interpreted some northwest-trending folds along some major north-striking faults, best developed along the Darling Fault zone, which they argued resulted from transcurrent movement, with uplift and inversion, during breakup. The Warro and Gingin Anticlines adjacent to the Darling Fault are interpreted as two such inversion structures (Latent Petroleum, 2009). Song et al. (2001) also recognized a restraining bend along the Beagle Fault, consistent with dextral strike-slip movement. Although it is plausible that localized compression could occur at jogs along northerly striking faults during oblique extension, fault patterns favourable

for this type of reactivation have not been clearly demonstrated for some folds in Song and Cawood (2000).

Timing and nature of major structures

Darling Fault System

The Darling Fault is a major crustal scar that separates the Archean Yilgarn Craton from the Perth Basin. Forward gravity modelling presented in Iasky (1993) and Hackney et al. (2012) suggested that the Darling Fault is a planar, through-going structure that offsets the Moho. The continuity and length (>1000 km) of the Darling Fault has been used as an indicator of strike-slip movement (e.g. Crostella and Backhouse, 2000).

The Urella and Muchea Faults are interpreted to branch off the Darling Fault to form part of the Darling Fault System (Mory and Iasky, 1996), and also have significant normal, dip-slip offsets. The Urella Fault intersects the Darling Fault near Waroo, with part of the large throw (indicated by depth contours of seismically mapped horizons of Mory and Iasky, 1996) on the Darling Fault relayed onto the Urella Fault at this intersection. Therefore, the Urella Fault, rather than the Darling Fault, appears to have accommodated most of the presently observable strain in the northern Perth Basin. When the Urella Fault initiated is uncertain, but a thickening of Permian strata in the hangingwall of the fault was reported by Mory and Iasky (1996) in what is now considered the Wicherina Terrace.

The region surrounding the Darling Fault has accommodated strain since at least the Proterozoic Pinjarra Orogeny (the 'proto-Darling Fault'; Blight et al., 1981; Dentith et al., 1994a), as evidenced by the presence of fault-subparallel mylonites and dolerite dykes in Archean and Proterozoic rocks of the Yilgarn Craton and Pinjarra Orogen, respectively (Wilde and Low, 1978; Janssen et al., 2003). This orogeny records the suturing of India to Australia (Yilgarn Craton), and produced predominantly north to north-northwesterly trending, mainly ductile structures, as observed in the Northampton and Leeuwin Inliers (Peers, 1971; Janssen et al., 2003). These structures likely influenced the later trend of faults in the Perth Basin, including the Darling Fault System (Byrne and Harris, 1992).

Hocking et al. (1982) noted an increase in the intensity of north-trending folds and cleavage planes in Proterozoic metasedimentary rocks at the margin of the Yilgarn Craton near the Darling Fault, and Beeson (1992) suggested that brittle deformation adjacent to the Darling Fault commenced during east–west compression sometime during the Precambrian, based on measurements of smaller scale structures in several quarries along the fault's footwall. Beeson (1992) also found that the next most recent event to produce brittle faults in the zone was northeast–southwest extension, associated with inception of the Perth Basin, and consistent with the northeast–southwest Permian rifting postulated by Harris (1994).

However, there is no consensus whether the Darling Fault existed in its present form at that time.

Evidence for Paleozoic activity

U–Pb ages from detrital zircons in the Perth Basin have been used to determine if the Yilgarn Craton was a potential source for basin sediments, thereby determining whether the craton had positive relief at the time of deposition. This in turn may indicate if the Darling Fault was active at the time of deposition. For the Ordovician–Silurian Tumblagooda Sandstone, the scarcity of Archean zircons in the sediments has been used to suggest that the Yilgarn Craton and Darling Fault were subdued features during deposition of this formation (Cawood and Nemchin, 2000; Veevers et al., 2005). This is in conflict with the interpretation of Hocking (1991) that the Darling Fault formed the boundary to Tumblagooda Sandstone deposition, although the basis for that interpretation is unclear.

Evidence for Permian activity

One way to assess whether the Darling Fault was active during the Permian is to estimate the original thickness of Permian strata on the Darling Fault footwall (i.e. on the Yilgarn Craton and western Albany–Fraser Orogen), and compare this estimate to thicknesses observed in the hangingwall (i.e. in the Coolcalalaya Sub-basin, the Irwin, Yarra Yarra, Barberton and Mandurah Terraces, and the Dandaragan and Bunbury Troughs). This is not an easy task, however, because published estimates of Permian strata originally on the Yilgarn Craton vary wildly, and because of the uncertainty in picking the top-of-basement and Permian horizons in seismic west of the Darling Fault, especially in the deep Bunbury and Dandaragan Troughs. Seismic mapping indicates that up to 2000 m of lower Permian rocks are preserved in the Irwin Terrace directly west of the Darling Fault (Mory and Iasky, 1996), and a succession up to ~6000 m thick is preserved in the Bunbury Trough (Crostella and Backhouse, 2000; based on mapping by Iasky, 1993). Given the evidence for widespread late Permian uplift and erosion, the original thickness of these sections may have been greater than seen today, especially on the Irwin Terrace. The main line of evidence put forward for early Permian movement on the Darling Fault is the overall thickening of lower Permian strata in the hangingwall, as interpreted in seismic sections (Iasky, 1993; Song and Cawood, 2000), and in isopachs based entirely on well data in the northern Perth Basin (e.g. Mory and Iasky, 1996; Eyles et al., 2006). However, seismic coverage and quality for the deep section is extremely poor, and none of the seismic interpretation studies reported synrift wedge-geometries in the lower Permian succession. This is significant, as a thickening of the succession in the hangingwall cannot be used to satisfactorily conclude syndepositional fault displacement if not also compared to the original thickness of the same succession in the footwall. An alternative explanation for the observed eastward thickening is that it points towards the centre of an intracratonic sag, later crosscut by the Darling or Urella Faults with subsequent erosion of the lower Permian succession from their footwalls.

How much Permian strata was there on the Yilgarn Craton?

Evidence currently suggests that an extensive sheet of lower Permian rocks once covered the Yilgarn Craton, of which the Collie, Boyup, Wilga Sub-basins are preserved outliers (Le Blanc Smith, 1993). Crostella and Backhouse (2000) indicated that correlative lower Permian palynological zones in Sue 1 and in the Collie Sub-basin had similar thicknesses based on Backhouse (1993). However, Sue 1 was drilled 40 km west of the Darling Fault on the Vasse Shelf, which is structurally higher than the intervening Bunbury Trough. Whether this fault block was also higher relative to the Bunbury Trough during deposition of the lower Permian succession remains uncertain, so the comparison between thicknesses of lower Permian strata in Sue 1 and the Collie Basin does not help with estimating how much accommodation space was generated immediately adjacent to a possibly active Darling Fault in the Permian. Early Permian palynomorphs recovered from a shallow borehole (DDB-3; Fig. 4) drilled on the Yilgarn Craton, ~1 km east of the interpreted Darling Fault trace near Donnybrook, are highly mature (Backhouse and Wilson, 1989), but whether this is due to burial as opposed to volcanic activity or the hydrothermal event responsible for gold mineralization in the overlying Donnybrook Sandstone, is unclear. Several methods have been used to determine the original thickness of Permian strata covering the western Yilgarn Craton: those studies have produced substantially different results.

Kohn et al. (2000) suggested that up to 4.5 km of overburden was removed from the Yilgarn Craton sometime during the late Carboniferous – Permian, based on apatite fission track studies of exposed basement rocks throughout the southwest of the craton, with a further 3–4 km of strata removed during the Late Jurassic – Cretaceous (during breakup). However, fission track data alone cannot conclusively differentiate between the removal of basement as opposed to sedimentary rock, and estimates of overburden removal based on such data are highly sensitive to the value assumed for past geothermal gradients, which in turn partly depends on the assumed overburden lithology. Gleadow et al. (2002) suggested that, if it is assumed that removed rock were exclusively crystalline basement, estimates of overburden thickness based on thermal conductivity of granitic or gneissic rocks that also satisfy the fission track data are unreasonably high. Therefore, Gleadow et al. (2002) surmised that much of the removed rock must have been lower thermal conductivity sedimentary strata. This is consistent with the suggestion that the craton was once overlain by a more extensive sheet of younger strata.

Le Blanc Smith (1993) estimated removal of up to 4 km of overburden in the Collie Sub-basin sometime after deposition of the youngest (middle Permian) coal measures, but before the Barremian, to account for vitrinite reflectance values obtained from samples of lower to middle Permian coal currently preserved in the sub-basin. He also suggested a shorter erosional event sometime during the earliest middle Permian, giving a total missing section of 6.5 km. However, from the same vitrinite reflectance data (values of 0.43 – 0.7%; Sappal, 1986), Kohn et al. (2002), Norvick (2004), and Millar

et al. (2011) thought this estimate was too high. Instead, Kohn et al. (2002) estimated four kilometres of erosion, using a different surface temperature in their model to that assumed by Le Blanc Smith (1993), and Norvick (2004) and Millar et al. (2011) estimated no more than 2000 m of post-middle Permian, pre-Barremian sedimentary rock eroded from the Collie Basin.

Vitrinite reflectance or AFTA alone does not give the exact age of eroded strata, and so the missing section could be entirely Permian, or include all or parts of the Triassic – earliest Cretaceous that is not represented in the Collie, Boyup or Wilga Sub-basins, or at Donnybrook. Even if the more conservative estimates of missing mid-Permian – Mesozoic section in the Collie Sub-basin by both Norvick (2004) and Millar et al. (2011) are assumed to be entirely Permian, then that would still suggest that Permian strata were deposited more thinly over the Yilgarn Craton than to the west of the Darling Fault, implying an active Darling Fault throughout the Permian. The higher estimates (>4 km) of missing section determined from AFTA and vitrinite reflectance measurements can only be used to argue against Permian movement on the Darling Fault if it is assumed that most of the missing section was Permian, and if it is accepted that the Permian succession is only up to 5 – 6.5 km thick adjacent to the fault in the Bunbury Trough and southern Mandurah Terrace (Crostella and Backhouse, 2000; based partly on horizon interpretations of Iasky, 1993).

Sedimentological evidence for Permian activity?

Sedimentological evidence for positive relief of the Yilgarn Craton during parts of the early Permian were provided by Mory and Iasky (1996), who demonstrated an east-to-west facies variation in the High Cliff Sandstone, wherein sandstones become ‘cleaner’ towards the Darling Fault. Based on well data, they also noted thickening of this unit in the axis of a trough between the Darling Fault and the Beagle Ridge, further suggesting that, like the Beagle Ridge, the Yilgarn Craton was a positive topographic feature at this time. However, detrital zircon provenance studies have found a scarcity of Archean zircons in the lower Permian succession of the northern Perth Basin (Cawood and Nemchin, 2000) and Collie Sub-basin (Veevers et al., 2005), indicating that the Yilgarn Craton did not provide much sediment to the basin at this time. Based on ages alone, Cawood and Nemchin (2000) instead identified the Leeuwin Inlier, Albany–Fraser Orogen, and the Wilkes Province in Antarctica as the main source regions. Based on the age spectra of the detrital zircons, combined with the consistent northwesterly palaeocurrent directions seen in the basal section of coal measures in the Collie Sub-basin (Wilson, 1989), Veevers et al. (2005) considered the Albany–Fraser Orogen to the south the most likely source terrane during the early Permian. From this it may be inferred that there was no emergent footwall along the Darling Fault in the Permian at this time, because it is likely that sediment from the southeast would have been deflected away from an uplifted footwall — a scenario which is seen in modern rifts (Lambiase and Bosworth, 1995). However, despite rift flank uplift within modern rift basins, drainage from the rift shoulder and hinterland into such basins has been documented at points

along the rift border fault where throw is diminished; for example, at relay ramps or at intersections with accommodation zones or transfer faults (Lambiase and Bosworth, 1995; Gupta et al., 1999).

Sedimentological evidence of fault movement during the late Permian is provided by Bergmark and Evans (1987) and Tupper et al. (1994), who both interpreted rifting and an uplifted Darling Fault footwall in the late Permian, based on facies analysis of the Wagina and Dongara Sandstones. Further, the emergence of the Yilgarn Craton, and by implication movement on the Darling Fault, can be inferred from the appreciable percentage of Archean zircons in the upper Permian Beekeeper Formation, and Wagina and Dongara Sandstones in the northern Perth Basin, notwithstanding possible contributions from the East Antarctic Craton (Cawood and Nemchin, 2000). Cawood and Nemchin (2000) interpreted the euhedral form of these zircons to indicate that they are first-cycle material, and not reworked from older sedimentary rocks. Veevers et al. (2005) attributed this input to the erosion of Archean gneisses and granites from the emergent rift shoulder along the Darling Fault, which subsequently drained into the rift basin. Alternatively, Norvick (2004) concluded that the Archean detritus was derived from Antarctica or India, because he interpreted that the Yilgarn Craton was 'quarantined' from the basin during the late Permian by overlying sediment.

Other geophysical evidence for Permian activity?

An indication of activity on the Darling Fault throughout the history of the Perth Basin was provided by Hackney et al. (2012), who argued that, given the constant thickness of crystalline crust (i.e. from the top basement down to Moho recognized in seismic) beneath the Dandaragan Trough and adjacent sub-basins, accommodation space was generated solely from displacement along the Darling and Urella Faults, with no concomitant lower crustal thinning. Iasky (1993) also proposed that the crystalline crust maintains a similar thickness across the Darling Fault in the Bunbury Trough so, from similar lines of reasoning, it is likely that the Darling Fault exerted control on sedimentation in the southern Perth Basin throughout the basin's history.

Mesozoic activity

The lack of post-middle Permian to pre-breakup sedimentary strata on the western part of the Yilgarn Craton, apart from along Fly Brook near the south coast (Lowry, 1964), leaves a large time gap unaccounted for. The coal seams at Fly Brook, likely age-equivalents of the Cattamarra Coal Measures (Chappell, 1984), outcrop about 2–4 km east of the Darling Fault and are interpreted to overlie rocks of the Albany–Fraser Orogen. These coals are sub-bituminous, which gives a theoretical vitrinite reflectance value of ~0.4 to 0.5% using the table in figure 24 of Stach et al., (1982) and that up to 2 km of overburden has been removed. Whether or not rocks of this age were once more widespread and extended over the craton is uncertain.

A lack of Archean detritus in sandy intervals within the Lower Triassic section of the Kockatea Shale, was attributed by Cawood and Nemchin (2000) to minimal erosion of the Yilgarn Craton at this time. However, this lack of basement detritus may be more a reflection of the marine to marginal marine facies of this unit, for which sediments were derived from local sources (i.e. the Northampton Inlier), with no contributions arriving via craton-draining or northwards-flowing rivers. This interpretation is supported by the abundance of angular feldspar and garnet grains in thin transgressive sandstones at the base of the Kockatea Shale (Bergmark, 1987). Alternatively, Veevers et al. (2005) attributed the lack of Archean zircons in Triassic rocks to positive topographic relief of the Darling Fault footwall preventing northwesterly sediment transport from the Yilgarn Craton. Another alternative explanation was given by Norvick (2004), who accounted for the lack of Archean detritus in the lower Kockatea Shale by suggesting that the Yilgarn Craton was still overlain by a blanket of Permian sediments in the early part of the Mesozoic. Detrital zircon analysis of the age-correlative Sabina Sandstone in the southern Perth Basin could shed light on this enigma, because if this unit contains Archean detritus with an age signature indicative of a Yilgarn Craton provenance, then Norvick's (2004) assumption may not be tenable.

Evidence for Darling Fault activity during deposition of the Lesueur Sandstone is ambiguous, and more detailed seismic mapping may be required to resolve this issue. Mory and Iasky (1996) noted pebble-sized, angular feldspar clasts, in outcrop mapped as Lesueur Sandstone in the Cadda Terrace, and measured predominantly northwesterly paleocurrent directions, and suggested this formation was deposited in an alluvial fan with sediment derived from east of the Darling Fault. Veevers et al. (2005) considered this same interpretation as evidence for continued rifting and Darling Fault rift shoulder uplift well into the Triassic. However, farther south on the onshore Harvey Ridge, Archean detrital zircons are rare in the Lesueur Sandstone retrieved from GSWA Harvey 1, and the bulk of the sampled zircons are thought to be derived from the Proterozoic Leeuwin Inlier and Albany–Fraser Orogen (Millar and Reeve, 2014). The rarity of Archean detritus in this unit could similarly be explained by an uplifted Darling Fault footwall, because tilting of the rift shoulders can deflect drainage away from the rift basin; where this happens, detritus sourced along strike of the rift axis are the dominant type of sediment in the rift, with a much lower percentage of detritus derived from the rift shoulder (Lambiase and Bosworth, 1995). The fact that the Leeuwin Inlier and AFO were source areas located along strike of the Perth Basin is also consistent with the mostly northerly to northwesterly paleocurrent directions measured in the Lesueur Sandstone from GSWA Harvey 1 (Millar and Reeve, 2014), which may further imply that sediments derived from the south were confined by a topographic high to the east. However, there is no evidence of synrift wedge-geometries of the Lesueur Sandstone in seismic lines abutting the Darling Fault anywhere on the Harvey Ridge illustrated by Zhan (2014). It is possible that some sections of the fault were active during this time, whereas others were not.

Movement during the interval from Middle Jurassic to breakup is likely given the considerable thickening of the Yarragadee and Parmelia Formations towards the Urella and Darling Faults in the Dandaragan Trough (maximum thickness >6 km; Mory and Iasky, 1996) and Bunbury Trough (maximum thickness ~2 km; based on data from Iasky, 1993 and Crostella and Backhouse, 2000). These observations are consistent with the Early Jurassic onset of rifting suggested by some studies (Fig. 6). Conversely, Dentith et al. (1994a,b) interpreted the Darling Fault as a Late Jurassic – Early Cretaceous, late rift-stage structure of the Perth Basin, crosscutting the original basin margin. This interpretation is supported by the unweathered nature of coal seams in the Boyup and Collie Sub-basins, implying short subaerial exposure time prior to deposition of the Lower Cretaceous Nakina Formation (Griffin Coal, 2003), and therefore that the Darling Fault footwall was not emergent before the Cretaceous. Further, the presence of reworked Permian coal and palynomorphs in the Cretaceous succession suggests coeval erosion of Permian strata (Backhouse et al., 1996). However, this interpretation of Dentith et al. (1994a,b) would either imply a similar thickness of Permian–Mesozoic strata on the Yilgarn Craton as in the Bunbury and Dandaragan Troughs — a thickness that exceeds most estimates of removed overburden over the southwest Yilgarn and Collie Sub-basin based on apatite fission track or vitrinite reflectance data (e.g. Kohn et al., 2000; Millar et al., 2011) — or it would imply a sharp thickness gradient from the basin to the craton that has come about without faulting.

Continued movement on the Darling Fault after breakup is suggested by Leyland (2011), who interpreted a thickening and tilting of the post-rift Leederville Formation and Coolyena Group towards the fault. The Leederville Formation contains a large proportion of Archean zircons (Descourvieres et al., 2011; Millar and Reeves, 2014), indicating that the Yilgarn Craton was a positive feature following breakup. Furthermore, the shallow (<5°) inclination of Upper Cretaceous post-rift strata (Molecap Greensand) towards the east in the Beermullah Trough suggests hangingwall subsidence, implying some post-rift movement on the fault. Beeson (1992) interpreted continued east–west to northwest–southeast extension after breakup, based on a series of normal faults of inferred Cretaceous age crosscutting the Donnybrook Sandstone in the Darling Fault footwall. However, the age of the Donnybrook Sandstone is not resolved, because the sandstone contains few fine-grained intervals suitable for palynological dating. Balme (1957), Backhouse and Wilson (1989), and Backhouse et al. (1996) believed it to be Early Cretaceous, as they interpreted the overlying shale to be conformable with the sandstone. In contrast, Morant (1988) considered this same unit to be of early Permian age, due to an apparent conformity with underlying lower Permian tillites. Given these different ages, it is possible that rocks with similar lithofacies but different ages have been assigned to the same formation.

Whether the Darling Fault has been reactivated in the Neogene or more recently has not been established and this requires more work. However, there does appear to be a spatial correlation between Quaternary sagpond deposits and modern lakes, and the interpreted trace of the Darling Fault at the surface.

‘Transfer faults’

Many of the major north-northwesterly striking normal faults in the Perth Basin, especially the northern Perth Basin, appear to have a left-stepping arrangement, whereby major ‘steps’ are broadly aligned along northwest-trending lineaments (Fig. 5). These structures have been interpreted as transfer faults, and are commonly regarded as discrete, through-going strike-slip faults (cf. Bally, 1981; Gibbs, 1984; Lister et al., 1986). Reports of dextral or sinistral strike-slip movement on these transfer faults have mostly been inferred from interpreted extension vectors, rather than directly observed. Transfer faults were first interpreted by Marshall et al. (1989a,b, 1993) in the offshore Vlaming and Abrolhos Sub-basins, where they were invoked to explain the disjointed pattern of seismically mapped normal faults. These transfer structures were treated as northwest-trending strike-slip faults parallel to oceanic fracture zones, and subparallel to lineaments on the Yilgarn Craton, where they apparently offset north-northeasterly striking normal faults either dextrally or sinistrally (Marshall et al., 1993). A pervasive set of transfer faults was inferred in the Vlaming Sub-basin, where northerly trending normal faults were interpreted to be offset laterally by 1.5 to 25 km (Marshall et al., 1993). These faults were not mapped directly from seismic data, but were inferred from features interpreted as abrupt lateral displacements of normal faults. However, this approach assumes the structures used as markers for offset were originally continuous, linear, normal faults, but this interpretation cannot be adequately demonstrated from the available data. Many of these interpreted normal faults, especially in the south of the Vlaming Sub-basin, are each based on a single seismic line, so their strike cannot be accurately defined; this makes the location of normal-fault – transfer-fault intersections, and the interpreted lateral offset of these normal faults, questionable. Moreover, Nicholson et al.’s (2008) interpretation of more recent seismic data in the sub-basin is significantly different and lacks the pervasive set of transfer faults.

Onshore transfer faults were first interpreted by Hall and Kneale (1992), which they termed ‘transfer zones’. They argued that the transfers are underlain by basement strike-slip faults that formed during the Pinjarra Orogeny, and which were reactivated during Phanerozoic tectonism, although it was conceded that the putative faults are not visible. Nevertheless, strike-slip shear zones of similar orientation have been recorded in the Leeuwin Inlier, which lends some credence to the idea (Janssen et al., 2005).

Dentith et al. (1994b) suggested that previously interpreted transfer faults are in fact accommodation zones that relate to a series of northwest-trending lineaments seen in potential-field data on the adjacent Yilgarn Craton. They considered the accommodation zones to correspond either to intersections between the Darling Fault and the accreted terrane boundaries postulated by Wilde et al. (1996) within the southwestern Yilgarn Craton, or to reactivated northwest-trending Archean structures in the Yilgarn Craton. Dentith et al. (1994a,b) concluded that these accreted terranes and structures in the Yilgarn Craton controlled the geometry of the Perth Basin margin (now represented by the Darling Fault), which in turn influenced

fault orientations in the adjacent basin as it developed. Based on changes in strike, or along-strike changes in polarity or throw, of some major north-striking normal faults across these northwest-trending lineaments, and the lack of seismically imaged ‘transfer fault’ displacements, the term ‘accommodation zones’ (cf. Bosworth, 1985; Faulds and Varga, 1998) is considered here to be more appropriate than ‘transfer fault’, because this interpretation does not invoke strike-slip displacement along these lineaments. However, how these accommodation zones relate to the lineaments on the Yilgarn Craton is debatable. Whereas it is true that a change in the pattern of normal faulting along the basin axis can be explained by changes in basin-margin geometry (McClay et al., 2002) or underlying basement rheology (e.g. Miller et al., 2002), the terranes of Wilde et al. (1996) remain controversial, and are not yet widely recognized. Future research could focus on better understanding these enigmatic lineaments in the southwestern Yilgarn Craton, and the basement to the Perth Basin.

Abrolhos Transfer Fault

Hall and Kneale (1992) introduced the concept of the northwest-trending Abrolhos Transfer Fault, which they delineated by linking the change in strike of the Beagle Fault, from north–south to northwest–southeast, to the intersection of the Darling and Urella Faults. The Eneabba Fault peters out north of the interpreted location of the Abrolhos Transfer Fault (Mory and Iasky, 1996), but no verifiable ‘transfer fault’ has been imaged using seismic data.

Mory and Iasky (1996) argued that the short northwesterly striking fault between the Urella and Darling Faults is a faulted expression of the Abrolhos Transfer Fault (Fig 3b). Furthermore, they interpreted the kink in the Urella Fault at this location to be due to ~4 km of sinistral offset along this northwest-striking fault; however, their subsurface horizon maps do not show any lateral displacement of the Darling Fault. An alternative interpretation is that the small, northwest-striking normal fault between the Darling and Urella Faults is a breached relay ramp, and the kink in the Urella Fault formed through hard-linking of what were initially two separate, left-stepping en echelon normal faults.

Cervantes Transfer Fault

The Cervantes Transfer Fault was identified from features including: the petering out of north–south striking faults in the Coomallo Trough and Cadda Terrace; and the Coomallo Fault changing strike at the interpreted transfer fault to northwest–southeast from a north–south trend further north (Mory and Iasky, 1995; 1996). However, no fault has been interpreted directly from seismic or outcrop, and the basis for this fault is considered here to be insufficient.

Turtle Dove Transfer Fault

The northwest-trending Turtle Dove Transfer Fault was identified and named by Crostella and Backhouse (2000);

however, the basis for their interpretation is unclear. Although Crostella and Backhouse (2000) showed the Badaminna Fault System and the Geraldton Fault terminating at this transfer fault, it is unclear if this was interpreted from seismic. Overall, the transfer fault is very poorly defined, it is not adequately imaged seismically, and its continuity is very poorly established. Furthermore, it does not conform to any offshore lineaments seen in the Bouguer gravity image of Hackney (2012; Figs 2 and 3). An appearance of sinistral strike-slip displacement across the Turtle Dove Transfer Fault is given by the leftward shift in higher gravity response, as well as a ~30 km leftward shift of some basement highs and depocentres offshore (Bradshaw et al., 2003). However, Jones et al. (2011) subsequently concluded from reprocessed seismic data there was a lack of evidence for offshore strike-slip faulting.

Harvey Transfer Fault

The northwest-trending Harvey Transfer Fault (Crostella and Backhouse, 2000; Fig. 5) is interpreted to form the southern boundary of the Harvey Ridge, and to extend further offshore into the Vlaming Sub-basin. However, few seismic lines cross the southern boundary of the Harvey Ridge, and no transfer fault associated with the abrupt deepening of Mesozoic and older rocks into the Bunbury Trough is evident in any seismic profile, although the distribution and quality of seismic lines is poor in this region. Marshall et al. (1993), Crostella and Backhouse (2000) and Iasky and Lockwood (2004) inferred sinistral displacement along the transfer, based on interpreted lateral displacements of normal faults and basement highs in the Vlaming Sub-basin. Dentith et al. (1994a,b) noted that the Harvey Ridge appears to be aligned with a swathe of northwest-trending lineaments shown by aeromagnetic data in the southwestern Yilgarn Craton along which the Collie Sub-basin lies, but, in contrast to the sinistral offset interpreted by Crostella and Backhouse (2000) and Marshall et al. (1993), Dentith et al. (1994a,b) interpreted these lineaments to have dextrally offset the Darling Fault and west-trending structures within the Albany–Fraser Orogen sometime in the Phanerozoic. However, Dentith et al. (1994b) did not interpret a transfer fault along the Harvey Ridge and into the Vlaming Sub-basin. Instead, they argued that these Archean lineaments in the Yilgarn Craton helped define the geometry of the basin’s eastern margin as it evolved, which consequently controlled the orientation of structures in the Darling Fault hangingwall. This concept was tested by Harris et al. (1994) using analogue modelling from which they implied strong strain localization at points along the western boundary of the Yilgarn Craton (modelled using a rigid clay slab) where the boundary changed strike. Although it is plausible that Perth Basin faults were influenced by structures in the Yilgarn Craton in this way, the precise kinematics of how a basement high can arise from this interaction, and the role of the Harvey Ridge as an ‘extensional accommodation zone’, was not clearly illustrated or explained by Dentith et al (1994b).

Discussion and conclusions

Structure

Given the present understanding of modern and ancient rift basins — enhanced by the profusion of 3D seismic data and increasing sophistication of modelling techniques over the last twenty years — some of the assumptions previously made regarding the structure of the Perth Basin should be re-evaluated. An example is the apparent lateral displacement of the north-trending normal-fault traces in the Perth Basin, which can no longer be regarded as good evidence for strike-slip displacement on northwest-trending transfer faults. A better explanation for this pattern, consistent with current models of fault dynamics, is the relaying of throw of en echelon normal faults that were later hard-linked via relay ramp breaching. En echelon intrarift faults and depocentres have been widely documented in present-day oblique-rift settings (e.g. Corti, 2008; Brune and Autin, 2013), and simulated in physical and numerical models (e.g. McClay et al., 2002; van Wijk, 2005). Given the current absence of discrete, through-going structures in published seismic interpretations or structure maps for the Perth Basin, these transfer faults might be more appropriately thought of as accommodation zones. This interpretation does not require the features to be discrete faults, nor do they need to be the result of the reactivation of basement structures of similar orientation.

Another unresolved question involves the timing of Phanerozoic movement on the Darling Fault. Although seismic data are important for correlating strata in the hangingwall of the Darling Fault, few lines cross or come close to the fault itself and their quality is mostly poor, especially at depth. Also, except in a few places (e.g. the Harvey Ridge), there are very few wells to constrain the age of hangingwall strata, and even fewer that are tied to good quality seismic data. For those wells that are available, paleocurrent data may provide clues to whether the footwall of the Darling Fault was emergent at different times.

Possible past activity on the Darling Fault may be interpreted from changes in sediment provenance through time using detrital zircon analysis. This could indicate periods when the Yilgarn Craton shed sediment into the developing basin (assuming direct derivation from the craton), which in turn may indicate periods of its emergence associated with rift flank uplift along the Darling Fault. However, this method assumes that detritus from the craton was conveyed directly into the rift basin, rather than having been deflected by a possibly uplifted rift shoulder, as is the case in some modern rifts (Lambiase and Bosworth, 1995). In addition, throw along the Darling Fault varies greatly, and it remains unclear if it has always been the long, continuous structure it is today. Drainage into the rift basins could have been localized at points along the rift margin where there was little or no throw and hence less uplift, a situation seen in present-day rift systems, commonly at relay ramps or where accommodation zones meet the border fault (Lambiase and Bosworth, 1995; Gupta et al., 1999). To date, there

have been few published studies on ancient detrital zircons in the Perth Basin (e.g. Cawood and Nemchin, 2000; Veevers et al., 2005; Descourvieres et al., 2011), all of which focussed on Permian or post-breakup Cretaceous strata, with only a few, relatively closely spaced wells and outcrops sampled. Therefore, as only one potential sample from the Lower Jurassic Eneabba Formation has been analysed for detrital zircons to date (from GSWA Harvey 1; Millar and Reeve, 2014) — and that single sample is as yet unconfirmed as being derived from the Eneabba Formation — it is still unclear if the Darling Fault was active during deposition of this formation, which is mostly considered to have been deposited in an active rift setting. Another uncertainty which may be resolved through detrital zircon analysis is whether sediments for the fluvial Sabina Sandstone were sourced from Pinjarra Orogen terranes like those in the partly correlative Kockatea Shale in the north of the basin. In addition to the scarcity of detrital zircon analyses for Perth Basin units, there is also a conspicuous lack of data on the Cardup and Moora Groups, the Proterozoic metasedimentary rocks along the western margin of the Yilgarn Craton. The provenance of these rocks is important, as they also likely contributed sediment to the Perth Basin.

Due to the rarity of basement intersections within wells away from the Beagle Ridge, Vasse Shelf and northern tectonic units adjacent the Northampton Inlier, the role of basement in the structural evolution of the Perth Basin is unknown, and the extent to which the Pinjarra Orogen — exposed in the Northampton, Leeuwin and Mullingar Inliers — underlies the basin is largely unresolved. The Pinjarra Orogen is considered to comprise several amalgamated terranes (Janssen, 2003), but whether the rheological heterogeneity introduced by this amalgamation helped to localize strain in the overlying basin has yet to be investigated. An investigation of this kind would initially require predictive mapping of basement from potential-field or deep-crustal seismic datasets integrated with deep basement intersections, as attempted by Hall et al. (2012). These maps could also be used to see if there is a correlation between basement character and areas of greater subsidence or uplift, or strain localization.

Stratigraphy

The past tendency for well correlations to rely heavily upon lithostratigraphy alone has obscured the timing and patterns of uplift and generation of accommodation space in parts of the Perth Basin. This is particularly a problem where lithostratigraphic nomenclature defined in the northern Perth Basin has been applied in other parts of the basin. For example, the most recent well correlations in the Bunbury Trough (Crostella and Backhouse, 2000) interpreted the ‘Eneabba Formation’ as absent due to the lack of ‘distinctive’ oxidized sandstone, which is characteristic in the Eneabba Sandstone type section some 400 km to the north. As a result, Bunbury Trough sections that are age-correlative with the Eneabba Formation in the northern Perth Basin, but lack the oxidized sandstone facies, were instead considered part of the Cattamarra Coal Measures, resulting in a Cattamarra Coal Measures package that appears strongly diachronous across the

basin. If isopachs derived from such a correlation are used, there are obvious implications for interpreting the timing of important structures, such as the Harvey Ridge and Darling Fault. Clearly, a thorough understanding of the basin's tectonic framework can only be accomplished with improved intrabasinal stratigraphic correlations of broadly time-equivalent packages. This requires a greater emphasis on biostratigraphy — although poor outcrop, the lack of marine strata, sparse published or open-file subsurface data, and the high potential for spore and pollen to be oxidized or reworked all combine to make this difficult. Future efforts should focus on achieving greater biostratigraphic coverage, both laterally and with depth, across the entire basin, especially for the Mesozoic section in the Mandurah Terrace and southwards. Unfortunately, due to the paucity of deep onshore wells and good quality seismic around the Perth metropolitan area, and the widely spaced distribution of offshore wells, the stratigraphic transition from the southern to northern Perth Basin is poorly documented, presenting another challenge to resolving stratigraphic issues within this basin.

Future work

To resolve the uncertainties mentioned above, the following work is suggested:

- detailed resampling of suitable facies in petroleum wells, water bores, mineral drillholes, and outcrop for biostratigraphy
- detrital zircon analyses for provenance studies that systematically cover both the stratigraphy of the basin, and its areal extent. This, combined with paleocurrent data, will also greatly improve our understanding of sediment dispersal into and throughout the basin
- acquisition of new seismic and reprocessing of legacy seismic data, especially those lines traversing wells in the southern Perth Basin
- thermal maturation analyses, including vitrinite reflectance, for selected boreholes
- careful tying of well and drillhole data to seismic sections, which will also help ascertain potential missing sections in wells due to faults, and help well-to-well correlation especially if combined with dipmeter or image analysis.

A more refined chronostratigraphic framework integrated with seismic and maturity data is needed to provide additional constraints on the nature and timing of deformation events. A robust tectonostratigraphic framework for the basin will also help guide seismic interpretation in areas with sparse well coverage. Ultimately, all of this work will lead to a better correlation with the stratigraphy of the North West Shelf — for example, the scheme of Marshall and Lang (2013) — and beyond. This will enable a more complete picture of the evolution and breakup of Gondwana, and the formation of the Indian and Southern Oceans.

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