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NEW EXPLORATION OPPORTUNITIES IN THE OFFSHORE NORTHERN PERTH BASIN

ACREAGE ADDRESS

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ABSTRACT

Release Area W11-18 is a very large block in the offshore northern Perth Basin, covering parts of the Abrolhos, Houtman and Vlaming sub-basins and the Beagle and Turtle Dove ridges. Geoscience Australia (GA) has assessed the petroleum prospectivity of this area as part of the Australian Government's Offshore Energy Security Program. This assessment includes the first published synthesis of data from 14 new field wildcat wells drilled in this part of the basin since the Cliff Head–1 discovery (2001), and the interpretation of new regional 2D seismic data acquired during GA survey 310 (2008–9). A refined tectono-stratigraphic model for the offshore basin provides insights into basin evolution and prospectivity.

Oil has been produced since 2006 from the Cliff Head oil field in WA-31-L, which is directly adjacent to Release Area W11-18. Three petroleum discoveries are included in the release area, with oil and gas in Dunsborough–1, and gas in Frankland–1 and Perseverance–1. These accumulations are reservoired in Permian sandstones and have primarily been sourced from the Hovea Member of the Kockatea Shale, which has also sourced the majority of producing oil and gas fields of the onshore Perth Basin.

New seismic data show that Permo-Triassic strata stratigraphically equivalent to the productive onshore and nearshore Perth Basin petroleum system also occur in Permian half-graben in the outer Abrolhos and Houtman sub-basins. Source rock, oil stain and fluid inclusion sampling from this interval suggest that the proven onshore-nearshore petroleum system is also effective and widespread in the offshore. There is also evidence for an active Jurassic petroleum system in the release area. The release area offers a range of plays in a variety of water depths, predominantly less than 200 m, and is highly prospective for oil and gas.

KEYWORDS

Perth Basin, Acreage Release, tectonostratigraphic model, basin evolution, petroleum systems, hydrocarbon prospectivity, exploration oppotunities.

INTRODUCTION

Release Area WA11-18 is located about 200 km northwest of Perth and directly offshore from Geraldton (Fig. 1). The release area comprises 260 graticular blocks, and covers an area of 17,475 km^2. The majority of the release area is in less than 200 m of water, although water depths vary across the area from around 5 m adjacent to state waters in the east, to around 2,800 m on the continental slope to the west (Fig. 1).

Release Area WA11-18 is situated in the offshore portion of the northern Perth Basin (Fig. 2). Exploration in this part of the Perth Basin commenced in 1965 with the acquisition of the Abrolhos Marine Seismic Survey, partially in the release area. The first well in the offshore Perth Basin, Gun Island–1, was drilled in 1968 adjacent to the release area. Four wells were drilled in the release area during the subsequent 15 years (South Turtle Dove–1B, 1975; Geelvink–1A, 1978; Batavia–1, 1978; Leander Reef–1, 1983). A general lack of drilling success led to a period of decreased exploration activity in the offshore northern Perth Basin and an 18-year hiatus between the drilling of Leander Reef–1 in 1983 and Cliff Head–1 in 2001.

Cliff Head–1 intersected a 4.8 m waxy (31.6° API) oil column in the Permian Irwin River Coal Measures immediately beneath the Triassic Kockatea Shale regional seal (Jones and Hall, 2002). Five extension/appraisal wells were drilled between 2002 and 2005 to delineate the extent of the Cliff Head field, and seven development/water injection wells were drilled between 2005 and 2006. Production from the Cliff Head field commenced in 2006 with a total of 8.99 mmbl of oil produced, as at 31 December 2009 (DMP, 2010).

The discovery of the Cliff Head oil field and a series of onshore oil discoveries in the early 2000s (Hovea, Jingemia and Eremia), changed the perception of the northern Perth Basin

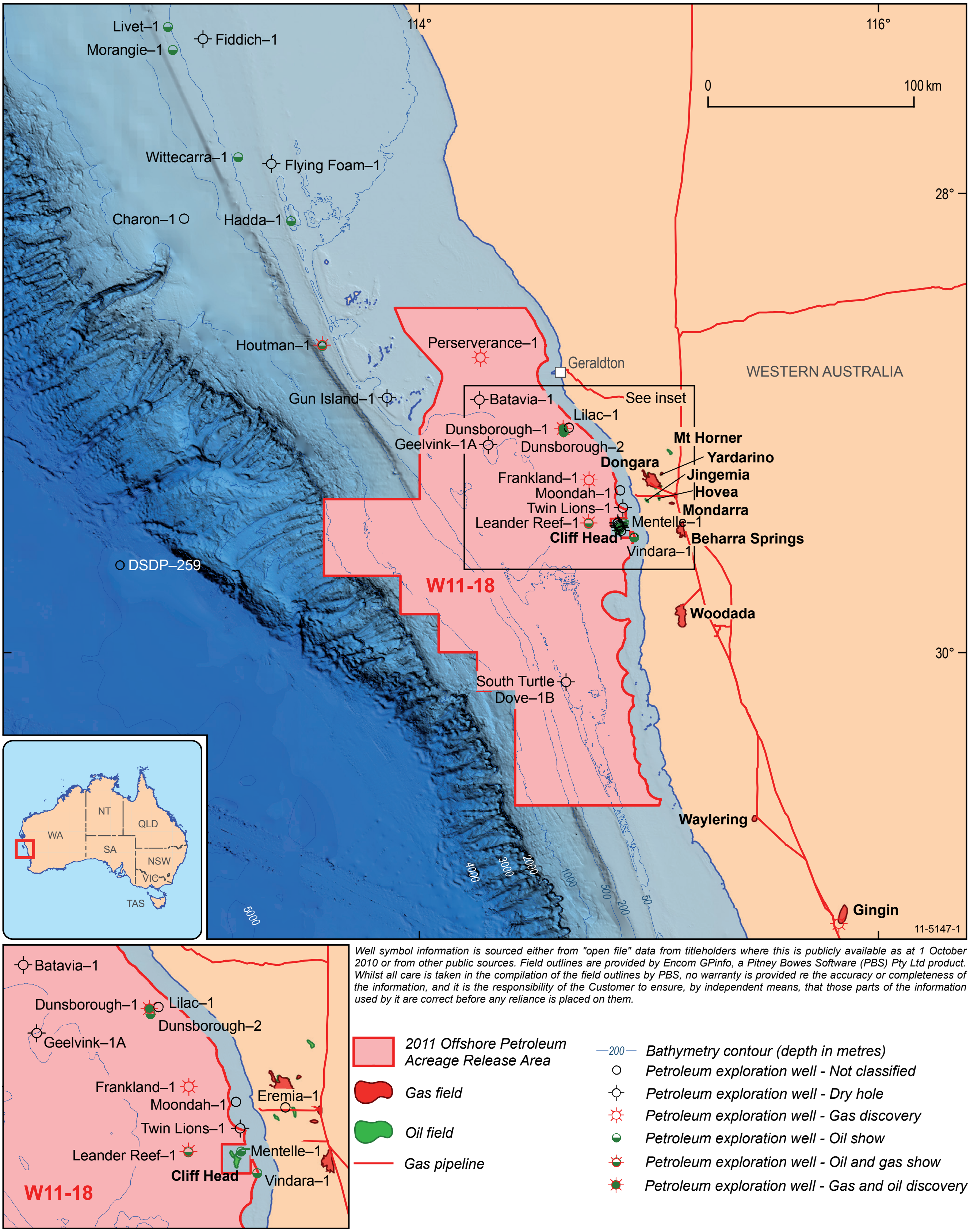


Figure 1. Location of Release Area W11-18, offshore northern Perth Basin.

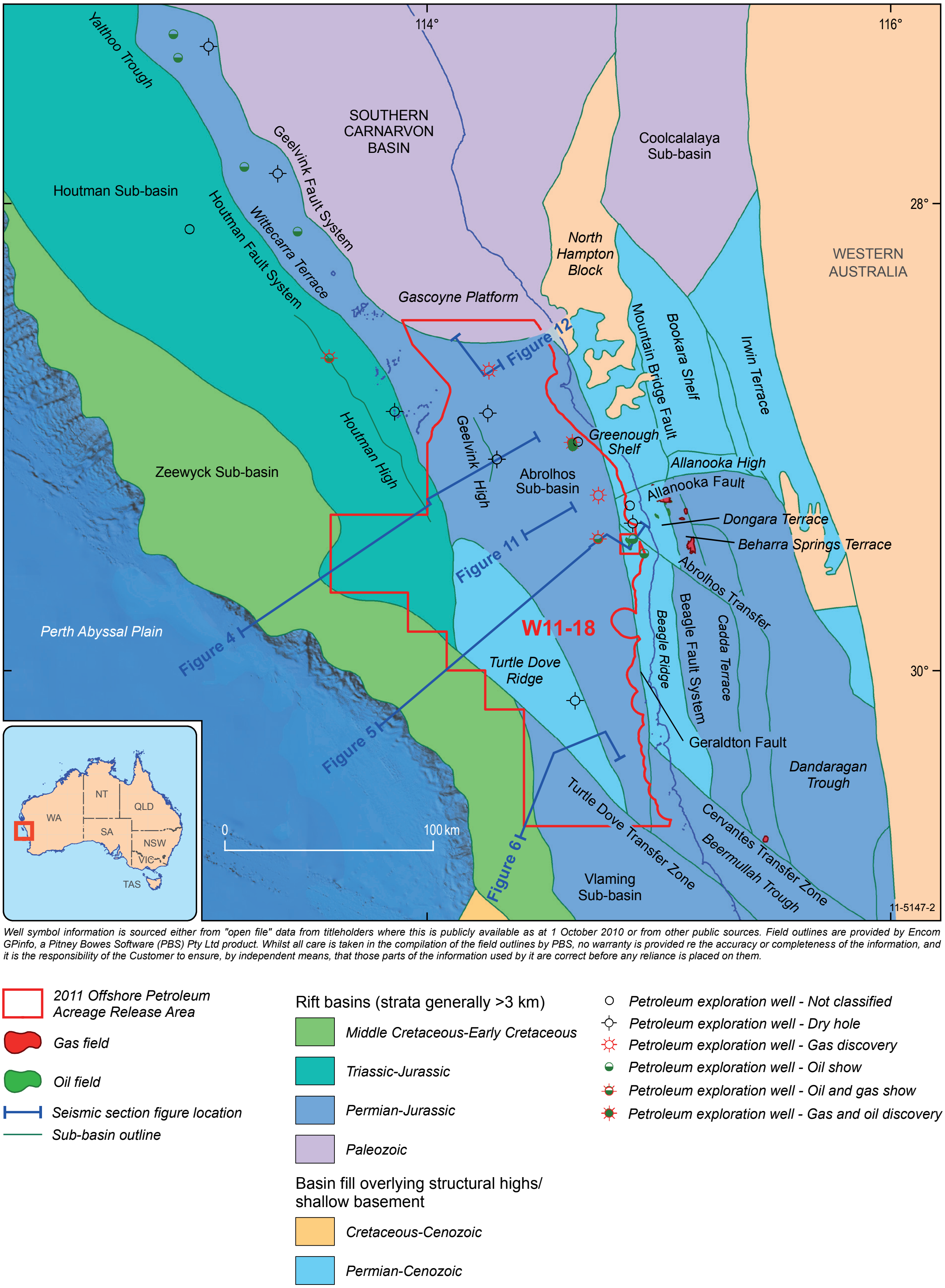


Figure 2. Structural elements of the offshore northern Perth Basin showing Release Area W11-18 and location of seismic sections, shown in Figs 4–6, 11 and 12.

from being marginally prospective for gas, to one that is highly prospective for gas and oil (Buswell et al, 2004). This led to significant uptake of exploration permits covering much of the offshore region in 2002–3. The widespread permit coverage in the offshore decreased from 2004–5, and new petroleum exploration acreage released in the offshore northern Perth Basin in 2003, 2004 and 2006 was not taken up by industry.

Recent drilling in the offshore northern Perth Basin was undertaken primarily by Roc Oil (WA) Pty Ltd, who drilled eight new field wildcat wells in or directly adjacent to Release Area W11-18 between 2001 and 2008. Three discoveries were made in Release Area W11-18 in 2007 as part of Roc Oil's drilling campaign, with Frankland–1, Dunsborough–1 and Perseverance–1 all intersecting gas columns. Dunsborough–1 also included a light oil leg. Roc Oil (WA) Pty Ltd surrendered Exploration Permit WA-286-P in November 2010, and as a result there are no exploration permits presently active outside state waters in the offshore northern Perth Basin.

Geoscience Australia (GA) assessed the petroleum prospectivity of Release Area W11-18 as part of the Australian Government's Offshore Energy Security Program, to stimulate exploration activity and reduce exploration risk in this part of the basin. This assessment represents the first published synthesis of data from 14 new field wildcat wells drilled in this part of the basin since the Cliff Head–1 discovery, and includes 120 new palynological samples from 10 wells. New biostratigraphic data and interpretations from these samples have been used in conjunction with legacy palynological data, well logs and lithological interpretations of cuttings and cores, to define a new chronostratigraphic sequence framework for the offshore northern Perth Basin (Fig. 3). The prospectivity assessment also includes 244 new Rock-Eval/TOC and 85 VR measurements from 15 wells, which have been used in conjunction with legacy geochemical data to assess the potential source rock character of the chronostratigraphic sequences. The new palynological and geochemical data and stratigraphic analysis of wells in the offshore northern Perth Basin are presented in Jorgensen et al (in prep.). Sequences defined in the new chronostratigraphic framework have been tied to new and reprocessed seismic data acquired by GA (Figs 4, 5 and 6), with the aim of characterising the distribution of potential source, seal and reservoir intervals.

REGIONAL GEOLOGY OF THE OFFSHORE NORTHERN PERTH BASIN

Tectonic setting

Release Area W11-18 incorporates parts of the Abrolhos, Houtman and northern Vlaming sub-basins of the Perth Basin, and abuts the Zeewyck Sub-basin to the west (Fig. 2). It also incorporates the Turtle Dove Ridge and minor parts of the Beagle Ridge, Dongara Terrace and Greenough Shelf. These depocentres and structural features formed in an obliquely-oriented extensional rift system on Australia's southwestern margin during the Paleozoic to Mesozoic breakup of eastern Gondwana.

ABROLHOS SUB-BASIN

The Abrolhos Sub-basin (Playford, 1971) is the easternmost depocentre in Release Area W11-18. It is located on the continental shelf (5–300 m water depth) and covers an area of 15,400 km^2. It is an elongate north–south-oriented depocentre (Fig. 2) containing up to 6,000 m of Early Permian (Cisuralian) to Early Cretaceous sedimentary rocks deposited during multiple rift episodes (Fig. 3). These rocks are overlain by a westerly-thickening (up to 850 m thick), carbonate-dominated, passive margin succession.

The majority of the sedimentary fill in the Abrolhos Sub-basin comprises Permian–Early Jurassic strata overlain by thinner Middle Jurassic–Early Cretaceous strata (where they have not been eroded) (Figs 3 to 6) (Marshall et al, 1989; Quaife et al, 1994). In the central and southern parts of the sub-basin, Permian rifting resulted in the formation of predominantly west-dipping, en échelon half-graben. The bounding faults of the half-graben have been the focus of subsequent Jurassic–Cretaceous faulting that developed during the second phase of rifting. Two major half-graben are present in the southern Abrolhos Sub-basin, forming an eastern and a western depocentre for Permian–Triassic strata. A structural high between these two features (Geelvink High) (Figs 2 and 4), which formed through the rotation of fault blocks, has been the target of previous exploration (Geelvink–1 and Batavia–1).

The Geraldton Fault delineates the boundary between the Abrolhos Sub-basin to the west and the Beagle Ridge, Dongara Ridge and Greenough Shelf to the east (Figs 2 and 5; Tyler and Hocking, 2001). This is a north to north-northwest-striking, west-southwest-dipping fault system that formed as an antithetic structure to the Permian half-graben, and was subsequently reactivated during later tectonic events (Jones and Hall, 2002).

The Wittecarra Terrace is a northern extension of the Abrolhos Sub-basin (Fig. 2), over which Permian and Mesozoic rift strata thicken from east to west. The Geelvink Fault System (Iasky et al, 2003), previously referred to as the Abrolhos Hinge Zone (Quaife et al, 1994; Enterprise Oil Exploration Ltd and Nippon Oil Exploration [Perth Basin] Ltd, 1994b), marks the boundary between the Wittecarra Terrrace to the west and the predominantly onshore Gascoyne Platform of the Southern Carnarvon Basin to the east (Fig. 2). It is characterised by west-southwest-dipping faults that vary from minor faults developed above a prominent hinge, to a major fault system (Bradshaw et al, 2003).

The northern Abrolhos Sub-basin is bounded to the west by the Houtman Fault System, previously referred to as the Houtman Hinge Zone (Quaife et al, 1994). The Houtman Fault System is an extensive north–south-striking, westerly-dipping normal fault system (possibly oblique slip), across which there is a significant increase in the thickness of Jurassic and Triassic strata into the Houtman Sub-basin (Fig. 4). In some areas the fault system exhibits en échelon relationships, with relay ramps forming soft linkages between the Abrolhos and Houtman sub-basins (Figs 7 and 8).

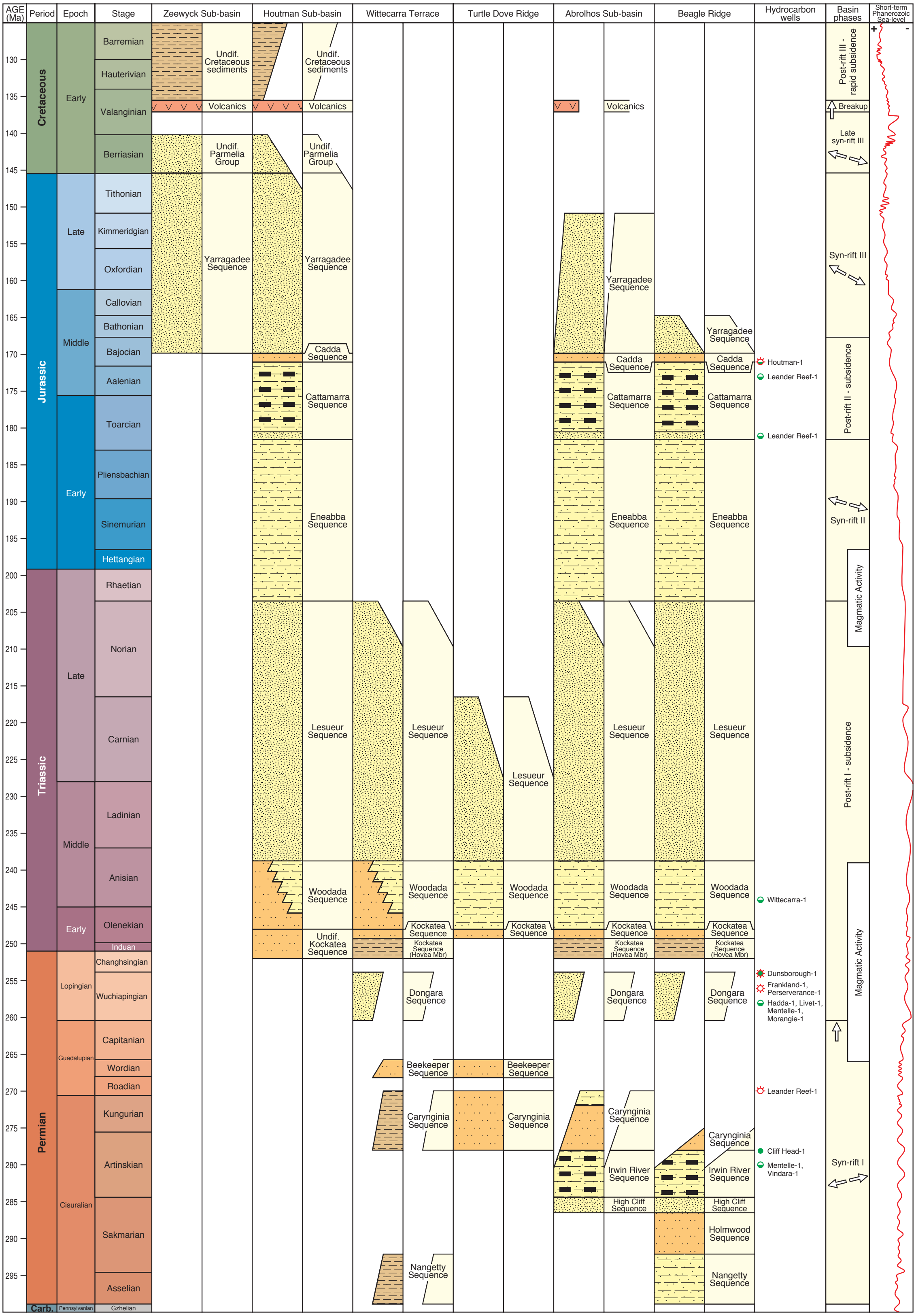


Figure 3. Stratigraphic chart of the offshore northern Perth Basin, showing depositional sequences, hydrocarbon shows and accumulations, and major phases of basin development. Geological timescale after Gradstein et al (2004) and Ogg et al (2008). Sea level curve after Hardenbol et al (1998), Haq and Al-Qahtani (2005) and Haq and Schutter (2008).

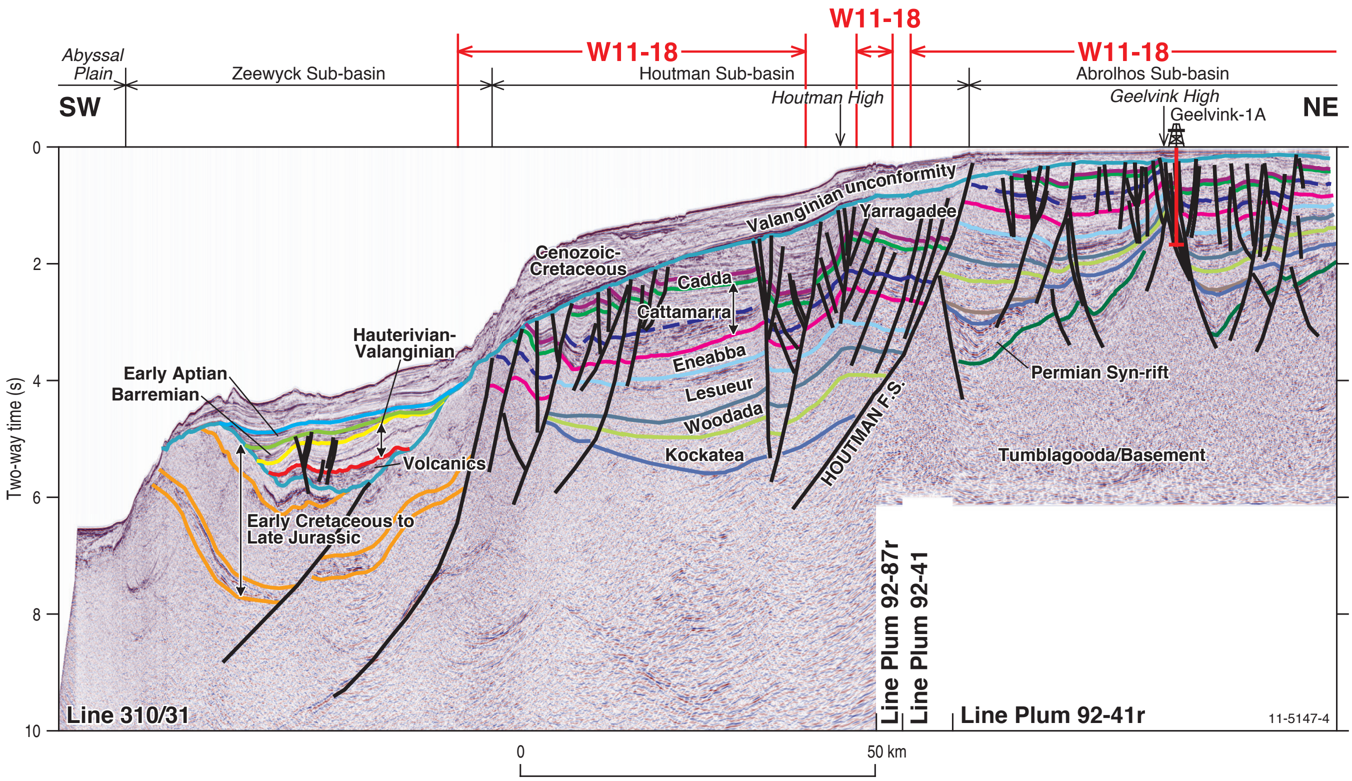


Figure 4. Seismic transect (portions of seismic lines 310-31, Plum 92-87r, Plum 92-41 and Plum 92-14r) through the Abrolhos, Houtman and Zeewyck sub-basins in the central-northern part of Release Area W11-18. Location of transect shown in Fig. 2.

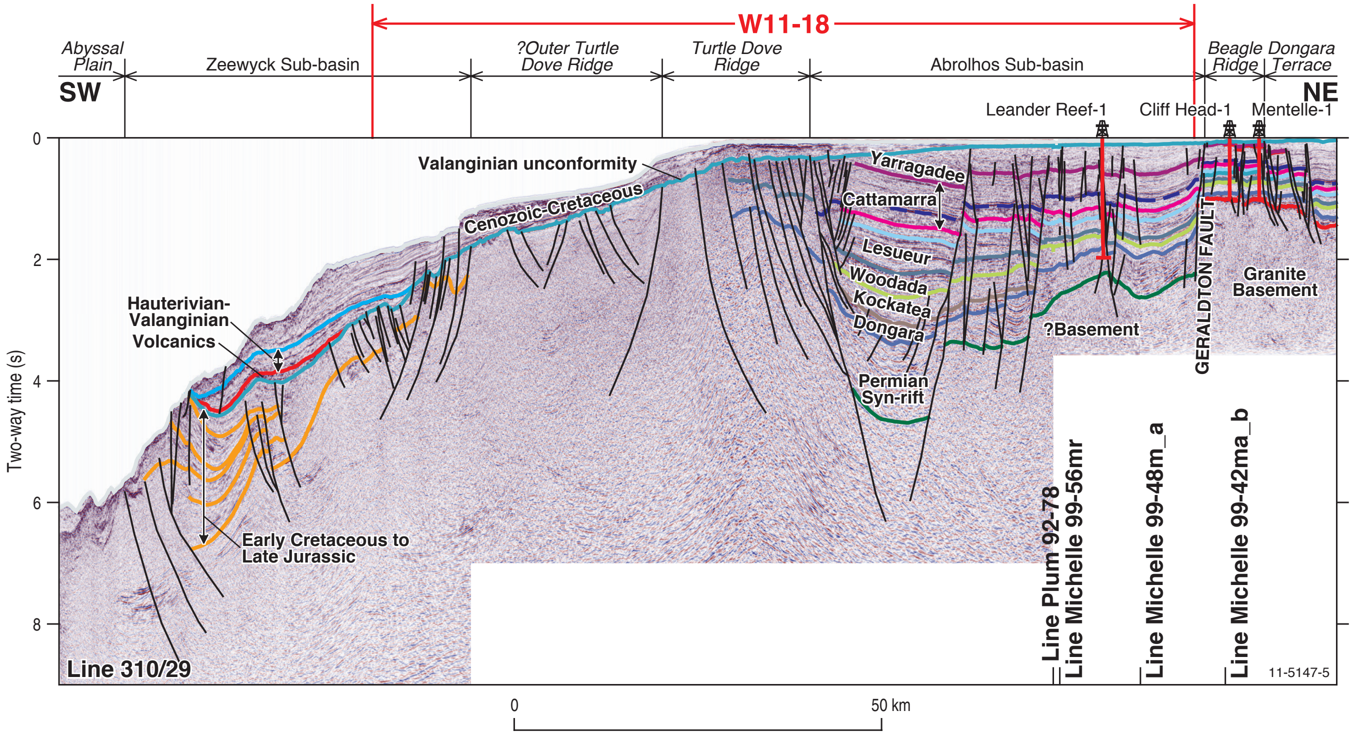


Figure 5. Seismic transect (portions of seismic lines 310-29, Plum 92-78, Michelle 99-56mr, Michelle 99-48m_a and Michelle 99-42ma_b) through the Beagle Ridge, Abrolhos Sub-basin, Turtle Dove Ridge and Zeewyck Sub-basin in the central-southern part of Release Area W11-18. Location of transect shown in Fig. 2.

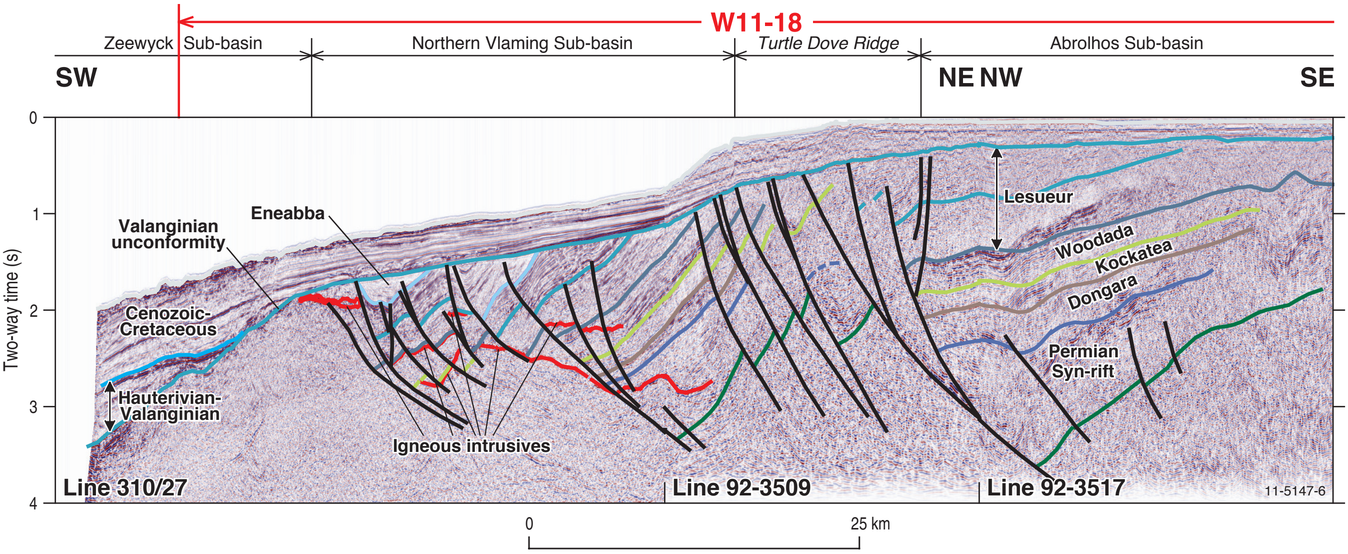


Figure 6. Seismic transect (portions of seismic lines 310-27, 92-3509 and 92-3517) through the Abrolhos Sub-basin, Turtle Dove Ridge, northern Vlaming Sub-basin and Zeewyck Sub-basin in the southern part of Release Area W11-18. Location of transect shown in Fig. 2.

To the south, the Abrolhos Sub-basin becomes increasingly narrow, as the western and eastern boundaries converge at the northern end of the Vlaming Sub-basin (Figs 2 and 7). In this region, the western boundary of the sub-basin is defined by the Turtle Dove Ridge.

HOUTMAN SUB-BASIN

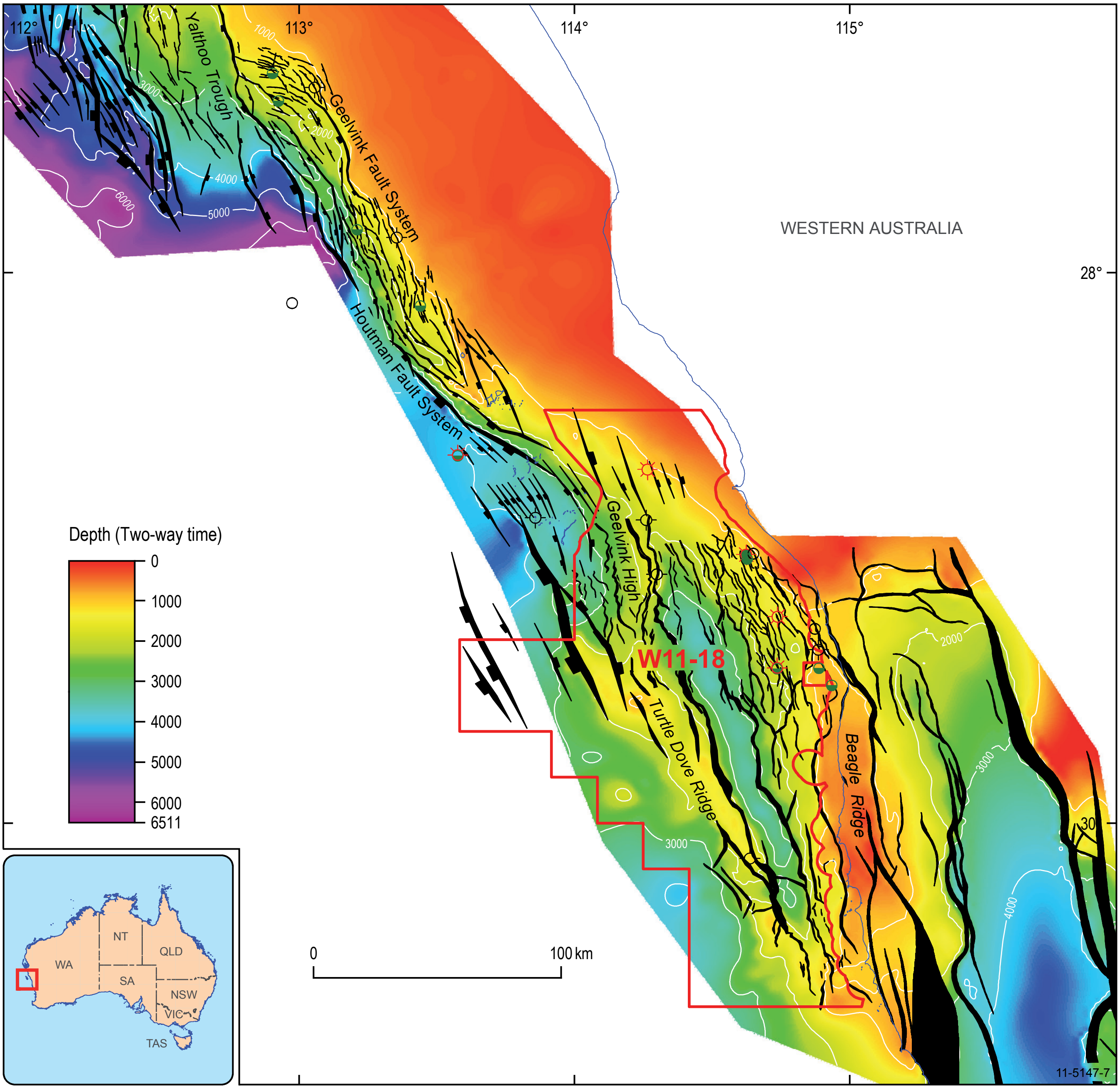
The Houtman Sub-basin (Symonds and Cameron, 1977) is the largest depocentre in the offshore northern Perth Basin (56,800 km^2), and is located on the continental shelf and slope in water depths ranging from 100–3,500 m. It is an elongate, north-northwest to north–south-oriented depocentre (Fig. 2) containing up to 14,000 m of sediment (Copp, 1994). It is dominated by a westerly-thickening succession of Triassic–Middle Jurassic strata, which was intensely faulted during Late Jurassic–Early Cretaceous northwest–southeast-oriented extension (Figs 4 and 8). Faulting is characterised by closely spaced, predominantly westerly-dipping, normal faults, with larger faults possibly becoming listric at depth and detaching into the Early Triassic Kockatea Shale. Erosion during regional uplift in the Valanginian has removed most of the original Middle Jurassic–Early Cretaceous syn-rift section (Quaife et al, 1994). While Permian half-graben are visible in the north, they are not seismically resolvable in the release area. Post-breakup deposits form a westerly-thickening (up to ~1,500 m thick), carbonate-dominated, passive margin succession across the sub-basin (Fig. 4).

The eastern boundary of the Houtman Sub-basin is defined by the Houtman Fault System, as described above, which separates it from the Abrolhos Sub-basin and Southern Carnarvon Basin (Figs 2, 4, 7 and 8). Immediately to the west of the Houtman Fault System is a parallel-striking roll-over structure (Houtman High), which may be a faulted ramp-flat anticline formed against the listric fault system (Figs 2 and 4). This element strikes north-northwest for about 120 km, and forms the structural high over which Houtman–1 was drilled.

In the northern part of the basin, the eastern boundary of the Houtman Sub-basin steps westward across a large (~30 km wide) relay ramp zone onto another north- to northwest-striking, westerly-dipping fault system (Figs 2 and 7). This relay ramp was previously identified by Smith and Cowley (1987) and Purcell and Fisher (1997) as a Permian–Triassic depocentre (Yalthoo Trough). West of the Yalthoo Trough is a major easterly-dipping Permian half-graben. Mesozoic sag, extension and breakup have superimposed a regional westerly tilt over the half-graben and the overlying stratigraphy.

To the north of the study area, the Houtman Sub-basin is bordered by the Wallaby Saddle to the northwest, which is represented by a seaward-dipping reflector sequence in seismic data. The seaward-dipping reflector sequence has previously been interpreted as flood basalts emplaced during, or just after, Valanginian breakup (Colwell et al, 1994; Symonds et al, 1998). In the study area, the western boundary of the Houtman Sub-basin strikes north-northwest and correlates with a distinct magnetic anomaly (Fig. 9). On seismic data it is imaged as a zone of high-amplitude reflectors over a basement high, which are interpreted to be flood basalts and shallow sills emplaced in submarine environments (Symonds et al, 1998). The interpretation of submarine igneous activity, including flood basalts, indicates that the northwestern boundary of the Houtman Sub-basin is a volcanic-rifted margin. To the southwest, however, the Houtman Sub-basin is bordered by a north-northwest-striking, listric fault zone that steps down into the outboard deep-water Zeewyck Sub-basin (Figs 2 and 4).

The southeastern boundary of the Houtman Sub-basin is characterised by strata that have been uplifted onto the Turtle Dove Ridge (Fig. 5).



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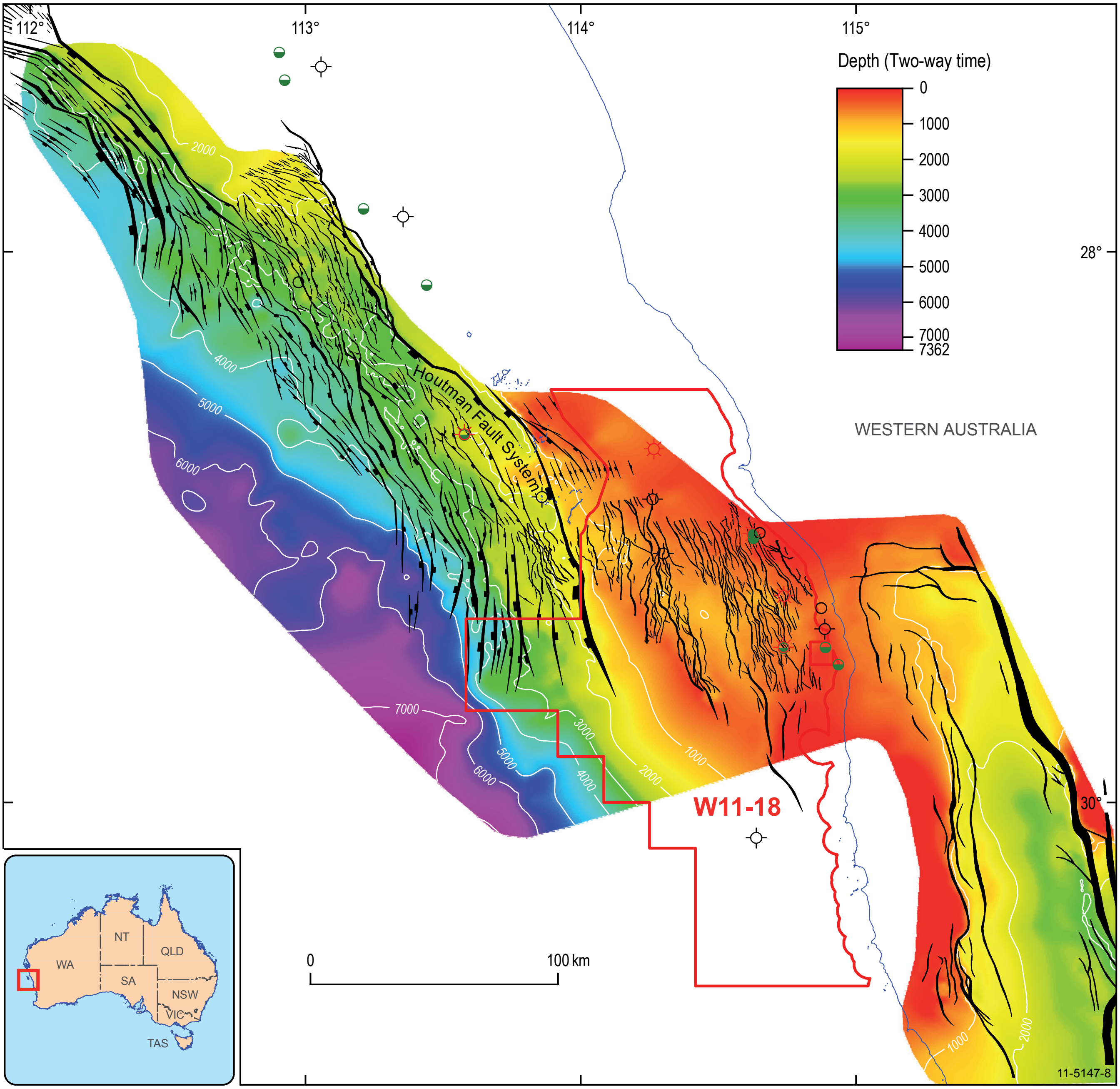
2011 Offshore Petroleum Acreage Release Area
Contour (depth in two-way time)
Late Permian fault
Petroleum exploration well - Not classified
Petroleum exploration well - Dry hole
Petroleum exploration well - Gas discovery
Petroleum exploration well - Oil show
Petroleum exploration well - Oil and gas show
Petroleum exploration well - Gas and oil discovery

Figure 7. Late Permian unconformity structure map of the offshore northern Perth Basin in ms TWT (fault polygons sourced from Enterprise Oil Exploration Ltd and Nippon Oil Exploration [Perth Basin] Ltd, 1994a; Gorter et al, 2004; Roc Oil, pers. comm.; GSWA, pers. comm.).



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2011 Offshore Petroleum Acreage Release Area
Contour (depth in two-way time) 1000
Middle Jurassic fault
Petroleum exploration well - Not classified
Petroleum exploration well - Dry hole
Petroleum exploration well - Gas discovery
Petroleum exploration well - Oil show
Petroleum exploration well - Oil and gas show
Petroleum exploration well - Gas and oil discovery

Figure 8. Middle Jurassic structure map of the offshore northern Perth Basin in ms TWT (fault polygons sourced from Enterprise Oil Exploration Ltd and Nippon Oil Exploration [Perth Basin] Ltd, 1994a; Gorter et al, 2004; Roc Oil, pers. comm.; GSWA, pers. comm.).

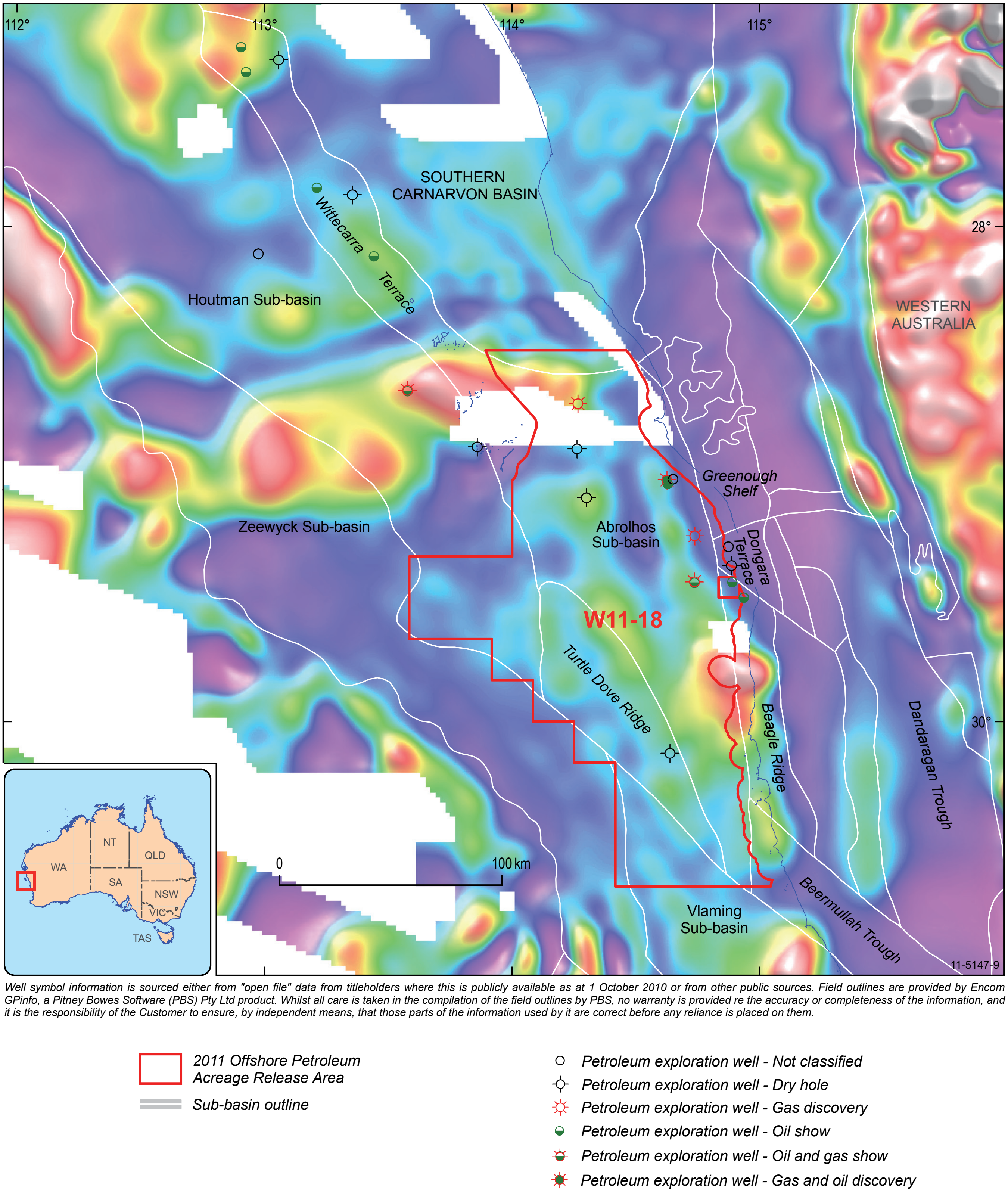

Figure 9. Magnetic anomalies overlain by structural elements of the offshore northern Perth Basin. Offshore data are derived from levelled and gridded ship-track data and onshore data are from the Fifth Edition of the Magnetic Anomaly Map of Australia (Milligan et al, 2010). Both grids were low-pass filtered (cut-off wavelength 15 km) before merging.

ZEEWYCK SUB-BASIN

The Zeewyck Sub-basin extends across the western part of the continental margin under the continental slope, in water depths ranging from 1,000–5,000 m. It covers an area of 17,700 km^2 in a narrow zone that borders the Perth Abyssal Plain to the west (Fig. 2). While originally interpreted as the northern extent of the Vlaming Sub-basin (Hocking, 1994), work on new and reprocessed seismic data has confirmed a distinct sedimentary trough exists westward of the Vlaming and Houtman Sub-basins, as suggested by Bradshaw et al (2003).

Cretaceous strata in the Zeewyck Sub-basin thin onto an extensively-faulted section on the eastern margin, and basement highs and transitional crust to the west (Figs 4 and 5). Underlying ?Jurassic strata vary in geometry from a distinctly westerly-thickening wedge to a uniformly thick package. The most prominent unconformity across the Zeewyck Sub-basin correlates up-dip with the Valanginian Breakup unconformity in the Houtman Sub-basin (Fig. 4). The underlying section is interpreted as a hanging-wall block containing over 4,000 m of ?Jurassic strata that have been downthrown from the Houtman Sub-basin through highly-rotational upper crustal faulting, as a result of lower crustal extension and margin collapse (Bradshaw et al, 2003). The Zeewyck Sub-basin contains both east- and west-dipping tilted fault blocks and is overlain by an oceanward-thinning passive margin succession up to 1,200 m thick. This succession includes Aptian–Holocene deepwater, calcareous, and argillaceous rocks that were penetrated by the Deep Sea Drilling Program (DSDP) hole 259 (Veevers and Johnstone, 1974) on the Perth Abyssal Plain to the west of the sub-basin (Fig. 1).

The eastern boundary of the Zeewyck Sub-basin is defined by a westerly-dipping, northwest-striking fault zone, across which Jurassic strata from the Houtman Sub-basin are downthrown to the southwest (Figs 2 and 4). This fault zone has previously been interpreted as the basinward continuation of the Turtle Dove Transfer (Bradshaw et al, 2003); an interpreted sinistral strike-slip fault formed during Early Cretaceous breakup (Crostella and Backhouse, 2000). The Zeewyck Sub-basin has been interpreted as a pull-apart basin associated with strike-slip movement along this transfer (Bradshaw et al, 2003); however, recent interpretation and structural mapping using new and re-processed seismic data have not found evidence of major strike-slip faults in the sedimentary section. The Zeewyck Sub-basin is likely to have developed by transtensional extension rather than pure strike-slip motion.

The western boundary of the Zeewyck Sub-basin has recently been revised using new seismic data and anomalies in ship track magnetic data (Fig. 9), and upward continued residual gravity data (Fig. 10). The boundary correlates with the rapid thinning of strata over a basement ridge complex that represents the beginning of a continent-ocean transition zone, with oceanic crust to the west (Figs 4 and 5).

TURTLE DOVE RIDGE

The Turtle Dove Ridge (Jones and Pearson, 1972) is a north-northwest-oriented structural high covering an area of 3,190 km2 beneath the continental shelf and slope (50–1,000 m water depth). It correlates with a strong gravity high (Fig. 10), but has no distinctive magnetic signature (Fig. 9). The Turtle Dove Ridge separates the southern part of the Abrolhos Sub-basin in the east from the southern Houtman, Zeewyck and northern Vlaming sub-basins to the west. The eastern boundary of the ridge is defined by a major easterly-dipping fault that originated during Permian rifting and was reactivated during latest Jurassic–Early Cretaceous extension and breakup (Figs 5 and 6). To the northeast, the boundary with the Abrolhos Sub-basin is mapped, where possible, using seismic data to identify the first evidence of significant inversion. The western boundary is more ambiguous but is defined by a prominent uplifted hanging-wall block in places (Fig. 6). Hocking (1994) suggested that the northeastern and southwestern boundaries are associated with northwest-striking, sinistral, strike-slip faults; however, Permian rift faults from the Abrolhos Sub-basin extend into the Turtle Dove Ridge with no commensurate strike-slip offset (Fig. 7). Furthermore, the southwestern boundary is difficult to resolve using the limited seismic data available, and is therefore mapped based on the extents of the inferred Turtle Dove Transfer (Tyler and Hocking, 2001). Up to ~3,400 m of Permian–Early Triassic strata are interpreted to underlie the Valanginian unconformity over the ridge in a series of small westerly-dipping half-graben. These half-graben appear to be uplifted Permian rift structures that continue north into the Abrolhos Sub-basin and south into the northern Vlaming Sub-basin.

BEAGLE RIDGE, DONGARA TERRACE AND GREENOUGH SHELF

The Beagle Ridge (Playford and Willmott, 1958; Dickins et al, 1961; McTavish, 1965) is an intra-basin high of Pre-Cambrian granite between the Abrolhos Sub-basin to the west and Dandaragan Trough to the east (Fig. 2), and has a prominent gravity expression (Fig. 10). Permian strata in the Dandaragan Trough thin westward onto the ridge, suggesting it was a positive feature during the Permian. The eastern boundary of the Beagle Ridge is marked by the Beagle Fault System, a series of en échelon north-northwest-oriented faults downthrown to the east, across the Cadda Terrace into the Dandaragan Trough. The western boundary is defined by the Geraldton Fault, across which the Mesozoic section thickens to the west (Fig. 5). Post-Permian tectonic episodes have reactivated north-northeast and north-west-oriented fault sets, developed in the Permian extension phase, into an additional northwest-orientated series of hard- and soft-linked fault systems. This has resulted in the compartmentalisation of the western Beagle Ridge into a series of discrete structures, one of which hosts the producing Cliff Head oil field (Roc Oil, 2004).

North of the Beagle Ridge, the Dongara Terrace (Dongara Saddle—Jones and Pearson, 1972) and Greenough Shelf (Mory and Iasky, 1996) form a continuation of the fault-bounded basement ridge (Fig. 7). The Dongara

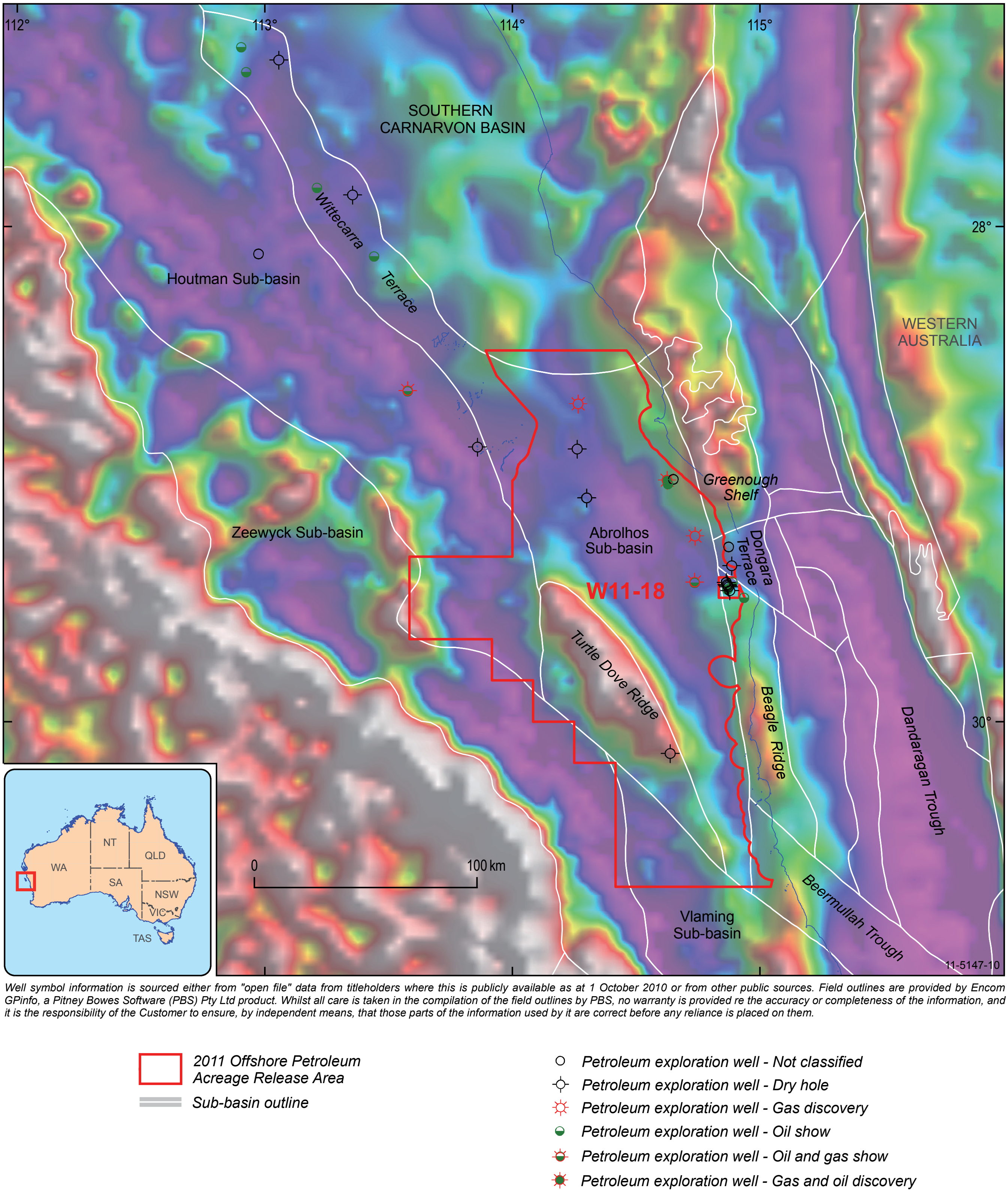

Figure 10. Residual gravity image overlain by structural elements of the offshore northern Perth Basin. The gravity image is based on version 16.1 Sandwell and Smith satellite altimetry-derived data converted to Bouguer anomalies using a correction density of 2,670 kg/m^3. The residual field is computed from the difference between Bouguer gravity upward continued by 2 km and 4 km.

Terrace is bounded to the south by the northwest-trending Abrolhos Transfer Zone and to the north by the Allanooka Fault, which marks its boundary with the Greenough Shelf. Both the Dongara Terrace and Greenough Shelf step down to the east, across the Mountain Bridge Fault, onto the Beharra Springs Terrace and Allanooka High, respectively, and to the west, across the Geraldton Fault, into the Abrolhos Sub-basin.

Structural evolution and depositional history

The revised understanding of the tectonic evolution and depositional history of the offshore northern Perth Basin described herein and presented in Figure 3, is based on a sequence stratigraphic analysis of well and seismic data. Consequently, the Permian to Jurassic stratigraphy is described by sedimentary sequences rather than lithostratigraphic units. Lithostratigraphic unit names have been retained from previous schemes where possible (e.g. Kockatea Sequence), to provide greater context in discussing the sequences.

The offshore northern Perth Basin has had a complex, multi-phase history of extension and reactivation. Regional tectonic events that affected the basin and controlled sediment deposition include (Fig. 3):

- Early to mid-Permian (Cisuralian–Guadalupian) east-northeast–west-southwest extension;
- Mid-Permian (late Guadalupian) regional uplift;
- Late Permian (Lopingian) to Late Triassic thermal subsidence;
- Possible latest Triassic to Early Jurassic west-northwest–east-southeast extension;
- Early Jurassic to Middle Jurassic thermal subsidence;
- Middle Jurassic to Late Jurassic northwest–southeast extension;
- Early Cretaceous northwest–southeast extension and local transpression;
- Valanginian regional uplift and breakup;
- Early Cretaceous to Cenozoic passive margin subsidence; and,
- Miocene inversion.

BASEMENT/PRE-RIFT

Proterozoic rocks of the Pinjarra Orogen form the basement to the Perth Basin, although this basement terrane is poorly understood because outcrop is limited (Dentith et al, 1994). The Northampton Block, immediately onshore and to the northeast of the release area, is an example of one such exposure. It is a high-grade metamorphic inlier of Paleoproterozoic age, which was deformed in the Mesoproterozoic (Dentith et al, 1994). Major north–south and northwest–southeast-oriented faults and shear zones in this terrane provide a structural fabric that influenced basin architecture (Dentith et al, 1994). Precambrian granites sampled in Cliff Head–1 and –4, Mentelle–1 and Twin Lions–1, all on the Beagle Ridge, may be examples of where the Pinjarra Orogen basement terrane has been intersected offshore.

Pre-rift strata are interpreted to comprise the Tumblagooda Sandstone, which may exceed 4 km in thickness in some locations (Playford et al, 1976). This unit comprises a succession of very fine to coarse-grained sandstones, characteristically coloured red, which were deposited in continental fluviatile environments (Playford et al, 1976; Hocking, 1991; Mory and Iasky, 1996). The age of the Tumblagooda Sandstone is thought to be Late Cambrian to Ordovician, based on limited conodont recovery (Nicoll, pers. comm.). The Tumblagooda Sandstone was intersected at the base of Livet–1 and Hadda–1 on the Wittecarra Terrace and may underlie the majority of the release area, with the exception of the Beagle Ridge. This, however, is speculative and the true nature of the pre-rift strata for much of the offshore northern Perth Basin remains unclear.

EARLY TO MID-PERMIAN (CISURALIAN–GUADALUPIAN) NORTHEAST–SOUTHWEST EXTENSION: SYNRIFT I

Early- to mid-Permian east-northeast-oriented intra-cratonic extension saw the development of north-northwest-oriented half-graben in the offshore northern Perth Basin (Fig. 7). The half-graben switch polarity along the margin. For example, in the northern and southern parts of the Abrolhos Sub-basin the half-graben dip to the west (Figs 4 and 6), whereas towards the centre of the sub-basin, the half-graben dip to the east (Fig. 5). Early- to mid-Permian sedimentation reached a maximum thickness of ~6,500 m in the Houtman Sub-basin and 3,900 m in the Abrolhos Sub-basin.

Initial syn-rift sedimentation occurred in a glacial to pro-glacial marine shelf environment, with the deposition of the Nangetty and Holmwood sequences (Fig. 3). These sequences record a major transgression during the Asselian and Sakmarian. A subsequent regression led to the deposition of glacially-influenced paralic sediments in the High Cliff Sequence (Fig. 3). A downward base level shift near the end of the Sakmarian and subsequent slow transgression led to the accumulation of coal measures in the Irwin River Sequence. This transgression led to a major marine incursion in the Artinksian, with a maximum flooding event in the lower Caryngninia Sequence. The upper Carynigina and Beekeeper sequences were deposited as part of a regional regression until the mid-Permian (Fig. 3).

MID-PERMIAN (LATE GUADALUPIAN) REGIONAL UPLIFT

The top of the Early- to mid-Permian Syn-Rift I succession is marked by a major angular unconformity (Figs 4 to 6), interpreted to be the result of regional tectonic uplift. Widespread erosion resulting from this uplift may have been accentuated by a major eustatic sea level fall at the end of the mid-Permian.

Offshore marine shales of *Didecitriletes ericianus* or younger age (Wordian), assigned to the Beekeeper Sequence, are intersected in South Turtle Dove–1B and Wittecarra–1. The top of this sequence is represented by a major unconformity in both of these wells, therefore regional uplift is interpreted to have occurred in the Capitanian. Erosion resulting from late Permian uplift totally or partially removed the Beekeper and Carynigina sequences from the Beagle Ridge and parts of the Abrolhos Sub-basin (Fig. 3).

LATE PERMIAN (LOPINGIAN) TO LATE TRIASSIC THERMAL SUBSIDENCE: POST-RIFT I

Permian rifting was followed by thermal subsidence during the late Permian to Late Triassic. The sedimentary succession deposited during this phase is interpreted to be preserved over the entire release area, including the northern extension of the Vlaming Sub-basin on the western side of the Turtle Dove Ridge (Fig. 6); however, variable seismic quality at depth has prevented mapping of the package over parts of the Houtman Sub-basin (Fig. 7).

A thick second-order sedimentary sequence was deposited during this sag phase. Initial sedimentation occurred with the deposition of the Dongara Sequence. Highly reflective seismic facies preserved above the late Permian unconformity are interpreted to be a basin floor fan complex deposited during a second-order sea level lowstand in this sequence (Fig. 11). Marginal marine sandstones representing the Dongara Sequence in wells on the Beagle Ridge and in the Abrolhos Sub-basin are interpreted to represent the ensuing transgressive facies that filled incised valleys formed during the lowstand. The transgression continued to maximum flooding in the Early Triassic with the deposition of marine shales of the Kockatea Sequence. Relatively slow accumulation of the Hovea Member (maximum thickness in offshore wells of 45.7 m in Lilac–1) over ~2.7 million years in the latest Permian to earliest Triassic (Fig. 3) was followed by rapid accumulation of the remainder of the Kockatea Sequence (maximum thickness in offshore wells of 435 m in Batavia–1) over ~1.3 million years in the Early Triassic (Fig. 3).

A late Permian–earliest Triassic intrusion event accompanied this post-rift phase, with igneous rocks being intersected in Edel–1 (Southern Carnarvon Basin; 40 km northeast of Fiddich–1) and postulated below total depth in Geelvink–1 (Gorter and Deighton, 2002).

A gradual regression through the late-Early to Late Triassic led to the deposition of the deltaic to fluvial Woodada and Lesueur sequences. South to north flow of these axial fluvio-deltaic systems (Mory and Iasky, 1996; Norvick, 2004) resulted in these sequences, particularly the Woodada Sequence, being relatively coarse-grained in the south (southern Abrolhos Sub-basin) and fine-grained in the north (northern Wittecarra Terrace) (Fig. 3).

This phase of sedimentation was terminated by localised uplift and erosion, emplacement of igneous intrusions and renewed extension.

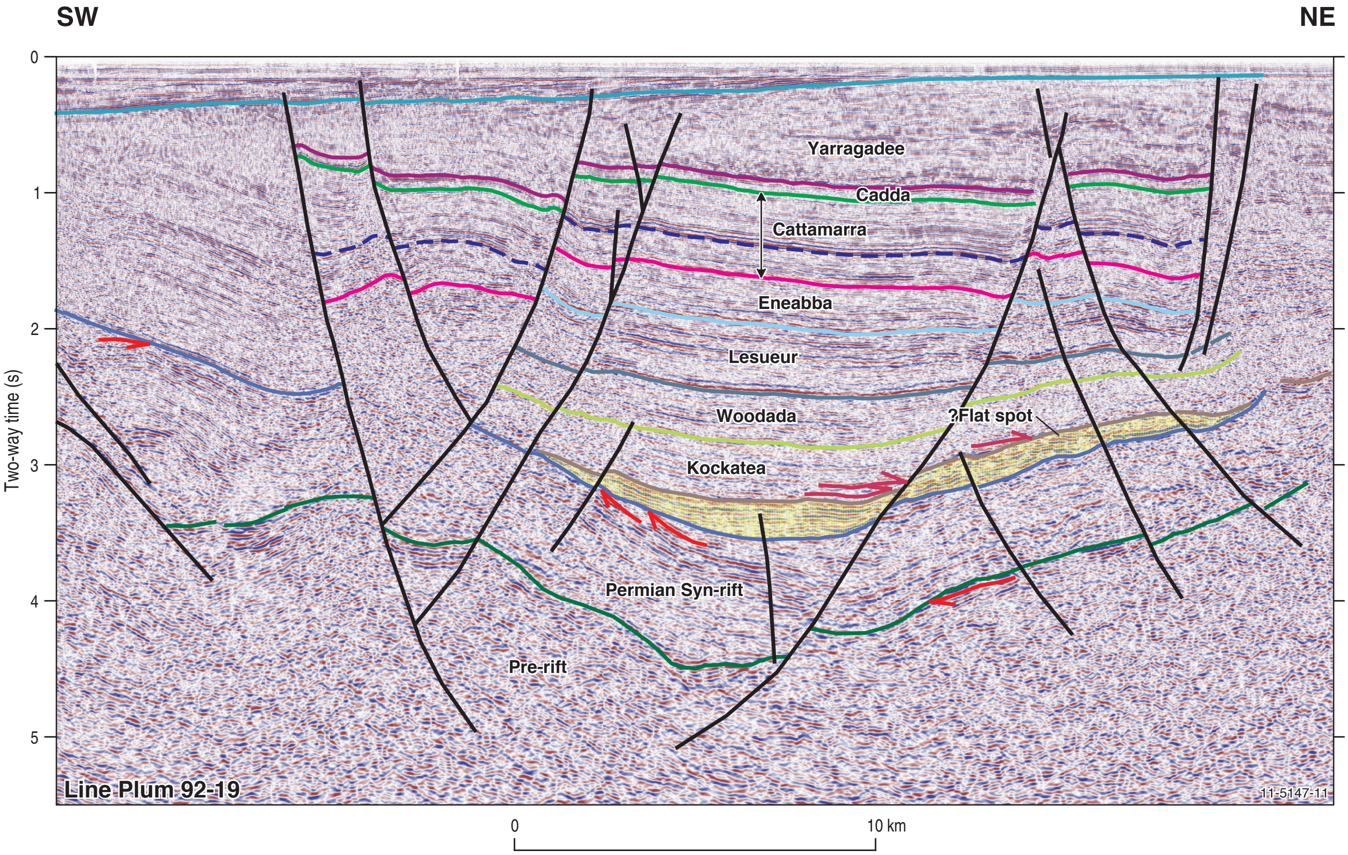

Figure 11. Portion of seismic line Plum92-19, in the Abrolhos Sub-basin, displaying a thick basinal succession of high amplitude continuous reflectivity interpreted as a lowstand clastic basin fan complex of the Dongara Sequence. Note possible flat-spot near the top of this succession. Location of seismic section shown in Fig. 2.

POSSIBLE LATEST TRIASSIC TO EARLY JURASSIC WEST-NORTHWEST–EAST-SOUTHEAST EXTENSION: SYN-RIFT II

Latest Triassic to Early Jurassic rifting has been interpreted to have occurred in the onshore Perth Basin with thickening of Early Jurassic strata (Eneabba Formation) in the hanging wall of major faults (Song and Cawood, 2000, Gorter et al, 2004). An angular unconformity in parts of the Abrolhos Sub-basin is interpreted to represent Late Triassic to Early Jurassic rift-related uplift, based on a seismic correlation with the basal Eneabba Sequence in Perserverance–1 (Fig. 12). Igneous intrusions mapped in seismic and aeromagnetic data in the vicinity of Perseverance–1 (Anderson et al, 2006) are interpreted to have been emplaced at about this time (Fig. 3), based on the relative age of intruded strata (Fig. 12), and as such may be related to the onset of rifting.

The Eneabba Sequence does not typically thicken into major faults at a basin-scale (Figs 4 to 6); however, seismic data in some areas of the Houtman Sub-basin suggest rift-related thickening of this sequence (Gorter et al, 2004). The Eneabba Sequence comprises fine- to coarse-grained sandstones interbedded with varicoloured siltstones and claystones deposited in an alluvial environment. It is interpreted to represent the basal lowstand succession of a Jurassic second-order depositional sequence.

EARLY JURASSIC TO MIDDLE JURASSIC THERMAL SUBSIDENCE: POST-RIFT II

A slow, relative sea level rise during a period of Early to Middle Jurassic subsidence led to the deposition of interbedded sandstones, siltstones and coals (Cattamarra Sequence) across Release Area W11-18 (Figs 4 to 6). The presence of the *Luehndea* Dinocyst Assemblage (Toarcian) in Dunsborough–1, and other ?Toarcian-Aalenian dinocysts in Gun Island–1, are evidence of marine incursions during this transgressive succession, which culminated in maximum flooding in the Cadda Sequence (Jorgensen et al, in prep). The subsequent regression commenced during this thermal subsidence phase, with the deposition of fluvio-deltaic sandstones and siltstones in the lower part of the Yarragadee Sequence.

MIDDLE JURASSIC TO LATE JURASSIC NORTHWEST–SOUTHEAST EXTENSION: SYN-RIFT III

The next major phase of rifting in the offshore northern Perth Basin occurred in the Middle Jurassic. In the Abrolhos Sub-basin, Jurassic syn-

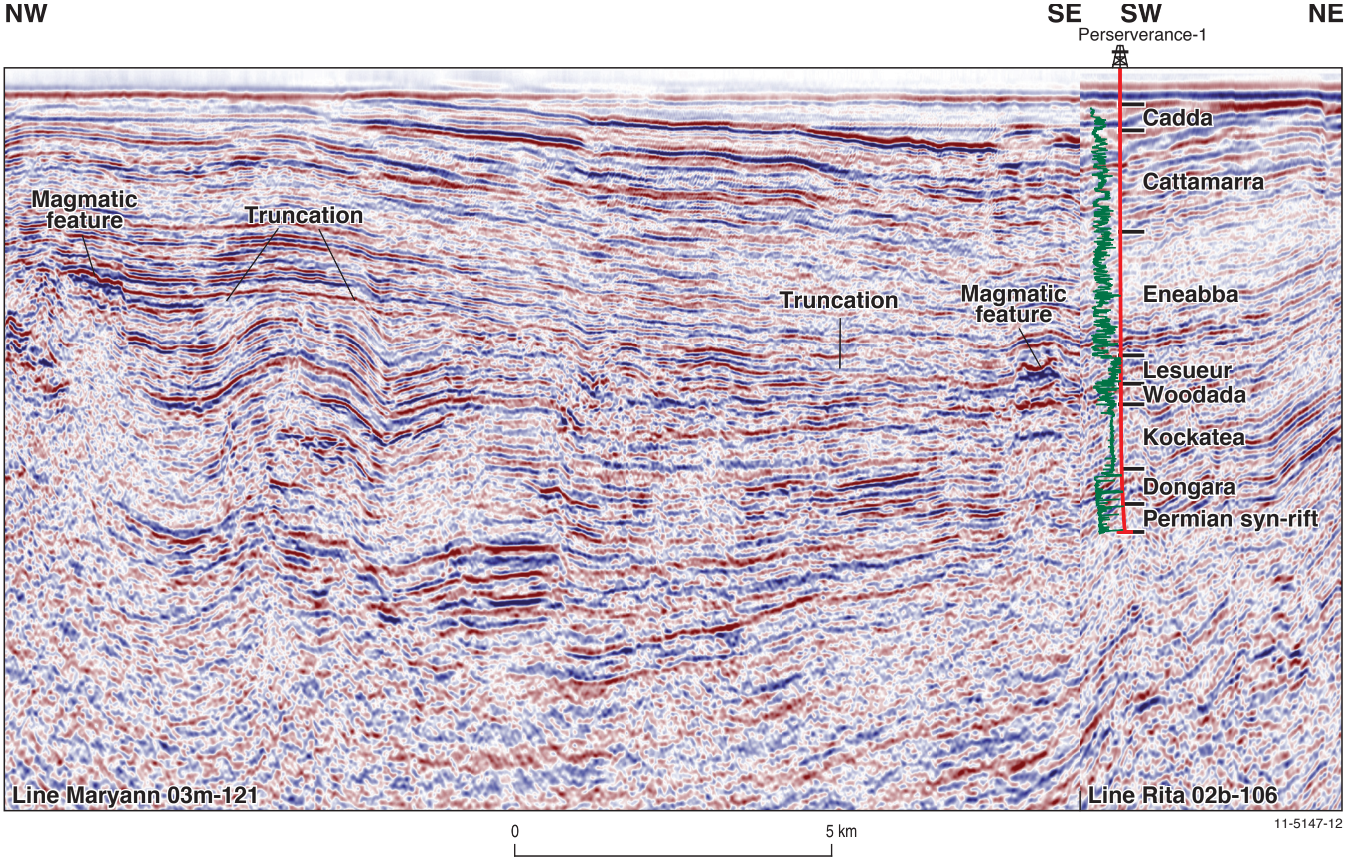

Figure 12. Uninterpreted seismic transect (portions of seismic lines MaryAnn 03m-121 and Rita 02b-106) in the Abrolhos Sub-basin, displaying igneous intrusives and potential extrusives, and inversion anticlines eroded by an angular unconformity that correlates with the base of the Eneabba Sequence in Perserverance–1. Green curve is gamma ray response. Location of transect shown in Fig. 2.

rift faults preferentially reactivated the Permian fault system. Generally, fault architecture across the basin is characterised by en échelon fault networks, resulting in the formation of relay ramps at a range of scales (Figs 7 and 8). The Houtman Fault System is likely to have been a major growth fault zone during this period of extension, with the primary depocentre for the rift fill in the Houtman Sub-basin (Figs 4 and 8). Uplift and erosion related to breakup, however, have resulted in poor preservation of the syn-rift package across most of the basin, making identification of major growth wedges difficult.

The Yarragadee Sequence forms the Middle to Upper Jurassic rift fill, and predominantly comprises coarse-grained fluvial sediments deposited in a northerly-flowing river system (Mory and Iasky, 1996; Norvick, 2004). Sparse Oxfordian to Kimmeridgian dinocyst assemblages in Houtman–1 (Wanaea spectablis or younger) and Charon-1 (Wanaea clathrata) are evidence of minor marine incursions during this time

EARLY CRETACEOUS NORTHWEST–SOUTHEAST EXTENSION AND LOCAL TRANSPRESSION: POSTRIFT III

Late-stage rifting in the Early Cretaceous preceded the separation of Australia and Greater India in the Valanginian (Larson et al, 1979; Veevers et al, 1985). This Early Cretaceous rift phase continued the development of a dense north-northwest-striking system of closely-spaced, predominantly westerly-dipping rotated fault blocks (Fig. 8). A series of small-scale north- to north-northwest-striking inversion anticlines and pop-up structures in the Houtman and Abrolhos sub-basins may have formed through transpressional stresses during the late stages of extension. The inversion structures are characterised by well-developed fault propagation folds that have been truncated by the Valanginian unconformity. Similar structures have been interpreted adjacent to constraining bends of major fault systems in the onshore Perth Basin (Song and Cawood, 2000).

There is no evidence for rift-related Cretaceous sediments in Release Area W11-18. All strata deposited in the area at that time are interpreted to have been eroded during breakup-related uplift. Early Cretaceous strata have been interpreted in the Zeewyck (Figs 4 and 5) and northern Houtman sub-basins (Fig. 3), where ages have been partially constrained by palynological dating of dredge samples (Daniell et al, 2010).

VALANGINIAN REGIONAL UPLIFT AND BREAKUP

Middle Jurassic to Early Cretaceous rifting culminated in continental breakup, extensive uplift and basin inversion, resulting in erosion (Song and Cawood, 2000). This erosion produced an angular breakup unconformity that truncated stratigraphy and syn-rift faults (Figs 4 to 6), and resulted in the total removal of Early Cretaceous strata and extensive erosion of Upper Jurassic strata throughout Release Area W11-18.

Breakup was preceded and/or accompanied by widespread continental margin volcanism (Symonds et al, 1998; Gorter and Deighton, 2002). Evidence for this volcanic activity is visible in seismic data across the offshore northern Perth Basin. For example, in Release Area W11-18 pinnacle features on the breakup unconformity have been interpreted as possible volcanic cones and dykes (Gorter and Deighton, 2002). Furthermore, high-amplitude seismic reflectors over the Valanginian unconformity in the Zeewyck Sub-basin, and seaward-dipping reflector sequences outboard of the Houtman Sub-basin, provide evidence of flood basalts emplaced during or just after breakup.

The Turtle Dove Ridge is interpreted to have formed primarily through uplift during Valanginian breakup. This uplift resulted in the erosion of up to 3,000 m of Cretaceous, Jurassic and Triassic strata (Figs 3, 5 and 6), and was driven by transpressional movement on deep-seated faults or deep-seated intrusions (although a magnetic anomaly is lacking) (Fig. 11; Blyth, 1994; Quaife et al, 1994; Enterprise Oil Exploration Ltd and Nippon Oil Exploration [Perth Basin] Ltd, 1994a).

EARLY CRETACEOUS TO CENOZOIC PASSIVE MARGIN SUBSIDENCE: POST RIFT III

A phase of rapid passive margin subsidence and widespread westward regional tilting followed in the Early Cretaceous (Valanginian–Aptian; Quaife et al, 1994). The deep-water Zeewyck Sub-basin was the primary depocentre in the northern Perth Basin during this time, with the accumulation of potentially marine equivalents of the Warnbro Group in the Vlaming Sub-basin.

Slowing of post-breakup thermal subsidence during the Late Cretaceous–Cenozoic resulted in sedimentation under stable passive margin conditions, which produced a thin cover of progradational marine carbonates and clastics across the offshore northern Perth Basin. These deposits attain a maximum thickness outboard of Release Area W11-18.

During the Neogene to Quaternary, there was a vertical transition from cool-water ramp sedimentation to reefal platform development (Houtman Abrolhos coral reefs) near the shelf edge in some places (Collins et al, 1998).

MIOCENE INVERSION

Evidence of late-stage fault reactivation and inversion, with minor folding deforming Cretaceous and younger strata to just below the seafloor, is evident along some of the major basin-bounding fault systems in the offshore northern Perth Basin (Gorter et al, 2004). This inversion event is interpreted to be the result of Miocene collision between the Australian and Eurasian plates. Post-Miocene seafloor pinnacles observed in seismic data and high-resolution swath bathymetry have been confirmed as volcanic cones using seafloor dredging and underwater photography (Daniell et al, 2010).

PETROLEUM SYSTEMS AND HYDROCARBON POTENTIAL

Regional hydrocarbon families

Geochemical studies of petroleum from the Perth Basin, using modern analytical techniques (i.e. biomarkers by gas chromatography-mass spectrometry [GCMS], carbon and hydrogen isotopes by compound specific isotopic analysis [CSIA]) have given detailed insights into the origin of the gaseous and liquid hydrocarbons (Summons et al, 1995; Boreham et al, 2001; Gorter et al, 2004; Thomas and Barber, 2004; Dawson et al, 2005a; Geoscience Australia and Geomark, 2005; Geotech, 2005; Grice et al, 2005; Volk et al, 2009; Kempton et al, 2011). Based on these studies and ongoing analyses of hydrocarbons recovered from more recent discoveries, as well as some legacy samples, several hydrocarbon families and associated petroleum systems are recognised in the Perth Basin: Permian, Triassic, mixed Permian–Triassic, Jurassic and Upper Jurassic/Early Cretaceous (Figs 13 to 15). The majority of oils and condensates from the northern Perth Basin are sourced entirely from the sapropelic interval of the Hovea Member of the Triassic Kockatea Shale (Table 1); however, there are locally important hydrocarbons in the Perth Basin that are sourced solely from older and younger successions, or which contribute to the Early Triassic marine petroleum system (Table 2).

PERMIAN-SOURCED HYDROCARBONS (SUE GROUP AND IRWIN RIVER COAL MEASURES)

A number of gas/condensate discoveries in the onshore Perth Basin were sourced entirely, or in part, from Permian coal measures. The Whicher Range condensates (and by inference, the associated gas) from the Bunbury Trough in the southern Perth Basin is believed to have been locally sourced from coal measures in the Permian Sue Group (Summons et al, 1995). It has an isotopic signature enriched in ^{13}C ($\delta^{13}C$ ~ –25‰) (Fig. 14; Summons et al, 1995) and a dominant land-plant biomarker assemblage (e.g. high pristane/phytane and C_{29}/C_{27} sterane ratios) that are distinctive of Permian-sourced hydrocarbons.

Similar isotopically heavy gas was recovered from the Irwin River Coal Measures in Elegans–1 on the Beharra Springs Terrace (Fig. 13), east of the Dongara Terrace (Fig. 14; Boreham et al, 2001). Thomas and Barber (2004) suggested a mixed Permian–Early Triassic source for the Elegans–1 gas, but given the weak maturity control on the carbon isotopic composition of the Perth gases (Fig. 14), a sole Permian source is favoured here (Table 2).

Other samples that are believed to have been sourced in part from Permian coal measures include gas from the Dongara field, oil from Woodada–3 and fluid inclusion oil from Leander Reef–1 (Table 2)—these are discussed separately below.

TRIASSIC-SOURCED HYDROCARBONS (HOVEA MEMBER, KOCKATEA SHALE)

From the beginning of petroleum exploration in the Perth Basin, the Early Triassic Kockatea Shale was recognised as the principal source for the oils from the Dongara Terrace and immediate surrounds (e.g. Dongara, Mondarra, Mount Horner, North Erregulla and Woodada fields) in the onshore northern Perth Basin (Table 1; Powell and McKirdy, 1973, 1976). More recent discoveries of Kockatea Shale-sourced oils have extended beyond the Dongara Terrace to the accumulations at Eremia, Hovea and Jingemia, and offshore at Cliff Head (Thomas and Barber, 2004). Significantly, oil and fluid inclusion oil from Hadda–1 (Table 1), and oil shows from Livet–1 and Morangie–1 (Thomas and Barber, 2004) have shown that a Kockatea source is effective in the northern part of the offshore Perth Basin (Fig. 13).

Thomas and Barber (2004) constrained the effective source rock to an earliest Triassic, middle sapropelic interval in the Hovea Member of the lower Kockatea Shale. This source zone is typically 10–40 m thick and is continuous over much of the onshore northern Perth Basin. Until recently, Hovea Member source rocks have only been recognised offshore in Leander Reef–1 (Thomas and Barber, 2004); however, based on extensive new sampling and analysis, the Hovea Member is now recognised in 18 wells on the offshore Beagle Ridge and in the Abrolhos Sub-basin, and shows good to excellent source rock potential for generating oil (Grosjean et al, 2010).

The Early Triassic marine-sourced oils are typically waxy, with the most ^{13}C-depleted carbon isotopic signature of any Australian Phanerozoic oil ($\delta^{13}C$ ~ –34‰; Powell and McKirdy, 1976). This extremely light signature is also reflected in individual n-alkanes ($\delta^{13}C$ < –32 ‰, Fig. 14) (Summons et al, 1995; Boreham et al, 2001; Gorter et al, 2004). Characteristic geochemical signatures of the oils include pristane/phytane ratio <3, C_{29} steranes slightly dominant over C_{27} steranes and abundant extended C_{28} + tricyclic hydrocarbons (Geoscience Australia and GeoMark, 2005). An anomalously high abundance of C_{33} n-alkylcyclohexane (Jefferies, 1984), phytanyltoluenes and long-chained alkylnaphthalenes (Thomas and Barber, 2004) is unique among Australian oils. These unusual biomarker signatures, however, have a strong maturity control and are generally absent in high-maturity condensates.

Most onshore Perth Basin gases were originally believed to be sourced from early Permian coals (Owad-Jones and Ellis, 2000); however, this is inconsistent with their depletion in ^{13}C (Fig. 14) and a Kockatea Shale source is more appropriate (Boreham et al, 2001).

MIXED PERMIAN–TRIASSIC-SOURCED HYDROCARBONS

Oil recovered from Woodada–3 contains the C_{33} alkylcyclohexane biomarker characteristic of the Hovea Member, but is isotopically heavier than the other Early Triassic-sourced oils (Fig. 14). This led Summons et al (1995) to suspect a variant Early Triassic organic facies; however, a mixed oil is more likely with input from either a Permian (Thomas and Barber, 2004) or Jurassic (Gorter et al, 2004) source.

Isotopic evidence for an admixture of Triassic and Permian-sourced liquids is also found in one of the two oils analysed from Yardarino–1 (Fig. 13). While one sample is essentially identical to oils sourced from the earliest Triassic sapropelic interval (e.g. Dongara–14; Fig. 14), the other (originally analysed by Summons et al, 1995) has a marked trend to heavier isotopic values at the low carbon end (C_9–C_{12}) of the CSIA profile (Fig. 14), which suggests an ad-

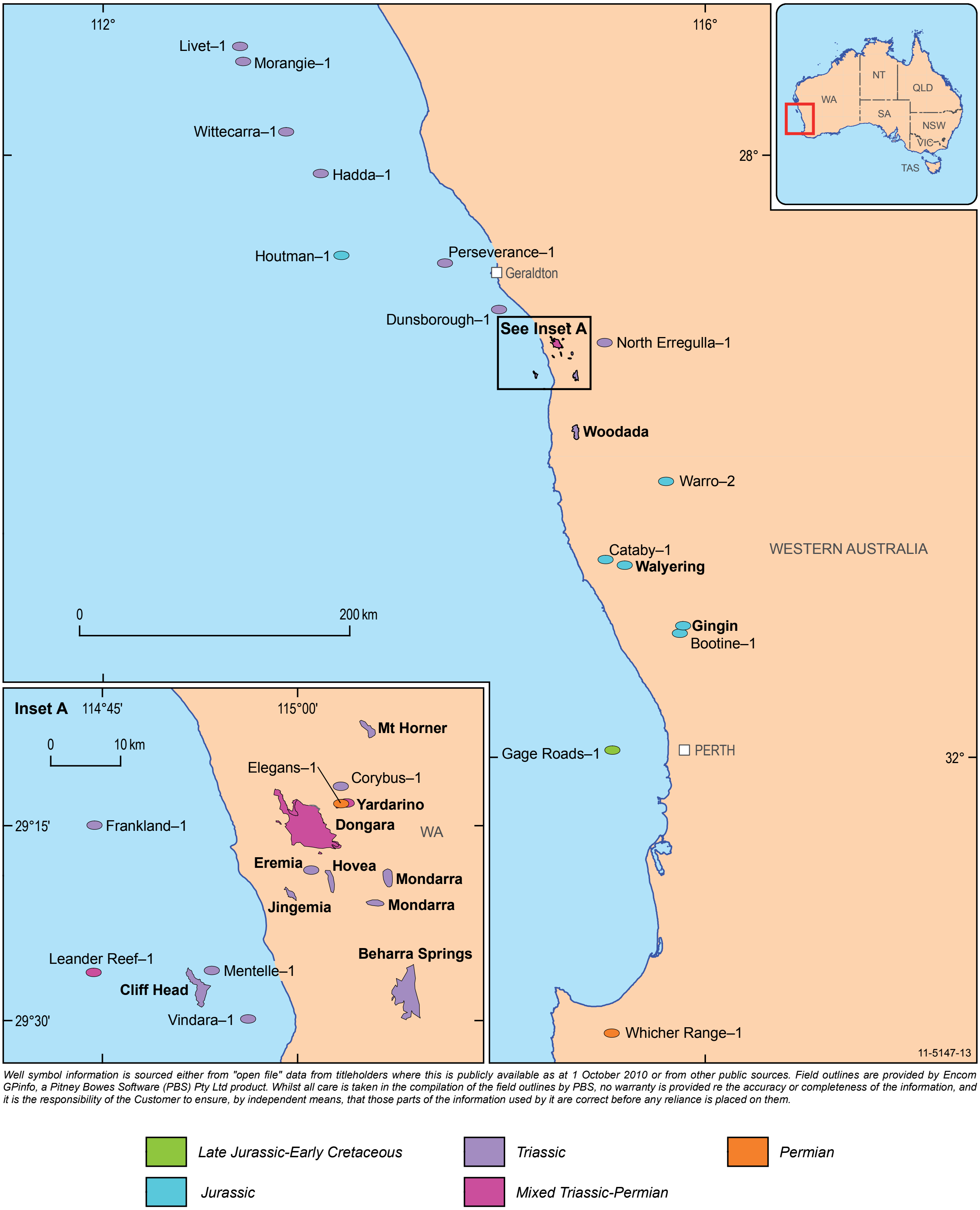

Figure 13. Oil and gas fields, and selected hydrocarbon discoveries and occurrences annotated by age of source rock as interpreted from geochemical evidence.

dition of Permian condensate. Support for active generation and charge from the Permian at this location comes from Elegans–1—a later deepening of the Yardarino–1 well—as discussed above.

Another example of a dual source charge is the Dongara gas field (Fig. 13). The gas is relatively dry and the isotopic difference between methane and ethane is much smaller than for other Perth gases from a single source (Fig. 14). At Dongara, the Permian charge is mainly isotopically heavy methane, which has added to a wet gas from the isotopically light sapropelic interval (Fig. 14). The hydrogen isotopes are more diagnostic of this dual source, with methane now isotopically heavier than ethane (Fig. 15) due to the input of Deuterium-enriched methane from the Permian.

The Leander Reef–1 fluid inclusion oil is also considered a mixture of Early Triassic and Permian sources (Volk et al, 2004; Fig. 13).

JURASSIC-SOURCED HYDROCARBONS (CATTAMARRA COAL MEASURES)

Hydrocarbons recovered from the Early Jurassic Cattamarra Coal Measures in the southern Dandaragan Trough (condensate at Walyering–1, –2) and Beermullah Trough (oil at Gingin–1, –2 and Bootine–1; gas at Gingin West–1) are locally sourced from the Early Jurassic Cattamarra Coal Measures, as originally suggested by Thomas (1984) and Summons et al (1995) (Fig. 13). The Walyering–1 and –2 condensates were previously interpreted to be derived from marine-influenced source inputs from either the Triassic (Summons et al, 1995) or the Early Jurassic Cattamarra Coal Measures (Gorter et al, 2004), consistent with their intermediate carbon isotopic composition (Fig. 14), lower pristane/phytane ratio and the presence of the diagnostic marine C_{30} desmethylsterane (Summons et al, 1995). The Bootine–1 and Gingin–1 condensates are enriched in ^{13}C and together with their saturated hydrocarbon biomarkers are consistent with a Permian terrestrial source (Geoscience Australia and GeoMark, 2005). Higher-plant aromatic biomarkers, however, confirm the Jurassic affinity for the organic matter (Gorter et al, 2004). The Gingin West–1 gas reservoired in the Cattamarra Coal Measures is also enriched in ^{13}C (Fig. 14) and is considered to have been sourced from the Cattamarra Coal Measures.

A marine interval in the Early Jurassic Cattamarra Coal Measures is interpreted to be the source of oil reservoired in the Early Jurassic Eneabba Formation at Cataby–1 in the Beermullah Trough (Gorter et al, 2004; Fig. 13).

Inclusion oil recovered from the top of the Cattamarra Coal Measures in Houtman–1, located in the offshore Houtman Sub-basin, is interpreted to represent an offshore extension of a similar Early Jurassic source facies (Volk et al, 2004; Fig. 13).

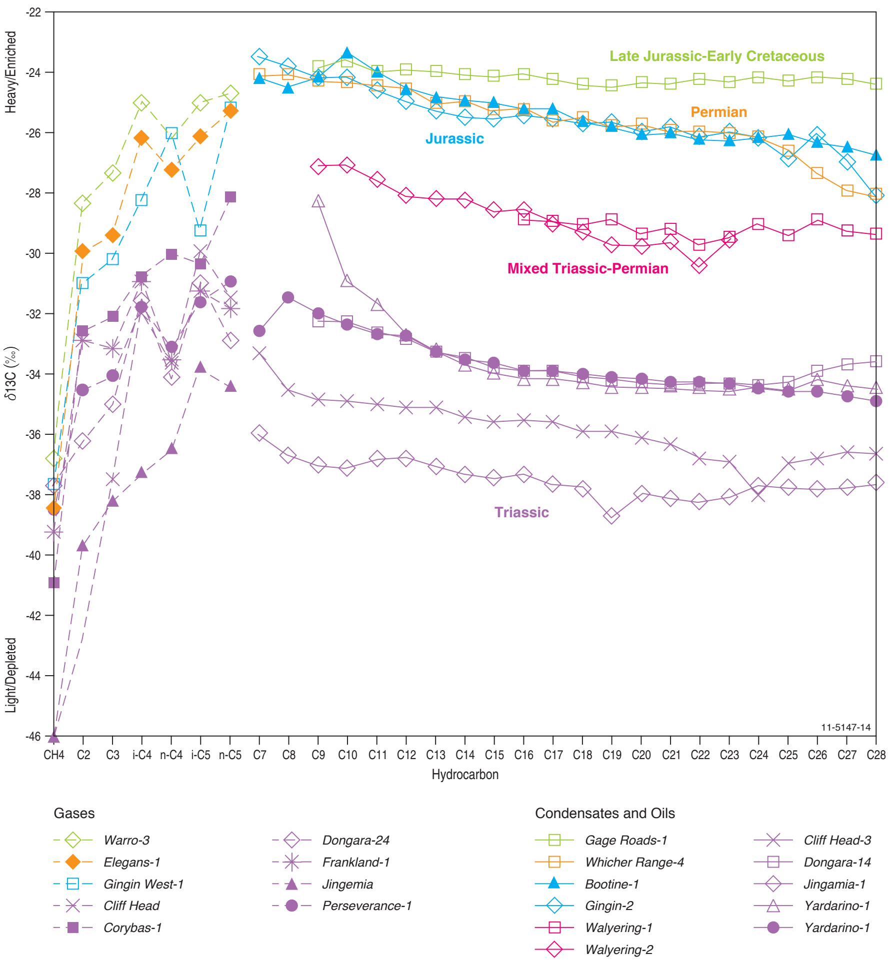

Figure 14. Carbon isotopic composition of C_1–C_5 gaseous hydrocarbons and C_7–C_{28} n-alkanes of oil from the Perth Basin. Colours correspond to interpreted age of generative source rock.

UPPER JURASSIC–EARLY CRETACEOUS-SOURCED HYDROCARBONS (YARRAGADEE)

Oil recovered from Gage Roads–1, in the Vlaming Sub-basin (Fig. 13), is waxy, isotopically heavy ($\delta^{13}C_{oil}$ ~ –24‰), displays a flat n-alkane ^{13}C isotopic profile (Fig. 14), and has a relatively high content of conifer-derived aromatic hydrocarbons (Summons et al, 1995). As well as being the most enriched in ^{13}C of all the Perth Basin oils, it also has the lightest hydrogen isotopes (δD) of any Perth Basin oil (Fig. 15; Dawson et al, 2005a, 2005b). Hydrogen isotopes of n-alkanes cannot be used to readily distinguish Kockatea Shale sources from either Jurassic (other than Gage Roads–1) or Permian sources (Fig. 15). The Gage Roads–1 oil is most likely derived from a source rock in either the

Upper Jurassic Yarragadee Formation or Early Cretaceous Parmelia Formation (Summons et al, 1995; AGSO and GeoMark, 1996). The lacustrine source influence, however, was downplayed by Volk et al (2004), who favoured a source in the Parmelia Formation.

The Warro–3 gas reservoired in the Yarragadee Formation is the most ^{13}C-enriched gas from the Perth Basin. As such, it has some affinity with the Gage Roads–1 oil (Fig. 14); however, its hydrogen isotopic composition is enriched in Deuterium compared to the Gage Roads–1 oil (Fig. 15), suggesting a different onshore source facies for this gas.

Source rocks

All available source rock geochemical data from offshore northern Perth Basin wells, including total organic carbon (TOC), Rock-Eval pyrolysis and vitrinite reflectance (VR) were compiled from well completion reports and destructive analysis reports. In addition, geochemical analyses for source rock evaluation were carried out on 234 samples from 15 offshore northern Perth Basin wells to fill data gaps. In particular, samples were collected from six recently drilled wells (Dunsborough–1, Fiddich–1, Flying Foam–1, Frankland–1, Moondah–1 and Perseverance–1) where geochemical data had not yet been acquired.

The plot of TOC versus hydrogen index (HI) shown in Figure 16 illustrates data from 22 offshore wells, subdivided by stratigraphic units as defined in GA's newly-revised sequence stratigraphy (Fig. 3). Based on these Rock-Eval pyrolysis data, several potential source rocks are recognised and described here in order of decreasing age.

PERMIAN IRWIN RIVER SEQUENCE

In the offshore northern Perth Basin, the Irwin River Coal Measures contain very good source rocks for generating mainly gas (Fig. 16). The bulk of the Irwin River Coal Measures samples are organic-rich with a TOC average of about 6% and more than 80% of samples showing a TOC content above 2%. This organic richness is associated with HI values of 50–200 mgHC/gTOC, typical of gas-prone organic matter. Samples believed to have been sourced in part from Permian coal measures include gas from the Dongara field, oil from Woodada–3 and fluid inclusion oil from Leander Reef–1.

The best source potential for the Irwin River Coal Measures is observed in the inner Abrolhos Sub-basin, particularly in Dunsborough–1, Cliff Head–4 and Frankland–1 (Fig. 17); however, the Irwin River Coal Measures are immature in Dunsborough–1 and marginally mature in Frankland–1 and Cliff Head–4 (Fig. 18).

In the outer Abrolhos Sub-basin (Batavia–1, Geelvink–1A and Leander Reef–1), the present-day source quality of the Irwin River Coal Measures is clearly not as good as in the inner Abrolhos Sub-basin, as it is consistently hydrogen poor (HI <100) despite having good to very good TOC (Fig. 17). The Irwin River Coal Measures are mature to overmature in the outer Abrolhos Sub-basin (Fig. 18; Tmax range: 441–465°C; VR range: 0.61–1.62% Ro) and could have generated gas in the past, leading to the low present-day HI values. Anomalously elevated levels of maturity in the Permian are interpreted by Gorter and Deighton (2002) and Gorter et al (2004) to be a consequence of localised late Permian to Early Triassic intrusions.

PERMIAN CARYNGINIA SEQUENCE

The Carynginia Sequence has only very limited source potential for generating gas. Although more than 80% of the Carynginia Formation samples have a TOC greater than 1%, consistently low HI values (<100 mgHC/gTOC) indi-

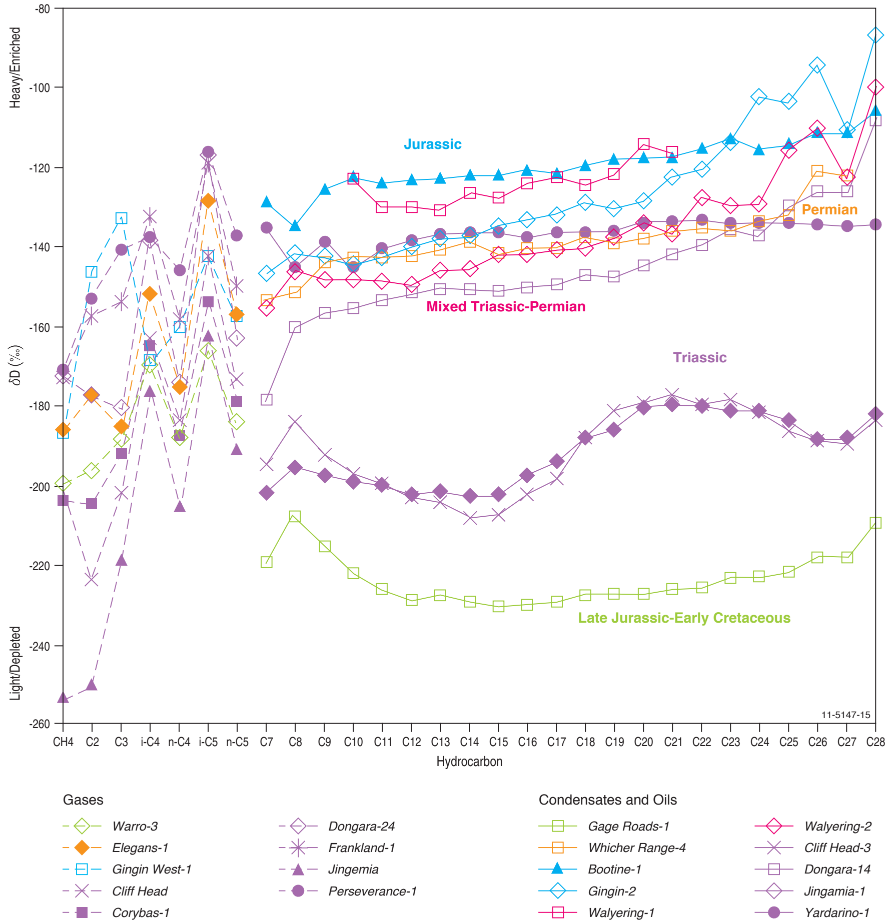

Figure 15. Hydrogen isotopic composition of C_1–C_5 gaseous hydrocarbons and C_7–C_{28} n-alkanes of oil from the Perth Basin. Colours correspond to interpreted age of generative source rock.

Table 1. Perth Basin gases and oils sourced from the Early Triassic Kockatea Shale.

	Well	Reference
Gas	Apium–2	This study
	Beharra Springs North–1	This study
	Beharra Springs North–1, –2, –3, –4	Boreham et al, 2001; this study
	Cliff Head[a]	This study
	Corybas–1	This study
	Dongara–11	Boreham et al, 2001
	Dongara–24A	Boreham et al, 2001
	Dongara–3U, –24A	Boreham et al, 2001
	East Lake Logue–1	Boreham et al, 2001
	Frankland–1	This study
	Hovea and Eremia[a]	This study
	Hovea–2	This study
	Indoon–1	This study
	Jingemia	This study
	Perseverance–1	This study
	Redback South–1	This study
	Tarantula–1	This study
	Woodada–6	Boreham et al, 2001
	Xyris	This study
Oil	Beharra Springs North–1	Thomas and Barber, 2004; Grice et al, 2005
	Beharra Springs South–1	Thomas and Barber, 2004; Grice et al, 2005
	Cliff Head–3 FI	Volk et al, 2009
	Cliff Head–3	This study
	Cliff Head–6	Volk et al, 2009
	Dongara–4, –8, –14	Summons et al, 1995; Currie et al, 1998; Gorter et al, 2004; Grice et al, 2005; this study
	East Lake Logue 1	Boreham et al, 2001; Gorter et al, 2004
	Eremia–1	Thomas and Barber, 2004
	Erregulla–1	Summons et al, 1995; Grice et al, 2005
	Hakia–1	Gorter et al, 2004
	Hadda–1	Geotech, 2005
	Hadda–1 FIO[b,d]	Kempton et al, 2011
	Hovea–1	Thomas and Barber, 2004; Grice et al, 2005
	Hovea–3[c]	This study
	Jingemia–1	Thomas and Barber, 2004; Grice et al, 2005; this study
	Mondarra–1, –2, –3, –5	Summons et al, 1995; Grice et al, 2005; this study
	Mount Horner–1, –9	Summons et al, 1995; Gorter et al, 2004; Thomas and Barber, 2004; Grice et al, 2005
	North Erregulla–1	Summons et al, 1995; Gorter et al, 2004; Grice et al, 2005
	North Yardanogo–1	Thomas and Barber, 2004
	North Yardarino–1	Grice et al, 2005
	Yardarino–1	Summons et al, 1995; Grice et al, 2005

[a] Solution gas from oil production plant
[b] FIO = fluid inclusion oil
[c] Oil stain in Dongarra Sandstone core
[d] Possible minor non-Kockatea input

Table 2. Perth Basin gases and oils of mixed origin or from Jurassic and Permian sources.

	Well	Previous source assignment	Preferred source assignment
Gas	Dongara–11, –24A	Basal Triassic[1] Mixed basal Triassic–Permian[3]	Mixed basal Triassic–Permian
	Elegans–1	Permian[1,3] Mixed Permian–basal Triassic[3]	Permian
	Gingin West–1		Jurassic[2]
	Warro–3		Jurassic[2]
Oil	Araucaria–1[a]	Jurassic[4]	Late Jurassic
	Cataby–1	Jurassic[4]	Jurassic
	Gage Roads–1	Early Cretaceous–Late Jurassic[5–7] Late Jurassic[4]	Late Jurassic
	Gingin–1, –2 (Bootine–1)	Jurassic[4, 5] Permian[6]	Jurassic
	Houtman–1 (FIO)[b]	Jurassic[4,8]	Jurassic
	Leander Reef–1 (FIO)[b]	Mixed basal Triassic–Permian[8]	Basal Triassic-Permian
	Walyering–1, –2	Jurassic[4, 5]	Jurassic
	Whicher Range–1, –4	Permian[5, 6] Jurassic or mixed[4, 5]	Permian
	Woodada–3	Basal Triassic (vagrant)[5] Mixed basal Triassic–Permian[3] Mixed basal Triassic–Jurassic[4]	Mixed basal Triassic–Permian

[1] Boreham et al, 2001; [2] this study; [3] Thomas and Barber, 2004; [4] Gorter et al, 2004; [5] Summons et al, 1995; [6] Geoscience Australia and GeoMark Research, 2005; [7] Grice et al, 2005; [8] Volk et al, 2004; [9] Kempton et al, 2011; [a] oil stain; [b] FIO = fluid inclusion oil.

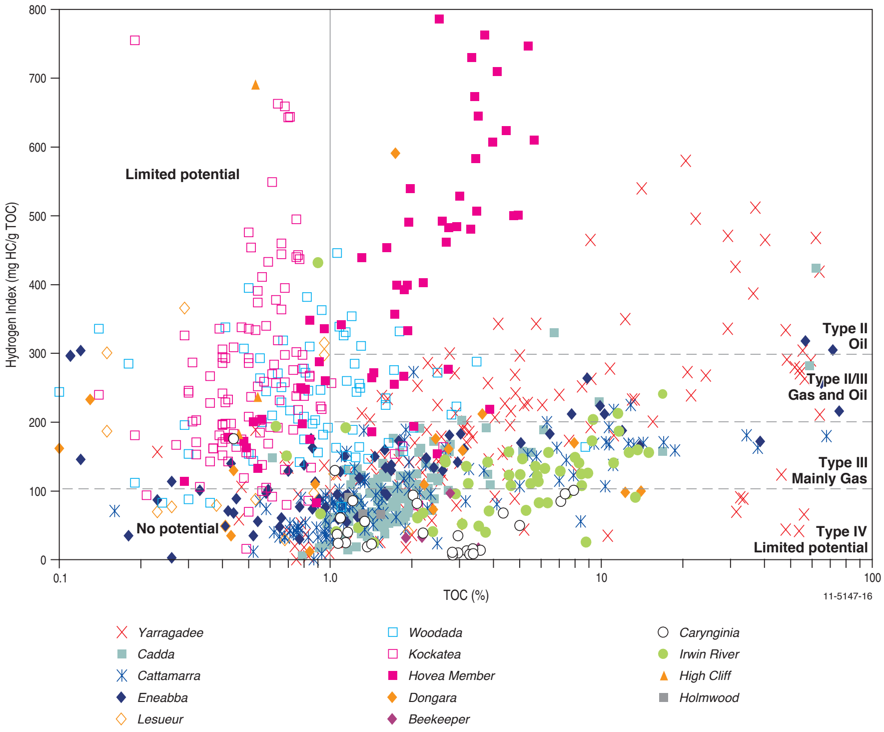

Figure 16. Source rock character (TOC vs HI) of samples from stratigraphic sequences in the offshore northern Perth Basin.

cate only very limited source potential for gas. The elevated maturity of this interval, where it is deeply buried in Batavia–1 and Geelvink–1A (>2,800 m) and VR values exceed 1% Ro, however, may account for the low HI values and imply likely generation of gas.

LATE PERMIAN–EARLY TRIASSIC KOCKATEA SHALE

The latest Permian to Early Triassic Kockatea Shale has long been known as the source of onshore oil and condensate accumulations from the greater Dongara area fields (Summons et al, 1995; Thomas and Barber, 2004). More specifically, the primary source of these oils is constrained to the sapropelic interval in the Hovea Member at the base of the Kockatea Shale, which was deposited in an anoxic marine environment (Thomas and Barber, 2004; Grice et al, 2005). The Hovea Member contains oil-prone sediments of excellent source quality onshore and

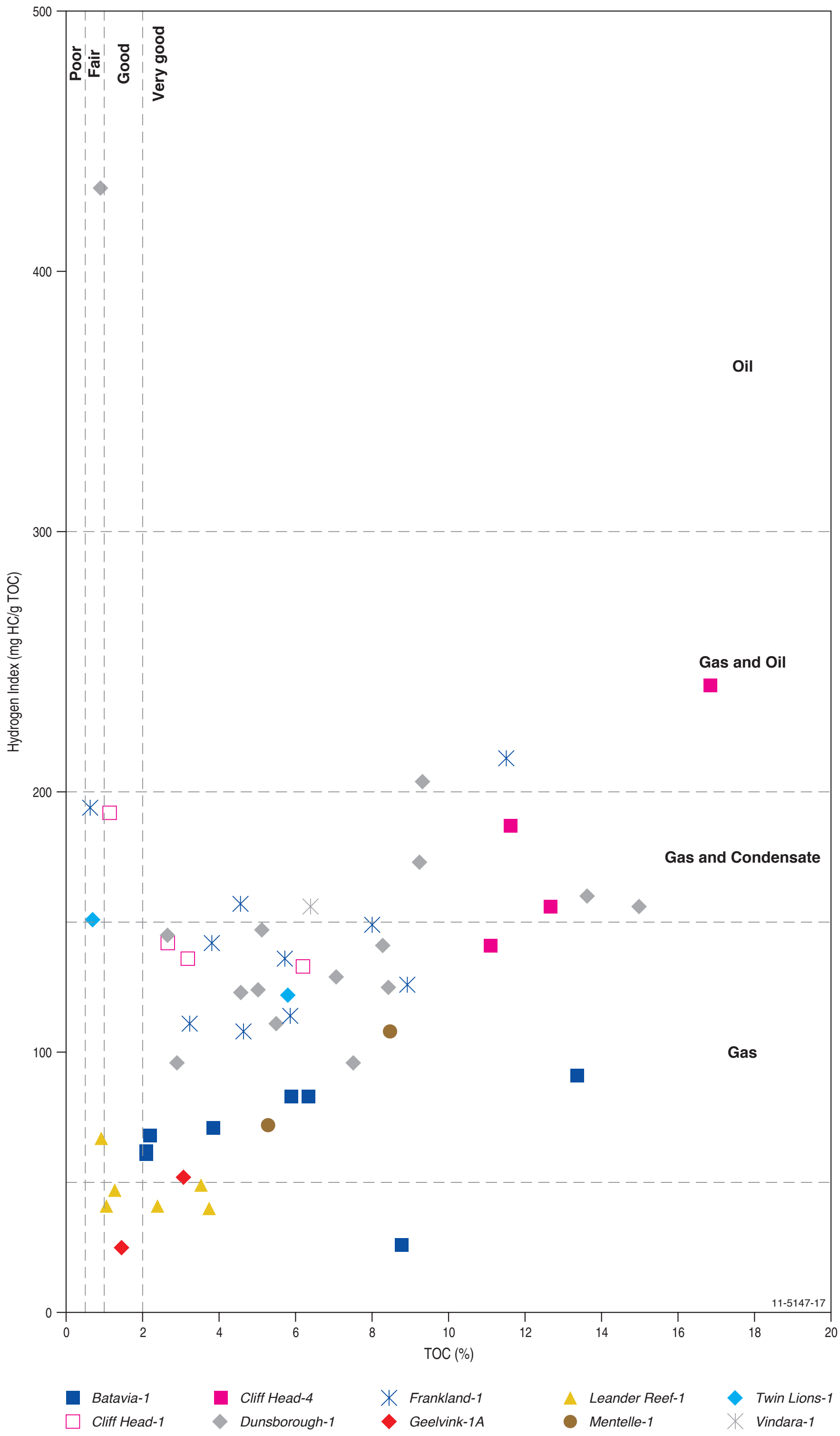

Figure 17. Source rock character (TOC vs HI) of samples from the Irwin River Sequence in wells from the offshore northern Perth Basin.

displays very distinct geochemical signatures, the most typical of which are the presence of C_{33} n-alkylcyclohexane and ^{13}C depleted carbon isotopic values (< –32‰).

In contrast to the onshore, the basal Kockatea Shale has previously been dismissed as a good source rock for generating oil offshore, based on limited offshore well data (Crostella, 2001; Jones and Hall, 2002; D'Ercole et al, 2003). The lack of well control at that time precluded a clear understanding of the source potential of the Hovea Member offshore. The discovery of oil sourced from the Kockatea Shale in the Cliff Head field has since called this assessment into question (Thomas and Barber, 2004).

The Hovea Member is now recognised in 18 wells in the offshore northern Perth Basin, based on GA's revised stratigraphic interpretation, and shows good to excellent source rock potential for generating black oil (Fig. 16). More than half of these samples are characterised by TOC greater than 1% and HI values exceeding 300 mgHC/gTOC, which is typical of rich oil-prone source rocks. The best source quality for the Hovea Member is in the wells located in the inner Abrolhos Sub-basin and Beagle Ridge, particularly Cliff Head–4, Dunsborough–1, Hadda–1, Mentelle–1, Perseverance–1 and Twin Lions–1, which have TOC values of up to 5.7% and HI values up to 786 mgHC/gTOC (Fig. 19). It has diminished gas and oil potential at Leander Reef–1, poor to fair—predominantly gas—potential in wells located on the northern Wittecarra Terrace (Fiddich–1, Livet–1 and Morangie–1), and only poor gas potential in Batavia–1 and Geelvink–1A in the outer Abrolhos Sub-basin (Fig. 19).

Standard VR measurements indicate that the Hovea Member source rocks are immature in the inner Abrolhos Sub-basin (VR range: 0.41–0.52% Ro) and early mature on the Beagle Ridge and at Leander Reef–1 (VR range: 0.50–0.66% Ro). Fluorescence alteration of multiple macerals (FAMM) analyses , however, reveal that the thermal maturity of the Hovea Member is actually underestimated by 0.1–0.3% due to vitrinite suppression (Sherwood and Russell, 2010). This interpretation is also supported by Tmax values (Fig. 20) showing that the Hovea Member is early mature in most wells of the inner Abrolhos Sub-basin.

The rest of the Kockatea Shale above the Hovea Member has only poor source potential due to uniformly low TOC of <1% (Fig. 16). Samples with TOC greater than 0.5% are fairly hydrogen-rich, with HI values averaging about 300 mgHC/gTOC; therefore they have some limited potential for oil and gas generation. VR data indicate that the middle and upper Kockatea Shale is immature in wells from the Beagle Ridge and inner Abrolhos Sub-basin (VR < 0.57%), marginally mature at Leander Reef–1 (VR from 0.49 to 0.62%) and well in the oil window in the outer Abrolhos Sub-basin (Batavia–1, Geelvink–1A and Wittecarra–1 have VR of 0.59–1.24% Ro).

EARLY-MIDDLE TRIASSIC WOODADA SEQUENCE

Fair to good source rocks occur in the Woodada Sequence offshore (Fig. 16). About 30% of the samples from the Woodada Sequence have TOC values exceeding 1% with the potential to generate mixed oil and gas. The best potential Woodada source rocks are found in the Batavia–1 and Wittecarra–1 wells in the outer Abrolhos Sub-basin, where vitrinite reflectance values (0.49–0.76% Ro) indicate they are immature to mature for oil generation.

EARLY JURASSIC ENEABBA SEQUENCE

The Early Jurassic Eneabba Sequence does not show much hydrocarbon-generating potential in most of the wells where data were available, due to low organic content (TOC <1%). The exception is Gun Island–1, where organic-rich sections are encountered throughout the interval (TOC up to 76%; Fig. 21). In Gun Island–1, Eneabba shales with TOC values of 1–7% mostly consist of Type III organic matter (HI of 59–183 mgHC/gTOC) capable of generating mainly gas, while carbonaceous shales and coals (TOC values of 7–76%) have the potential to generate mixed oil and gas (HI >200 mgHC/gTOC; Fig. 21). Two samples from the Eneabba Sequence in Batavia–1 show high TOC with gas-generating potential (Gorter et al, 2004). Tmax values (Fig. 22) and vitrinite reflectance data (VR = 0.75% Ro) indicate that the Eneabba Sequence is mature with respect to hydrocarbon generation in Gun Island–1 and capable of expelling hydrocarbons.

EARLY-MIDDLE JURASSIC CATTAMARRA SEQUENCE

The Early–Middle Jurassic Cattamarra Sequence appears to be a good source rock for generating gas, with minor liquid potential, based on the average TOC of 3.2% and average HI of 103 mgHC/gTOC (Fig. 21). The Cattamarra Coal Measures are immature in the Abrolhos Sub-basin (VR range: 0.21–0.52% Ro) and mature in the Houtman Sub-basin (VR range: 0.56–1.06% Ro; Fig. 22).

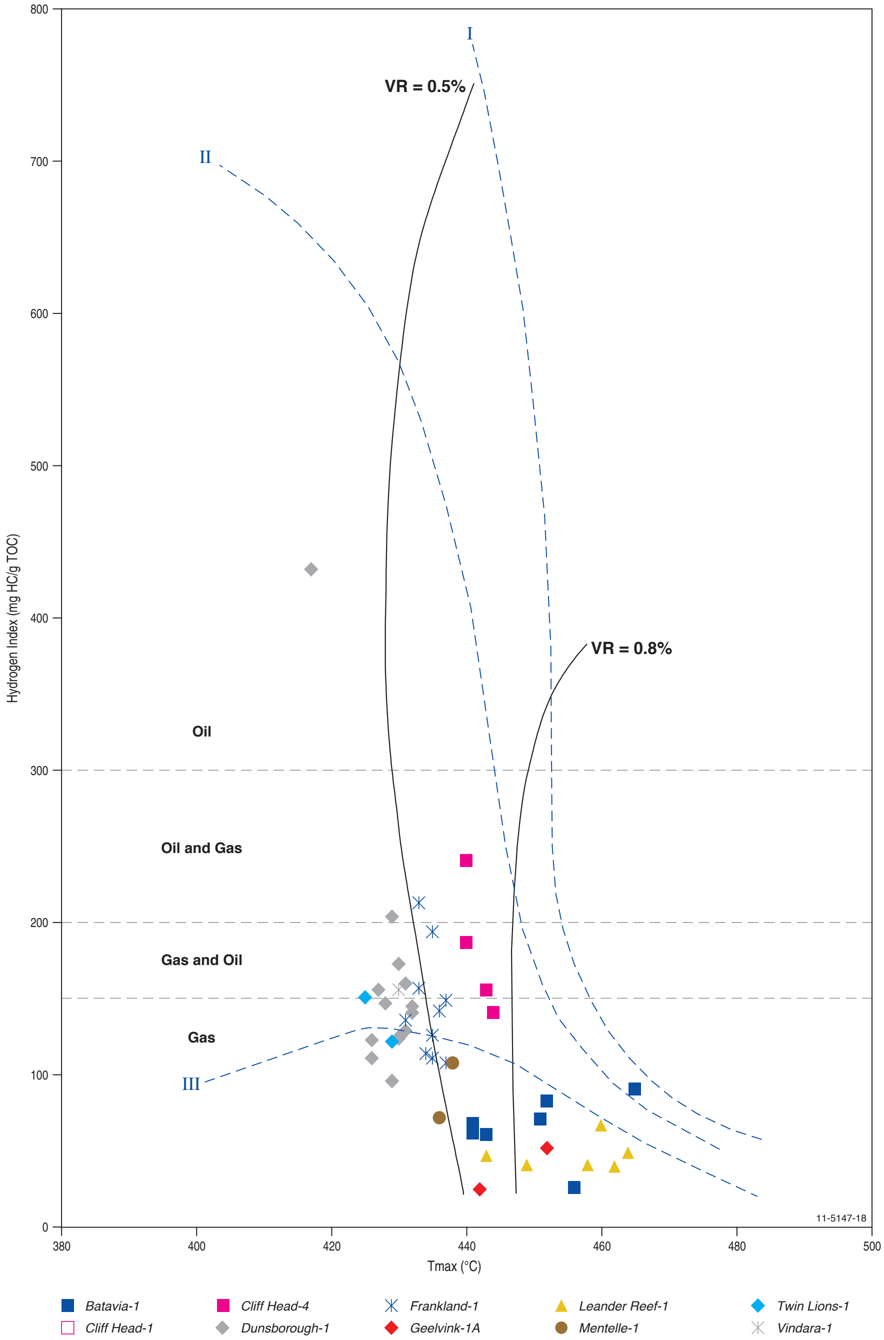

Figure 18. Tmax vs HI of samples from the Irwin River Sequence in wells from the offshore northern Perth Basin.

MIDDLE JURASSIC CADDA SEQUENCE

Sediments from the Middle Jurassic Cadda Sequence are organically rich with more than 90% of samples showing a TOC greater than 1%; however, only a third of these samples have HI values greater than 100 mgHC/gTOC with the potential to generate gas.

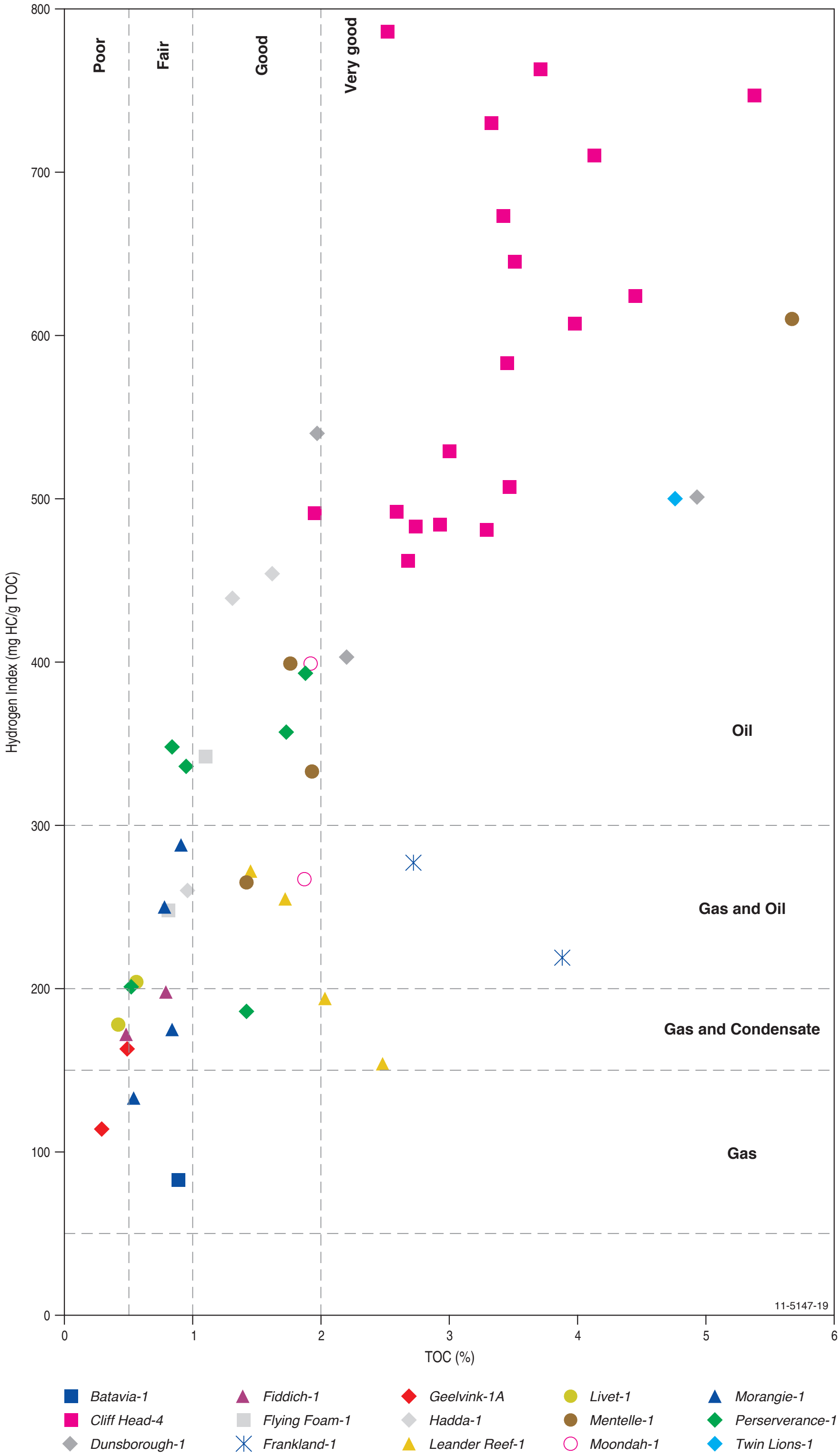

Figure 19. Source rock character (TOC vs HI) of samples from below the Hovea Flooding Surface in the Kockatea Sequence in wells from the offshore northern Perth Basin.

MIDDLE TO LATE JURASSIC YARRAGADEE SEQUENCE

The Middle to Late Jurassic Yarragadee Sequence is characterised by highly carbonaceous sediments, with more than 75% of samples having TOC exceeding 2%, while the average TOC of all samples is about 12% (Fig. 21). These organic-rich sediments consist of Type II to Type III kerogens with the potential to produce both gas and oil. HI values exceeding 300 mgHC/gTOC (typical of oil-prone organic matter), are observed for a number of coals and coaly shales in Houtman–1 from the Houtman Sub-basin. Vitrinite reflectance data and Tmax values (Fig. 22) indicate that the Yarragadee Sequence is immature for hydrocarbon generation in Charon–1 and Gun Island–1, but has reached the early oil window at about 2,700 m in Houtman–1 (VR >0.55% Ro).

Expulsion and migration

1D burial history modelling in the onshore and adjacent offshore northern Perth Basin indicates that present-day heat flow is a reliable indicator of the temperature history, although additional palaeo-heat flow, attributed to igneous intrusions, was needed to match present-day maturity profiles at the Woodada field and possibly at Beharra Springs (Thomas and Barber, 2004; Gorter et al, 2004). The oil window was defined to be between 0.7% and 1.2% Ro (Thomas and Barber, 2004) while the onset of maturation and significant liquids expulsion is at >0.75% Ro, and the onset of dry gas is at 1.3% Ro (Gorter et al, 2004). Using the oil window, four main Hovea Member effective source kitchens have been identified (Figure 31 in Thomas and Barber, 2004). From west to east these include the offshore Leander Reef kitchen, and onshore Jingemia, Warradong and Eneabba kitchens. In mature kitchen areas, the main pulse of hydrocarbon generation from the Hovea Member occurred between the Late Jurassic and earliest Cretaceous (160–130 Ma), coincident with the deposition of the Yarragadee Formation and Parmelia Group.

Burial history modelling by Thomas and Barber (2004) suggested the timing of oil generation from the Hovea Member is virtually coincident with gas generation from the underlying Permian Irwin River Coal Measures. Thus, in most areas the oil charge from the Hovea Member is in direct competition with any gas generated from the Permian section, as seen in the Dongara gas field and in the Carynginia Formation in Leader Reef–1 (2,849–52 mRD; Volk et al, 2004).

Using the 1D models developed onshore, Thomas and Barber (2004) extended modelling to the inboard, offshore North Perth Basin. At Leander Reef–1, the Hovea Member is in the early oil maturity window and more mature Hovea Member source rocks are predicted down-dip to the west and east of Leander Reef–1. This eastern generative Leander Reef kitchen was proposed to have charged the Cliff Head oil field to the east. The similarity in the compound-specific isotope analysis (CSIA) profiles for Jingemia–1 and Cliff Head–3 oils (Figs 14 and 15) indicates a similar Hovea Member organic facies on either side of the Beagle Ridge, or that the Cliff Head oil field was sourced from the Jingemia kitchen to the east. Other offshore source kitchens are demonstrated by occurrences of Hovea Member-sourced hydrocarbons, by shows and residual hydrocarbon columns on drilled structural highs, and are postulated from seismic data.

Gorter et al (2004) provide the main source of information for modelling hydrocarbon generation in the offshore northern Perth Basin. These authors modelled hydrocarbon generation from the basal Kockatea Shale, Cattamarra Coal Measures, Cadda Formation and lower Yarragadee Formation source rocks in the Houtman Sub-basin. In the deeper depocentres, the basal Kockatea Shale could have expelled oil in the Early to Middle Jurassic. Early Jurassic structures would be needed to trap migration from this basal Triassic source, but it is unlikely that there would have been an effective Cadda Formation regional seal at the time of migration. Modelled oil and gas expulsion from the Cattamarra Coal Measures occurred at about the time of deepest burial in the latest Jurassic to earliest Cretaceous (135–150 Ma), immediately preceding uplift and erosion. Minor oil and gas were also expelled during the latest Cretaceous and Cenozoic.

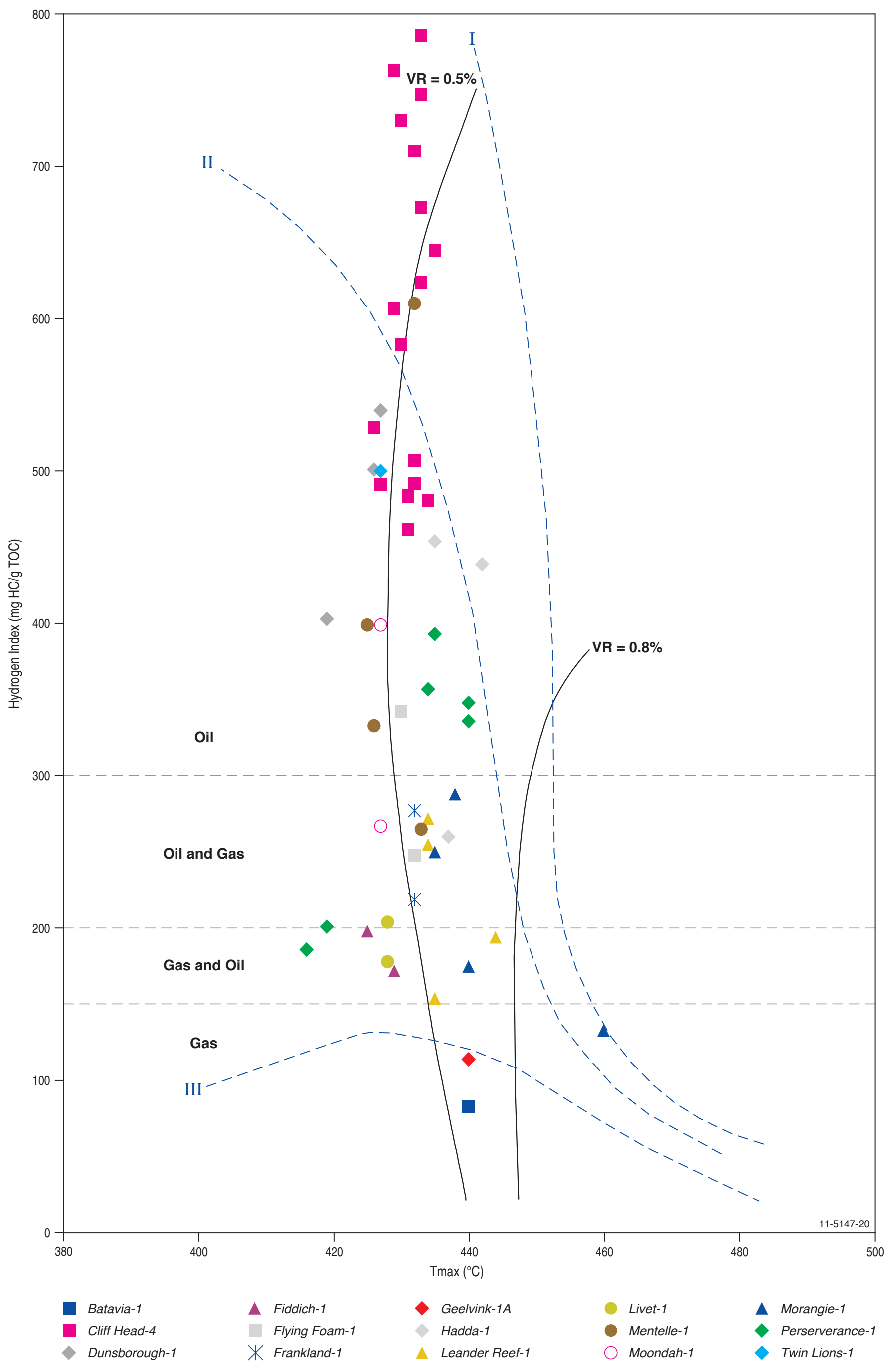

Figure 20. Tmax vs HI of samples from below the Hovea Flooding Surface in the Kockatea Sequence in wells from the offshore northern Perth Basin.

Reservoirs

PERMIAN

The primary reservoir units in the offshore northern Perth Basin are the Permian Dongara Sandstone and Irwin

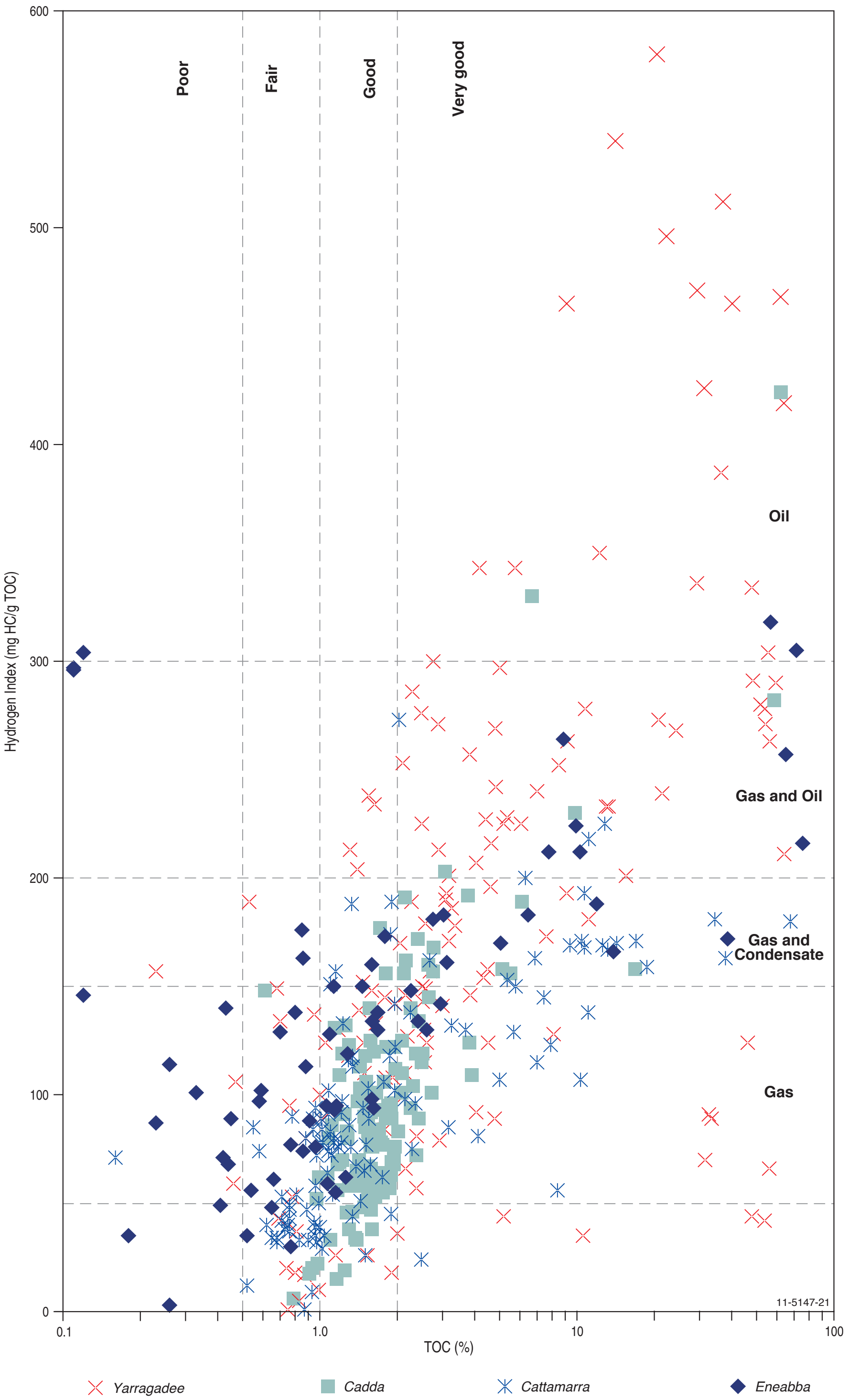

Figure 21. Source rock character (TOC vs HI) of samples from Jurassic sequences in wells from the offshore northern Perth Basin.

River Coal Measures, which host oil and gas sourced from the Hovea Member of the Triassic Kockatea Shale.

The late Permian Dongara Sandstone is a thin (typically less than 40 m thick in well intersections), discontinuous unit, which is difficult to map on seismic data as it is below seismic resolution (Roc Oil, 2006). In the offshore Perth Basin the Dongara Sandstone was deposited in lowstand basin floor fans in the Abrolhos Sub-basin (although this part of the unit has not been intersected in wells), and as transgressive shallow and marginal marine sandstones, primarily on the Beagle Ridge. The Dongara Sandstone attains maximum thickness where these transgressive sands have filled incised valleys that formed during the preceding lowstand (e.g. 171 m thick Dongara Sandstone in Perseverance–1). It is the primary reservoir for the Frankland and Perseverance gas accumulations, and the Dunsborough oil and gas accumulation.

The early Permian Irwin River Coal Measures are primarily a succession of fluvial sands and shales, with only very minor coal in the offshore part of the Perth Basin. The maximum well intersection of Irwin River Coal Measures is 266 m in Frankland–1, although the upper part of this unit has been eroded from most of the wells on the Beagle Ridge. The Irwin River Coal Measures comprise the primary reservoir for the Cliff Head oil field.

Fluorescence and gas shows were noted near the top of the early Permian Carynginia Formation in Leander Reef–1, but no significant hydrocarbon accumulations were present because of the lack of porosity.

The prospectivity of Permian reservoirs is thought to decrease significantly below depths of 2,500 m due to the growth of silica cement and resultant porosity degradation (Roc Oil, 2006). For example, the majority of the Dongara Sandstone in Mentelle–1 (1,278.8–84.1 m) has a porosity of 19.3%, but in Geelvink–1A the average porosity of sandstones in this unit (at 2,952–69 m) ranges from 2–6%.

TRIASSIC

The majority of the Triassic succession in the offshore northern Perth Basin comprises fluvial sandstones of the Middle to Upper Triassic Lesueur Sandstone, which is up to 1,064 m thick in well intersections (Wittecarra–1), and typically has relatively good porosity (e.g. 18–21% in Batavia–1). In contrast, the interbedded deltaic sandstones and siltstones of the underlying Early to Middle Triassic Woodada Formation have variable porosity. Oil

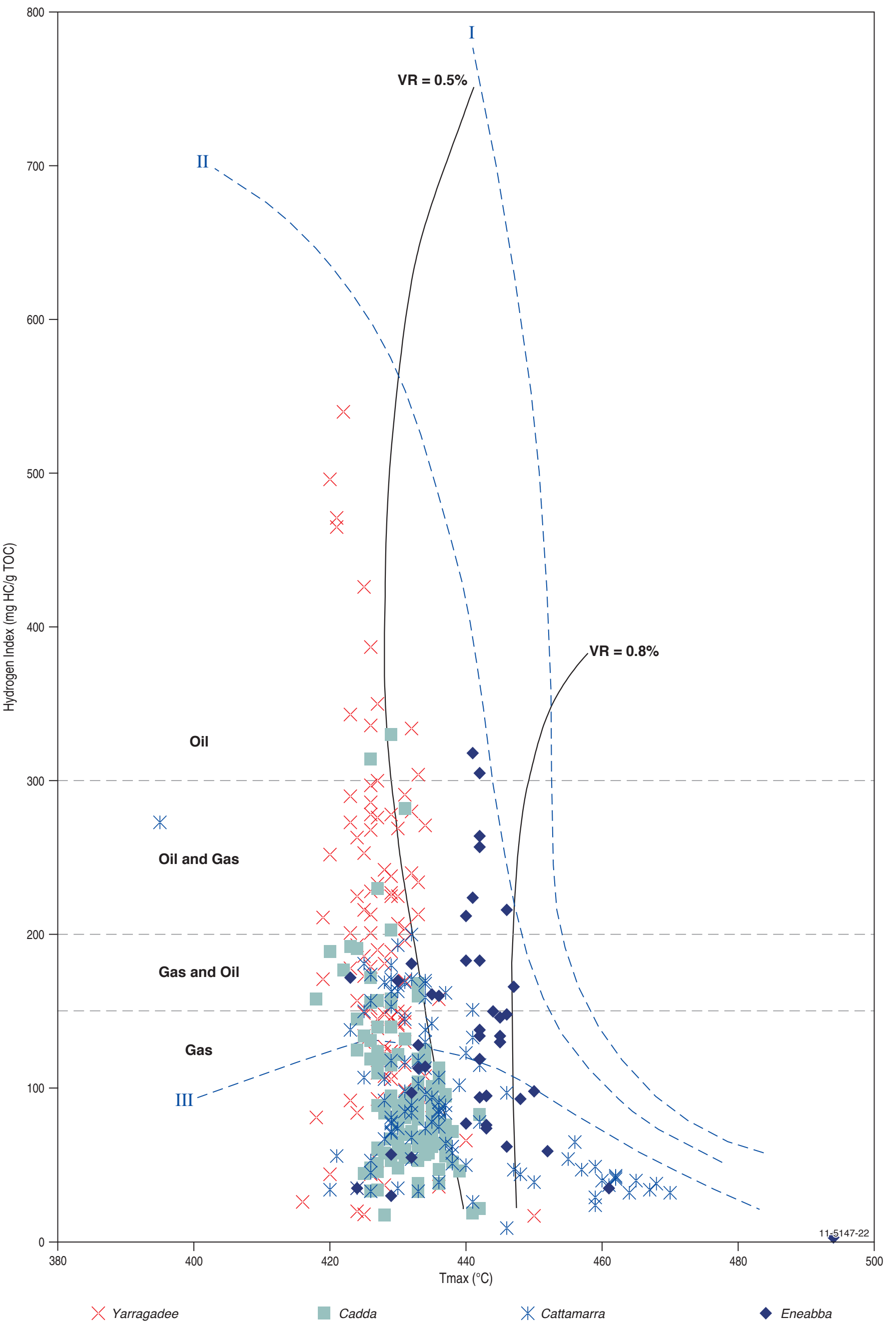

Figure 22. Tmax vs HI of samples from Jurassic sequences in wells from the offshore northern Perth Basin.

shows in the Woodada Formation in Wittecarra–1 to the north of Release Area W11-18—where this unit has a maximum well intersection thickness of 685 m—occur in a zone that has poor visual porosity (BHP Petroleum Pty Ltd, 1986).

JURASSIC

The primary candidate reservoir unit in the Jurassic succession of the offshore northern Perth Basin is the Early to Middle Jurassic Cattamarra Coal Measures. This unit is preserved as a series of interbedded sandstones, siltstones and coals that were deposited in a deltaic environment. The maximum well intersection for the Cattamarra Coal Measures is 734 m in Leander Reef–1 (although the base of the unit is not intersected in Houtman–1). The best potential reservoir sections in this unit comprise relatively coarse-grained sandstones underlying thick shales of the Middle Jurassic Cadda Formation (Crostella, 2001). Oil and gas shows are present in the upper part of the Cattamarra Coal Measures in Houtman–1 and Leander Reef–1. A palaeo-oil column was also detected over at least 15 m of this interval in Houtman–1 (Kempton et al, 2011).

Potential reservoir units are also present in sandstone intervals of the Upper Triassic to Early Jurassic alluvial Eneabba Formation, and the Upper Jurassic fluvial Yarragadee Formation.

Porosities in Jurassic sandstone successions in the offshore northern Perth Basin range up to 30% at depths of 1,000–1,500 m and decrease with depth to about 10–15% at 3,000–3,500 m (Gorter et al, 2004).

Seals

The main regional seal in the offshore northern Perth Basin is the Early Triassic Kockatea Shale, which is 150–443 m thick on structural highs in well intersections, and rapidly thickens to over 1,000 m in depocentres above Permian half-graben. The thickness of the unit is generally sufficient to provide a robust vertical and cross-fault seal, unless breached by subsequent fault reactivation.

The best potential seal in the post-Kockatea succession is the Middle Jurassic Cadda Formation, which is about 400 m thick in well intersections in the Houtman Sub-basin, but only 40–123 m thick in other offshore wells. Effective local seal by the Cadda Formation is demonstrated by a >15 m palaeo-oil column in Houtman–1 (Kempton et al, 2011); however, thin sandstone intervals in the Cadda Formation at Houtman–1 and Gun Island–1 may compromise fault juxtaposition seals (Gorter et al, 2004).

Other potential seals include intraformational shales in the Eneabba, Cattamarra and Yarragadee successions.

Fluid inclusion data indicate that these intraformational shales locally provide impedance barriers to oil migration (Kempton et al, 2011). Their potential to seal hydrocarbon accumulations remains speculative, however, especially in view of their high sand to shale ratios and extensive faulting with throws in excess of shale thicknesses that result in a high cross-fault seal risk. Nevertheless, effective intraformational seals are demonstrated onshore in these units at the following fields (from north to south): Mount Horner, Erregulla, North Yardanogo, Warro, Cataby, Walyering, Gingin and Bootine (Owad-Jones and Ellis, 2000; D'Ercole et al, 2003).

Play types

The dominant play type tested in the offshore northern Perth Basin is late Permian/basal Triassic sandstones (previously referred to as Dongara, Wagina or Wittecarra formations), sourced and sealed by the Kockatea Shale in tilted fault and horsts blocks (Figs 4 to 6). Prospective fault plays also occur at higher stratigraphic levels in the Triassic–Jurassic succession, especially in faulted roll-over anticlines, often associated with crestal collapse.

Several untested leads have been previously mapped in the release area. These include structures to the west of Leander Reef–1 and Batavia–1 (Enterprise Oil Exploration Ltd and Nippon Oil Exploration [Perth Basin] Ltd, 1994a), and multiple leads in the inboard Abrolhos Sub-basin adjacent to the Northampton Block, in the northern portion of Release Area W11-18 (Roc Oil, 2006). One of these was subsequently successfully tested by Perseverance–1 (2007). Other untested leads exist in the northern Vlaming Sub-basin in the southwestern part of Release Area W11-18, where a series of moderately-sized, westerly-dipping half-graben are interpreted on the basis of seismic facies to preserve thick successions of Kockatea Shale (Fig. 6).

A potential, large upper Permian stratigraphic play occurs in two large depocentres about 20 km and 50 km, respectively, to the west of Leander Reef–1. These depocentres contain a thick basinal succession with high amplitudes and continuous reflectivity, that progressively onlaps the upper Permian unconformity and is overlain by a thick section which, in part, includes the Kockatea Shale (Enterprise Oil Exploration Ltd and Nippon Oil Exploration [Perth Basin] Ltd, 1994a; Quaife et al, 1994; Fig. 11). The basinal succession has not been intersected by any wells. Quaife et al (1994) assigned an undifferentiated late Permian–Early Triassic age to this succession, and suggested that the seismic character is consistent with a marine, possibly interbedded carbonate and clastic unit up to 550 m thick, overlain by a basinal shale up to 500 m thick, in turn overlain by the transgressive Kockatea Shale. This basinal succession is interpreted as a clastic lowstand basin fan complex, correlative with lowstand incised valleys into which the Dongara Sandstone was deposited.

Key risks

The major exploration risks in Release Area W18-11, and the offshore northern Perth Basin more generally, are effective seals, trap breach and preservation of palaeo-accumulations. The degree of faulting generally increases outboard from the Abrolhos Sub-basin to the Houtman Sub-basin, but increased risk associated with this trend may be partially offset by a concurrent outboard increase in thickness of regional and intraformational seals. Ineffective traps at the time of migration is ascribed to fault breach and lack of cross-fault seal due to sand-sand juxtaposition. Widespread breach of previous oil accumulations is indicated by the identification of palaeo-oil columns in 11 offshore dry wells (Kempton et al, 2011). Breach of palaeo-accumulations could be attributed to fault reactivation and structuring associated with Early Cretaceous breakup, post-breakup regional westward tilting or Miocene inversion of faults (Kempton et al, 2011). In structures not breached by faults or subsequent structuring, gas displacement may contribute to preservation risk of oil (Kempton et al, 2011).

High CO_2 content in preserved gas accumulations is also a localised risk for the northeastern part of Release Area W11-18. The gas intersected in Perseverance–1 contains >40% CO_2 (WA DoIR, 2008) of magmatic origin, indicated by helium isotope ratio relative to that in air of ~0.6.

CONCLUSIONS

The offshore northern Perth Basin is structurally complex due to multiple periods of rifting during the Permian to Cretaceous, overprinted on structural trends inherent in the underlying basement terranes. This study has provided a new understanding of the extent, structural framework, and depositional fill of Permo-Triassic and Jurassic depocentres in the offshore northern Perth Basin, which facilitates the identification of proven and untested plays throughout Release Area W11-18.

Several hydrocarbon families and associated petroleum systems have been proven in the Perth Basin, with reservoir and source units ranging in age from Permian to Late Jurassic–Early Cretaceous. Hydrocarbon discoveries at Cliff Head, Frankland–1, Perseverance–1 and Dunsborough–1 have proven the effectiveness of the Triassic Hovea Member-sourced petroleum system in the offshore northern Perth Basin. Source rock sampling from recent exploration wells also proves that offshore, the Hovea Member has good to excellent source rock potential for generating oil. Permian (Irwin River) and Jurassic (Cattamarra) intervals in offshore wells have good to very good source rock potential, and indications of Permian- and Jurassic-sourced hydrocarbons in Leander Reef–1 and Houtman–1, respectively, suggest that older and younger petroleum systems may also be effective in the offshore part of the basin. Therefore, Release Area W11-18 is highly prospective for oil and gas sourced from one or more of these petroleum systems.

The key risk for exploration in Release Area W11-18 is trap breach due to major basin inversion associated with tectonic breakup in the Early Cretaceous. The preservation of numerous onshore oil and gas fields and the offshore Cliff Head field and Frankland, Dunsborough and Perseverance discoveries; however, proves that a variety of structures were not breached by this Valanginian breakup event, and other such examples are likely to exist in the offshore northern Perth Basin and Release Area W11-18.

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REFERENCES

AGSO AND GEOMARK, 1996—The Oils of Western Australia. Australian Geological Survey Organisation and GeoMark Research, Inc. Report. The Oils of Australia Series, Geoscience Australia, GeoCat # 68754.

ANDERSON, H, JONES, N. AND AMEGLIO, L., 2006—Reducing Seismic Risk From The Air: Utilising airborne geophysics to assist petroleum exploration. 6th International Conference & Exposition on Petroleum Geophysics, Kolkata 2006, India, January 9–11.

BHP PETROLEUM PTY LTD, 1986—Wittecarra 1 well completion report, unpublished.

BLYTH, C.I., 1994—Beagle seismic survey interpretation report WA-22-P (North). Woodside Offshore Petroleum, unpublished.

BOREHAM, C.J., HOPE, J.M AND HARTUNG-KAGI, B., 2001—Understanding source, distribution and preservation of Australian natural gas: a geochemical perspective. The APPEA Journal, 41 (1), 523–47.

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

BUSWELL, A.J., POWELL, W.D. AND SCHOLEFIELD, T., 2004—The northern Perth Basin—From marginally prospective for gas to highly prospective for both oil and gas. The APPEA Journal, 44 (1), 181–99.

COLLINS, L.B., ZHU, Z.R. AND WYRWOLL, K-H., 1998—Late Tertiary–Quaternary Geological Evolution of the Houtman Abrolhos Carbonate Platforms, Northern Perth Basin. In: P.G. Purcell and R.R. Purcell (eds) The Sedimentary Basins of Western Australia 2: Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 33–54.

COLWELL, J.B., SYMONDS, P.A. AND CRAWFORD, A.J., 1994—The nature of the Wallaby (Cuvier) Plateau and other igneous provinces of the west Australian margin. AGSO Journal of Australian Geology and Geophysics, 15 (1), 137–56.

COPP, I.A., 1994—Depth to base Phanerozoic map of Western Australia: Explanatory Notes. Geological Survey of Western Australia, Record 1994/9.

CROSTELLA, A., 2001—Geology and petroleum potential of the Abrolhos Sub-basin, Western Australia, Western Australia Geological Survey, Report 75.

CROSTELLA, A. AND BACKHOUSE, J., 2000—Geology and petroleum exploration of the central and southern Perth Basin, Western Australia. Western Australia Geological Survey, Report 57.

CURRIE, T.J., ALEXANDER, R. AND KAGI, R.I., 1998—Evidence for a submarine oil seep in the offshore northern Perth Basin. In: P.G. Purcell and R.R. Purcell (eds), The Sedimentary Basins of Western Australia 2. Proceedings of the PESA Western Australian Basins Symposium, 637–45.

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

DAWSON, D., GRICE, K. AND ALEXANDER, R., 2005a—Effect of maturation on the indigenous δD signatures of individual hydrocarbons in sediments and crude oils from the Perth Basin (Western Australia). Organic Geochemistry, 36, 95–104.

DAWSON, D., GRICE, K. AND ALEXANDER, R., 2005b—Stable hydrogen isotope ratios of sedimentary hydrocarbons: a potential method for assessing thermal maturity? The APPEA Journal, 45 (1), 253–61.

DENTITH, M.C., LONG, A., SCOTT, J., HARRIS, L.B. AND WILDE, S.A., 1994—The influence of basement on faulting within the Perth Basin, Western Australia. In: P.G. Purcell and R.R. Purcell (eds), The Sedimentary Basins of Western Australia. Proceedings of the Western Australian Basins Symposium, 791–9.

D'ERCOLE, C., PITCHFORD, A. AND MORY, A.J., 2003—Leads and prospects within tenements of the northern Perth Basin, Western Australia, 2002. Western Australia Geological Survey, Record 2003/4.

DICKINS, J.M., McTAVISH, R.A. AND BALME, B.E., 1961—The Beagle Ridge bore: Australian Oil and Gas Journal, 1960, 20–1.

DMP, 2010—Petroleum in Western Australia, September 2010, Department of Mines and Petroleum, Perth, Western Australia.

ENTERPRISE OIL EXPLORATION LTD. AND NIPPON OIL EXPLORATION (PERTH BASIN) LTD., 1994a—Plum MSS final report. Part E. Geophysical interpretation, unpublished.

ENTERPRISE OIL EXPLORATION LTD. AND NIPPON OIL EXPLORATION (PERTH BASIN) LTD., 1994b—Scarlet MSS final report. Part E. Geophysical interpretation, unpublished.

GEOSCIENCE AUSTRALIA AND GEOMARK, 2005—The Oils of Western Australia II. Geoscience Australia and GeoMark Research, Inc. The Oils of Australia Series, Geoscience Australia, GeoCat # 68754.

GEOTECH, 2005—Hydrocarbon characterisation study; Perth Basin study (WA-286-P) (Cliff Head-4, Mentelle-1, Vindara-1 and Twin Lions-1). Professional Opinion prepared for Roc Oil Pty Ltd, unpublished.

GORTER, J. AND DEIGHTON, I., 2002—Effects of igneous activity in the offshore northern Perth Basin – evidence from petroleum exploration wells, 2D seismic and magnetic surveys. In: Keep, M. and Moss, S.J. (eds.) The Sedimentary Basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 875–99.

GORTER, J.D., HEARTY, D.J. AND BOND, A.J., 2004—Jurassic petroleum systems in the Houtman Sub-basin, northwestern offshore Perth Basin, Western Australia: a frontier petroleum province on the doorstep? The APPEA Journal, 44 (1), 13–57.

GRADSTEIN, F.M., OGG, J. AND SMITH, A. (eds), 2004—A Geologic Time Scale 2004. Cambridge: Cambridge University Press.

GRICE, K., SUMMONS, R.E., GROSJEAN, E., TWITCHETT, R.J., DUNNING, W., WANG, S.X. AND BOTTCHER, M.E., 2005—Depositional conditions of the northern onshore Perth basin (basal Triassic). The APPEA Journal, 45 (1), 263–73.

GROSJEAN, E., BOREHAM, C.J., JONES, A.T. AND KENNARD, J.M., 2010—A reassessment of the petroleum systems in the offshore North Perth Basin. 16th Australian Organic Geochemistry Conference Program and Abstracts, Canberra, ACT, 7–10 December.

HAQ, B.U. AND Al-QAHTANI, A.M., 2005—Phanerozoic cycles of sea-level change on the Arabian Platform, GeoArabia, 10 (2), 127–60.

HAQ, B.U. AND SCHUTTER, S.R., 2008—A Chronology of Paleozoic Sea-Level Changes. Science, 322, 64–8.

HARDENBOL, J., THIERRY, J., FARLEY, M.B., JACQUIN, T., DE GRACIANSKY, P.C. AND VAIL, P.R., 1998—Mesozoic and Cenozoic sequence chronostratigraphic framework of Europeau basins. In: Graciansky, P.C. de, Hardenbol, J., Jacquin, T. and Vail, P.R. (eds) Mesozoic and Cenozoic sequence stratigraphy of European basins, SEPM Special Publication 60, 3–13.

HOCKING, R.M., 1991—The Silurian Tumblagooda Sandstone, Western Australia. Western Australia Geological Survey, Report 27.

HOCKING, R.M., 1994—Sub-divisions of Western Australian Neoproterozoic and Phanerozoic sedimentary basins. Geological Survey of Western Australia, Record 1994/4.

JONES, D.K. AND PEARSON, G.R., 1972—The tectonic elements of the Perth Basin. The APEA Journal, 12 (1), 17–22.

JONES, N.T. AND HALL, A.D., 2002—The Cliff Head Oil Discovery – Offshore Perth Basin. In: Keep, M. and Moss, S.J. (eds.) The Sedimentary Basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 901–9.

JORGENSEN, D.C., JONES, A.T., KENNARD, J.M., ROBERTSON, D., LECH, M., NELSON, G., MANTLE, D., GROSJEAN, E., AND BOREHAM, C.J., in prep—Offshore northern Perth Basin Well Folio. Geoscience Australia Record, unpublished.

KEMPTON, R., GONG, S., KENNARD, J., VOLK, H., MILLS, D., EADINGTON, P. AND LIU, K., 2011—Detection of palaeo-oil columns in the offshore northern Perth Basin: extension of the effective Permo-Triassic charge system. The APPEA Journal, 51, 377–396.

LARSON, R.L., MUTTER, J.C., DIEBOLD, J.B., CARPENTER, G.B. AND SYMONDS, P., 1979—Cuvier Basin: a product of ocean crust formation by Early Cretaceous rifting off Western Australia. Earth and Planetary Science Letters, 45, 105–14

MARSHALL J.F., LEE, C-S., RAMSAY, D.C. AND MOORE, A.M.G., 1989—Tectonic controls on sedimentation and maturation in the offshore north Perth Basin. The APEA Journal, 29, 450–65.

McTAVISH, R.A., 1965—Completion Report, BMR 10 and 10A, Beagle Ridge, Western Australia: Australia Bureau of Mineral Resources, Geology and Geophysics, Report 80.

MILLIGAN, P.R., FRANKLIN, R., MINTY, B.R.S., RICHARDSON, L.M. AND PERCIVAL, P.J., 2010—Magnetic Anomaly Map of Australia (Fifth Edition), 1:15 000 000 scale, Geoscience Australia, Canberra.

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

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

OGG, J.G., OGG, G. AND GRADSTEIN, F.M., 2008—The Concise Geologic Time Scale. Cambridge: Cambridge University Press.

OWAD-JONES, D.L. AND ELLIS, G.K., 2000—Western Australia atlas of petroleum fields, onshore Perth Basin. Petroleum Division, Department of Minerals and Energy Western Australia, Volume 1.

PLAYFORD, P.E., 1971—Petroleum exploration in Western Australia, past, present, and future. Royal Society of Western Australia Journal, 54, 1–13.

PLAYFORD, P.E., COCKBAIN, A.E. AND LOW, G.H., 1976—The geology of the Pert Basin. Western Australia

Geological Survey. Bulletin 124.

PLAYFORD, P.E. AND WILLMOTT, S.P., 1958—Stratigraphy and structure of the Perth Basin: West Australian Petroleum Pty Ltd, Western Australia Geological Survey, S-series report S103, unpublished.

PURCELL, P.G. AND FISHER, R.W., 1997—Livet 1 well completion report, Seafield Resources Plc, unpublished report.

QUAIFE, R., ROSSER, J. AND PAGNOZZI, S., 1994—The structural architecture and stratigraphy of the offshore northern Perth Basin. In: Purcell, P.G. and Purcell, R.R. (eds) The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 811–22.

ROC OIL, 2004—WA-286-P Cliff Head 3D MSS interpretation report, unpublished.

ROC OIL, 2006—WA-325-P MaryAnn MSS interpretation report, unpublished.

SMITH, G.C. AND COWLEY, R.G., 1987—The tectono-stratigraphy and petroleum potential of the northern Abrolhos Sub-basin, Western Australia. The APEA Journal, 27 (1), 112–35.

SONG, T. AND CAWOOD, P.A., 2000—Structural styles in the Perth Basin associated with the Mesozoic breakup of Greater India and Australia. Tectonophysics, 317, 55–72.

SUMMONS, R.E., BOREHAM, C.J., FOSTER, C.B., MURRAY, A.M. AND GORTER, J.D., 1995—Chemostratigraphy and the composition of oils in the Perth Basin, Western Australia. The APEA Journal, 35 (1), 613–32.

SYMONDS, P.A. AND CAMERON, P.J., 1977—The structure and stratigraphy of the Carnarvon Terrace and Wallaby Plateau. The APEA Journal, 17, 30–41.

SYMONDS, P.A., PLANKE, S., FREY, Ø. AND SKOGSEID, J., 1998—Volcanic evolution of the western Australian continental margin and its implications for basin development. In: P.G. Purcell and R.R. Purcell (eds) The Sedimentary Basins of Western Australia 2: Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 1998, 33–54.

THOMAS, B.M. AND BARBER, C.J., 2004—A re-evaluation of the hydrocarbon habitat of the northern Perth Basin. The APPEA Journal, 44 (1), 13–57.

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

VEEVERS, J.J. AND JOHNSTONE, M.H., 1974—Comparative stratigraphy and structure of the Western Australian margin and the adjacent deep ocean floor. In: Heirtzler, J.R., Veevers, J.J., Bolli, H.M., Carter, A.N., Cook, P.J., Krasheninnikov, V., McKnight, B.K., Decima, F.P., Renz, G.W., Robinson, P.T., Rocker, K. Jr and Thayer, P.A. (eds), Initial Report of Deep Sea Drilling Project, Volume 27, Washington.

VEEVERS, J.J., TAYTON, J.W., JOHNSON, B.D. AND HANSEN, L., 1985—Magnetic expression of the continent-ocean boundary between the western margin of Australia and the eastern Indian Ocean, Journal of Geophysics, 56, 106–20.

VOLK, H., BOREHAM, C.J., KEMPTON, R.H. AND GEORGE, S.C. 2004—Geochemical and compound specific isotopic characterisation of fluid inclusion oils from the offshore Perth Basin Western Australia: implications for recognising effective oil source rocks. The APPEA Journal, 44 (1), 223–39.

VOLK, H., KEMPTON, R.H., AHMED, M., GONG, S., GEORGE, S.C. AND BOREHAM, C.J., 2009—Tracking petroleum systems in the Perth Basin by integrating microscopic, molecular and isotopic information on petroleum fluid inclusions (abstract). Journal of Geochemical Exploration, 101, 109.

WA DOIR, 2008—Petroleum in Western Australia, April 2008. Perth: Western Australia Department of Industry and Resources.

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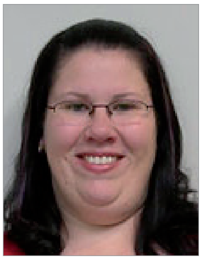

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