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Regional Geology of the northern Perth Basin

The Perth Basin is a large (172 300 km^2) north to north-northwest trending, onshore and offshore sedimentary basin extending about 1300 km along the western margin of the Australian continent (**Figure 1**). With the exception of Whicher Range and some isolated oil and gas shows in the Vlaming Sub-basin, hydrocarbon occurrences and production are confined to the northern part of the Perth Basin. This includes 20 commercial oil and gas fields and numerous additional significant discoveries of varying size, dominantly in the onshore northern part of the basin. Recent commercial onshore gas discoveries at Waitsia and West Erregulla have highlighted the hydrocarbon potential of the Permian and Triassic sedimentary sequences. The producing region of the basin is close to petroleum industry infrastructure, including two major gas pipelines and trucking facilities to an oil refinery near Perth (**Figure 2**).

Basin outline

The Perth Basin was originally named by Andrews (1938), and has been described and mapped by Playford et al (1976) and Hocking (1994). The maximum extent of the offshore part of the Perth Basin is placed at the limit of basin fill ranging in age from Cisuralian (early Permian) to Early Cretaceous (Bradshaw et al, 2003).

Crystalline basement beneath the Perth Basin comprises Proterozoic igneous and metamorphic rocks of the Pinjarra Orogen, which formed as an intercontinental mobile belt between the Australian and Indian parts of eastern Gondwana (e.g. Collins, 2003; Fitzsimons, 2003; Cawood and Korsch, 2008; Bodorkos et al, 2016). The Darling Fault system forms the eastern boundary of the Perth Basin, controlling its overall north-south orientation (**Figure 3**). This fault system originated as a shear zone during the Archean (Blight et al, 1981; Dentith et al, 1994) and was reactivated to form a major rift-border fault to the incipient Perth Basin during the Cisuralian (Crostella and Backhouse, 2000). The Perth Basin is separated from the Mentelle Basin in the southwest by the Leeuwin Complex and Yallingup Shelf, and from the Wallaby Plateau to the northwest by thick and extensive volcanic successions that formed during the Early Cretaceous breakup of Australia and Greater India (Colwell et al, 1994; Symonds et al, 1998; Sayers et al, 2002; Borissova et al, 2017).

The offshore part of the basin is composed of four sub-basins. The Abrolhos and Houtman sub-basins in the north contain a thick succession (8–13 km) of Permian to Lower Cretaceous sediments (**Figure 4** and **Figure 5**), overlain by an up to 1.5 km thick Upper Cretaceous to Cenozoic post-breakup succession. The Zeewyck Sub-basin in the northwest and Vlaming Sub-basin in the south (**Figure 3**) are predominantly Mesozoic depocentres containing 7–14 km of Middle Jurassic to Lower Cretaceous strata (**Figure 4** and **Figure 6**; Rollet et al, 2013a, 2013b). The boundaries between the sub-basins are interpreted to have formed through oblique-slip motion in a transtensional setting (Marshall et al, 1989a). In the northern Perth Basin, the offshore and onshore depocentres are separated by intrabasin highs comprising the Beagle Ridge and Dongara Terrace. Descriptions of the onshore structural elements are given by Iasky (1993), Hocking (1994), Mory and Iasky (1996), Crostella and Backhouse (2000) and Thomas (2014).

Northwest trending accommodation zones have been proposed as controlling the structural compartmentalisation of rift systems in the Perth Basin. For example, the Abrolhos and Cervantes transfer zones are interpreted to divide the northern Perth Basin into regions of significantly different structural character (Mory and Iasky, 1996).

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Both oil and gas are produced from a number of fields in the onshore Perth Basin. Oil is also produced from the offshore Cliff Head field (**Figure 1**)—the first commercial oil discovery in the offshore Perth Basin. Approximately 14.5 MMbbl (2.3 Gl) of oil was produced from the Cliff Head field between 2006 and 2015 (Elixir Petroleum Ltd, 2015). Significant gas resources have recently been discovered in the onshore northern Perth Basin, including a 2C contingent resource of 1185 Bcf (33.56 Bcm) at West Erregulla (Strike Energy, 2019), and 2P reserves plus 2C contingent resources of 910 PJ (22.9 Bcm) at the Waitsia gas field (AWE, 2018). There is an established gas pipeline network in Western Australia servicing the Perth Basin (**Figure 2**).

Basin evolution and stratigraphy

The Perth Basin formed through pre-breakup continental extension between the southwestern continental margin of Australia and Greater India (Matte et al, 1997; Ali and Aitchison, 2005). The tectonic and palaeogeographic history of the Perth Basin has been documented in several studies (Smith and Cowley, 1987; Marshall et al, 1989b, 1993; Harris, 1994; Quaife et al, 1994; Mory and Iasky, 1996; Song and Cawood, 2000; Crostella and Backhouse, 2000; Gorter and Deighton, 2002; Bradshaw et al, 2003; Norvick, 2004, Mory, 2017). These authors generally describe an early phase of rifting in the Permian, followed by a long period of widespread post-rift subsidence and a multi-phase extension in the Middle Jurassic to Early Cretaceous, culminating in breakup of Australia and Greater India.

Recent studies of the offshore northern Perth Basin (Jones et al, 2011, 2013; Jorgensen et al, 2011; Hall et al, 2013; Rollet et al, 2013a, 2013b; Thomas, 2014; Borissova et al, 2017; Hall et al 2017a; Owens et al, 2018a) have highlighted both similarities and differences in tectonic evolution of the onshore and offshore depocentres, which are described separately below.

Onshore Perth Basin

Early to Middle Permian extension

Early Permian to Middle (Cisuralian–Guadalupian) extension resulted in the formation of a series of half-graben in the onshore Perth Basin that are separated by saddles and bounded by en-echelon rift border faults (**Figure 3** and **Figure 5**; Norvick, 2004; Thomas, 2014). This rift complex extends at least from the Southern Carnarvon Basin in the north to the Bunbury Trough in the south. In many cases, but not exclusively, the original rift basins were aligned north-south (Quaife et al, 1994). Active faulting slowed in the north from the Sakmarian onwards (Norvick, 2004).

Initially, the basins were filled with glacial (Nangetty and Mosswood formations; **Figure 4** and **Figure 6**) to pro-glacial marine (Holmwood Shale, High Cliff and Woodynook sandstones) and deltaic sediments (Irwin River and Rosabrook coal measures; Mory and Iasky, 1996; Norvick, 2004; Mory, 2017). Deglaciation commenced in the Sakmarian as the rift basins continued to fill from the south to north with deltaic (Ashbrook Sandstone, Redgate Coal Measures and Willespie Formation) to progressively more marine sediments (Carynginia Formation; Norvick, 2004).

Late Permian uplift and erosion

In the onshore northern Perth Basin, the end of early Permian rifting is marked by a regional angular unconformity associated with uplifted tilted fault blocks that underwent subaerial erosion (Roc Oil, 2004). This uplift was followed by late Permian to Early Triassic early post-rift subsidence, and the deposition of coarse-grained alluvial fans and fan-deltas (Wagina Sandstone; **Figure 4**; Mory and Iasky, 1996). Deposition of proximal fan to coarse-grained deltaic and coastal sediments (Dongara Sandstone) occurred during approximately the same period (Mory and Iasky, 1996; Mory, 2017).

Triassic to Middle Jurassic post-rift subsidence

A rapid marine transgression at the beginning of the Triassic expanded depositional systems beyond the late Permian depocentres (**Figure 4** and **Figure 5**; Norvick, 2004). This regional marine transgression occurred throughout the Perth Basin (Kockatea Shale) and extended over basins to the north (Carnarvon, Browse, Roebuck, Canning and Bonaparte basins). Sandier proximal facies in the southern part of the Perth Basin (Sabina Sandstone) suggest that the basin was closed and filling from this direction (Norvick, 2004). Deltaic and fluvial facies were deposited throughout the Perth Basin in the Middle to Late Triassic (Woodada Formation and Lesueur Sandstone) during a subsequent regressive depositional phase (**Figure 4**, **Figure 5** and **Figure 6**; Mory and Iasky, 1996). Palaeocurrent data show that the Triassic rivers flowed from the south or southwest (Mory and Iasky, 1996), with their catchment areas extending over both the Perth Basin and much of the Yilgarn Craton (Norvick, 2004).

In some parts of the onshore Perth Basin, the prolonged phase of post-rift subsidence appears to have been interrupted by a minor phase of west-northwest–east-southeast extension during the latest Triassic to Early Jurassic (**Figure 4** and **Figure 6**; Song and Cawood, 1999, 2000; Bradshaw et al, 2003). Extension reactivated a number of faults in the basin, with syn-tectonic deposition of non-marine red beds (Eneabba Formation). Mild extension was followed by increased subsidence and the deposition of delta-top swamp deposits (Cattamarra Coal Measures), possibly associated with a slow regional transgression (Norvick, 2004). This transgression peaked in an extensive but short-lived marine flooding event in the Bajocian, which resulted in deposition of the marine shales of the Cadda Formation.

Middle Jurassic to Early Cretaceous rifting and breakup

The final rifting phase in the onshore Perth Basin occurred in the Late Jurassic to Early Cretaceous, in the lead up to continental breakup between Australia and Greater India (Norvick, 2004). An abrupt resumption of fluvial sedimentation in the Bajocian (Yarragadee Formation) was accompanied by the onset of major extensional faulting (**Figure 4** and **Figure 6**). A poorly delineated change to red bed sedimentation (Parmelia Group) occurred in the Tithonian to Berriasian, probably under ongoing syn-rift conditions (Norvick, 2004). Deeper water parts of the basin may have received deltaic or marine equivalent sediments at this time.

Northwest-southeast extension from the Middle Jurassic to earliest Cretaceous culminated in the breakup of Australia and Greater India during the Valanginian, and produced much of the final structural architecture of the Perth Basin (Bradshaw et al, 2003). Early Cretaceous breakup was associated with widespread uplift, erosion and volcanism (**Figure 4** and **Figure 6**).

Cretaceous to Cenozoic post-breakup

Post-breakup subsidence in the Early Cretaceous (Valanginian–Aptian; Quaife et al, 1994) has been associated with widespread volcanic activity in some parts of the Perth Basin (Gorter and Deighton, 2002) and on the Wallaby Plateau (Symonds et al, 1998). Marine sediments, including turbidites, were deposited as a result of localised subsidence (Norvick, 2004) in deeper parts of the basin (Warnbro Group; **Figure 4** and **Figure 6**).

Late Cretaceous and Cenozoic sedimentation occurred under stable, passive margin conditions and produced a thin cover of predominantly marine carbonates. In some places, there was a transition from cool-water ramp sedimentation to reefal platform development (Houtman Abrolhos coral reefs) near the shelf edge during the Neogene to Quaternary (Collins et al, 1998).

Offshore Perth Basin

The offshore northern Perth Basin also formed through a complex history of extension and reactivation, which controlled sedimentation (Jones et al 2011; Rollet et al, 2013a; Hall et al, 2017a; Owens et al, 2018a). Regional offshore tectonic events include:

Two main phases of rifting in the Permian, Early Jurassic to Early Cretaceous, with a third phase distinct phase of rifting restricted to some offshore areas north of the Abrolhos Sub-basin;

Two periods of subsidence during the late Permian to Early Jurassic, and Early Cretaceous to Cenozoic;

Two periods of uplift during the middle to late Permian, and Early Cretaceous;

Three periods of magmatism in the late Permian to Early Triassic, Late Triassic to Early Jurassic, and Early Cretaceous;

A phase fault reactivation and inversion in the Miocene.

Geoscience Australia's northern Houtman Sub-basin study (Borissova et al, 2017; Hall et al, 2017a; Owens et al, 2018a, 2018b; Southby et al, 2018) developed a revised tectonostratigraphic framework for the offshore northern Perth Basin (**Figure 7**) based on interpretations of the GA-349 seismic data (acquired in 2014-2015; **Figure 8**), together with regional seismic interpretations over the northern Perth Basin by Jones et al (2011; **Figure 9**). The revised framework integrates the regional geological knowledge from wells in the Houtman and Abrolhos sub-basins (Jorgensen et al, 2011), together with insights into the geology of the frontier northern Houtman sub-basin derived from seismic interpretations. Details of the mapped seismic sequences and their interpreted lithostratigraphic equivalents are discussed below, together with the tectonic development of the broader offshore Perth Basin.

Pre-rift

Basement is 12–18 km deep in the central part of the offshore basin and shallows to about 9–11 km in the west (Borissova et al, 2017). To the south, basement intersections on the Beagle Ridge (e.g. Cliff Head 1) encountered Precambrian granites probably belonging to the Proterozoic Pinjarra Orogen, which forms the basement to the onshore Perth Basin (Dentith et al, 1994). In the Houtman Sub-basin the overlying pre-Permian sequence (NH-Pz) is characterised by high amplitude, high continuity reflectors, and is confidently mapped throughout the inboard part of the depocentre (**Figure 8**) where it is at least 2–3 km thick (Owens et al, 2018a). This pre-rift sequence is tentatively correlated with the Ordovician–Silurian Tumblagooda Sandstone (**Figure 7**; Hocking, 1991), which has been intersected on the Wittecarra Terrace in Hadda 1 and Livet 1 (Jorgensen et al, 2011). In these well intersections, the Tumblagooda Sandstone consists predominantly of very light grey to red brown, very fine- to medium-grained, sub-angular to sub-rounded sandstone (quartz arenite) with minor amounts of claystone (Jorgensen et al, 2011). In onshore outcrop areas, the Tumblagooda Sandstone consists of red, very fine- to coarse-grained sandstones deposited in a fluviatile environment (Playford et al, 1976; Hocking, 1991; Mory and Iasky, 1996).

Permian extension

Early to middle Permian (Cisuralian–Guadalupian) extension also produced northwest-oriented half-graben separated by saddles and en-echelon rift-border faults in the offshore basin area (Norvick, 2004; Jones et al, 2011; Rollet et al, 2013a, 2013b; Bernardel and Nicholson, 2013; Thomas, 2014; Borissova et al, 2017). Pfahl (2011) noted that the timing of rifting in the offshore northern Perth Basin is not significantly different to rifting in the onshore parts of the basin. Northwest to southeast extension has been proposed for Permian rifting in the offshore northern Perth Basin (Pryer et al, 2002; Borissova et al, 2017), although the stress regime remains poorly understood.

Thermal history modelling of three wells in the Abrolhos Sub-basin by Pfahl (2011) indicates that the timing of Permian rifting appears to coincide with the deposition of a thick syn-rift succession. Wells drilled in the Houtman Sub-basin have not reached the Permian sequences. Syn-rift Permian sediments, however, are interpreted (Borissova et al, 2017) from seismic data in the northern Houtman Sub-basin.

The syn-rift succession in the central Permian half-graben is 7–10 km thick and extends the length of the northern Houtman Sub-basin (Borissova et al, 2017; Owens et al, 2018a; **Figure 8**). Two seismic sequences have been mapped: NH-P1 (Permian syn-rift 1) and NH-P2 (Permian syn-rift 2) (**Figure 7**). The age of the sequences is unconstrained, but the boundary between the two is interpreted to be at the base of the middle Permian, consistent with the onset of a regional marine transgression across the Perth Basin (Ferdinando and Longley, 2015). Based on the stratigraphy of the onshore northern Perth Basin, sequence NH-P1 is interpreted to contain glacial to pro-glacial marine sediments of the Nangetty Formation and Holmwood Shale; and glacially influenced paralic to non-marine fluvial and coal-rich sequences equivalent to the High Cliff Sandstone and Irwin River Coal Measures (Mory and Iasky, 1996; Norvick, 2004; Jones et al, 2013). In contrast, sequence NH-P2 is likely to consist of shallow marine shales of the Carynginia Formation. Further information on the syn-rift sedimentary successions in the offshore northern Perth Basin are documented by Rollet et al (2013a, 2013b).

Middle Permian uplift and erosion

The offshore northern Perth Basin experienced period of post-rift tectonic uplift in the Middle Permian (late Guadalupian) resulting in subaerial erosion of tilted fault blocks, and the formation of a regional post-rift unconformity (Roc Oil, 2004). Based on limited well data along the edge of the basin, Pfahl (2011) suggested that this uplift was relatively minor (~100 m). Erosion was most focussed over the Beagle Ridge and in parts of the Abrolhos Sub-basin, where the Beekeeper and Carynginia sequences were totally or partially removed (**Figure 5** and **Figure 7**). In the Houtman Sub-basin a prominent unconformity, separating the Permian syn-rift sequences from the younger succession, is correlated to the regional late Permian post-rift unconformity of the northern Perth Basin (Mory and Iasky, 1996).

Late Permian to Early Jurassic subsidence

Late Permian to Early Jurassic (Lopingian–Toarcian) thermal subsidence resulted in the formation of a westward-thickening sag succession. Seismic interpretations suggest that a thick succession was deposited across the entire offshore Perth Basin, reaching 4–5 km in the northern Houtman Sub-basin (Borissova et al, 2017). In the eastern Abrolhos Sub-basin, Early Jurassic subsidence rates show some variations, with initially greater subsidence at Leander Reef 1, and then increasing subsidence farther north at Cliff Head 1, Frankland 1 and Dunsborough 1 (Pfahl, 2011; Rollet et al, 2013a, 2013b).

Deposition of the upper Permian Dongara Sandstone or equivalents occurred during this sag period. The Dongara Sandstone transgressive facies filled incised valleys that formed during the previous post-rift erosional event on the Beagle Ridge and in the Abrolhos Sub-basin. In the Houtman Sub-basin is the 500–1000 m thick, relatively transparent, seismic sequence NH-P3 (**Figure 7** and **Figure 8**). This sequence is interpreted to consist of early post-rift sandstones equivalent to the upper Permian Dongara Sandstone, and mixed shales, limestones and clastics equivalent to the upper Permian Beekeeper Formation. This seismic sequence is only present over the Permian graben and has an onlapping, sag-fill geometry. A late Permian to Early Triassic intrusive event is recorded in Edel 1; igneous rocks associated with this event are also interpreted to be present below Geelvinck 1 (Gorter and Deighton, 2002).

Continued transgression and a maximum flooding event in the Early Triassic led to deposition of the Kockatea Shale. The Kockatea Shale is widespread across the Perth Basin and consists of shale, claystone and siltstone, with minor sandstone and limestone (Playford et al, 1976). The unit was deposited in a shallow marine environment, and records a major marine incursion as well as the onset of a subsequent regression (Jones et al, 2011; Jorgensen et al, 2011). Initially slow depositional rates resulted in the accumulation of organic-rich sediments within the Hovea Member, which has a maximum thickness in offshore wells of 45.7 m in Lilac 1. This was followed by rapid deposition of the remainder of the Kockatea Shale (435 m thick in Batavia 1), which thickens northwards in the northern Houtman Sub-basin (Borissova et al, 2017). In the Houtman Sub-basin the regionally extensive seismic sequence, NH-TR1—interpreted to be equivalent to the upper Permian–Lower Triassic Kockatea Shale (**Figure 7**; Owens et al 2018a)—extends over the main Permian half-graben, where it reaches a maximum thickness of 1800 m (**Figure 15**).

Gradual regional regression from the Early to Late Triassic and led to deposition of south-north orientated axial fluvio-deltaic systems of the Woodada Formation and the Lesueur Sandstone (Mory and Iasky, 1996; Norvick, 2004) before culminating in a lowstand in the Late Triassic–Early Jurassic (Jones et al, 2011; Jorgensen et al, 2011), and deposition of the Eneabba Formation (Jorgensen et al, 2011). The equivalent Triassic sequences NH-TR2, NH-TR3, NH-TR/J1 (**Figure 7**) are uniformly thick (about 4–5 km) throughout the central parts of the northern Houtman Sub-basin (**Figure 8**; Borissova et al, 2017). However, the succession thins outboard and also to the east, where there is some onlap within sequences and partial erosion by the Valanginian unconformity. If sequences NH-TR2 and NH-TR3 are distal components of the same fluvio-deltaic system responsible for the deposition of the Woodada and Lesueur formations further to the south, then finer lithologies may be expected in the northern Houtman Sub-basin.

Although the onshore Perth Basin shows evidence for an Early Jurassic extensional phase where the Eneabba Formation thickens in the hanging wall of a series of reactivated master faults (**Figure 5**); Song and Cawood, 2000; Gorter et al, 2004), most offshore seismic interpretations do not show rift-related thickening of the Eneabba Sequence, except locally in the Houtman Sub-basin (Gorter et al, 2004). Similarly, tectonic subsidence analysis does not show evidence of an offshore rifting event in the Early Jurassic (Pfahl, 2011). Early Jurassic rifting therefore seems to be restricted to the onshore part of the basin and only some offshore areas north of the Abrolhos Sub-basin (Rollet et al, 2013a).

Early Jurassic to Early Cretaceous syn-rift

In the Early to Middle Jurassic (181–169 Ma) rifting shifted outboard, becoming restricted to the Houtman Sub-basin during deposition of the Cattamarra and Cadda formations and equivalent sequences (Rollet et al, 2013a, 2013b; Borissova et al, 2017). The Early to Middle Jurassic syn-rift succession is thickest (about 4 km) in the central part of the Houtman Sub-basin and gradually thins to the north, where only the lower part of the Jurassic succession is present (**Figure 8**). Jurassic extension reactivated the Permian fault systems in the Abrolhos and Houtman sub-basins. Fault architecture across the basin is characterised by en-echelon fault networks separated by relay ramps at a range of scales. In the Houtman Sub-basin, mapped Lower Jurassic to Lower Cretaceous syn-rift sequences (NH-J2, NH-J3, NH-J4 and NH-K1, **Figure 7**) are characterised in seismic data by high frequency, high continuity reflectors. In addition, the base of sequence NH-J2 (Cattamarra Coal Measures equivalent) generally corresponds to a regional unconformity (Rollet et al, 2013a), although this unconformity is difficult to discern on seismic data over the northern Houtman Sub-basin. The rift-fill succession is predominantly non-marine, consisting of fluvial sandstones, carbonaceous shales and coals, with the exception of the Middle Jurassic sequence NH-J3 (Cadda Formation equivalent) which represents a short-lived marine incursion (Mory and Iasky, 1996; Jorgensen et al, 2011).

Fluvio-deltaic sandstones and siltstones were deposited in the lower part of the Yarragadee Formation during a Late Jurassic regression. This was followed by deposition of coarse-grained fluvial sediments through a northerly-flowing river system (Mory and Iasky, 1996; Norvick, 2004). According to Pfahl (2011), deposition of much of the Yarragadee Formation occurred during a post-rift subsidence phase, rather than a syn-rift phase as previously interpreted (Jones et al, 2011). Dinocyst assemblages in Houtman 1 and Charon 1 suggest that minor marine incursions also occurred during this time (Jones et al, 2011; Rollet et al, 2013a, 2013b). In the western part of the depocentre, adjacent to the Wallaby Saddle, the Jurassic–Lower Cretaceous section is heavily intruded and may underlie the Seaward Dipping Reflector Sequences (SDRSs) defining the volcanic margin (**Figure 8**).

Latest Jurassic rifting was largely restricted to the western Houtman and Zeewyck sub-basins (Pfahl, 2011; Rollet et al, 2013a, 2013b). This final rift phase preceded the separation of Australia and Greater India in the Valanginian (Larson et al, 1979; Veevers et al, 1985; Gibbons et al, 2012), and continued the development of a dense north-northwest-striking system of closely spaced, westerly dipping rotated fault blocks (Rollet et al, 2013a, 2013b). A series of small-scale north to north-northwest-trending inversion anticlines and pop-up structures (**Figure 9**) in the Houtman and Abrolhos sub-basins may have formed as a result of transpressional stress during this period. These inversion structures are characterised by prominent fault propagation folds, some of which are truncated by the Valanginian unconformity.

During this phase the upper part of the Yarragadee Formation and a Parmelia Group equivalent were deposited (Rollet et al, 2013a; Owens et al, 2018a). Intrusive rocks interpreted in the Yarragadee Sequence in the Houtman Sub-basin, coupled with a thickened Upper Jurassic to Lower Cretaceous succession in the outer Zeewyck Sub-basin, suggest that prior to breakup, rifting was restricted mostly to the far western offshore Perth Basin.

Early Cretaceous breakup

The Valanginian breakup unconformity marks the base of the Cretaceous–Cenozoic post-rift succession (**Figure 7**, **Figure 8** and **Figure 9**). This prominent angular unconformity truncates older Triassic–Cretaceous sequences. Diachronous breakup between segments of the southwest margin (Hall et al, 2013) influenced the timing and amount of subsidence in the Houtman and Zeewyck sub-basins (Rollet et al, 2013a, 2013b; Hall et al, 2017b). Plate reconstruction models (Gibbons et al, 2012) indicate that active transform motion lasted from approximately 137 to 124 Ma outboard of the Zeewyck Sub-basin, continuing until 115 Ma outboard of the northern Houtman Sub-basin (**Figure 10**; Hall et al, 2013). A ridge jump occurred at around 128 Ma (Barremian) in the Cuvier Abyssal Plain, transferring the Wallaby Plateau to the Australian Plate (Gibbons et al, 2012). In the northern Houtman Sub-basin adjacent to the Wallaby Saddle, a volcanic margin evolved with a large volume of igneous rocks being deposited on the western flank of the basin. This led to significant differences in thermal subsidence patterns between the southern and northern parts of the Houtman Sub-basin (Rollet et al, 2013a, 2013b; Borissova et al, 2017).

In the northern Houtman Sub-basin the post-rift succession is 500–1500 m thick (Borissova et al, 2017; Owens et al, 2018a). The oldest post-breakup sequence (NH-K2) is interpreted to have developed as the volcanic margin evolved and contains SDRSs extending onto the Wallaby Saddle. Lava flows and individual volcanoes are clearly imaged by the seismic data within this sequence, unique to the northern Houtman Sub-basin. The distribution of the SDRSs and major sill and dyke complexes has been confirmed by magnetic modelling of one of the seismic lines of the GA-349 survey (Sanchez et al, 2016). The lower Albian age of the upper boundary of this sequence is inferred from interpretation of the two regional seismic lines from survey GA-310, which extend from the Houtman Sub-basin across the Wallaby Saddle to the Wallaby plateau (**Figure 3**). On these lines, the angular unconformity on the Wallaby Plateau corresponds to the top of the SDRSs, while in the northern Houtman Sub-basin the Valanginian breakup unconformity is interpreted to underlie the SDRS. As the Wallaby Plateau did not separate from Greater India until about 120 Ma, the angular unconformity on the Wallaby Plateau is considered to be Lower Aptian. The SDRS wedge onlaps the Valanginian unconformity along the western margin of the northern Houtman Sub-basin (**Figure 8**), so both unconformities are imaged.

Tectonic subsidence analysis suggests an episode of regional uplift associated with breakup that lasted approximately 6 million years after the final rifting phase (Pfahl, 2011). The basin flanks experienced significant uplift resulting in removal of Lower Cretaceous rocks and erosion of the Upper Jurassic succession throughout most of the Abrolhos Sub-basin, Wittecarra Terrace, Beagle and Turtle Dove ridges and the northern part of the Houtman Sub-basin (**Figure 4; Figure 15**).

Early Cretaceous to Cenozoic subsidence

Breakup was followed by passive margin subsidence and regional westward tilting in the Early Cretaceous (Valanginian–Aptian). The overlying Cretaceous (NH-K3) and Cenozoic successions (NH-K/T1, NH-T2 and NH-T3, **Figure 7** and **Figure 8**) were mapped by tying to exploration well Herdsman 1 (Woodside Energy Ltd, 2003) and to Livet 1 (Seafield Resources Plc, 1997). The lower sequence (NH-K3) is interpreted to consist of siliciclastics equivalent to the Lower Cretaceous Winning Group, while the upper sequences (NH-K/T1, NH-T2 and NH-T3) consist largely of carbonate units prevalent across the Carnarvon Basin. NH-K/T1 is interpreted to mark the onset of widespread carbonate deposition and potentially includes Upper Cretaceous to Lower Paleogene equivalents to the Haycock Marl, Toolonga and Korojon calcilutites, Miria Formation and Cardabia Calcarenite. The base of the NH-T2 sequence is interpreted to correspond to a mid-Eocene regional unconformity (Hocking et al, 1987; Haig and Mory, 2003) and includes equivalents of the Giralia Calcarenite, Mandu Formation and Trealla Limestone.

Miocene inversion

Evidence of the Miocene convergence between the Australian and Eurasian plates is seen in the offshore northern Perth Basin as late-stage fault reactivation and inversion, in association with minor folding of Cretaceous and younger strata (**Figure 4**). This reactivation and inversion is primarily evident along some of the major basin-bounding fault systems of the offshore northern Perth Basin (Gorter et al, 2004; Borissova et al, 2017). In the Houtman Sub-basin, the base of seismic sequence NH-T3 is interpreted as a late Miocene regional unconformity related to this convergence (Owens et al, 2018a).

Exploration history

Petroleum exploration in the Perth Basin commenced in the late 1940s with an onshore field survey and evaluation of water well drilling commissioned by Ampol and Richfield Oil companies and gravity surveys by the Bureau of Mineral Resources (BMR) (Mory and Iasky, 1996). Oil shows recorded in BMR wells drilled on the Beagle Ridge in 1959-60 led West Australian Petroleum Pty Ltd (WAPET) to drill the first wildcat hole, Eneabba 1, in 1961. The first discovery in the Perth Basin was the Yardarino gas field in 1964, with mixed Permian and Triassic sourced hydrocarbons reservoired in the Wagina Formation (Crostella, 1995). The Dongara oil and gas field (**Figure 11**), with oil and gas sourced from the Lower Triassic Kockatea Shale and additional gas sourced from lower Permian shales and coals, was discovered in 1966 and commenced production in 1971 (Crostella, 1995). The discovery of gas and oil in Gingin 1 and 2, drilled between 1964 and 1966, although uneconomic, was significant in that it proved the effectiveness of sources from the Jurassic succession (Crostella, 1995). In the 50 year period between 1964 and 2014, eight significant producing gas fields and five oil fields were discovered in the onshore Perth Basin, with total ultimate proved and probable reserves totalling 740 Bcf of gas and 14 MMbbl of oil—about 95% of these resources were produced by 2015 (Tupper et al, 2016).

Exploration in the onshore northern Perth Basin has recently been reinvigorated following several large commercial discoveries (Waitsia, West Eregulla and Beharra Springs Deep) along a new Permian gas fairway. These gas discoveries have been in lower Permian (Kingia and High Cliff sandstones) sandstones at significantly greater depths (>3000 m) than previously thought could preserve the reservoir quality required for conventional hydrocarbon production. Prior to 2014, commercial hydrocarbon were mainly discovered in younger Permo-Triassic plays. A new focus on exploration for lower Permian plays followed the discovery of the Waitsia gas field in 2014—the largest onshore discovery in Australia for 40 years (Tupper at al, 2016; AWE, 2018). The Waitsia Field (**Figure 12**) commenced production in 2016 and is estimated to have a total 2P reserve of 820 PJ (20.6 Bcm) in good quality reservoirs (>11 % primary porosity, 10 to >100 mD permeability) from the Kingia and High Cliff sandstones to depths of 3750 m, and a further 2C contingent resource of 90 PJ (2.3 Bcm; AWE, 2018).

The success of Waitsia has been followed up with recent (2019) discoveries at West Erregulla and Beharra Springs Deep (Beach Energy and Mitsui E&P Australia; Cockerill, 2020). West Erregulla 2 flowed at 69 MMcfd (1.9 Mcm) from the Kingia Sandstone at depth of 4500 m, and has a 2C contingent resource of 1185 Bcf (33.56 Bcm; Strike Energy, 2019). Exploration is continuing over the greater Erregulla area to test additional resource potential in the South Erregulla prospect. Beharra Springs Deep 1 discovered a net gas pay of 36 m in the Kingia Sandstone, which flowed at a rate of 35 MMcfd (0.99 Mcm) on test over depths of 3940–3977 m (Beach Energy, 2019). Well test data is now being integrated with other subsurface data to estimate the size of the gas resource, and planning is underway for potential appraisal drilling in financial year 2021.

Offshore exploration commenced in 1965, with the acquisition of the Abrolhos and Perth Marine Seismic Surveys in the northern Abrolhos and southern Vlaming sub-basins, respectively. Seismic data have been acquired consistently since that time, giving a coverage that is a mixture of older regional reconnaissance grids and more detailed surveys and scientific studies (Soames et al, 2014). Seismic coverage is most concentrated in the Abrolhos Sub-basin, the Wittecarra Terrace and the central Vlaming Sub-basin. The southern Houtman and southern Vlaming sub-basins are also covered by relatively tight (<1–5 km line spacing) industry grids. Four 3D seismic surveys were acquired in 2003 and 2004, and one later in 2008, all in the northern Perth Basin. A series of regional 2D lines were acquired over the frontier northern Houtman and Zeewyck sub-basins, as part of Geoscience Australia seismic survey 310 in 2008–09 (Foster et al, 2009). In 2008–10, Geoscience Australia commissioned the reprocessing of approximately 11 665 line km (180 lines) of seismic data from 17 surveys with vintages spanning 1976–2003. Recent 2D seismic acquisition has been undertaken in the basin by Spectrum Geo Pty Ltd and Geoscience Australia, with the acquisition of 8292 line km (Rocket 2D) and 3455 line km (GA-349) respectively (Borissova et al, 2015, 2016; Owen, 2016).

The first well drilled in the offshore Perth Basin was Gun Island 1 (**Figure 11**), a stratigraphic well drilled by BP Petroleum Development Australia Pty Ltd in 1968. This was followed by the first hydrocarbon discovery in the offshore Perth Basin at Gage Roads 1 by WAPET in 1969. A total of 98.5 barrels (15.66 m^3) of oil were recovered from the Stragglers Member of the Carnac Formation at Gage Roads, which remains the only accumulation found in the Vlaming Sub-basin. A series of wells were then drilled in a campaign by WAPET from 1971–1978, including Roe 1, Warnbro 1, Charlotte 1, Sugarloaf 1, Bouvard 1 and Challenger 1 in the Vlaming Sub-basin, South Turtle Dove 1B on the Turtle Dove Ridge, and Geelvink 1A in the Abrolhos Sub-basin.

A general lack of success in the WAPET drilling campaign subsequent to the Gage Roads discovery led to a period of decreased exploration activity in the basin, with only 10 wells drilled in the 1980s and 1990s, by companies such as Esso Exploration and Production Australia Ltd and Ampol Exploration Limited. In the offshore northern Perth Basin there was an 11 year hiatus between the drilling of Wittecarra 1 in 1985 and Livet 1 in 1996.

Between 2001 and 2008, ROC Oil (WA) Pty Ltd drilled 11 new field wildcat wells in the northern Perth Basin. The first of these exploration wells discovered the Cliff Head oil field (**Figure 12**). The Cliff Head discovery, and a series of onshore oil discoveries in the early 2000s (Hovea, Jingemia, Eremia), changed the perception of the northern Perth Basin from being marginally prospective for gas to one that is highly prospective for gas and oil (Buswell et al, 2004).

Cliff Head 1 (**Figure 11**) intersected a 4.8 m waxy (31.6°API) oil column in the Irwin River Coal Measures immediately beneath the Kockatea Shale regional seal (Jones and Hall, 2002). Seismic interpretation of the Cliff Head oil field has shown it to be structurally complex with reverse, strike-slip and listric normal faults mapped at both field and reservoir scale within the Permo-Triassic succession (Hodge, 2005). 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 14.5 MMbbl (2.3 Gl) of oil produced to 2015 (Elixir Petroleum Ltd, 2015) and 0.48 MMbbl (76 Ml) of oil in the 12 months to June, 2016 (AWE, 2016). Production License WA-31-L over the Cliff Head oil field is currently held by Triangle Energy (Global) Ltd. and ROC Oil (WA) Pty Ltd. The Cliff Head field has reported 2P and 2C reserves of 1.71 MMbbl and 4.79 MMbbl, respectively (Triangle Energy, 2019).

Three other discoveries were made in 2007 as part of ROC Oil’s drilling campaign, with Frankland 1, Dunsborough 1 and Perseverance 1 all intersecting gas columns, and Dunsborough 1 including a light oil leg (**Figure 11**). However, the Frankland 2 and Dunsborough 2 appraisal wells returned disappointing results, and the Frankland and Dunsborough discoveries were deemed non-commercial. GOI™ (Grains containing Oil Inclusions) analyses indicate paleo-oil columns in both Frankland 2 and Dunsborough 2, implying loss of oil through breach of structure or redistribution (e.g. tilting or displacement by gas; Kempton et al, 2011), or both.

In 2015, AWE was awarded WA-512-P located in the central Houtman Sub-basin. While active in the permit AWE fulfilled commitments of the primary work programme that including reprocessing of 535 km^2 of 3D and 4048 km^2 of 2D seismic data, and geological and geophysical studies resulting in the identification of a number of Permo-Triassic leads (RISC Advisory, 2018). The permit was subsequently acquired as part of the Mitsui & Co Ltd takeover of AWE and has since been surrendered.

The most recent drilling in the offshore northern Perth Basin was a three-well program (Koel 1, Cisticola 1, Munia 1; **Figure 11**) in exploration permit WA-481-P, the only active offshore exploration permit in the offshore Perth Basin (**Figure 12**). Undertaken by Murphy Oil Corporation, with joint venture partners KUFPEC Australia Pty Ltd and Samsung Oil and Gas Australia Pty Ltd, all three wells were plugged and abandoned as dry holes with minor gas shows (Cisticola 1, Munia 1) and oil indications (Koel 1; Murphy Oil Corporation, 2015a, 2015b, 2015c). WA-481-P has since been acquired by Pilot Energy Ltd with joint venture partner Key Petroleum Ltd (Pilot Energy, 2016; Key Petroleum, 2016), and Pilot Energy have subsequently issued a prospectivity update and undertaken a prospective resource assessment (Pilot Energy, 2017).

Between 2009 and 2013, Geoscience Australia undertook work in the northern Perth Basin as part of the Australian Government's Offshore Energy Security Program. As a part of this program, numerous studies were conducted in an attempt to reduce exploration risk to industry by providing pre-competitive data for the northern Perth Basin. These studies include an offshore northern Perth Basin well folio of 23 composite well logs incorporating new biostratigraphic data and a sequence stratigraphic interpretation (Jones et al, 2011, 2013; Jorgensen et al, 2011; Robertson et al, 2011); and organic geochemical analyses (Grosjean et al, 2012, 2013). Additional collaborative studies on the detection of paleo-oil columns in wells in the offshore northern Perth Basin (Kempton et al, 2011) and trap integrity (Langhi et al, 2012) were also undertaken. Further to this, a marine survey was conducted in 2011 aboard the RV Southern Surveyor, which included the use of a remotely operated vehicle (ROV). Underwater video footage taken by the ROV identified a dark coloured fluid proximal to sidescan flares (Jones et al, 2012b). A range of geophysical studies has provided additional insights into the geology of the northern Perth Basin (Hackney, 2012; Johnston and Goncharov, 2012; Johnston and Petkovic, 2012; Petkovic, 2012; Hackney et al, 2014). Basin geology and prospectivity compilations have been produced by Jones et al (2011; 2012a, 2012b), Rollet et al (2013 a, 2013b) and Totterdell et al (2014).

Recent work by Geoscience Australia in the northern Houtman Sub-basin includes a prospectivity study following acquisition of a 3455 line km 2D seismic survey, GA-349, in 2015–16. The GA-349 data has allowed imaging of the full sedimentary sequence as well as the Moho and deep basement structures, providing insight into the architecture and evolution of this sub-basin and the wider Western Australian margin (Sanchez et al, 2016; Borissova et al, 2017). Interpretation of the new data has been combined with regional mapping of the northern Perth Basin, geophysical modelling (Sanchez et al, 2016) and petroleum systems analysis (Hall et al, 2017b) to assess prospectivity and tectonic evolution (Hall et al, 2017a). To date, results of this ongoing work indicate substantial prospectivity in this region. Also undertaken in 2015 was the Rocket 2D multi-client seismic survey by Spectrum Geo with acquisition of 8292 line km covering much of the Houtman sub-basin and Southern Carnarvon Basin (O'Neill et al, 2016). Spectrum Geo also reprocessed the GA-349 data to achieve an integrated regional coverage of modern data providing improved seismic imaging of this underexplored region (O'Neill et al, 2016).

Regional petroleum systems

Several hydrocarbon families are recognised from the geochemistry of oils, gases and oil shows from wells across the offshore Perth Basin: Permian, Triassic, mixed Permian-Triassic, Jurassic and Upper Jurassic/Lower Cretaceous (**Figure 13**). The majority of oils and condensates from the northern onshore and offshore Perth Basin are sourced from the sapropelic interval of the Hovea Member of the Lopingian–Lower Triassic Kockatea Shale. However, there are locally important hydrocarbons accumulations that are sourced solely or partially from older and younger successions.

The northern Perth Basin is a proven hydrocarbon province and includes the Cliff Head oil field in the Abrolhos Sub-basin and the recent onshore Waitsia gas discovery (Tupper et al, 2016). While the Houtman Sub-basin is an under-explored region, the regional seismic stratigraphic correlation with wells across the offshore northern Perth Basin indicates that this depocentre has the potential to contain multiple petroleum systems equivalent to those identified in the adjacent producing depocentres.

Well control

Petroleum geological control in the hydrocarbon-bearing northern offshore part of the Perth Basin is provided by 26 wells (Figure 11), the last three of which were drilled in 2015 by Murphy Oil Corporation as the operator of permit WA-481-P. Summaries for those wells are given below; details for about 23 wells drilled between 1968 and 2007 can be studied in the dedicated well folio, published by Geoscience Australia in 2011 (Jorgensen et al, 2011).

Koel 1 (2015)

Koel 1 was drilled in January–February, 2015, reaching a TD of 3034 m, falling short of the planned TD of 3522.3 m. The well was designed to test a fault-dependant north-south oriented fault block targeting potential hydrocarbon accumulations hosted by Permian sandstones. The targeted sandstone sequence, comprising the Lower Permian Irwin River Coal measures and the High Cliff Sandstone, was intersected as anticipated. However, overall porosity values in the reservoir facies were lower than expected. The secondary objective, the Upper Permian Dongara Sandstone and Middle Permian Wagina Formation, was not intersected due to local erosion across the fault block. Although no hydrocarbon accumulations were encountered, Koel 1 recorded minor oil shows in the section below 2670 mDRT confirming the presence of a petroleum system. The well was plugged and abandoned with minor oil shows (Murphy Oil Corporation, 2015a).

Cisticola 1 (2015)

Cisticola 1 was drilled in February–March, 2015, to a total depth of 1580 m. The well targeted a prominent fault-bounded horst structure on the Turtle Dove Ridge. The main objective was the Permian sandstones beneath the regional seal provided by the Kockatea Shale. The well intersected the prognosed reservoir sequence of the Lower Permian Irwin Coal Measures and High Cliff Sandstones, however, the reservoir sequences were thinner than anticipated. The secondary objective, the Middle Permian Wagina Formation was thicker than expected and consisted predominantly of siltstone. No wireline logs were acquired and the well was plugged and abandoned as a dry hole with minor gas shows (Murphy Oil Corporation, 2015b).

Munia 1 (2015)

Munia 1 was drilled in March–April, 2015, and reached a TD of 2260 m. The exploration targets were Permian fluvial sandstones beneath the regional seal of the Kockatea Shale. The well failed to reach the objective intersecting a significantly expanded section of Upper Permian shales. Munia 1 was plugged and abandoned as a dry hole with minor gas shows (Murphy Oil Corporation, 2015c).

Petroleum Systems Elements

Sources	• Permian gas prone shales and coals • Marine oil-prone Hovea Member of the Upper Permian-Lower Triassic Kockatea Shale • Triassic oil- and gas-prone marine shales • Jurassic marine and non-marine oil- and gas-prone shales and coals
Reservoirs	• Permian fluvio-deltaic and marine sandstones • Triassic shallow marine sandstones • Jurassic fluvial and deltaic sandstones
Seals	• Regional seals associated with marine shales of the Triassic Kockatea Shale • Regional seals associated with marine shales of the Jurassic Cadda Formation • Intraformational seals throughout the Triassic-Jurassic section
Traps	• Large stratigraphic pinch-outs • Variety of fault block plays and rollover anticlines • Sub-unconformity plays

Source rocks

The potential for oil and gas generation from source rocks in the offshore basin has been described previously by Jones et al (2011) and Rollet et al (2013a, 2013b). A comprehensive geochemical study of source rocks in the offshore northern Perth Basin is provided by Grosjean et al (2017). Regional stratigraphic correlation with well and seismic data across the offshore Perth Basin extends this framework into the northern Houtman Sub-basin and suggests the potential presence of a range of Permian to Jurassic source rocks (**Figure 7**) consisting of marine and non-marine carbonaceous shales and coals (Borissova et al, 2017; Hall et al, 2017b, 2017c).

Permian source rocks

Permian rocks are the source of gas for multiple Perth Basin onshore fields, including Elegans (Boreham et al, 2011) and Waitsia (Tupper et al, 2016). Time equivalent source rocks are intersected in the Abrolhos Sub-basin and Beagle Ridge and may be present in the Houtman Sub-basin.

The Cisuralian Irwin River Coal Measures (IRCM) are intersected in 13 wells on the Beagle Ridge and in the central Abrolhos Sub-basin (Jorgensen et al, 2011). Source intervals comprise non-marine shales and coals—evidence for a contribution from these source rocks has been observed in gases retrieved from Dunsborough 1, Frankland 1 and Perseverance 1 (Rollet et al, 2013a). The IRCM has excellent organic richness with mean Total Organic Carbon (TOC) of 5.9%. While its mean Hydrogen Index (HI) of 120 mgHC/gTOC is indicative of a predominantly type III gas-prone kerogen derived from terrigenous organic matter, some IRCM HI values reach 250 mgHC/gTOC suggesting the potential for some liquids generation (**Figure 14**).

The shallow-marine Cisuralian—Guadalupian Carynginia Formation is intersected in the Abrolhos Sub-basin, Beagle Ridge and Wittecarra Terrace. Despite good organic richness (TOC up to 7.9% and mean of 2.4%), the offshore wells indicate that the Carynginia Formation has limited potential for present day gas generation (HI <100 mgHC/gTOC; **Figure 14**).

Within the northern Houtman Sub-basin, the thick Permian syn-rift sequences NH-P1 and NH-P2 have the potential to contain source rocks equivalent to those from both the IRCM and Carynginia Formation (Owens et al, 2018a).

Triassic source rocks

The Lopingian–Lower Triassic Kockatea Shale, long recognised as the primary source of oil onshore (Summons et al, 1995; Thomas and Barber, 2004), is intersected in all offshore wells of the Abrolhos Sub-basin. Although the Kockatea Shale has not been intersected in wells from the Houtman Sub-basin, seismic interpretation suggests that it is likely to be present at depth (**Figure 8** and **Figure 16**; Borissova et al, 2017). The Kockatea Shale has the potential to contain multiple regionally extensive source rock intervals. At the base of the Kockatea Shale, a sapropelic interval within the Lopingian to Lower Triassic Hovea Member has the best potential for oil generation. This sapropelic interval of the Hovea Member was deposited under anoxic marine conditions during a period of rapid marine transgression as a condensed section (Thomas and Barber, 2004). This source rock has been intersected in most offshore northern Perth Basin wells (Jorgensen et al, 2011; Rollet et al, 2013a) and is the source for oil and condensate accumulations in the onshore greater Dongara area and the offshore Cliff Head area (**Figure 13**; Summons et al, 1995; Thomas and Barber, 2004).

Onshore, the Hovea Member has been shown to begin with an Upper Permian interval characterised by mostly inert material (the inertinitic interval), followed by oil-prone sediments of excellent source quality (the sapropelic interval), and ending with a thin limestone unit (Thomas and Barber, 2004).

Extensive oil-charge from the Hovea Member source has been recorded in the offshore Perth Basin based on the geochemical composition of reservoired and migrated hydrocarbons, as well as fluid inclusions (Geotech, 2005; Kempton et al, 2011; Rollet et al, 2013b). Offshore, samples of the Hovea Member are typically organic-rich with an average TOC of 2% (**Figure 14**), consisting predominantly of liptinite-rich type II kerogen derived from marine algae (Rollet et al, 2013a).

The best Hovea Member source rocks for oil are found on the Beagle Ridge and adjacent areas. The source potential gradually declines farther north and outboard, with only fair potential for mixed oil and gas observed in wells of the northern Wittecarra Terrace, and very limited potential for gas in outboard wells (Batavia 1 and Geelvink 1A). In the Houtman Sub-basin sequence, NH-TR1 has the potential to include a Hovea Member equivalent. Deposition of the Hovea Member equivalent would be most likely have been localised within depocentres where post-rift thermal subsidence was greatest.

Younger Triassic oil-prone source rocks may also be present rocks within the upper Kockatea Shale and the Woodada Formation. Across the northern Perth Basin the middle and upper Kockatea Shale source intervals are leaner than those in the Hovea Member, with only a fair generative potential (mean TOC 0.5%; mean HI 280 mgHC/gTOC) for both oil and gas. Fair to good oil potential has also been recorded in the Woodada Formation (TOC >0.5%; HI >200 mgHC/gTOC; **Figure 14**), particularly at Wittecarra 1, with the potential for both oil and gas generation.

Jurassic source rocks

The Jurassic succession (Eneabba Formation, Cattamarra Coal Measures, Cadda and Yarragadee formations) also contains potential source rocks (Gorter et al, 2004; Jones et al, 2011; Rollet et al, 2013a, 2013b; Borissova et al, 2017), including both marine and non-marine shales, and coals. The presence of a working Jurassic petroleum system in the Houtman Sub-basin is suggested by fluid inclusion data, which shows that a palaeo-oil column in the Cadda Formation at Houtman 1 was most likely sourced from Jurassic strata (Volk et al, 2004).

Overall, the organic content of the Eneabba Formation is low (mean TOC <1%), although predominantly gas-prone organic-rich source rocks were intersected in Gun Island 1. Its source potential in the Abrolhos Sub-basin is, however, limited. In contrast, where intersected by wells, the overlying Cattamarra Coal Measures contains terrestrial organic matter with good to excellent potential for generating gas (mean TOC 3.2%; mean HI 126 mgHC/gTOC; **Figure 14**). Marine shales may also be present in the Cattamarra Coal Measures over the northern part of the basin (Robertson et al, 2011).

Marine shales of the Cadda Formation typically contain type III kerogens, and are predominantly gas-prone (mean TOC >1%; mean HI 50–200 mgHC/gTOC), although a few organic-rich samples show this source rock may have some liquids potential (>250 mgHC/gTOC). Coals and coaly shales within the Yarragadee Formation (TOC >4%) are variable in quality, although some samples show excellent potential to generate oil (HI >300 mgHC/gTOC; **Figure 12**).

Reservoirs

Potential reservoirs are present throughout the Permian to Lower Cretaceous sequences in the offshore Perth Basin. The interpretation of reservoir facies and characteristics in the northern offshore Perth Basin is largely based on well intersections in the Abrolhos Sub-basin as well as regional correlations with stratigraphic units from farther south and the onshore Perth Basin (**Figure 7**).

Permian reservoirs

The Permian succession includes several potential reservoir units. These include the Cisuralian Irwin River Coal Measures (IRCM) and High Cliff Sandstone, and the Lopingian Dongara Sandstone (**Figure 7**).

The IRCM is a succession of fluvial sands, shales and coals that hosts several discoveries, and forms the primary reservoir for the Cliff Head oil field. In offshore well intersections, the High Cliff Sandstone is a broadly upward-coarsening sequence of silty sandstone interpreted to record a major regression (Jorgensen et al, 2011), while onshore occurrences indicate deposition in glacially influenced shallow marine, beach and lower deltaic environments (Mory and Iasky, 1996). In the thick Permian half-graben mapped in the northern Houtman Sub-basin (**Figure 9**), seismic sequence NH-P1 is interpreted to include equivalents to the Cisuralian IRCM and High Cliff Sandstone, both of which have good reservoir potential.

The Lopingian Dongara Sandstone (time equivalent to Wagina Sandstone and Beekeeper Formation in other parts of the Perth Basin), is one of the primary reservoirs in the offshore northern Perth Basin (Jones et al, 2011). This unit is thought to have been deposited in a shallow marine environment (Ferdinando and Longley, 2015) and is interpreted to represent nearshore to dunal facies along the rims of exposed land and over paleo-highs. It hosts several sub-commercial hydrocarbon discoveries including Frankland 1, Perseverance 1 and Dunsborough 1. In the northern Houtman Sub-basin, seismic sequence NH-P3 is interpreted to be equivalent to the Dongara Sandstone and potentially contains reservoir facies (**Figure 7** and **Figure 8**). Here, the distribution and thickness of NH-P3 broadly follows the geometry of the Permian depocentres, attaining thicknesses of more than 1 km near the eastern border fault.

Although the prospectivity of these Permian reservoirs is thought to decrease significantly at depths greater than 2.5 km, due to porosity degradation by silica cementation (Roc Oil, 2006), their viability may be maintained at depth (>3 km) where cementation has been inhibited by grain-coating clay, preserving intergranular porosity (Ferdinando et al, 2007). This process has resulted in preservation of excellent primary porosity and permeability at significant depths for the Wagina Sandstone in the Beharra Springs Field (Tupper et al, 1994), and for the Kingia and High Cliff sandstones in the recently discovered Waitsia Field (Tupper et al, 2016).

Triassic reservoirs

The Triassic succession in the offshore northern Perth Basin includes the Lower to Middle Triassic interbedded deltaic sandstones and siltstones of the Woodada Formation and the fluvial sandstones of the Middle to Upper Triassic Lesueur Sandstone (**Figure 7**). In wells the Lesueur Sandstone reaches thicknesses over 1 km (Wittecarra 1), and, typically, has relatively good porosity (e.g. 18–21% in Batavia 1), whereas the interbedded sandstones and siltstones of the underlying Woodada Formation have variable porosity.

In the northern Houtman Sub-basin, seismic sequence NH-TR2 (Woodada Formation equivalent; **Figure 7**), has a relatively constant thickness of about 1 km, with some thinning to the east, near the main rift-border fault, and to the west of the main Permian depocentre. Similarly, the NH-TR3 sequence (Lesueur Sandstone equivalent) extends across the northern part of the sub-basin and attains a maximum thickness of 3–4 km.

Jurassic reservoirs

Upper Triassic to Upper Jurassic intervals of reservoir sandstones are potentially present within the Eneabba Formation, Cattamarra Coal Measures and Yarragadee Formation (**Figure 7)**.

Of the Jurassic sequences, the Lower to Middle Jurassic Cattamarra Coal Measures is considered to have the best reservoir potential in the offshore northern Perth Basin (Jones et al, 2011), comprising a series of interbedded sandstones, siltstones and coals deposited in a deltaic environment. Houtman 1 and Leander Reef 1 contain oil and gas shows in the upper part of the Cattamarra Coal Measures, while a palaeo-oil column has been detected over at least 15 m of this interval in Houtman 1 (Kempton et al, 2011). Intersections of a relatively coarse-grained sandstone interval, underlying the thick shales of the Middle Jurassic Cadda Formation, have been shown to have good reservoir potential (Crostella, 2001). In the offshore northern Perth Basin, porosities in Jurassic sandstone successions range up to 30% at depths of 1–1.5 km, but decrease to about 10–15% at 3–3.5 km depth (Gorter et al, 2004).

In the northern Houtman Sub-basin, NH-J2 (Cattamarra Coal Measures equivalent) is mapped as a 1000–1800 m thick package at depths of 1.5–7 km and is mostly confined to the Jurassic depocentre outboard of the Permian depocentre (Figure 3). The NH-TR/J1 (Eneabba equivalent) is mapped at depths of 2—7.5 km as a relatively constant 600–800 m thick package over the central to outer portion of the sub-basin, and is mostly absent inboard. Farther southwest, NH-J4 (Yarragadee equivalent) is mapped as a 400–1400 m (locally >1800 m) thick sequence at depths of 2–6 km.

Lower Cretaceous reservoirs

The post-rift succession in the Abrolhos and southern Houtman sub-basins is thin, ranging from about 400 m in the inboard part of the basin to 800 m outboard—no reservoir units have been intersected in wells. The post-rift succession is dominated by prograding carbonate shelf units (Toolonga Calcilulite, Korojon Calcarenite and undifferentiated Cenozoic to Holocene shelfal carbonates). In most wells, the siliciclastic Winning Group overlying the Valanginian unconformity is very thin (<100 m) or absent, with no hydrocarbon indications recorded (Jorgensen et al, 2011).

In the northern region, a much thicker post-rift succession is mapped, ranging from about 1000 m in the inboard part to 1500 m over the central part of the Houtman Sub-basin. The Lower Cretaceous NH-K3 sequence (Winning Group equivalent) is 500–600 m thick and is likely to contain siliciclastics; however, the lithologies are not constrained by well data. Seismic mapping indicates a possible regionally extensive thin (30–80 m) transgressive sand interval overlying the Valanginian unconformity (**Figure 7**), which has been tied back to Livet 1 where it has been identified as a clean sandstone interval overlying the breakup unconformity (Jorgensen et al, 2011). This unit may be analogous to, though not a direct time equivalent of, the Lower Cretaceous transgressive sandstones found across the Carnarvon Basin (e.g. Mardie Greensand Member of the Muderong Shale, and the underlying Birdrong Sandstone), which form reservoirs for many petroleum accumulations in the Northern Carnarvon Basin (Hocking et al, 1987).

Seals

The Kockatea Shale is proven to be an effective regional seal across the offshore northern Perth Basin (Jones et al, 2011). The Kockatea Shale is 150–443 m thick in well intersections on structural highs, and rapidly thickens to over 1000 m in depocentres above Permian half-graben. It is interpreted to be present across the Permian depocentre of the northern Houtman Sub-basin, with mapped thicknesses of NH-TR1 (Kockatea Shale equivalent) of up to 1800 m (Borissova et al, 2017). The thickness of the unit is generally sufficient to provide robust vertical and cross-fault sealing, unless breached by subsequent reactivation.

A general south-north fining of the Woodada Formation in the offshore northern Perth Basin (Jorgensen et al, 2011) suggests that the NH-TR2 sequence (Woodada Formation equivalent) may be clayey or contain clayey intervals in the northern Houtman Sub-basin, thus providing a potential regional or intraformational seal in this part of the basin. Intraformational seals are also potentially present within Jurassic Eneabba Formation, Cattamarra Coal Measures and Yarragadee Formation, and their mapped equivalents (**Figure 7**; Jones et al, 2011; Robertson et al, 2011; Borissova et al, 2017). Fluid inclusion data from the Abrolhos and southern Houtman sub-basins indicate that these intervals can provide impedance barriers to oil migration, such as in Leander Reef 1 (Kempton et al, 2011). Effective intraformational seals are demonstrated onshore in these units, but their potential to seal hydrocarbon accumulations offshore remains speculative (Jones et al, 2011).

Marine shales from the Cadda Formation are demonstrated to be an effective local seal at Houtman 1, where they overly a 15 m palaeo-oil column detected in a sandy basal Cadda Sequence (Jones et al, 2011; Kempton et al, 2011). The Cadda Formation is 400 m thick in well intersections in the Houtman Sub-basin (Jones et al, 2011). Thin sandstone intervals in the Cadda Formation were also intersected by Houtman 1 and Gun Island 1, potentially compromising fault juxtaposition seals (Gorter et al, 2004). Marine shales associated with sequence NH-J3 (Cadda Formation equivalent, **Figure 8**) have the potential to form a regional seal covering the outboard part of the sub-basin.

No regional seals have been described in the post-breakup section in the offshore Perth Basin, apart from the Lower Cretaceous South Perth Shale in the Vlaming Sub-basin of the southern Perth Basin (Nicholson et al, 2008). In the Carnarvon Basin, the regionally extensive Muderong Shale that overlies the Birdrong Sandstone is known as a good quality seal (Baillie and Jacobson, 1997). In the Houtman Sub-basin, age-equivalent units are likely to be absent inboard due to non-deposition or erosion, while in outboard areas the post-breakup sequence (NH-K2) contains Seaward Dipping Reflector Sequences which developed as the volcanic margin evolved. However, considering the substantial thickness (500–600 m) of the siliciclastic NH-K3 sequence (Winning Group equivalent), the potential for regional or intraformational seals cannot be excluded.

Timing of generation

Results of petroleum systems modelling in the Houtman Sub-basin indicate that potential source rocks within both the upper and lower Permian syn-rift sequences (NH-P2 and NH-P1) may have generated large amounts of gas, along with some liquids (Hall et al, 2017b, 2017c). However, peak generation occurred in the Triassic, and the majority of the Permian source kitchen is now overmature (**Figure 15** and **Figure 16**). This is in contrast to the onshore Perth Basin where generation from Permian source rocks occurred much later in the Late Jurassic–Early Cretaceous (Thomas and Barber, 2004).

Petroleum systems analyses have shown that the timing and level of maturity of the Hovea Member varies significantly across the offshore northern Perth Basin (Pfahl, 2011; Rollet et al, 2013b; Hall et al, 2017b, 2017c). In most of the Houtman Sub-basin the Hovea Member is modelled to have entered the main oil window in the Triassic, with a subsequent further rapid increase in maturity during the Jurassic and Early Cretaceous (Pfahl, 2011; Hall et al, 2017b). In contrast, throughout much of the Abrolhos Sub-basin, including the Wittecarra Terrace and along the inboard margin of the northern Houtman Sub-basin, the Hovea Member is modelled to have entered the oil window during the final Late Jurassic–Early Cretaceous phase of rifting (Pfahl, 2011; Hall et al, 2017b). The exception to this is in the outer western Abrolhos Sub-basin, where the Hovea Member is modelled to have reached the late oil/wet gas window (Pfahl, 2011).

In the northern Houtman Sub-basin, if the oil-prone Hovea Member is present at the base of the NH-TR1 sequence, it has the potential to have generated large volumes of oil and gas across the depocentre (**Figure 16**; Hall et al, 2017b). This source kitchen is modelled as overmature in the central basin, but remains within the oil window along the basin margin (**Figure 16**). Modelling suggests that peak oil expulsion occurred in the Triassic (Hall et al, 2017b), earlier than predicted by Gorter et al (2004) for the southern part of the Houtman Sub-basin. Deposition of an additional 500–1500 m of post-breakup overburden (**Figure 8**) resulted in some additional Late Cretaceous and Cenozoic oil and gas expulsion along the basin margin (Gorter et al, 2004; Hall et al, 2017b).

The younger Triassic oil-prone source rocks within the Woodada Formation and upper Kockatea Shale, if present in the mapped equivalents NH-TR2 and NH-TR1, respectively, are of a more favourable maturity than the Hovea Member, at the base of NH-TR1, with a larger area of source kitchen remaining in the late oil to early gas window (Hall et al, 2017b However, the total generative potential of these sources is expected to be much lower than the Hovea Member. The presence of significant thicknesses of higher quality source rock within these sequences remains speculative.

In the central and southern Houtman Sub-basin modelled oil and gas expulsion from the Cattamarra Coal Measures occurred in the latest Jurassic to earliest Cretaceous (135–150 Ma), immediately preceding uplift and erosion. In the northern Houtman Sub-basin, Lower Jurassic source rocks (Eneabba Formation, lower Cattamarra Coal Measures) reached the oil window in the outer part of the basin, with peak hydrocarbon generation occurring in the Early Cretaceous (Hall et al, 2017b). Middle Jurassic and younger source rocks (upper Cattamarra Coal Measures, Cadda and Yarragadee formations) remained predominantly immature in the northern Houtman sub-basin (Hall et al, 2017b). However, increased heat-flow associated with Lower Cretaceous volcanism (Borissova et al, 2017) may have resulted in localised hydrocarbon generation from potential source intervals (Gorter and Deighton, 2002; Hall et al, 2017b).

Although peak generation for all source intervals generally occurred pre-breakup, some additional generation and expulsion from multiple source rocks is modelled to have occurred after Valanginian breakup resulting from the deposition of 1–1.5 km of Upper Cretaceous-Cenozoic overburden (Gorter et al, 2004; Hall et al, 2017b).

Play types

The offshore northern Perth Basin is structurally complex and contains a wide range of structural and stratigraphic traps at several stratigraphic levels (Jones et al, 2011; Rollet el al, 2013b; Borissova et al, 2017). Plays have been identified in the Permian, Triassic and Jurassic successions. They include large stratigraphic plays in the Upper Permian/Lower Triassic, rollover anticlines within the Lower Triassic and Jurassic, and fault propagation folds and fault block plays in the Jurassic. The presence of shallow plays immediately above (stratigraphic) or below (sub-cropping) the Valanginian unconformity is uncertain due to the lack of knowledge on reservoir and seal lithologies in the post-breakup succession. However, the potential for these plays being present in the sub-cropping Triassic and Jurassic sandstone reservoirs should be considered.

The dominant play type tested in the offshore Perth Basin is the Upper Permian/basal Triassic sandstone reservoirs (variably referred to as Dongara, Wagina or Wittecarra sandstones), sourced and sealed by the Kockatea Shale in tilted fault and horsts blocks. Lower Permian reservoirs (IRCM and High Cliff Sandstone) in a fault bounded horst blocks have also been targeted (e.g. Cliff Head 1, Cisticola 1, and Dunsborough 1).

Petroleum system elements are summarised in **Figure 7**, while play types for the Houtman Sub-basin are illustrated in **Figure 17** and described below.

Upper Permian and Triassic plays

1. Stratigraphic pinch-out of the upper Permian/Lower Triassic sandstones (Dongara and Wagina sandstones, NH-P3 sequence) against the major basin bounding fault. The overlying marine shales of the Kockatea Shale (NH-TR1) form both the source and top seal.

2. Triassic Fault block plays and rollover anticlines bounded by listric faults in the fluvio-deltaic sandstones of the Woodada Formation and equivalents (NH-TR2 sequence). These plays could be charged by underlying source rock intervals in the Kockatea Shale (NH-TR1 sequence) and sealed by intraformational shales, providing both top and cross fault closure.

3. Sub-cropping plays below the Valanginian unconformity. Provided a viable seal is present directly above the unconformity, sub-cropping fluvio-deltaic sandstones of the Lesueur Formation and equivalents (NH-TR3 sequence) may contain hydrocarbons expelled by source rocks of the Kockatea Shale (NH-TR1 sequence) in the Early Cretaceous.

Jurassic plays

4. Fault block plays, including fault propagation fold anticlines within the Eneabba Formation or equivalents (NH-TR/J1 sequence). The mixed lithologies of this sequence, including both sandy and shaly facies, suggests there is potential for viable intraformational source, reservoir and seal combinations.

5. Fault block plays within fluvio-deltaic sandstones of the Cattamarra Coal Measures and equivalents (NH-J2) with top seal provided by the Cadda Formation marine shale (NH-J3). Potential source rocks include shales and coals from the Eneabba Formation, Cattamarra Coal Measures and Cadda Formation (and equivalent sequences, NH-TR/J1, NH-J2, NH-J3).

6. Sub-cropping plays below the Valanginian unconformity reservoired within the Eneabba Formation or fluvio-deltaic sandstones of the Cattamarra Coal Measures and Yarragadee Formation (or equivalent sequences, NH-TR/J1, NH-J2, NH-J4). Potential source rocks for this play include shales and coals from the Eneabba Formation, Cattamarra Coal Measures and Cadda Formation (and equivalent sequences, NH-TR/J1, NH-J2, NH-J3).

Critical risks

The major exploration risks in the offshore northern Perth Basin are the presence of effective seals, trap breach and preservation of accumulations (Jorgensen et al, 2011; Langhi et al, 2012; O'Neill et al, 2016). This is particularly important for the main Permian–Triassic oil/gas play, as the frequent palaeo-oil accumulations in the numerous dry wells on the Wittecarra Terrace indicate hydrocarbon loss from breached traps. Trap breach has been attributed to: fault reactivation and structuring associated with Late Jurassic extension and/ or Valanginian breakup; the tilting of the margin following the breakup; or, inversion of faults during the Miocene (Kempton et al, 2011). 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. 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 a risk in some areas (WA DoIR, 2008).

Although a variety of trap types have been identified at multiple stratigraphic levels in the Houtman Sub-basin, there are several overarching risks to the validity of the identified plays, particularly in the lesser explored northern area. These include: i) the absence of well data to provide lithological control on presence and characteristics of the identified potential source, reservoir and seal intervals; ii) uncertainties in the relative timing of hydrocarbon generation and trap formation; and iii) reactivation of some major basement-involved faults during the Jurassic and in the Valanginian potentially resulting in trap breaches.

Production status

The producing region of the Perth Basin is close to petroleum industry infrastructure, including two major gas pipelines and trucking facilities to an oil refinery near Perth (**Figure 2**). Producing fields within the onshore and offshore Perth Basin in 2014 were Beharra Springs, Beharra Springs North, Cliff Head, Dongara, Gingin West, Hovea, Redback, Red Gully and Tarantula (Department of Mines and Petroleum, 2016). Most recently, the Waitsia Field commenced production in 2016 within the onshore Perth Basin (Evans et al, 2016).

Geoscience Australia products and data

A range of Geoscience Australia's publications, data and products cited throughout the text are available via the links provided in the references. Key works are detailed below. Themes include basin geology, stratigraphy, organic geochemistry, petroleum systems and prospectivity. The project webpages for the Northern Houtman Sub-basin Project and Vlaming Sub-basin CO_2 Storage Project provide useful summaries and links to related publications and data.

Regional geology

- Geology and prospectivity of the northern Houtman Sub-basin, Geoscience Australia Record 2018/25 by Owens et al, summarising findings from the Northern Houtman Sub-basin Project
- Geology and hydrocarbon prospectivity of the northern Houtman Sub-basin, APPEA Conference Extended abstract and oral presentation by Borissova et al, 2017
- Crustal Structure and Tectonic Evolution of the Northern Perth Basin, AAPG Datapages/Search and Discovery Article by Hall et al, 2017
- Frogtech and Geoscience Australia Houtman Sub-basin Geophysical Modelling, report by Sanchez et al, 2016
- New exploration opportunities in the offshore Houtman and Abrolhos Sub-basins, APPEA Journal article by Rollet et al, 2013
- Northern extension of active petroleum systems in the offshore Perth Basin, PESA conference proceedings by Rollet et al, 2013
- Combined marine and land potential-field datasets for the southwest margin of Australia. Geoscience Australia Record 2012/37 by Hackney
- Offshore northern Perth Basin 2D and 3D models of depth to magnetic basement, Geoscience Australia Record, 2012/39 by Johnston and Petkovic
- New exploration opportunities in the offshore northern Perth Basin, APPEA Journal article by Jones et al, 2011
- Tectonic and stratigraphic history of the Perth Basin, Geoscience Australia, Record, 2004/16 by Norvick

Well control and stratigraphy

- Offshore Northern Perth Basin Well Folio, Geoscience Australia Record 2011/009, by Jorgensen et al, 2011
- Geoscience Australia's Basin Biozonation and Stratigraphy Chart Series: Offshore Northern Perth Basin Biozonation and Stratigraphy, 2013, Chart 38 by Jones et al and Onshore Perth Basin Biozonation and Stratigraphy, 2015, Chart 39 by Mory et al

Petroleum systems

- Source rock geochemistry of the offshore northern Perth Basin, Geoscience Australia Record 2017/018, by Grosjean et al, 2017
- Petroleum Prospectivity of the Houtman Sub-Basin, Offshore Perth Basin, Australia. AAPG Datapages/Search and Discovery Article by Hall et al, 2017
- Petroleum Systems Modelling of the Northern Houtman Sub-basin, APPEA Conference Extended abstract and poster presentation by Hall et al, 2017

Data products

- Houtman Sub-basin Seismic Survey GA349 - Seismic Field Data and Processed Seismic Data. Available on request from ausgeodata@ga.gov.au
- High resolution bathymetry grids from dataset collected along ship tracks during the Geoscience Australia Houtman Sub-basin 2D Seismic Survey (GA0349), by Spinoccia, 2016.

Data discovery tools

- The National Offshore Petroleum Information Management System (NOPIMS) provides access to wells and survey data acquired primarily in Commonwealth waters and submitted under legislation, currently the Offshore Petroleum and Greenhouse Gas Storage Act 2006. This data can be downloaded or packaged on request. NOPIMS has been upgraded to provide access to over 50 years of data submission of well and survey information. It represents more than 1 million records and includes an interactive mapping tool for data discovery.
- Geoscience Australia's Data Discovery Portal provides full access to Geoscience Australia data and other publically available data sources as well as a suite of analytical and multi-criteria assessment tools. This includes an Energy persona that allows access to a wide range of geological and geospatial data. Themes include source rock geochemistry, petroleum wells, stratigraphic information, province and basin geology, geophysical survey data coverage and other fundamental geospatial and administrative datasets.
- The National Petroleum Wells Database application provides access to Geoscience Australia's Oracle petroleum wells databases. Data themes include header data, biostratigraphy, organic geochemistry, reservoir and facies, stratigraphy, velocity and directional surveys. Data is included for offshore and onshore regions, however scientific data entry is generally limited to offshore wells and is dependent on Geoscience Australia's project activities.

Marine and environmental information

The following section contains information about the existing marine parks, their special habitat zones and physiographic features within or adjacent to the Northern Perth Basin (**Figure 18**). The information is provided in support of business decisions with respect to planned exploration and development activities. The Northern Perth Basin is located on the southwest margin of Australia and primarily includes continental slope with canyon and terrace geomorphological features and is located offshore from the Gascoyne region.

Australian marine parks

Australian Marine Parks (Commonwealth marine reserves proclaimed under the EPBC Act in 2007 and 2013) are located in Commonwealth waters that start at the outer edge of state and territory waters, generally 3 nautical miles (nm) (5.6 km) from the shore, and extend to the outer boundary of Australia's Exclusive Economic Zone, 200 nm (370.4 km) from the shore. Marine parks have also been established by the state and territory governments in their respective waters. The marine parks operate under management plans that provide a balance between protection and conservation of the marine environment, and sustainable use of the area. Links to these management plans are provided for each Marine Park or marine park network in the Northern Perth basin region.

Extracts from these plans are included below.

Australian Marine Parks: North-west Marine Parks Network

The North-west Marine Parks Network comprises thirteen marine parks within the North-west Marine Region, which extends from the Western Australian-Northern Territory border to Kalbarri, south of Shark Bay. The marine environment of the area is characterised by shallow-water tropical marine ecosystems, a large area of continental shelf (including the narrowest part of continental shelf on Australia's coastal margin), and continental slope, with two areas of abyssal plain to depths of 6000 m. The region has high species diversity and globally significant populations of internationally significant threatened species. A small number of species are found nowhere else but most of the region's species are tropical and found in other parts of the Indian Ocean and the western Pacific Ocean.

Four of the marine parks within the North-west Marine Parks Network are within proximity or directly adjacent to the Northern Perth Basin; Ningaloo Marine Park, Gascoyne Marine Park, Carnarvon Canyon Marine Park and Shark Bay Marine Park.

Management plans for the North-west Marine Parks Network are in place, and can be viewed at: https://parksaustralia.gov.au/marine/pub/plans/north-west-management-plan-2018.pdf.

Ningaloo Marine Park

The Ningaloo Marine Park is located offshore Cape Range Peninsula, Western Australia, extending approximately 300 km between Exmouth and Coral Bay and up to 22 km offshore. The Marine Park is adjacent to the World Heritage listed Ningaloo Reef which sits within the Western Australian Ningaloo (State) Marine Park. Ningaloo Marine Park covers an area of 2435 km^2 and water depths between 30 m and 500 m.

Statement of significance

The Ningaloo Marine Park is significant because it contains habitats, species and ecological communities associated with the Central Western Shelf Transition, Central Western Transition, Northwest Province, and Northwest Shelf Province. It includes three key ecological features: canyons linking the Cuvier Abyssal Plain and the Cape Range Peninsula (valued for unique seafloor features with ecological properties of regional significance); Commonwealth waters adjacent to Ningaloo Reef (valued for high productivity and aggregations of marine life); and continental slope demersal fish communities (valued for high levels of endemism and diversity).

The Marine Park provides connectivity between deeper offshore waters of the shelf break and coastal waters of the adjacent Western Australian Ningaloo Marine Park. It includes some of the most diverse continental slope habitats in Australia, in particular the continental slope area between North West Cape and the Montebello Trough. Canyons in the Marine Park are important for their role in sustaining the nutrient conditions that support the high diversity of Ningaloo Reef. The Marine Park is located in a transition zone between tropical and temperate waters and sustains tropical and temperate plants and animals, with many species at the limits of their distributions.

The Marine Park is assigned IUCN category IV and includes two zones assigned under the North-west Marine Parks Network Management Plan (2018): National Park Zone (II), Multiple Use Zone (VI), and Recreational Use Zone (IV).

Gascoyne Marine Park

The Gascoyne Marine Park is located approximately 20 km off the west coast of Cape Range Peninsula, adjacent to the Ningaloo Reef Marine Park and the Western Australian Ningaloo Marine Park, and extends to the limit of Australia's exclusive economic zone. The Marine Park covers an area of 81,766 km² and water depths between 15 m and 6000 m.

Statement of significance

The Gascoyne Marine Park is significant because it contains habitats, species and ecological communities associated with the Central Western Shelf Transition, Central Western Transition, and Northwest Province. It includes four key ecological features: Canyons linking the Cuvier Abyssal Plain and the Cape Range Peninsula (valued for unique seafloor features with ecological properties of regional significance); Commonwealth waters adjacent to Ningaloo Reef (valued for high productivity and aggregations of marine life); continental slope demersal fish communities (valued for high levels of endemism and diversity); and the Exmouth Plateau (valued as a unique seafloor feature with ecological properties of regional significance).

The Marine Park includes some of the most diverse continental slope habitats in Australia, in particular the continental slope area between North West Cape and the Montebello Trough. Canyons in the Marine Park link the Cuvier Abyssal Plain to the Cape Range Peninsula and are important for their role in sustaining the nutrient conditions that support the high diversity of Ningaloo Reef.

The Marine Park is assigned IUCN category IV and includes three zones assigned under the North-west Marine Parks Network Management Plan (2018): National Park Zone (II), Habitat Protection Zone (IV) and Multiple Use Zone (VI).

Carnarvon Canyon Marine Park

The Carnarvon Canyon Marine Park is located approximately 300 km north-west of Carnarvon. It covers an area of 6177 km² on the continental slope and a water depth range of 1500–5000 m.

Statement of significance

The Carnarvon Canyon Marine Park is significant because it contains habitats, species and ecological communities associated with the Central Western Transition—a bioregion characterised by large areas of continental slope, a range of topographic features such as terraces, rises and canyons, seasonal and sporadic upwelling, and benthic slope communities comprising tropical and temperate species. This includes deep-water ecosystems associated with the Carnarvon Canyon. The Marine Park lies within a transition zone between tropical and temperate species and is an area of high biotic productivity.

The Marine Park is assigned IUCN category IV and includes one zone assigned under the North-west Marine Parks Network Management Plan (2018): Habitat Protection Zone (IV).

Shark Bay Marine Park

The Shark Bay Marine Park is located approximately 60 km offshore of Carnarvon, adjacent to the Shark Bay world heritage property and national heritage place. The Marine Park covers an area of 7443 km² on the continental shelf, extending from the Western Australian state water boundary, and a water depth range between 15 m and 220 m.

Statement of significance

The Shark Bay Marine Park is significant because it contains habitats, species and ecological communities associated with the Central Western Shelf Province and Central Western Transition. The Marine Park provides connectivity between deeper Commonwealth waters and the inshore waters of the Shark Bay world heritage property.

Australian Marine Parks: South-west Marine Parks Network

The South-west Marine Parks Network comprises fourteen marine parks within the South-west Marine Region, which extends from Kangaroo Island in South Australia to the waters off Shark Bay in Western Australia. The region covers approximately 1.3 million km^2 of temperate and subtropical waters of the Great Australian Bight and Indian Ocean adjacent to the coastal waters of South Australia and Western Australia.

The marine environment of the region is characterised by ecosystems associated with the continental shelf, slope and rise, and the abyssal plain (deep ocean floor). Large parts of the continental shelf are high-energy environments with high exposure to waves. The continental slope of the region is relatively steep and narrow, with broad mid-slope terraces deeply incised by submarine canyons, including Australia's largest underwater canyon, the Perth Canyon. The region also contains some of the largest and deepest (mostly >4000 m deep) areas of abyssal plain within Australia's exclusive economic zone. The region is strongly influenced by the shallow, warm Leeuwin Current which extends the length of the region and has a significant impact on biological productivity and biodiversity. The interactions of the ocean currents with the region's diverse seafloor features, the low level of run-off from the land and the relatively stable geological history generate low levels of nutrients and high species diversity, including a large number of species found nowhere else.

One marine park within the South-west Marine Parks Network is within proximity or directly adjacent to the Northern Perth; Abrolhos Marine Park.

Management plans for the South-west Marine Parks Network are in place, and can be viewed at:

https://parksaustralia.gov.au/marine/pub/plans/south-west-management-plan-2018.pdf

Abrolhos Marine Park

The Abrolhos Marine Park is located adjacent to the Houtman Abrolhos Islands, covering a large offshore area extending from the Western Australian state water boundary to the edge of Australia's exclusive economic zone. It is located approximately 27 km south-west of Geraldton and extends north to approximately 330 km west of Carnarvon. The northernmost part of the shelf component of the Marine Park, north of Kalbarri, is adjacent to the Shark Bay World Heritage Area. The Marine Park covers an area of 88,060 km^2 and a water depths ranging from <15 m to 6000 m.

The Marine Park is assigned IUCN category VI and includes four zones assigned under this plan: National Park Zone (II), Habitat Protection Zone (IV), Multiple Use Zone (VI) and Special Purpose Zone (VI).

Statement of significance

The Abrolhos Marine Park is significant because it contains habitats, species and ecological communities associated with four bioregions: Central Western Province; Central Western Shelf Province; Central Western Transition; and South-west Shelf Transition. It includes seven key ecological features: the Commonwealth marine environment surrounding the Houtman Abrolhos Islands (valued for high levels of biodiversity and endemism); demersal slope and associated fish communities of the Central Western Province (valued as a species group that are nationally or regionally important to biodiversity); mesoscale eddies (valued for high productivity and aggregations of marine life); Perth Canyon and adjacent shelf break, and other west-coast canyons (valued for high biological productivity and aggregations of marine life, and unique seafloor features with ecological properties of regional significance); western rock lobster (valued as a species that plays a regionally important ecological role); ancient coastline between 90 m and 120 m depth (valued for relatively high productivity, aggregations of marine life and high levels of biodiversity and endemism); and Wallaby Saddle (valued for high productivity and aggregations of marine life).

The southern shelf component of the Marine Park partially surrounds the Western Australian Houtman Abrolhos Islands Nature Reserve. The islands and surrounding reefs are renowned for their high level of biodiversity, due to the southward movement of species by the Leeuwin Current. The Marine Park contains a number of seafloor features including the Houtman Canyon, the second largest submarine canyon on the west coast, after the Perth Canyon.

Western Australian Marine Parks

Western Australian State Waters contain 20 marine parks, nature reserves, and management areas. These marine protected areas were created to protect natural features and aesthetic values of the marine environment whilst also allowing recreational and commercial uses that do not compromise conservation values. Two Western Australian Marine Parks are proximal to the Northern Perth Basin: Ningaloo Marine Park; Shark Bay Marine Park.

Ningaloo Marine Park

The Ningaloo Marine Park is located off the North West Cape of Western Australia, approximately 1200 km north of Perth. Ningaloo Reef is the largest fringing coral reef in Australia. Temperate and tropical currents converge in the Ningaloo region resulting in highly diverse marine life including spectacular coral reefs, abundant fishes and species with special conservation significance such as turtles, whale sharks, dugongs, whales and dolphins. The region has diverse marine communities including mangroves, algae and filter-feeding communities and has high water quality.

The zoning scheme for the Ningaloo Marine Park comprises

- eighteen sanctuary zones
- one special purpose zone (benthic protection)
- one special purpose zone (shore based activities)
- one recreation zone
- general use in the remainder of the park

Sanctuary zones provide the highest level of protection for areas of high ecological or cultural significance and represent 34% of the park. The special purpose (benthic protection) zone protects benthic communities and covers 2% of the park. Shore-based activity zones provide an opportunity for shore-based recreational and commercial activities that are compatible with the maintenance of the park values and cover <0.3% of the park coastline. The recreation zone extends allows appropriate opportunity for visiting tourists to conduct recreational activities, whilst providing protection for nesting turtles, turtle hatchlings, waterbirds, and their habitats and cover 14% of the park. Areas not covered by these zones are for general use i.e. providing for biodiversity conservation alongside a range of recreational and commercial activities and cover 50% of the park.

Shark Bay Marine Park

Shark Bay Marine Park lies within the Shark Bay World Heritage Area, valued internationally for its rich and abundant marine life and desert coastline scenery. Shark Bay is in a transition zone between temperate and tropical waters. There are at least 320 fish species, many of them tropical, and more than 80 coral species in Shark Bay. Extensive seagrass meadows support over 10,000 dugongs and create environments that favour stromatolites, fragum cockles and a pink snapper unique to Shark Bay. Also noted in the World Heritage values of Shark Bay is the large number of humpback whales that visit the bay during their southward migration in spring.

The zoning scheme for the Shark Bay Marine Park comprises

- six sanctuary zones
- four special purpose zone (benthic protection)
- two recreation zones

- general use in the remainder of the park

Heritage

There are no shipwrecks listed in the vicinity of the northern Perth Basin area. However, the HMAS Sydney, a naval cruiser wrecked in 1941, is located approximately 207 km west of Steep Point (coordinates: 26.24°S, 111.22°E) in 2470 m water depth. This and other shipwrecks can be identified and located using the Australian National Shipwreck Database map search tool.

Fisheries

The following Commonwealth fisheries occur in the Northern Perth Basin area:

- The Western Deepwater Trawl Fishery operates in water deeper than 200 m off the coast of Western Australia from Exmouth to Augusta.
- The North West Slope Trawl Fishery operates in the area between 200 m water depth to the outer limit of the Australian fishing zone, 200 nm from the coast.
- The Western Tuna and Billfish Fishery covers the sea area west from the tip of Cape York in Queensland, around Western Australia, to the border between Victoria and South Australia. Fishing occurs in both the Australian Fishing Zone and adjacent high seas.

The Western Australian Government manages 10 fisheries within the North-West Marine Region, including the West Coast Rock Lobster, Pearl Oyster, Exmouth Gulf Prawn, Shark Bay Prawn, Shark Bay Scallop and the Northern Demersal Scalefish Fisheries (Fletcher and Santoro, 2015). The South-west Marine Region Network overlaps some high-value fishing areas, particularly areas on the shelf in the Perth Canyon and Abrolhos Marine Parks (Fletcher and Santoro, 2015).

Climate of the region

The climate of the Carnarvon bioregion is semiarid to arid with predominantly winter rainfall. The Carnarvon Airport weather station, indicates that the annual mean maximum and minimum temperatures were 27.3°C and 17.2°C respectively, for the time period from 1945 to 2020. Mean annual rainfall during this interval was 223 mm. Temperatures range from an average maximum of 32.5 °C (90.5 °F) in February to 22.4 °C (72.3 °F) in July. Average minimums are 23 °C (73.4 °F) and 11 °C (51.8 °F) respectively. Occasional tropical cyclones affect Carnarvon during the summer months (most commonly in January and February) bringing heavy rain, extreme waves, and higher than normal wind-driven currents.

Oceanic regime

The oceanic regime of the southwest continental margin is characterised by general poleward flow of near-surface currents in the offshore within the Leeuwin Current (Waite et al 2007). The Leeuwin current is strongest in autumn, and diminishes in strength during the wet monsoon season. In contrast to the monsoonal climate of the north-west, the wettest months for most of the region are June and July. Surface waters, generally sourced from the north, are warm and in summer grade from 25°C offshore from Carnarvon to 22°C offshore from Perth, and winter surface waters are generally 4°C cooler. These waters are nutrient poor and of slightly lower salinity compared to normal marine values (Waite et al, 2007). The Leeuwin Current strongly influences the types and ranges of biota in this region (Richardson et al, 2005). Tidal ranges are microtidal. Oceanic swells are from the south-west, and wave heights are significant, at 2 to 3.5 m in the offshore, with extreme storm wave heights of 9–10 m (Bosserelle et al, 2012; Li et al, 2012).

Seabed environments

The seabed of the Northern Perth Basin is situated in water depths that range from ~200 m on the outer continental shelf to over 3000 m on the continental slope (Daniell et al, 2009). The sea floor morphology of the continental slope is characterised by the extensive Carnarvon Terrace and several slope-confined canyons that incise the lower slope toward the southern end of the northern Perth Basin (Heap and Harris, 2008; Huang et al, 2014). The Carnarvon Terrace is a geographic term for an arcuate shallow portion of the Carnarvon Basin on the upper continental slope that extends approximately 830 km along the continental margin and is 120 km wide at its widest (Heap and Harris, 2008). Carbonate fringing and isolated reef systems have developed discontinuously along the length of the Western Australian margin extending south into the predominantly warm temperate seas in the region, enabled by the warm, southerly-directed Leeuwin Current (Collins, 2010).

Seabed sediments across the Northern Perth Basin region range from carbonate-dominated sand on the continental shelf to mud and sandy mud on the continental slope and terrace. Detailed grain size data for 28 sample observations are held within the national marine sediments database (MARS: http://www.ga.gov.au/oracle/mars).

Ecology

The Northern Perth Basin overlaps the transition between the North-West and South-West Marine Region Marine. At the smaller scale of provincial bioregions (IMCRA 4.0), the Northern Perth Basin is significant because it contains habitats, species and ecological communities associated with the Central Western Transition and Central Western Provinces (Commonwealth of Australia, 2005), the former of which falls within the biogeographic transition between tropical and temperate marine species. The continental slope in the Northern Perth Basin is incised by several canyons, which are important ecological features that attract krill and fish aggregations that in turn attract larger species such as predatory fish and pygmy blue whales.

Sampling of deep-water (641–4827 m) benthic habitats in the Zeewyck and Houtman sub-basins, Cuvier margin, and the Cuvier Plateau suggest that seabed habitats across the west Australian margin are largely depauperate of marine organisms with bioturbation marks (tracks, burrows and mounds) the most common sign of marine life (Daniell et al, 2009). However, high occurrences of suspension-feeders were recorded on the volcanic pinnacle located over the north Houtman Sub-basin, with surrounding low-lying rock outcrops characterised by often high-density patches of gorgonians, crinoids, echinoids, crustaceans (e.g. Galathaid lobster), sponges (e.g. tulip-shaped glass sponges) soft corals, brittlestars and acorn worms (Daniell et al, 2009). Several types of holothurians (sea cucumbers) were also identified from video and still photographs at the head of the Houtman Canyon, including high-densities of small pink elasipodid sea cucumbers (or sea piglets, Family: Elpidiidae) and deep-sea swimming cucumbers (Family: Pelagothuriidae). While these data provide an important contribution to our knowledge of Australia's deepwater (water depths >1000 m) seabed environments, few biological surveys have been undertaken in the northern Perth Basin, and as a result the benthic ecology for this region remains largely unknown (Daniell et al, 2009).

National seabed mapping data and information

Geoscience Australia provides acoustic datasets including bathymetry, backscatter, sidescan sonar and sub-bottom profiles to assist in understanding the shape and composition of the sea floor. Geoscience Australia also maintains the Marine Sediment database (MARS), comprising information (e.g. percentage mud/sand/gravel, mean grain size, and sediment texture) from seabed sediment samples collected during marine surveys between 1905 and 2018.

These data are discoverable and accessible through the AusSeabed Marine Data Discovery Portal. AusSeabed is an innovative national seabed mapping initiative designed to coordinate data collection efforts in Australian waters and provide open access to quality-controlled seabed data.

Other online information resources

Please follow these links for more detailed information pertaining to the marine and environmental summaries provided in this section.

- Australian Marine Parks Science Atlas

- Bureau of Meteorology: climate statistics
- National Conservation Values Atlas
- Australian Marine Parks: North-west Marine Parks Network; South-west Marine Parks Network
- Western Australian marine parks and reserves
- AusSeabed
- Commonwealth Fisheries
- WA Department of Fisheries—Commercial Fisheries
- Historic shipwrecks
- Protected Matters Search Tool

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Figure Captions

Figure 1 Map showing the location and extent of the Perth Basin, the distribution of petroleum exploration wells, oil and gas fields and basin bathymetry.

Figure 2 Map showing petroleum production facilities, petroleum fields and pipeline infrastructure in the Perth Basin.

Figure 3 Structural elements map for the Perth Basin showing depocentre age and major faults (modified from Bradshaw et al, 2003).

Figure 4 Stratigraphic chart for the northern Perth Basin showing lithostratigraphy, basin phases and hydrocarbon occurrences. Modified after Jones et al (2013) and Mory et al (2015). Geologic Time Scale after Ogg et al (2016).

Figure 5 Regional geological transect through the northern Perth Basin (modified from Norvick, 2004).

Figure 6 Stratigraphic chart for the southern Perth Basin showing lithostratigraphy, basin phases and hydrocarbon occurrences. Modified after Jones et al (2013) and Mory et al (2015). Geologic Time Scale after Ogg et al (2016).

Figure 7 Tectonostratigraphic chart for the northern Houtman Sub-basin. Basin phases, seismic sequences, interpreted lithostratigraphy, key regional events and potential petroleum systems elements are based on mapping and interpretation of seismic survey GA-349 and regional stratigraphy of the Houtman Sub-basin. Also shown are the NW Shelf Supersequences (updated from Smith et al, 2015) and short-term relative sea-level curve (modified from Haq and Schutter, 2008; and Hardenbol et al,1998). Geologic Time Scale after Ogg et al (2016).

Figure 8 Interpreted seismic lines from survey GA-349 in the northern Houtman Sub-basin: **a)** GA-349/1011; **b)** GA-349/1031; and **c)** GA-349/1023. Sequence ages and interpreted Perth Basin lithostratigraphic equivalents are shown in Figure 7. Location of the lines is shown in Figure 11.

Figure 9 Regional seismic lines through the Perth Basin: **a)** seismic line GA 349/1024 through the northern Houtman Sub-basin; **b)** composite seismic transect (portions of seismic lines GA 310/31, Plum 92-87r, Plum 92-41 and Plum 92-41r) through the Abrolhos, Houtman and Zeewyck sub-basins; and **c)** composite seismic transect (seismic lines PV91-40r and V82A-67r) through the northern Vlaming Sub-basin. Locations of lines are shown in Figure 11.

Figure 10 Plate reconstruction model for the southwest margin Continent-Ocean Boundary at **(a)** 140 Ma, **(b)** 130 Ma, **(c)** 120 Ma, and **(d)** 110 Ma, showing timing and evolution of breakup across the margin (modified from Hall et al, 2013). B: Batavia Knoll; CAP: Cuvier Abyssal Plain; EP: Exmouth Plateau; G: Gulden Draak Knoll; GB: Gascoyne Block; H: Houtman Sub-basin NP: Naturaliste Plateau; PAP: Perth Abyssal Plain; V: Vlaming Sub-basin; WM: Western Mentelle Sub-basin; WP: Wallaby Plateau; Z: Zeewyck Sub-basin; ZP: Zenith Plateau.

Figure 11 Structural elements map for the Perth Basin showing the location of petroleum wells and regional cross-sections shown in Figure 8 and Figure 9.

Figure 12 Map of the Perth Basin showing current petroleum licences and operators.

Figure 13 Map showing selected hydrocarbon discoveries and occurrences coloured by age of source rock, as interpreted from geochemical evidence in the northern Perth Basin (after Jones et al, 2011).

Figure 14 Source rock characteristics (TOC vs HI) by formation based on wells in the Abrolhos and southern Houtman Sub-basin (modified from Jones et al, 2011).

Figure 15 Burial history models for two Houtman Sub-basin pseudo-wells, calibrated with corrected temperature, maturity (Ro, FAMM) and AFTA data from wells in adjacent areas. a) Pseudo-well 1030-0 located on the basin margin, calibrated with well data from the Abrolhos Sub-basin. b) Pseudo-well 1030-2 located over the deepest part of the northern Houtman Sub-basin, calibrated with well data from the southern Houtman Sub-basin (modified from Hall et al, 2017).

Figure 16 Petroleum systems modelling results for potential Hovea Member source rock in the NH-TR1 Kockatea Shale equivalent: a) gross NH-TR1 seismic sequence thickness; b) maturity of Hovea Member; c) cumulative oil expelled from the Hovea Member; and d) cumulative gas expelled from the Hovea Member (modified from Hall et al, 2017).

Figure 17 Conceptual play diagram for the northern Houtman sub-basin showing a range of possible structural and stratigraphic plays at different stratigraphic levels.

Figure 18 Map showing marine reserves, marine parks, multiple use zones, ecological features in the Perth Basin.