



## Regional Geology of the Roebuck Basin

The Roebuck Basin forms the central part of the Westralian Superbasin (**Figure 1**), and covers approximately 90 000 km<sup>2</sup> on the North West Shelf between the Northern Carnarvon Basin to the south and the Browse Basin to the north, the Canning Basin to the east, and the Argo Abyssal Plain to the northwest (**Figure 3**). The discovery of oil and gas-condensate at Phoenix South, Roc and Dorado has led to the establishment of the Bedout Sub-basin as an emerging hydrocarbon province in the otherwise underexplored Roebuck Basin (**Figure 2**). The existence of an active petroleum system has been proven in the Bedout Sub-basin and future production is highly probable. Gross 2C contingent resources at these discoveries, together with the historical discovery at Phoenix, are 1080 Bcf (30.58 Bcm) of gas, and 205 MMbbl (32.59 GL) of oil and condensate (Carnarvon Petroleum Ltd, 2019a). A resurgence in exploration activity in the basin, following these recent discoveries, is providing new data that illuminates the basins geology, structural architecture and prospectivity, particularly for the highly prospective Triassic succession.

### Basin outline

The Roebuck Basin is subdivided into the Bedout Sub-basin in the south and the Rowley Sub-basin in the north, which are separated by a structural trend that includes the Bedout High (**Figure 3**). The geology of the Roebuck Basin is described by Lipski (1993; 1994), Colwell and Stagg (1994), and Smith et al (1999). Recent updates to various aspects of Roebuck Basin geology include Abbott et al (2019a; 2019b), Minken et al (2018), Rollet et al (2019a; 2019b), and Thompson et al (2018).

The Bedout Sub-basin is an east-northeast trending depocentre (**Figure 3**) that is filled with approximately 2.5 km of Paleozoic and 7 km of Mesozoic sediments (Smith et al, 1999). The sub-basin is separated from the Beagle Sub-basin to the west by the North Turtle Hinge Zone. The sub-basin is bounded to the south by the Lambert Shelf of the Northern Carnarvon Basin and to the east by the Willara Sub-basin and Broome Platform elements of the Canning Basin.

The Rowley Sub-basin (**Figure 3**) contains up to 16 km of Mesozoic–Holocene section, including up to 10 km of volcanics (Orlov et al, 2019b; Rollet et al, 2019b). The sub-basin is separated from the Beagle Sub-basin and Exmouth Plateau of the Northern Carnarvon Basin to the west by the North Turtle Hinge Zone and Thouin Graben. To the east, the Oobagooma High separates the Rowley Sub-basin from the Oobagooma Sub-basin (Canning Basin). To the northeast, the Rowley Sub-basin passes into the Barcoo Sub-basin and Scott Plateau elements of the Browse Basin.

The Bedout High consists of uplifted and eroded Permo-Carboniferous sedimentary rocks above a faulted basement core, and is capped by Permian volcanics (Colwell and Stagg, 1994; Smith et al, 1999). It has a maximum relief of approximately 6 km above the surrounding depocentres. Lower to Middle Triassic sediments onlap the feature from all directions and it is draped by approximately 3 km of Upper Triassic–Holocene sediments. The upper surface of the Bedout High is an approximately 30 km wide peneplain (Smith et al, 1999; Müller et al, 2005).

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## Tectonic elements

The Roebuck Basin is one of a series of extensional basins that together form the Westralian Superbasin (Yeates et al, 1987; AGSO North West Shelf Study Group, 1994; Etheridge and O'Brien, 1994). Structural elements of the Roebuck Basin (**Figure 3**) are after Hocking et al (1994), except for the Oobagooma Sub-basin which was re-allocated by Totterdell et al (2014) from the Roebuck Basin to the offshore Canning Basin. The Roebuck Basin is divided into two depocentres, the Rowley Sub-basin, and the Bedout Sub-basin. The stratigraphy and structure of these Westralian (mid-Carboniferous to Holocene) depocentres have been described by Colwell and Stagg (1994), Etheridge and O'Brien (1994), Lipski (1993, 1994) and Smith et al (1999). In the Roebuck Basin, the Westralian depocentres are underlain by an older Paleozoic succession that at least in part represents a continuation of the Canning Basin.

### Rowley Sub-basin

The Rowley Sub-basin contains up to 16 km of Mesozoic to Holocene strata (**Figure 4**) that extends to the modern, fault-bound, continent-ocean boundary (**Figure 5**). The main structural orientation is northeast-southwest and is linked to northwest-southeast extension associated with the evolution of the Westralian Superbasin. Although the Rowley Sub-basin is regarded as mildly structured in comparison to other Westralian basins, several structural features of interest are observed (Orlov et al, 2019b). In the western Rowley Sub-basin are the: Naranco High, a prominent rhomboidal fault-bound structural high at the Rowley–Exmouth transition; the Whitetail Graben, a north-south oriented graben at the Rowley–Exmouth–Beagle junction, with a distinctive sigmoidal architecture; and the Thouin Graben, a major depression in the outboard northeast Exmouth Plateau and Rowley Sub-basin (**Figure 7**). In the northwest Rowley Sub-basin is the Steel Dragon Structure (Maher, 2017), a circular depression with a Triassic fill that may be related to a volcanic depocentre (Abbott et al, 2019a). The Paleozoic part of the sub-basin fill includes several Permo-Carboniferous syn-rift wedges attributed to the initiation of the Westralian succession. An older Paleozoic succession has been mapped in seismic profiles across the Rowley Sub-basin (Smith et al, 1999).

### Bedout Sub-basin

The Bedout Sub-basin contains up to 2.5 km of Paleozoic strata and up to 7 km of Mesozoic strata (**Figure 4**) with north to northeast trending normal faults characterising the structural architecture of the sub-basin. Triassic level faulting is largely concentrated in the western sub-basin where the North Turtle Hinge Zone is observed. The underlying Canning Basin succession is characterised by east-southeast trending faults, associated with northeast-southwest extension. Paleozoic deposition was thickest in the extensions of the Fitzroy Trough (Oobagooma Sub-basin) and Willara Sub-basin, where seismic mapping indicates thick Ordovician to Devonian successions. The Mesozoic fill was deposited during a regional sag phase of basin development.

### Bedout High and Oobagooma High

The Bedout and Oobagooma highs are prominent features that lie on a structural trend that separates the Rowley Sub-basin from the Bedout Sub-basin and the Oobagooma Sub-basin. This trend represents a hinge line between Westralian northwest-southeast extension (Rowley Sub-basin) and northeast-southwest extension (Oobagooma and Bedout sub-basins). The Bedout High forms part of an anticlinal structure that separates the Rowley and Bedout sub-basins (**Figure 5**). Development of the Bedout High is linked to the late Permian Bedout Movement (Forman and Wales, 1991). Paleozoic strata within the Bedout High are unconformably overlain by volcanics that have been isotopically dated at about 253 Ma (i.e. near the Permian-Triassic boundary). The structure is onlapped from all sides by Triassic strata, and overlain by 3 km of Mesozoic strata. The Oobagooma High lies on the boundary between the Rowley Sub-basin and the Oobagooma Sub-basin. This feature is fault bounded along its eastern side and a magnetic anomaly on its western side indicates volcanic lithologies. The Oobagooma High is also onlapped by Triassic strata.

The origin of the Oobagooma and Bedout highs remain poorly understood. Smith (1999) proposed that these structures formed to accommodate differential northeast-oriented extension during the Paleozoic, with the Bedout High subsequently reactivated during Westralian extension. Colwell and Stagg (1994) regarded the Bedout High as an intruded basement high underlain by magmatic upwelling, with a degree of thrust control. Others (Gorter, 1997; Becker et al, 2004) have invoked an extraterrestrial impact origin for the Bedout High.

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## Basin evolution

The Roebuck Basin succession comprises six basin phases modified after Colwell and Stagg, 1994; Smith et al, 1999):

- Extension 1: Cambrian to Silurian northeast-southwest extension and deposition in pre-Westralian intracratonic basins.
- Extension 2: Early Carboniferous to Late Permian northwest-southeast extension linked to initiation of the Westralian Superbasin. Regarded as a transitional phase in the Roebuck Basin because of the persistence of east-northeast-trending structures in the Bedout Sub-basin.
- Sag 1: Triassic thermal subsidence terminated by a tectonic event attributed to the Fitzroy Movement.
- Sag 2: Thermal subsidence during a period of Jurassic extension in the Northern Carnarvon and Bonaparte sectors of the Westralian Superbasin, terminated by a Callovian unconformity formed by separation of Argoland from the outboard Roebuck and Browse basins.
- Passive Margin: Post Callovian thermal subsidence.
- Inversion: Middle Miocene to Holocene northeast-southwest compression in response to convergence of the Australian and Eurasian tectonic plates.

Pre-Westralian strata beneath the Roebuck Basin are at least in part contiguous with the Canning Basin. In particular, the extensional depocentre beneath the Bedout Sub-basin is inferred from seismic mapping to be a continuation of the Willara Sub-basin that contains Ordovician strata including the Willara, Goldwyer and Nita formation equivalents from the onshore Canning Basin (Lipski, 1993). The Paleozoic succession beneath the Westralia Superbasin is regarded as part of a system of intracratonic rift basins formed under northeast-southwest extension (Lipski, 1993, AGSO North West Shelf Study Group, 1994). Veevers (1988) regarded these early Paleozoic basins, including the Canning and Bonaparte basins, as aulacogens initiated during the breakup of an 'ancestral' northwest margin. According to Metcalfe (2013), rifting culminating in the separation of North China and associated crustal blocks, and the opening of Palaeo-Tethys, occurred in the Middle Devonian.

The Roebuck Basin was initiated, as part of the broader Westralian Superbasin, by a phase of early Carboniferous to late Permian, northwest-southeast extension (Etheridge and O'Brien, 1994; AGSO North West Shelf Study Group, 1994). Extension was related to the Early Permian separation of the Cimmerian continent from the northwest margin of Gondwana and the opening of Meso-Tethys (Metcalfe, 1988). Smith et al (1999) recognised the presence of half-graben up to 120 km long in the Rowley Sub-basin formed during this extension phase, but also observed that northeast-southwest extension persisted in the Bedout Sub-basin (and offshore Canning Basin).

Apart from the Bedout Volcanics, Permo-Carboniferous syn-rift strata in the Roebuck Basin remains undrilled. The early Carboniferous unconformity (*G. maculosa* spore-pollen zone, late Viséan) in the neighbouring Browse Basin (Blevin et al, 1998b) provides the best indication of the initiation of Westralian syn-rift wedges in the Roebuck Basin.

In the Bedout Sub-basin, the Westralian syn-rift succession is inferred to include the Grant and Liveringa groups from the onshore Canning Basin (Lipski, 1994). The upper Permian Bedout Volcanics unconformably overlie the inferred Liveringa Group on the Bedout High. The Westralian syn-rift basin phase was terminated by basin-wide uplift and erosion related to the Bedout Movement (Smith et al, 1999).

A recent study of the central North West Shelf (NWS) by Geoscience Australia using an updated sequence stratigraphic framework has provided new insights into the structural and depositional evolution of the area during the Triassic (**Figure 6, Figure 7, Figure 8**; Abbott et al, 2019a, 2019b; Nguyen et al, 2019a; Orlov et al, 2019a, 2019b; Rollet et al, 2019a, 2019b). Mapping shows a large Triassic depocentre centred in the adjacent Beagle Sub-basin with an embayment extending into the Bedout Sub-basin (**Figure 7**; Orlov et al, 2019b; Abbott et al, 2019a). This is filled with the fluvio-deltaic sediments of the Keraudren Formation. An interpreted carbonate build-up is observed at the base of this fill, atop the antecedent Paleozoic succession, including the Bedout Volcanics (**Figure 6a, Figure 7**; Abbott et al, 2019a).

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During Triassic time, the Rowley Sub-basin was part of a broad intracratonic sag that encompassed the adjacent Northern Carnarvon and Browse basins. The Early Triassic of the Rowley Sub-basin is now interpreted to include a thick volcanic complex that prograded into the depocentre from an adjacent Argo landmass located to the north (**Figure 6**; MacNeill et al., 2018; Abbott et al, 2019a, 2019b; Rollet et al, 2019b). Elsewhere in the sub-basin, a succession of Early Triassic marine mudstones and fluvial-deltaic sediments (lower Keraudren Formation), fed from the Fitzroy palaeo-river (Norvick, 2002; Abbott et al, 2019b), was deposited. This was followed by deposition of a Middle Triassic to Lower Jurassic carbonate-rich siliciclastic facies (**Figure 4**, **Figure 6**, **Figure 8**; Abbott et al, 2019b), including the regionally widespread Middle Triassic Cossigny Member limestone.

The Fitzroy Movement (Sinemurian) marked basin-wide uplift and erosion, and a change in gross stratal geometry within the Roebuck Basin from predominantly back-stepping and aggrading to prograding and aggrading. Following the Fitzroy Movement, a broad prograding wedge of fluvio-deltaic sediments (Depuch Formation) was deposited over a base Jurassic unconformity during a period of regional thermal subsidence. A breakup unconformity generated by separation of Argo Land from the outboard Roebuck and Browse basins in the Callovian (Müller et al, 1998; Veevers et al, 1991) marked the end of a Jurassic phase of rifting throughout the Westralian Superbasin (Marshall and Lang, 2013).

With the formation of oceanic crust in the Argo Abyssal Plain, a passive margin basin phase commenced with transgression and accumulation of condensed marine mudstone (Baleine and Egret formations) until the end of the Jurassic. Early Cretaceous (Berriasian-Valanginian) rifting and separation of Greater India from Australia is linked in the Roebuck Basin to minor fault reactivation and an influx of sand (Broome Sandstone). This unconformity-bounded succession is the equivalent of the Barrow Delta succession in the Northern Carnarvon Basin. Subsequent deposition in the Roebuck Basin during the Early Cretaceous was dominated by marine mudstone (Mermaid Formation, Nelson Rocks Formation), with a change to mainly fine-grained carbonate and calcareous lithologies in the Late Cretaceous (Toolonga and Miria formations). Deposition of fine-grained carbonate-rich lithologies continued into the Cenozoic. The post-Oligocene succession comprises a carbonate clinoform wedge that extends across the inner Rowley Sub-basin (Smith, 1999). The effects of late Miocene collision of the Australian continent with Eurasia were limited in the Roebuck Basin to transtensional wrenching along footwalls of northeast-southwest-oriented Paleozoic half-graben in the Rowley Sub-basin (Smith, 1999).

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## Exploration history

The Roebuck Basin is one of the least explored regions of the North West Shelf. The initial phase of seismic exploration in the Roebuck Basin extended from the late 1960s to 1982, and focussed on the Bedout Sub-basin and inboard Rowley Sub-basin. During the period from 1986 to 1994, predecessor organisations of Geoscience Australia acquired several regional seismic lines across the Roebuck Basin. Over this same period, six industry seismic surveys were conducted, including tightly spaced seismic grids in the Bedout and Rowley sub-basins. Later activity included several 2D seismic surveys conducted between 1998 and 2001.

2D seismic surveys acquired in recent years are NWS Australia Geostreamer “New Dawn” (PGS, 2017) and WestraliaSPAN 2D (ION, 2017). These are deep regional surveys that extend across the North West Shelf and each includes several lines within the Roebuck Basin. The 14 000 km Bilby non-exclusive 2D seismic survey over the central Bedout Sub-basin and offshore Canning Basin was completed in 2016 (Searcher Seismic, 2017).

In the Rowley Sub-basin, 3D seismic survey acquisition commenced in 2001 with small 3D grids that delineated drilling prospects for Huntsman 1 and Whitetail 1. Between 2012 and 2014, Polarcus Limited, on behalf of Woodside Petroleum Ltd, completed the Lord 3D, Admiral 3D and Curt 3D surveys across the outer Rowley Sub-basin.

In the Bedout Sub-basin, acquisition of the 1100 km<sup>2</sup> Phoenix MC3D multiclient survey was completed over the greater Phoenix Area in 2011 (Spectrum, 2017a). The 3854 km<sup>2</sup> Zeester MC3D 3D multiclient seismic survey, located north of Phoenix, was acquired in 2011/2012 (Spectrum, 2017b). In 2015, Polarcus Seismic Limited acquired the 22 385 km<sup>2</sup> Capreolus high-resolution broadband 3D multi-client survey that straddles the boundary between the Northern Carnarvon and Roebuck Basins (Pedley et al, 2015). The Capreolus survey covers the greater Phoenix area in the Bedout Sub-basin, and extends into the southwestern Rowley Sub-basin. The Keraudren 3D MSS covering 3090 km<sup>2</sup> was conducted in 2019 and will enable further assessment of recent discoveries and near-field prospects in the Bedout Sub-basin (Carnarvon Petroleum Ltd, 2019e). Approvals are currently being sought for an extension of the survey, Keraudren Extension 3D MSS, with commencement intended in 2020 and coverage of approximately 8620 km<sup>2</sup> (NOPSEMA, 2020).

In 2010 Fugro Airborne Surveys acquired a 21 622 line km aeromagnetic survey in the Bedout Sub-basin on behalf of joint venture partners Carnarvon Petroleum Ltd and Finder Exploration. The survey was designed to provide information about the tectono-structural evolution of the sub-basin, depth to magnetic basement, and an estimation of total sediment thickness (Chowdhury et al, 2012).

Geoscience Australia conducted a hydrocarbon seepage survey of the Roebuck and offshore Canning basins in June 2006 (Jones et al, 2007). No evidence of natural hydrocarbon seepage was detected. Head-space gas analyses of gravity core sub-samples, and biomarker screening of sediments and carbonate concretions, revealed no thermogenic hydrocarbons or biomarkers diagnostic of methane oxidation. Re-evaluation by Logan et al (2010) of vertical seismic features distributed throughout the region, with a strong clustering over the Bedout High, suggests that they more likely represent zones of either small-scale faulting or fracture with little or no displacement, while velocity pull-ups are associated with late Miocene channels, rather than hydrocarbon-related diagenetic zones and gas chimneys as previously interpreted by O'Brien et al (2003).

As of 2019, twenty-one wells have been drilled in the Roebuck Basin. An initial phase of drilling occurred between 1970 and 1974, with drilling in both the Bedout Sub-basin (Bedout 1, Keraudren 1 and Minilya 1) and Rowley Sub-basin (East Mermaid 1). Three further wells were drilled in the Bedout Sub-basin (Phoenix 1, Phoenix 2, and Lagrange 1) between 1980 and 1983. Subsequent drilling in the Rowley Sub-basin has tested the deep-water potential with the following wells: Whitetail 1 (2003), Huntsman 1 (2006), Hannover South 1 (2014), Steel Dragon 1 (2014) and Anhalt 1 (2015).

The wells drilled by Woodside in 2014-15 in the Rowley Sub-basin were all dry, with Hannover South 1 and Anhalt 1 intersecting Middle Triassic basaltic volcanics rather than the expected lower Keraudren Formation target. In Steel Dragon 1 the primary target, the Bedout Formation, was found to be absent, though reservoir quality sands were encountered within the Depuch, Brigadier and Mungaroo formations.



A recent string of discoveries has led to the establishment of the Bedout Sub-basin as an emerging hydrocarbon province (**Figure 2**). Commencing with the discovery of oil at Phoenix South 1 (2014), renewed interest has resulted in one of the largest oil discoveries in Australia at Dorado (Dorado 1, 2018; Dorado 2, 2019; Lockart and Spring, 2019), and additional gas-condensate discoveries at Roc 1 (2015), Roc 2 (2016) and Phoenix South 2 (2017), while Phoenix South 3 (2018) encountered a significant gross column (131 m) of hydrocarbons. Subsequently, Roc South 1 (2019) failed to encounter producible hydrocarbons. Most recently, results from Dorado 3 (2019) confirm the establishment of the Bedout Sub-basin as a new hydrocarbon province. Each of these discoveries is reservoirised within the Keraudren Formation, largely within a series of informal members of the lower Keraudren Formation (**Figure 9**); namely the Barret, Hove, Caley, Baxter, Crespín and Milne members (Thompson et al, 2018).

In Phoenix South 1, at least four oil columns, ranging in thickness from 26 m to 46 m, were discovered (Carnarvon Petroleum Ltd, 2014). This discovery has opened up the first new oil play on the North West Shelf in 25 years. In light of this discovery it is now believed that the Phoenix 1 well had intersected an unrecognised significant gross oil pay in the Barret and Hove members, and was incorrectly classified as a gas well, and that Phoenix 2 was drilled outside of closure (Carnarvon Petroleum Ltd, 2015; Thompson et al, 2018).

Roc 1 (2015) was designed to target the same lower Keraudren Formation reservoir (i.e. Barret member sandstone) as the oil discovery at Phoenix South 1 (Carnarvon Petroleum Ltd, 2016a). The Barret member sandstone was water-wet but a liquids-rich gas pay was discovered in the deeper secondary target in the Caley member (lower Keraudren Formation). In addition, the Roc 1 well exhibited excellent oil shows in the upper Keraudren Formation reservoir, and reservoir quality sandstones that extended to the base of the well.

The Roc 2 (2016) well was designed to appraise the Roc 1 discovery in the Caley member, and to test the Milne and Huxley members where oil shows were recorded at Roc 1 (Carnarvon Petroleum Ltd, 2016b). The well flow tested at equipment-constrained rates up to 51.2 MMcf (1.45 Mm<sup>3</sup>) per day of gas and 2943 bbl (467.9 m<sup>3</sup>) of condensate per day (Carnarvon Petroleum Ltd, 2016c).

Phoenix South 2 (2016) was drilled by Quadrant Energy to appraise the Phoenix South 1 oil discovery and evaluate the Roc 1 and Roc 2 gas-condensate discoveries (Carnarvon Petroleum Ltd, 2016d). The well intersected an estimated 39 m gas-condensate zone between 5176 m and 5215 m within the Caley reservoir. Drilling ceased at 5215 m because of high formation pressure, and as much as 185 m of Caley reservoir below this depth could not be assessed (Carnarvon Petroleum Ltd, 2016e).

Phoenix South 3 (2018) was the second appraisal well for the Phoenix South 1 oil discovery drilled by Quadrant Energy to further evaluate the Caley member reservoir (that Phoenix South 2 drilled into but was unable to fully evaluate). The well intersected an estimated 131 m gross column of hydrocarbons between 5173 m and 5304 m. Sampling failed to extract hydrocarbons. Wireline logging and samples indicate 16 m of net reservoir, with potential for a larger hydrocarbon column remaining in the structural crest (Carnarvon Petroleum Ltd, 2018a).

Following the Roc 1 and Roc 2 discoveries Carnarvon Petroleum Ltd drilled the Dorado structure, <20 km to the southwest, which comprises lower Keraudren Formation reservoir facies sealed by fine-grained incised valley fill (Carnarvon Petroleum Ltd, 2017b). Dorado 1 (2018) was a breakthrough discovery, encountering oil columns in the Caley, Crespín and Milne members and a gas and condensate column in the Baxter member, with a combined 132 m total net hydrocarbon pay. Each of the encountered reservoirs were high quality (Carnarvon Petroleum Ltd, 2018b). Gross contingent resources on a 2C basis are assessed to be 171 MMbbls (27.19 GL) of oil, 16 MMbbls (2.54 GL) of condensate, and 552 Bcf (15.63 Bcm) of gas, making the Dorado discovery one of the largest oil resources to be found on the North West Shelf (Carnarvon Petroleum Ltd, 2018c).

Appraisal well Dorado 2 (2019), located 2.2 km north-east of Dorado 1, encountered hydrocarbons within the Caley (40 m of net oil and 11 m condensate pay), Baxter and Milne (32 m net pay combined, light oil/condensate rich gas) members and demonstrated connectivity between the Dorado 1 and 2 wells within each of these reservoirs (Santos Limited, 2019a). The well confirmed Dorado as a major oil and gas resource, encountering high quality and productive reservoirs in each target (Santos Limited, 2019a).

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Dorado 3 (2019) is located 900 m north-west of Dorado 1 and targeted the Caley, Baxter, Crespin and Milne members. Hydrocarbons were intersected in the Caley, Baxter and Crespin intervals (Carnarvon Petroleum Ltd, 2019b). The Caley member reservoir intersected in Dorado 3 is predominantly oil-bearing and in communication with Dorado 1 and Dorado 2. Similarly, a hydrocarbon column was encountered in the Baxter member reservoir and pressure data indicate this is in communication with Dorado 1 and Dorado 2. Unexpectedly, hydrocarbons were also encountered in the Crespin member. The Milne member reservoir was found to be water-wet. Dorado 3 flow tested up to 11 000 bbl (1.75 ML) of oil per day from the Caley reservoir (Carnarvon Petroleum Ltd, 2019d) and 48 MMcf (1.36 Mm<sup>3</sup>) of gas and 4500 bbl (0.715 ML) of condensate per day from the Baxter reservoir (Carnarvon Petroleum Ltd, 2019c), all at equipment-constrained rates.

Uptake of exploration acreage in the basin has been strong on the back of these discoveries, with the award of WA-521-P to Carnarvon Petroleum in 2016, WA-527-P to 3D Oil in 2017, and WA-540-P and WA-541-P to Santos in 2019 resulting in the Bedout Sub-basin being entirely tenanted (**Figure 10**).

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## Development status

The Phoenix, Roc and Dorado discoveries are proximal to Western Australia's main gas pipeline at Port Hedland, the Fortescue River gas pipeline that links to Pilbara iron ore mines, and to LNG export facilities (**Figure 11**; Carnarvon Petroleum Ltd, 2017b).

Results of appraisal drilling at Dorado support progression to development planning and investment decisions with the front end engineering and design (FEED) phase set to commence in 2020. The preferred development approach is an initial phase of oil and condensate extraction, with gas reinjection to enhance recoveries, via a wellhead platform and floating production storage and offloading (FPSO) facility (Santos Ltd, 2019b).



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## Regional petroleum systems

The 2014 discovery of oil in Phoenix South 1 challenged the perception that the Roebuck Basin was only prospective for gas. This discovery and others that followed (gas-condensate in Roc 1 in 2015, Roc 2 in 2016, Phoenix South 2 in 2016, Phoenix South 3 in 2018; oil and gas in Dorado 1 in 2018, Dorado 2 in 2019) have revealed a new play on the central North West Shelf in Lower Triassic reservoirs (**Figure 12**; Thompson et al, 2018). Prior to this, the only discovery made in the Roebuck Basin was a gas discovery in Phoenix 1 within the lower Keraudren Formation (within the Hove and Barrett members, i.e. between the TR15.0\_SB and TR16.0\_SB unconformities of Marshall and Lang, 2013). The Phoenix 1 gas discovery has since been reinterpreted as an oil discovery based on the results in Phoenix South 1 and re-evaluation of the Phoenix 1 log data (Thompson et al, 2018).

Carbon isotopic analyses combined with biomarker data indicate that the Phoenix South 1 oil reservoired within the Barret member (TR15 sequence) has unique characteristics compared to other oils of the North West Shelf and therefore represents a new petroleum system in Australia (**Figure 13**; Thompson et al, 2015; Grosjean et al, 2018). The oil is distinct from the oils of the Perth Basin, which are derived from the earliest Triassic anoxic marine Hovea Member source rock (**Figure 13**; Grosjean et al, 2018). Overall, the geochemical composition of the Phoenix South 1 oil is consistent with derivation from a Triassic source rock deposited in a paralic/deltaic environment (Thompson et al, 2015; Grosjean et al, 2018). The oil and other fluids in the Greater Phoenix area are likely sourced by fluvial-deltaic source rocks within the Lower Keraudren Formation in the Bedout Sub-basin (TR10–TR15 sequences), as these show fair to excellent potential for generating gas and liquids (Rollet et al, 2019a). Lagoonal facies Caley member source rocks (within TR10–TR14 sequences) are particularly organic-rich and oil-prone in Roc 2 and have been typed to hydrocarbons reservoired within the Caley member in the same well (Woodward et al, 2018).

## Petroleum Systems Elements

Sources	<ul style="list-style-type: none"> <li>• Permian marine mudstones, siltstones and shales equivalent to the Noonkanbah Formation (onshore Canning Basin)</li> <li>• Triassic transgressive shales of the Locker Shale</li> <li>• Fluvio-deltaic mudstones within the Lower-Middle Triassic lower Keraudren Formation</li> <li>• Upper Triassic carbonate dominated succession (in the Rowley Sub-basin)</li> <li>• Jurassic thin coaly and algal-rich mudstones and prodelta marine shales in the Depuch Formation</li> <li>• Lower Cretaceous transgressive marine shales of the Egret Formation, Broome Sandstone and Mermaid Formation</li> </ul>
Reservoirs	<ul style="list-style-type: none"> <li>• Possible upper Permian reefs</li> <li>• Lower Triassic sandstone-prone facies of the Locker Shale and sandstones of the Lower Triassic lower Keraudren Formation and Middle Triassic upper Keraudren Formation</li> <li>• Middle Jurassic fluvio-deltaic sandstones of the Depuch Formation</li> <li>• Jurassic fluvio-deltaic sandstones of the Depuch Formation (including Athol Formation, North Rankin Formation, and Rankin Beds equivalents from the Northern Carnarvon Basin)</li> <li>• Lower Cretaceous deltaic sandstones of the Egret Formation, Broome Sandstone and Mermaid Formation</li> </ul>
Seals	<p><i>Regional seal</i></p> <ul style="list-style-type: none"> <li>• Lower Cretaceous claystones of the Baleine and Mermaid formations which overlie the Callovian unconformity.</li> <li>• Intraformational seals</li> <li>• Triassic seals in the upper and lower Keraudren Formation, Cossigny Member and Locker Shale</li> <li>• Jurassic transgressive shales and mudstones of the Bedout Formation (North Rankin Formation equivalent)</li> <li>• Jurassic nearshore claystone beds and prodelta shales of the Depuch Formation (Athol Formation equivalent)</li> </ul>
Play Types (see Figure 13)	<ul style="list-style-type: none"> <li>• Upper Permian reef plays (8).</li> <li>• Faulted anticline plays (2).</li> <li>• Lower Triassic lower Keraudren Formation stratigraphic plays (e.g. sandstones, floodplain sandstones, marine incursion sandstones, amalgamated channels and other fluvio-deltaic plays) (3).</li> <li>• Combination structural and stratigraphic plays in the Lower Triassic (e.g. lower Keraudren Formation) (4) including the Dorado Canyon style play.</li> <li>• Lower Triassic structural horst plays (5).</li> <li>• Triassic to Lower-Middle Jurassic structural (horst, faulted anticline) and stratigraphic plays (e.g. 6 &amp; 7)</li> <li>• Upper Triassic faulted anticline and stratigraphic plays (7).</li> <li>• Upper Triassic (upper Keraudren Formation) delta front and nearshore sandstone stratigraphic plays (7).</li> <li>• Lower Jurassic fluvio-deltaic delta front and nearshore sandstone plays (6).</li> <li>• Lower Jurassic Depuch Formation fluvio-deltaics: delta front, barrier island, amalgamated channels, nearshore sandstones and sub-unconformity plays (6).</li> <li>• Rollovers against basin-bounding faults plays (structural plays).</li> <li>• Triassic onlap along the Bedout High (1).</li> </ul>

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## Source rocks

Potential Cisuralian (Lower Permian) source rocks comprise transgressive marine shales of the Poole Sandstone and Noonkanbah Formation, which are known to be organic-rich in the Fitzroy Trough of the onshore Canning Basin (Kennard et al, 1994). Marine shales of the Grant Group, which underlie the Poole Sandstone and Noonkanbah Formation, are also locally organic-rich, but generally have poor hydrocarbon generation potential. The presence of these source rock units has not been established in the Roebuck Basin.

The Lower to Middle Triassic transgressive marine Locker Shale is potentially widespread in the Roebuck Basin. The Locker Shale is in part coeval with the Kockatea Shale in the northern Perth Basin. However, the presence of an equivalent of the oil-prone Hovea Member of the Kockatea Shale, which is the source of many of the gas and oil discoveries of the Perth Basin (Summons et al, 1995; Thomas and Barber, 2004; Grice et al, 2005; Edwards et al, 2013; Grosjean et al, 2017), has not been demonstrated in the Roebuck Basin (Molyneux et al, 2016; Grosjean et al, 2018).

The recently interpreted oil column in the lower Keraudren Formation at Phoenix 1, and hydrocarbon discoveries at Phoenix South 1, 2 and 3, Roc 1 and 2, and Dorado 1, 2 and 3, are all inferred to have been locally charged from source rocks within the Lower Triassic lower Keraudren Formation (TR10–TR15 sequences) and possibly the Locker Shale (Pedley et al, 2015; Molyneux et al, 2016; Thomson et al, 2015; Woodward et al, 2018; Rollet et al, 2019a). Lower to Middle Triassic source rocks within the lower part of the lower Keraudren Formation (TR10–TR14 sequences) are found within claystones of the Milne and Caley members (**Figure 9**; Thompson et al., 2018) and have highly variable organic richness, with TOC values ranging from 2–27.5% (**Figure 14**; Rollet et al, 2019a). These source intervals are associated with a mean Hydrogen Index (HI) value of 178 mg hydrocarbons (HC)/g TOC and have the potential to generate gas and liquids (Rollet et al, 2019a). In particular, samples in Roc 1 and 2 are excellent oil-prone source rocks with TOC>4% and HI>300 mg HC/g TOC (**Figure 14**; Grosjean et al, 2019 a, 2019b). The Lower Triassic succession is peak mature for oil generation in wells of the Bedout Sub-basin (Rollet et al, 2019a).

The Middle Triassic sediments of the upper part of the lower Keraudren Formation (TR15–TR16 sequences) in the Bedout Sub-basin indicate fluvial-deltaic deposition, related to the Mungaroo delta, followed by a phase of carbonate platform development (Cossigny Member) that extended into the southeastern Rowley and inner Beagle sub-basins (Abbott et al, 2019b). During this time, basaltic volcanics were deposited in the Rowley depocentre. Geochemical data for source rocks for this time (Middle Triassic, upper *T. playfordii* spore-pollen zone) are limited to wells in the Bedout Sub-basin and show poor to excellent potential for generating mostly gas (mean TOC of 1.5% and a mean HI value of 116 mg HC/g TOC; Rollet et al, 2019a). Some samples from Phoenix 1 and 2 show excellent potential to generate oil and/or gas (with TOC> 4% and HI> 200 mg HC/g TOC, **Figure 13**). The Middle Triassic succession has reached maturity for oil generation in wells of the Bedout Sub-basin (Rollet et al, 2019a).

These newly recognised Lower to Middle Triassic source rocks are potentially widespread in the Roebuck Basin. Modelling by Smith et al (1999), O'Brien et al (2003) and Woodside Energy Ltd (2003, 2007) indicates that these source rocks should be mature in certain parts of the Rowley Sub-basin, although this requires reassessment given that much of the outer to central Rowley is now interpreted to represent a volcanic complex.

The source rock potential within the Middle–Upper Triassic sediments of the upper Keraudren Formation (and time equivalents; TR17–TR30 sequences) is variable, with the Rowley Sub-basin dominated by shallow marine mixed carbonate-siliciclastics and fluvial-deltaics in the Bedout Sub-basin (Abbott et al, 2019a; Rollet et al, 2019a). In the Bedout Sub-basin poor to excellent source rocks capable of generating gas are found, with coaly facies in sandy mudstones showing high organic content (TOC up to 24%) in Phoenix 2. In the outer Rowley Sub-basin several marine incursions are identified within the Upper Triassic, with associated source rocks showing poor to excellent organic richness (TOC up to 8%) and the potential to generate both gas and liquids (HI up to 458 mg HC/g TOC). Based on Tmax and vitrinite reflectance data from wells, Upper Triassic source rocks have reached thermal maturity for oil generation in both the Bedout and Rowley sub-basins (Rollet et al, 2019a; **Figure 14**).

The fluvio-deltaic Depuch Formation (Jurassic) includes coaly and algal-rich mudstones and pro-delta marine shales that may have source potential. These Jurassic source rocks may be early to late mature beneath the Oligocene carbonate wedge (Smith et al, 1999). At Huntsman 1, Woodside Energy Ltd (2007) identified the Middle Jurassic organic-rich rocks within the middle Depuch Formation (equivalent to the Athol Formation of the Northern Carnarvon Basin) as a potential gas-prone source rock with liquids potential. However this source rock was found to be immature. At Whitetail 1, Woodside Energy Ltd (2003) found that potential source rocks in the upper Depuch formation (equivalent to the Legendre Formation of the Northern Carnarvon Basin) were marginally mature for oil and immature for gas. The lack of significant hydrocarbon shows in either Jurassic or Cretaceous reservoirs suggests that Jurassic source rocks may not be effective in the Roebuck Basin. In the Bonaparte and Northern Carnarvon basins, the Westralian 2 Petroleum System is characterised by Upper Jurassic, rift-related, restricted marine source rocks (Edwards and Zumberge, 2005). Equivalent rift structures and facies were apparently not developed in the Roebuck Basin.

Potential Lower Cretaceous source rocks documented in the Browse Basin and parts of the Bonaparte Basin (Westralian 3 Petroleum System; Blevin et al, 1998a; Edwards and Zumberge, 2005), are absent or immature in the Roebuck Basin. However, Lower Cretaceous marine mudstones might be mature beneath the thickest parts of the Cenozoic carbonate wedge (Smith et al, 1999). Potential Cretaceous source rocks were found to be immature at Whitetail 1 (Woodside Energy Ltd, 2003).

A detailed fluid inclusion investigation of potential reservoirs within the offshore Canning and Roebuck basins indicates that widespread oil migration has occurred at multiple Mesozoic and Paleozoic levels (Lisk et al, 2000). Samples from multiple horizons in Bedout 1, East Mermaid 1, Keraudren 1, Lagrange 1 and Phoenix 1 were tested. Grains with oil inclusions (GOI<sup>TM</sup>) were discovered in each well but GOI values were below 0.6%, except in Phoenix 1 where it reached 1.7%. The widespread distribution of oil inclusions led Lisk et al (2000) to propose that a lack of valid traps, rather than a lack of oil charge, was the principal reason for the discouraging results experienced prior to the oil discovery at Phoenix South 1.

## Reservoirs and seals

Potential reservoirs in the Roebuck Basin occur at several stratigraphic levels, including, fluvio-deltaic facies of the Keraudren Formation, Locker Shale, Depuch Formation, and Lower Cretaceous (Lipski, 1993; Smith et al, 1999).

In the greater Phoenix and Dorado areas in the Bedout Sub-basin, which includes the Phoenix, Phoenix South, Roc and Dorado accumulations, the Lower to Middle Triassic Lower Keraudren Formation has been subdivided into several informal lithostratigraphic units (**Figure 9**; Carnarvon Petroleum Ltd, 2017a; Minken et al, 2018). The reservoir units are the Huxley member, Barret member (Phoenix South 1 oil discovery), sandstone within the Hove member (Phoenix South 2 oil), Caley member (Roc 1, Roc 2, Phoenix South 2 Phoenix South 3 gas-condensate; Dorado 1, Dorado 2 and Dorado 3 oil), sandstone within the Baxter member (Dorado 1, Dorado 2 and Dorado 3 gas-condensate), the Crespin member (Dorado 1 and Dorado 3 oil), and the Milne member (Dorado 1 and Dorado 2 oil, Roc 1 and Roc 2 shows; Thompson et al, 2018; Carnarvon Petroleum Ltd, 2018b, 2019a, 2019c).

Despite being buried to depths of more than 4 km, these reservoirs exhibit good preservation of porosity and permeability (Woodward et al, 2018). The Caley member reservoir, as intersected in the Roc wells, is of excellent quality and is characterised as a well sorted quartz arenite, of a mature sedimentary provenance, and deposited in a high-energy sedimentary environment. A low geothermal gradient in the Bedout Sub-basin is thought to have restricted the development of quartz cements, contributing to the preservation of high permeabilities in the area (Woodward et al, 2018). Drilling at Dorado (Dorado 1, 2 and 3) has similarly encountered high quality reservoirs within the Caley, Baxter, Crespin and Milne members (Carnarvon Petroleum Ltd, 2019a, 2019d; Santos, 2019a).

The sandstone-prone intervals of the Caley, Baxter, Crespin and Milne members are separated by mudstone-prone intervals that act as intraformational seals. The Hove member, which comprises claystone deposited during a regional flooding event, provides a regional seal (Woodward et al, 2018). The uppermost seal is the Palma member, a thin claystone interval that overlies the Barret member. At Dorado, seal to the Caley, Baxter, Crespin and Milne member reservoirs is provided by the fine-grained fill of an incised valley (the Dorado Canyon, originating from the top of the Caley member; Thompson et al, 2018).

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The Jurassic Depuch Formation comprises several fluvio-deltaic progradational wedges (Smith et al, 1999). Potential reservoir units that have been the subject of exploration interest (e.g. Woodside Energy Ltd, 2003, 2007) include the Legendre Formation (upper Depuch Formation), a regressive package at the base of the Athol Formation (middle Depuch Formation) and sandstone intervals within the North Rankin Formation (basal Depuch Formation). The mudstone-prone Athol Formation equivalent provides the seal for the basal Athol and North Rankin reservoirs, while Lower Cretaceous shales (e.g. Baleine Formation) provide seal for the Legendre Reservoir.

Cretaceous deposition in the Roebuck Basin is dominated by marine mudstone, marl, and fine-grained carbonate. Smith et al (1999) inferred that these fine-grained lithologies dominated as the result of a relatively lower sediment supply to the basin during prolonged thermal subsidence. The main potential reservoir unit is the Lower Cretaceous Broome Sandstone, which is linked by Smith et al (1999) to the separation of Greater India in the Valanginian.

## Timing of generation

Early modelling of the thermal history of the Roebuck Basin (Smith et al, 1999) suggests thermal maturity did not increase until the deposition of the thick carbonate wedge that commenced in the Oligocene; this carbonate wedge is clearly visible on seismic line s120-01 (**Figure 5**) and is well developed in the inboard Rowley Sub-basin. Increased source rock maturities are expected as the sediments have been exposed to increased temperatures since the onset of the carbonate wedge development. Further assessment of the thermal history and timing of generation in the Roebuck Basin is required in light of recent discoveries and advances in understanding of basin evolution..

The Lower Keraudren Formation lies within the peak-oil maturity window, as indicated by  $T_{max}$  and vitrinite reflectance data from wells (**Figure 14**; Pathfinder Energy Pty Ltd, 2015; Rollet et al, 2019a). Similarly, the upper Keraudren Formation has reached maturity for oil generation in wells in the Bedout Sub-basin (Rollet et al, 2019a). Thermal modelling suggests that in the Bedout Sub-basin Early Triassic source rocks entered the oil window in the Early Jurassic with subsequent expulsion occurring between the Oligocene and the Quaternary due to loading from the regional carbonate wedge (Smith et al, 1999).

Well data in the Rowley Sub-basin show that Upper Triassic source rocks have reached thermal maturity for oil generation (**Figure 14**; Rollet et al, 2019a). Petroleum systems modelling by Woodside Energy Ltd (2007) for Triassic and Middle Jurassic source rocks in the outer Rowley Sub-basin demonstrated that the main phase of hydrocarbon generation took place during the Jurassic, with expulsion occurring at a slower rate during the Cretaceous, and with no significant hydrocarbon generation during the Cenozoic. However, this modelling may need to be revisited given the recent advances in understanding of the evolution of the basin, particularly in the outer Rowley Sub-basin.

## Play types

The majority of targets in the Roebuck Basin have been structural traps comprising tilted fault blocks and fault bound anticlines with Triassic and Jurassic reservoirs (**Figure 15**).

### *Bedout Sub-basin*

Exploration successes in the Bedout Sub-basin have targeted plays within the Lower Keraudren Formation (**Figure 12**) that are older and deeper than traditional North West Shelf targets.

At Phoenix South and Roc a self-contained petroleum system play exists with large faulted anticlinal structures at the Lower Keraudren Formation level that includes stacked reservoirs, source rocks and seals (Thompson et al, 2018). A structural-stratigraphic play has also been proven (Phoenix South 2) with sandy intervals within the dominantly fine grained Hove member (the lower Keraudren Formation).

Most recently, a sub-unconformity play has been realised where an incised valley system has developed along the southern margin of the sub-basin at the Caley-Hove unconformity (TR15.0 SB; **Figure 4**, **Figure 6**, **Figure 9**; Minken et al., 2018). These incisions, some of which are more than 500 m deep, developed in response to uplift and were subsequently back-filled with the Hove member. As for the Phoenix South and Roc plays, Dorado is likely self-sourced, and has stacked reservoirs with intra-formational seals (**Figure 12**). Further examples of this play type have been identified in the sub-basin and are being actively explored.

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### **Rowley Sub-basin**

In the Rowley Sub-basin structural features are not as strongly developed as in neighbouring sub-basins, limiting the range of potential structural plays to be explored. Early exploration focused, without success, on Jurassic sandstones within structural traps, both inboard (East Mermaid 1, anticline play), and outboard (Whitetail 1 and Huntsman 1, tilted fault block plays). In the outboard parts of the sub-basin, where the post-breakup section thins and the Triassic and older section thickens, deeper plays within the Permian–Triassic section, and Jurassic fault blocks with access to hydrocarbons generated by Triassic or Permian source rocks may have some potential. Drilling of Anhalt 1 and Hanover South 1 intersected Late Triassic volcanics, that together with interpretations of geophysical data rule out plays relying on Middle-Lower Triassic source rocks and reservoirs. Tilted fault-blocks and faulted anticline structures with target reservoirs at the Late Triassic–Early-Middle Jurassic level remain prospective.

Potential also exists for a range of stratigraphic plays in the Rowley Sub-basin. For example, fluvio-deltaic sandstone bodies in the Jurassic Depuch Formation, charged from intraformational or underlying source rocks (Lipski, 1993; Smith et al., 1999), and onlap/pinchout plays associated with growth of Triassic anticlines. In addition, the Rhaetian reef play tested in the outer Exmouth Plateau at Tiberius 1 (Grain et al., 2013) may also be a viable exploration target along the outer margins of the Rowley Sub-basin where Late Triassic shelfal carbonates have been dredged (Colwell et al, 1994) and drilled (Anhalt 1, Hannover South 1).

### **Critical Risks**

Until the recent discoveries at Phoenix South, Roc and Dorado, the lack of a proven petroleum system was the major risk. The lack of discoveries in the Roebuck Basin was originally attributed to the lack of valid traps caused by the relatively gentle structuring, rather than a lack of hydrocarbon charge. A poor understanding of the petroleum systems, migration pathways and play types across the broader Roebuck Basin is due to the relative paucity of exploration wells. Recent drilling discoveries and good coverage by modern 3D seismic data has significantly improved the understanding of the basin and de-risked some aspects of exploration in the Roebuck Basin.

The Bedout Sub-basin was initially thought to be gas-prone due to the misinterpreted gas discovery at Phoenix 1 (which is now believed to possess a significant oil column). However, evidence of palaeo-oil columns exist within the basin and the recent discoveries indicate that the Roebuck Basin is both oil- and gas-prone.

A critical risk for plays targeting reservoirs at depths greater than 4 km is the preservation of reservoir quality, which is dependent on sedimentary facies and the provenance of reservoir sediments (Woodward et al, 2018). For the Lower Keraudren Formation self-contained plays, the absence of any of the source, reservoir or sealing facies is a critical risk.

Weathered or altered igneous lithologies, such as the Permian Bedout Volcanics (Lagrange 1, Bedout 1), and the Triassic volcanics recently intersected in several Rowley Sub-basin wells (Anhalt 1, Hannover South 1) downgrade the prospectivity for the Lower Triassic for the outer Rowley Sub-basin, where a lack of source rocks is a key critical risk.



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## Geoscience Australia products and data

### Regional geology

- Geoscience Australia Triassic Horizon and Isochron Grids, Central North West Shelf, [Digital Dataset by Orlov et al, 2019a](#) resulting from regional mapping program conducted to address stratigraphic and structural aspects of exploration risk
- Geoscience Australia's new tectonostratigraphic framework, that also includes lithostratigraphy, gross depositional facies and tectonic extension phases, as well as palaeogeographic interpretations by [Abbott et al, 2019a](#) and [Abbott et al, 2019b](#)
- Crustal structure and distribution of volcanics in the Northern Carnarvon and Roebuck basins, central Australian Northwest Shelf. [Geoscience Australia, Record 2019/022 by Rollet et al, 2019b](#)
- Enhanced gravity and magnetic grids for Northern Australia, [Digital Dataset by Shi and Rollet, 2019](#)

### Well control

- A summary of the target and outcome of petroleum wells drilled in the Roebuck Basin is available via Geoscience Australia's [Acreage Release webpage](#).
- [A well folio by Nguyen et al, 2019b](#) of 24 offshore wells across the Beagle, Bedout, Rowley and Barcoo sub-basins has been compiled as part of Geoscience Australia's hydrocarbon prospectivity assessment across the region. The folio consists of composite well log plots summarising lithology, stratigraphy, Geoscience Australia's newly acquired biostratigraphic and geochemical data and petrophysical analysis, in conjunction with revised sequence stratigraphic interpretations.

### Petroleum systems

- Results from the [Triassic and Older Source Rock Petroleum Systems Study](#) that explores the extent and potential of Triassic and older systems, across the central north-west margin. Including organic geochemical data and interpretations on recently discovered hydrocarbons by [Grosjean et al, 2019a](#), and [Grosjean et al, 2019b](#)
- Triassic petroleum systems on the central North West Shelf. [Extended Abstract by Rollet et al, 2019a](#) detailing findings from an integrated study of the structural architecture, sequence stratigraphy, palaeogeography and geochemistry that has mapped the spatial and temporal distributions of Triassic source rocks on the central NWS.

### 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 such as 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.

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## Marine and environmental information

The following section contains information about the existing marine parks, their special habitat zones and physiographic features within the Roebuck Basin (**Figure 16**). The information is provided in support of business decisions with respect to planned exploration and development activities. The Roebuck Basin is located on the northwest margin of Australia and primarily includes continental slope with terrace and ridge geomorphological features and is located offshore from the Kimberley 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 Roebuck Basin region.

#### *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 600 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.

Two of the marine parks within the North-west Marine Parks Network overlie or intersect the Roebuck Basin; Argo-Rowley Terrace Marine Park and Mermaid Marine Park. In addition, two marine parks are proximal to the Roebuck Basin; Kimberley Marine Park and Eighty Mile Beach 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>

Extracts from these plans are included below.

#### *Argo-Rowley Terrace Marine Park*

The [Argo-Rowley Terrace Marine Park](#) is located approximately 270 km northwest of Broome, Western Australia, and extends to the limit of Australia's exclusive economic zone. The Marine Park is adjacent to the Mermaid Reef Marine Park and the Western Australian Rowley Shoals (State) Marine Park. The Marine Park covers an area of 146 003 km<sup>2</sup> and water depths range between 220 m and 6000 m.

#### **Statement of significance**

The Argo-Rowley Marine Park is significant because it contains habitats, species and ecological communities associated with the Northwest Transition and Timor Province. It includes two key ecological features: canyons linking the Argo Abyssal Plain with the Scott Plateau (valued for high productivity and aggregations of marine life); and Mermaid Reef and Commonwealth waters surrounding Rowley Shoals (valued for enhanced productivity, aggregations of marine life and high species richness).

The Marine Park is the largest in the North-west Network, surrounding the existing Mermaid Reef Marine Park and reefs of the Western Australian Rowley Shoals Marine Park. It includes the deeper waters of the region and a range of seafloor features such as canyons on the slope between the Argo Abyssal Plain, Rowley Terrace and Scott Plateau. These are believed to be up to 50 million years old and are associated with small, periodic upwelling that result in localised higher levels of biological productivity.

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

#### *Mermaid Reef Marine Park*

The [Mermaid Reef Marine Park](#) is located approximately 280 km northwest of Broome and is adjacent to the Argo-Rowley Terrace Marine Park and Rowley Shoals State Marine Park.

#### **Statement of Significance**

The Mermaid Reef Marine Park is significant because it contains habitats, species and ecological communities associated with the Northwest Transition. It includes one key ecological feature: Mermaid Reef and Commonwealth waters surrounding Rowley Shoals (valued for its high productivity, aggregations of marine life and high species richness).

Mermaid Reef is one of three reefs forming the Rowley Shoals. The other two are Clerke Reef and Imperieuse Reef, to the southwest of the Marine Park, which are included in the Rowley Shoals State Marine Park. The reefs of the Rowley Shoals are ecologically significant in that they are considered stepping stones for reef species originating in Indonesian/Western Pacific waters, are one of a few offshore reef systems on the North West Shelf, and may also provide an upstream source for recruitment to reefs further south.

Major Conservation Values:

- Mermaid Reef has national and international significance due to its pristine character, coral formations, geomorphic features and diverse marine life;
- key area for over 200 species of hard corals and 12 classes of soft corals with coral formations in pristine condition;
- important areas for sharks including the Grey Reef Shark, the Whitetip Reef Shark and the Silvertip Whaler;
- important foraging area for marine turtles;
- important area for toothed whales, dolphins, tuna and billfish;
- important resting and feeding sites for migratory seabirds;
- the reserve, along with nearby Rowley Shoals Marine Park, provides the best geological example of shelf atolls in Australia.

The reserve is currently zoned as a Marine National Park IUCN Category II and includes one zone under the North-west Marine Parks Network Management Plan (2018): National Park Zone (II).

#### *Eighty Mile Beach Marine Park*

The [Eighty Mile Beach Marine Park](#) is located approximately 74 km northeast of Port Hedland, adjacent to the Western Australian Eighty Mile Beach Marine Park. The Marine Park covers an area of 10 785 km<sup>2</sup> and water depths range from less than 15 m to 70 m.

#### **Statement of significance**

The Eighty Mile Beach Marine Park is significant because it contains habitats, species and ecological communities associated with the Northwest Shelf Province and consists of shallow shelf habitats, including terrace, banks and shoals. The Marine Park is adjacent to the Eighty Mile Beach Ramsar site, recognised as one of the most important areas for migratory shorebirds in Australia; and the Western Australian Eighty Mile Beach Marine Park, providing connectivity between offshore and inshore coastal waters of Eighty Mile Beach.

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

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### ***Kimberley Marine Park***

The [Kimberley Marine Park](#) is located approximately 100 km north of Broome, extending from the Western Australian state water boundary north from the Lacepede Islands to the Holothuria Banks offshore from Cape Bougainville. The Marine Park is adjacent to the Western Australian Lalang-garram/Camden Sound (State) Marine Park and the North Kimberley (State) Marine Park. The Marine Park covers an area of 74 469 km<sup>2</sup> and water depths from less than 15 m to 800 m.

#### **Statement of Significance**

The Kimberley Marine Park is significant because it includes habitats, species and ecological communities associated with the Northwest Shelf Province, Northwest Shelf Transition and Timor Province. It includes two key ecological features: the ancient coastline at the 125 m depth contour (an area of enhanced productivity and migratory pathway for cetaceans and pelagic marine species); and continental slope demersal fish communities (valued for high levels of endemism and diversity and the second richest area for demersal fish species in Australia). The Marine Park provides connectivity between deeper offshore waters, and the inshore waters of the adjacent Western Australia North Kimberley Marine Park and Lalang-garram/Camden Sound Marine Park.

Major Conservation Values:

- important foraging areas for migratory seabirds, migratory Dugong, dolphins and threatened and migratory marine turtles;
- important migration pathway and nursery areas for the protected Humpback Whale;
- adjacent to important foraging and pupping areas for sawfish and important nesting sites for the Green Turtle;
- the reserve provides protection for the communities and habitats of waters offshore of the Kimberley coastline ranging in depth from less than 15 m to 800 m;
- continental shelf, slope, plateau, pinnacle, terrace, banks and shoals, and deep hole/valley seafloor features are all represented in this reserve.

A summary of [recent research in Kimberley Marine Park](#) is provided in Puotinen et al. (2019).

The Marine Park is assigned IUCN category VI 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).

### **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. One Western Australian Marine Park is proximal to the Roebuck Basin: Eighty Mile Beach Marine Park.

#### ***Eighty Mile Beach Marine Park***

The [Eighty Mile Beach Marine Park](#) protects Eighty Mile Beach, an extensive stretch of remote coastal country located between Port Hedland and Broome, about 1700 km north of Perth. Eighty Mile Beach stretches for approximately 220 km from Cape Missiessy to Cape Keraudren.

The park contains vast intertidal sand and mudflats that extend up to four kilometres wide at low tide, and provide a rich food source for many species. Eighty Mile Beach is one of the world's most important feeding grounds for migratory shore birds and is a major nesting site for flatback turtles, which are found only in northern Australia.

The zoning scheme for the Eighty Mile Beach Marine Park comprises:

- three sanctuary zones;
- four special purpose zones (cultural heritage);

- one special purpose zone (mangrove protection);
- two special purpose zones (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. Cultural heritage zones provide for the recognition and protection of areas of high cultural significance to the traditional owners. The mangrove protection zone provides improved protection for mangroves, saltmarshes, and species inhabiting these areas, whilst allowing for some compatible recreational use. Shore-based activity zones provide an opportunity for shore-based recreational and commercial activities that are compatible with the maintenance of the park values. The recreation zone extends approximately 10 km north and south of the Eighty Mile Beach Caravan Park, and allows appropriate opportunity for visiting tourists to conduct recreational activities, whilst providing protection for nesting turtles, turtle hatchlings, waterbirds, and their habitats. Areas not covered by these zones are for general use i.e. providing for biodiversity conservation alongside a range of recreational and commercial activities.

Eighty Mile Beach Marine Park is managed in partnership with the traditional owners, the Karajarri, Nyangumarta, and Ngarla people. The traditional owners maintain connection to their tradition coastal and sea country through identity and place, family networks, spiritual practice, and resource gathering. Native title rights and interests have been recognised over the intertidal areas of the park.

## Heritage

The *Lively*, a sailing ship wrecked in 1810, is located near Mermaid Reef (coordinates: 17.09°S, 119.59°E). The *Sea Taube*, wrecked in 1954, is located north of Cunningham Island (coordinates: 17.00°S, 118.75°E). These and other shipwrecks can be identified and located using the [Australian National Shipwreck Database](#) map search tool.

The Dampier Archipelago and Murujuga, also known as the Burrup Peninsula, are National Heritage listed. <http://environment.gov.au/heritage/heritage-places>

## Fisheries

The following Commonwealth fisheries occur in the Roebuck Basin area:

- North West Slope Trawl Fishery operates in the area between 200 m water depth to the outer limit of the Australian fishing zone 200 nautical miles from the coast. The fishing season runs year round.

The Roebuck Basin is located in the Western Australian North Coast bioregion. The Western Australian Government manages 15 commercial fisheries within the North Coast bioregion (Fletcher and Santoro, 2015). Tropical finfish, Spangled Emperor, Snapper and Cod are targeted in the Northern Demersal Scalefish (trap and line) fishery. The Mackerel Managed Fishery targets Spanish Mackerel (Fletcher and Santoro, 2015).

## Climate of the region

The northwest shelf region experiences an arid tropical climate with two distinct seasons: the northwest monsoon (October-March) and the northeast to southeast monsoon (April-September), with a rapid transitional period between each season. At the nearby onshore [Port Hedland Airport weather station](#), approximately half of the precipitation is associated with tropical cyclones, and most precipitation occurs between December and March. The annual mean maximum and minimum temperatures recorded at Port Hedland were 36.8°C and 12.4°C respectively, for the time period from 1948 to 2019. Mean annual rainfall during this interval was 317.7 mm. Mean maximum and minimum temperatures and precipitation for Barrow Island are similar; 30.2°C and 21.5°C, and 318.2 mm of rainfall per annum. Tropical cyclones often occur, most commonly in January and February. The region between Broome and Exmouth is the most cyclone-prone region of the Australian coastline, and has the highest frequency of cyclone crossings (~2 per annum). The impacts of tropical cyclones include extreme waves, and higher than normal wind-driven currents.

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## Oceanic regime

The offshore marine environment of the Roebuck Basin is strongly influenced by the seasonal (May to September), largely wind-driven, Holloway current (Wilson, 2013). This current comes from the Indonesian Throughflow Current (ITC), and combines with the Eastern Gyral Current in the vicinity of the Rowley Shoals to form the headwaters of the Leeuwin Current (Wilson, 2013).

Sea surface temperatures in this region are comparatively warm for Australian waters (around 27°C) and are predicted to increase by 0.2°C per decade in the immediate future (Foster et al, 2014). Locally, water temperature is approximately 24°C adjacent to Rowley Shoals, with little annual variation. Internal tides affect water depths of 50–150 m and can generate near-bed currents of 10–50 cm/s, while shore-normal saline bottom flows that likely vary seasonally in intensity, affect shallower coastal seabed (Rayson et al. 2011; Collins et al, 2014). Conductivity, Temperature and Depth (CTD) data indicates there may be four different water masses in this region, with bottom water temperatures of 7°C at 670 m depth (Jones et al, 2007).

## Seabed environments

The seabed of the Roebuck Basin comprises gently sloping to steep continental shelf and slope, with several terraces aligned sub-parallel to the modern coastline (Heap and Harris, 2008). Biogenic reef growth, initiated in the Miocene (Jones, 1973; Ryan et al, 2009) is ongoing on three topographic highs in the Rowley Shoals on the outer shelf ramp (Mermaid, Clerke and Imperieuse: Ryan et al, 2009; Collins, 2010), where growth has kept pace with subsidence. These shelf edge atolls exhibit central lagoons and steep to vertical perimeter walls (Wilson, 2013).

Water depths are 230 m at Imperieuse Reef, 390 m at Clerke Reef and 440 m at Mermaid Reef. Tidal range is reported as 4.5 m at the offshore shelf reef edges (Wilson, 2013)

Sediment texture (mud, sand, gravel) distribution across the north-west shelf region has been modelled by Li (2017a, 2017b and 2017c). Sediment size across the Roebuck Basin is distinctly different between the areas seaward and shoreward of the Rowley Shoals (McLoughlin et al, 1988). This division essentially coincides with the boundary of two internal sub-basins: the more landward Bedout Sub-basin and more seaward Rowley Sub-basin. The seafloor of the Bedout Sub-Basin is characterised by gravelly sand (>50% sand, with up to 30% gravel and only minor mud). In contrast, the seabed of Rowley Sub-Basin, which includes the Rowley Shoals, is typically sandy mud (>60% mud and <30% sand), although the bed material coarsens markedly towards the shoreward limit of the sub-basin, in the vicinity of the Shoals (which are fringed by gravelly, muddy sand; Passlow et al, 2005). Away from the reefs, sediment in this area is likely to be dominated by pelagic deposits, commonly as green planktonic foraminifera–pteropod-rich carbonate sand or muddy carbonate sand (James et al, 2004; Jones et al, 2007). Riverine-derived sediments are restricted to the inner ramp (James et al, 2004).

Ryan et al (2009) examined the drivers for reef development in this area and were unable to find any direct evidence that active or ancient hydrocarbon seepage has triggered or controlled growth of the Rowley Shoals reefs (or their buried Miocene predecessors). Sand waves, with crests oriented roughly perpendicular to the local tidal currents, and fluid expulsion features (pockmarks) have been identified immediately to the east of the Roebuck Basin, on the Offshore Canning Basin (Jones et al, 2007, 2009). Jones et al (2009) defined two types of sand waves in the region: a low-amplitude composite form comprising dunes and ripples, and a more laterally restricted form with high bedforms and high surface slopes. The latter were associated with seabed fluid flow. Pockmarks have also been identified ~50 km to the northeast on the Leveque Shelf and their formation at both of these locations has been attributed to the expulsion of seawater at the seabed, driven by tidal pumping through the shallow sub-surface (Nicholas et al, 2016).



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## Ecology

The Roebuck Basin is part of the North-West Marine Bioregion which extends from the Western Australia-Northern Territory border to Kalbarri, south of Shark Bay. This region has comparatively low rates of endemism and high biodiversity and is dominated by Indo-west Pacific tropical flora and fauna; it is also home to globally significant populations of internationally threatened species (Commonwealth of Australia, 2008). At the smaller scale of provincial bioregions (IMCRA 4.0), the Roebuck Basin is included in the Northwest Transition, which is an area of overlap (i.e. it does not have distinct fauna, flora and ocean conditions compared to adjacent areas; Commonwealth of Australia, 2005). The deep ocean seafloor of the Roebuck Basin likely supports meiofauna, infauna and patches of epibenthic communities (Brewer et al, 2007), as well as mobile animals such as holothurians, decapods, polychaetes, cephalopods, and benthic-pelagic fish (Daniell et al 2009). The Roebuck Basin includes part of the north-west slope which has been shown to support the second richest demersal fish assemblage in Australia (Last et al, 2005).

## Recent geological history

The Roebuck Basin was previously (prior to 1994) known as part of the Offshore Canning Basin, and is located on the central North West Shelf between the Northern Carnarvon and Browse Basins and outboard of the offshore portion of the predominantly Paleozoic Canning Basin. It has recently been proposed that a seismically active fault system deforms Pliocene to Holocene strata across the Browse, Roebuck and Carnarvon basins (Hengesh and Whitney, 2015). Buried Miocene reefs provide a major stratigraphic marker in this region over which more recent stratified sediment has been deposited. During the Miocene, the Rowley Shoals area formed a narrow continental shelf. Post-Miocene subsidence has occurred in this area, and since the last interglacial interval of higher than present sea level, differential subsidence of the Rowley Shoals reefs has occurred (Collins, 2002). Apart from reef areas, the seabed would not have been exposed during intervals of lower sea level during the Quaternary, and the presence of stratified sediment layers overlying the Miocene reefs appear to support this. However, unconformities are present in these young strata, most likely the result of changing oceanographic conditions (Jones et al, 2007). Additionally, shallow sub-bottom seismic data indicates that in places, recent, possibly Quaternary, fault movement has occurred (Jones et al, 2007).

## 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](#)
- [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** Location map showing the sedimentary basins of the Westralian Superbasin on Australia's North West Shelf.
- Figure 2** Map of the Roebuck Basin showing bathymetry, petroleum well distribution and oil and gas fields.
- Figure 3** Tectonic elements map of the Roebuck Basin showing major faults, petroleum well distribution and oil and gas fields. The locations of the seismic sections shown in Figures 5, 6 and 12 are also shown.
- Figure 4** Stratigraphic chart for the Roebuck Basin showing North West Shelf Supersequence Framework, basin phases and hydrocarbon occurrences (Geologic Time Scale after Ogg et al, 2016).
- Figure 5** Seismic line s120/01 across the Roebuck Basin and Argo Abyssal Plain. Interpretation by Geoscience Australia. Location of the seismic section is shown in Figure 3.
- Figure 6** **a)** Interpreted seismic line across the Bedout and Beagle sub-basins showing a basin thickening Triassic wedge and a transition from relatively unstructured to highly faulted structural style. The location of the Dorado Canyon is indicated. **b)** Seismic line from the Rowley Sub-basin showing the interpreted Lower Triassic volcanic depocentre, minor Middle to Late Triassic growth, conspicuous onlap on to the base Triassic horizon, and a Paleozoic growth wedge adjacent to the East Mermaid fault. The locations of the seismic sections are shown in Figure 3. Refer to Figure 4 for sequence boundary ages. Modified from Abbott et al, 2019a.
- Figure 7** **a)** Structure map of the base Triassic (TR10.0\_SB seismic horizon) across the central North West Shelf. **b)** Triassic isochron map illustrating the location of major Triassic depocentres in the Rowley Sub-basin and Beagle Sub-basin/Exmouth Plateau. Modified from Abbott et al, 2019a.
- Figure 8** Palaeogeographic maps of four Triassic intervals on the central North West Shelf (after Abbott et al, 2019b): **a)** Early–Middle Triassic Interval (TR10.0\_SB–TR15.0\_SB); **b)** Middle Triassic Interval (TR15.0\_SB–TR17.0\_SB); **c)** Middle–Late Triassic Interval (TR17.0\_SB–TR30.1\_TS); **d)** Late Triassic Interval (TR30.1\_TS–J10.0\_SB). Intervals are bound by the mapped unconformities shown in Figure 6. Refer to Figure 4 for sequence boundary ages.
- Figure 9** Stratigraphy of the Bedout Sub-basin for the Triassic showing the informal members within the Keraudren Formation and their related lithology, petroleum system elements, discoveries and shows (after Thompson et al, 2018). Disc: Discovery, Res: Reservoir, SR: Source Rock.
- Figure 10** Map showing the current main operators, active exploration permits, retention leases and production licences in the Roebuck Basin.
- Figure 11** Petroleum production facilities, petroleum fields and pipeline infrastructure in the vicinity of the Roebuck Basin.
- Figure 12** Schematic cross-section showing Phoenix South, Roc and Dorado hydrocarbon discoveries in the Bedout Sub-basin. Informal stratigraphy is shown in Figure 9, location of the section is shown in Figure 3. Modified after Thompson et al, 2018.
- Figure 13** Carbon isotopic data of Phoenix South 1 oils compared to Perth Basin and other North West Shelf fluids (after Grosjean et al. 2018, 2019c).
- Figure 14** Rock-Eval pyrolysis data plots indicating source rock type, quality and maturity for selected wells on the central North West Shelf. Plots are TOC vs HI and Tmax vs HI for: **a)** and **b)** the Early Triassic (sequences TR10–TR14); **c)** and **d)** the Middle Triassic (sequences TR15–TR16); and, **e)** and **f)** the late Middle–Late Triassic (sequences TR17–TR30). Wells are grouped by colour according to their location. Blue: Rowley Sub-basin; purple: Bedout Sub-basin; orange: Barcoo Sub-basin; green: Beagle Sub-basin (after Rollet et al, 2019a).
- Figure 15** Play diagram illustrating potential hydrocarbon plays in the Roebuck Basin. Modified from Carnarvon Petroleum Ltd., 2016f
- Figure 16** Map showing marine reserves, marine parks, multiple use zones and ecological features in the Roebuck Basin.