



## Regional Geology of the Southern Carnarvon Basin

The Southern Carnarvon Basin is a large (192 000 km<sup>2</sup>) predominantly Paleozoic sedimentary basin covering onshore and offshore regions of north-western Western Australia. It lies to the south of the Mesozoic Northern Carnarvon Basin, Australia's premier oil and gas producing basin. The Southern Carnarvon Basin comprises the Gascoyne, Merlinleigh and Byro sub-basins and the Bernier Platform (**Figure 1**, **Figure 2** and **Figure 3**). Of these, the Bernier Platform and western Gascoyne Sub-basin lie offshore. The offshore part of the Gascoyne Sub-basin lies mostly in shallow water (50–200 m), whereas the Bernier Platform is in much deeper water (200–2000 m). The offshore part of the Southern Carnarvon Basin covers an area of approximately 95 000 km<sup>2</sup>.

Petroleum exploration of the Southern Carnarvon Basin began with the discovery of Rough Range oil field in 1953. It was followed by two decades of regional mapping and unsuccessful drilling. By the mid-1970s, petroleum discoveries in the adjacent Northern Carnarvon Basin attracted exploration focus and exploration in the Southern Carnarvon Basin almost ceased. Systematic mapping of the onshore basin by the Geological Survey of Western Australia and offshore exploration by industry in the 1990s demonstrated the potential prospectivity of this underexplored region. To date, 76 onshore (including 57 stratigraphic tests) and only two offshore wells (Pendock 1a and Edel 1; **Figure 1**) have been drilled in the Southern Carnarvon Basin. No offshore fields or accumulations have yet been discovered. The Southern Carnarvon Basin is close to infrastructure at Carnarvon which connects to the West Australian pipeline network (**Figure 1**).

### Basin outline

The Southern Carnarvon Basin is underlain by the Pinjarra Orogen and Paleoproterozoic Capricorn Orogen. It borders the Exmouth Sub-basin (Northern Carnarvon Basin) in the northwest, the Yilgarn Craton in the southeast, and the Houtman and Coocalalaya sub-basins (Perth Basin) in the south (**Figure 1**).

### Gascoyne Sub-basin and Bernier Platform

The Gascoyne Sub-basin and the Bernier Platform contain an Ordovician (possibly as old as Cambrian) to Carboniferous sedimentary succession deposited in a northwards-opening intracratonic basin (Mory et al, 2003; Lockwood and D'Ercole, 2004). From the middle Carboniferous to the earliest Cretaceous these areas were structural highs with little or no deposition. Only a thin cover of Cretaceous and Cenozoic strata extends across the Gascoyne Sub-basin and into the Merlinleigh Sub-basin (**Figure 4**). The Merlinleigh and Byro sub-basins were formed during Pennsylvanian–Cisuralian rifting. Syn-rift deposition in these basins continued into the late Permian. They contain thick Pennsylvanian to Permian sequences over Devonian to Mississippian age pre-rift strata (**Figure 4**, Iasky et al, 2003). Mory et al (2003) suggested that a single depocentre may have existed connecting the Merlinleigh and Byro Sub-basins with the Coolcalalaya Sub-basin of the Perth Basin to the south (**Figure 1** and **Figure 2**). Along the eastern margin of the Merlinleigh and Byro Sub-basins, the mid-Carboniferous to Permian succession onlaps the Archean Yilgarn Craton and Paleoproterozoic Gascoyne Complex (**Figure 4**). In the north this succession extends to the Rough Range Fault (**Figure 4**, Crostella and Iasky, 1997).

A major lineament, the Rough Range Fault, separates the Gascoyne Sub-basin from the hydrocarbon-bearing Exmouth Sub-basin (**Figure 2** and **Figure 5**). Along this large arcuate normal fault local displacements of more than 4000 m have been identified (Partington et al, 2003). The Rough Range Fault was active throughout the Jurassic, resulting in the deposition of several kilometres of Jurassic sediments in the northern part of Exmouth Sub-basin.

The architecture of the southernmost part of the Exmouth Sub-basin extending into Southern Carnarvon Basin is poorly known. Steeply dipping normal faults define the boundary between the Paleozoic platform and Mesozoic depocentres (**Figure 5**). Geoscience Australia seismic data collected during 2008-09, under the Offshore Energy Security program, defines several en-echelon Mesozoic depocentres with complex fault geometries (**Figure 6**). A strike line across one of these depocentres (**Figure 7**) shows significant faulting and folding within the syn-rift strata as well as a large number of sills and dykes. The rapidly thickening Mesozoic sediments within these depocentres exceed 3.5 s TWT, equivalent to about 8 000 m according to Partington et al (2003). This includes about 2.5 s TWT of syn-rift and 1 s TWT of post-rift strata.

Santonian inversion structures are widespread both in the Mesozoic depocentres and on the Bernier Platform (**Figure 5** and **Figure 6**). This inversion is coincident with and may have been caused by the major plate re-organisation in the Indian Ocean, when Greater India changed its path from northwest to north (Gibbons et al, 2010).

Miocene inversion is even more evident on the seismic (**Figure 5**). It also affected the whole region and is related to the collision of Australia and Eurasia in the middle Miocene (Partington et al, 2003). A large number of major faults have been inverted and form well defined local anticlines in the post-breakup strata.

In the Exmouth Sub-basin, igneous rocks (predominantly sills and dykes) are widespread within the Mesozoic and possibly within the pre-rift upper Paleozoic succession (**Figure 7**). Most of the igneous activity is associated with the Early Cretaceous breakup on the western Australian margin (Muller et al, 2002). The volume of volcanic rocks noticeably increases to the south, towards the Wallaby Plateau. This part of the margin is described as a volcanic rifted margin characterised by excessive volcanism overprinting all pre-existing structures (Direen et al, 2008; Symonds et al, 1998)

## Merlinleigh Sub-basin

In the Merlinleigh Sub-basin, the Pennsylvanian to Permian successions are considered to be the most prospective for petroleum, whereas in the Gascoyne-Bernier area the best potential is considered to lie within the Silurian (Coburn Formation) and Upper Devonian (Gneudna Formation) successions (**Figure 8**; Ghori, 1998). Source rocks within these formations are described as thin intervals of limited extent (Mory et al, 2003). By comparison, Permian source rocks (Cisuralian Wooramel and Byro Groups; **Figure 8**) within the Merlinleigh and Byro sub-basins appear to be thick and widespread. Geohistory modelling indicates that petroleum generation (and consequently migration) from Silurian and Devonian source rocks peaked during the Permian, whereas generation from Permian source rocks peaked during the Triassic (Ghori et al, 2005; Mory et al, 2003). Therefore, in the Gascoyne Sub-basin, mid-Carboniferous–Cisuralian structures are the most prospective, whereas within the Merlinleigh and Byro sub-basins hydrocarbon accumulations are more likely in Early Cretaceous or Miocene structures.

## Basin evolution and stratigraphy

The geological evolution of the Southern Carnarvon Basin has been influenced by multiple extensional episodes related to the breakup of Gondwana accompanied by reactivation of Archean and Proterozoic structures (Mory et al, 2003). The Gascoyne Sub-basin and Bernier Platform contain gently folded and faulted Ordovician to Devonian sequences, unconformably overlain by thin Mesozoic and younger rocks, while the Merlinleigh and Byro sub-basins to the east are characterised by thick Pennsylvanian to Permian sequences over Devonian to Mississippian sequences. Due to collision between Australia and Eurasia in Mid-Miocene, the region has undergone major fault reactivation and inversion during this time.

## Ordovician (?Cambrian) to mid-Carboniferous

Deposition in the Southern Carnarvon Basin probably began in the Cambrian when the breakup of Rodinia caused uplift of the Pilbrara and Northampton Blocks and basement subsidence to the west (Lockwood and D'Ercole, 2004). The first depositional package is an unnamed unit with patchy distribution identified only from seismic. The unconformable relationship between this package and the overlying Tumblagooda Sandstone, coupled with its growth geometry along basement faults (**Figure 4**), indicates that deposition occurred during a poorly understood early rifting phase (lasky et al, 2003). It is inferred to be a fluvial succession initially interpreted to be equivalent to the thick Silurian siliciclastic section in Wandagee 1 and later revised to be Cambrian to Ordovician age (lasky et al, 2003; Ghori et al, 2005).

The Tumblagooda Sandstone (**Figure 8**) unconformably overlying the unnamed unit is well documented from outcrops in the Southern Carnarvon Basin. It is a package of coarse grained redbeds with minor siltstone and mudstone deposited in a braided fluvial and coastal environment (Hocking, 1991, lasky et al, 2003). The latest Cambrian to Ordovician age of this unit is bracketed by the earliest Silurian fauna identified within the overlying Ajana Formation (Mory et al, 1998), and interpreted eurypterid tracks in the middle part of the formation which would be no older than Early-Middle Ordovician (Mory et al, 2003). The Tumblagooda Sandstone extends into the Northern Carnarvon Basin and south into the North Perth Basin, where it outcrops along the southwestern margin of the adjacent Coolcalalaya Sub-basin.

In the Silurian, a broad, north-plunging syncline formed on the Southern Carnarvon margin. A thick succession of Paleozoic (Silurian to Permian) sediments deposited during this time is preserved in the Gascoyne Sub-basin (lasky et al, 2003). Latest Ordovician to Silurian deposition of the Dirk Hartog Group (**Figure 8**) occurred in restricted marine environments with short periods of open marine conditions (Lockwood and D'Ercole, 2004). Carbonates of the Dirk Hartog Group were first encountered in Dirk Hartog 17B, which was drilled by WAPET in 1957. This group is present throughout the Gascoyne Sub-basin and thickens towards the west, with a maximum known thickness of 740 m in Dirk Hartog 17B and at least 650 m in Pendock 1a. In ascending order, the Dirk Hartog Group comprises: the Ajana Formation of upwards shoaling sandy mudstones, laminated mudstones and wackestone, the Yaringa Formation of dolomite and evaporitic rocks, and the Coburn Formation of dolomitic carbonates (Mory et al, 1998).

Early Devonian tectonism led to deposition of the Faura Formation, Kopke Sandstone and Sweeney Mia Formation (**Figure 8**; Mory et al, 2003). The deposition of the mudstone, dolomite, and fine-grained sandstone of the Faure Formation (Coburn 1, Mooka 1, Hamelin Pool 1, Tamala 1, and Yaringa 1) occurred in a low-energy, saline to hypersaline, shallow depositional environment (Gorter et al, 1994). Preservation of this formation is largely restricted to the southern Gascoyne Sub-basin, whereas the Kopke Formation (type section in Yaringa 1), a package of coarsening upwards sandstone unit with minor dolomite and siltstone, extends further north to the central part of the Gascoyne Sub-basin (lasky and Mory, 1999, lasky et al, 2003). Deltaic to fluvial environments of the Kopke Formation transition into the lagoonal to tidal environments of the Sweeney Mia Formation (Hamelin Pool 1 and 2, Yaringa 1, and Yaringa East 1), also preserved mostly within the central part of the Gascoyne Sub-basin. This formation is a package of carbonates and siliciclastic rocks with minor evaporitic beds.

After a depositional hiatus lasting until the late Middle Devonian, sedimentation commenced with the deposition of the Nannyarra Sandstone (**Figure 8**), a transgressive sandstone package with minor siltstone deposited in a low-energy intertidal environment (lasky et al, 2003). The maximum penetrated thickness of the Nannyarra Sandstone is 190 m from Quobba 1 (1528–1718 m). This unit grades into the overlying Gneudna Formation, which is composed of interbedded carbonates, siltstones and minor evaporitic rocks deposited in a near-shore to restricted marine environment. The unit is present in the northern Gascoyne Sub-basin where it conformably overlies the Nannyarra Sandstone and has a maximum thickness of 1092 m in Quobba 1 (436–1528 m). Point Maud Member of this formation is a massive dolomite representing platform carbonate accumulation (lasky et al, 2003). The Point Maud Member was penetrated only in Barrabiddy 1a (276–607 m) and Pendock 1a (1289–1609 m) in the northern Gascoyne Sub-basin. Conformably overlying and interfingering with the Gneudna Formation is the Upper Devonian Munabia Sandstone; a barrier complex accumulation of sandstone with minor claystone, conglomerate and dolomite. The Munabia Formation was penetrated in Barrabiddy 1 and 1a and outcrops along the eastern margin of the Merlinleigh Sub-basin between Lyndon River and Mount Sandiman Station. This siliciclastic unit is tied to renewed tectonic activity in the hinterland, and correlates onshore with the alluvial-fan accumulation of the Willaraddie Formation (Mory et al, 2003; Partington et al, 2003).

Carbonate platform deposition resumed in the northern Gascoyne Sub-basin in the earliest Carboniferous with the deposition of Moogooree Limestone (**Figure 8**; lasky et al, 2003). This shallow-marine formation is locally overlain by the Quail Formation, which is a siltstone and sandstone unit probably deposited in a shallow marine to shore face environment and laterally equivalent to alluvial fan deposits of the Williambury Formation and shallow marine siliciclastics and carbonates of the Yindagindy Formation (Mory et al, 2003).

## Mid-Carboniferous to Late Permian

Tectonism associated with the collision of Gondwana and Laurasia in the Carboniferous folded and faulted the Devonian to Carboniferous sequences along north-trending axes (Geary, 1994). This was followed by the first major rifting event in the latest Carboniferous to Cisuralian with the formation of north-northeast—south-southwest trending graben across the Southern Carnarvon Basin and the development of the Merlinleigh, Byro and Coolcalalaya Sub-basins. At the same time, the Gascoyne Sub-basin and Bernier Platform were uplifted and partially eroded (lasky et al, 2003).

Deposition during the Pennsylvanian to Cisuralian mostly comprises the Lyons Group (**Figure 8**), a shale and sandstone unit deposited in a glaciomarine environment (Hocking et al, 1987). In the Merlinleigh Sub-basin the Lyons Group is up to 3000 m thick (lasky et al, 1998; lasky et al, 2003). This Group is restricted to the northernmost part of the Gascoyne Sub-basin. Recent seismic data indicate that some Carboniferous-Permian strata may also be present in the northern part of the Bernier Platform (Partington et al, 2003).

Over large areas of the Gascoyne Sub-Basin and Bernier Platform Pennsylvanian–Permian tectonism caused uplift and erosion (Hocking et al, 1987; Ghori et al, 2005). It is inferred that, following the Permian glaciation, most of the Gascoyne Sub-basin and the Bernier Platform were emergent until the earliest Cretaceous (Mory et al, 2003).

## Triassic to Early Cretaceous

During the Triassic, rifting continued within the Exmouth-Barrow-Dampier intra-cratonic rift system in the northwest and in the Perth Basin in the southwest. This allowed the accumulation of a thick Triassic, Jurassic and Lower Cretaceous succession. This succession is largely absent from the offshore Southern Carnarvon Basin, although in the southernmost part of the Gascoyne Sub-basin a thin section (about 300 m) of the Triassic Kockatea Shale above the mid to Late Permian unconformity (lasky et al, 2003) has been interpreted from seismic data.

At the same time large areas of the Gascoyne Sub-basin were tectonically uplifted. This uplift may have allowed for up to 6 km erosion between the Late Permian and Early Cretaceous (lasky et al, 2003). The only confirmed Jurassic unit in the Gascoyne Sub-basin is the Woodleigh Formation (**Figure 8**), which consists of interbedded shale and sandstone of lacustrine origin within the Woodleigh impact structure (lasky and Mory, 1999; Mory et al, 2003). The unit has been dated as Early Jurassic from abundant spores and pollen (Mory et al, 2001) and its maximum thickness is 286 m in GSWA Woodleigh 2a.

## Earliest Cretaceous to Recent

The last significant rifting episode in the region occurred during Middle Jurassic to Early Cretaceous northwest–southeast extension preceding the breakup with Greater India. The early extensional phase was characterised by significant uplift and faulting which was accompanied by extensive erosion across the Gascoyne Sub-Basin and Bernier Platform (lasky et al, 2003; Lockwood and D’Ercole, 2004). Pre-Cretaceous units are commonly truncated at an angle below the overlying Cretaceous units. Rapid subsidence following the breakup resulted in a widespread transgression and deposition of a fining-upward marine sequence over the Valanginian unconformity surface. The Cretaceous Winning Group extends throughout most of the North West Shelf and across the western part of the Southern Carnarvon Basin. The average thickness of the Cretaceous succession in the Gascoyne Sub-basin is about 300 m, with strata thickening north towards the Exmouth Sub-basin and Peedamullah Shelf.

The Winning Group (**Figure 8**) consists of a basal transgressive sandstone (Birdrong Sandstone) overlain by low-energy marine shale (Muderong Shale), in turn overlain by low-energy marine, silica-rich, fine-grained clastic rocks (Windalia Radiolarite) and glauconitic siltstone (Gearle Siltstone). The Birdrong Sandstone, and possibly the glauconitic Mardie Greensand in the northern Gascoyne Sub-basin, were deposited in a coastal plain to shelf environment. This localised sedimentation was followed by the basin-wide deposition of the transgressive marine Muderong Shale, followed by the Windalia Radiolarite and Gearle Siltstone. After a minor break in deposition, a change in sediment supply and ocean currents in the Turonian led to deposition of the carbonaceous claystone and bioturbated calcilutite of the Haycock Marl.

Following another brief depositional hiatus, carbonate sedimentation resumed with the onset of full ocean circulation in the Turonian and concomitant deposition of the Toolonga Calcilutite. This unit (**Figure 8**) is widespread in the Gascoyne Sub-basin, and disconformably overlies the Winning Group. It consists of fossiliferous calcilutite and calcisiltite deposited in a low-energy, middle-shelf environment. In the northern Gascoyne Sub-basin, the Toolonga Calcilutite grades up into the overlying Korojon Calcarenite (**Figure 8**), which consists of silty calcarenite and calcisiltite deposited in a moderate-energy marine environment. The Korojon Calcarenite is unconformably overlain in the north by the latest Cretaceous Miria Formation, which consists of calcarenite and calcisiltite deposited in a low- to medium-energy, marine shelf environment.

The Cenozoic succession in the Southern Carnarvon Basin is predominantly flat lying and consists of shallow-marine carbonate rocks (Cardabia and Giralia Calcarenites and Trealla Limestone; **Figure 8**). Offshore, thick prograding carbonates were deposited throughout most of the Cenozoic, whereas onshore, the Gascoyne Sub-basin remained largely subaerial, with minor deposition in the Eocene and Miocene (Hocking et al, 1987).

Miocene collision between Australia and Eurasia reactivated pre-existing major faults and led to the widespread formation of inversion structures (Iasky et al, 2003).

## Exploration history

Exploration of the onshore Southern Carnarvon Basin dates back to the 1950s.

In 1953, West Australian Petroleum Pty Ltd (WAPET) made the first oil discovery in Western Australia on the Rough Range Anticline in Rough Range 1. However, successive wells drilled on the Rough Range structure proved to be dry. Although Rough Range 1 recorded several additional oil shows at depth, the only producing horizon remained the thin (8 m) zone in the Birdrong Sandstone. Rough Range Oil Pty Ltd (a wholly owned subsidiary of Empire Oil and Gas NL) brought the field into commercial production in 2000, trucking the oil to the Kwinana refinery, until the well was closed because of safety issues. Based on the map of the field produced by Empire Oil and Gas, the Department of Industry and Resources estimated that original in-place oil reserves in the field were 1.8 MMbbl, 19 000 bbl of which were produced during testing and sold, and the remaining recoverable reserves are about 500 000 bbl (Playford, 2003).

Of the 40 follow-up wells drilled in the Cape Range peninsula over the following 40 years, only Roberts Hill 1 (interpreted 2.5 m oil column) and Parrot Hill 1 (6 m oil column) recovered significant hydrocarbons. The Parrot Hill 1 well was completed as an oil well but never went into production. Ampolex plugged and abandoned the Parrot Hill 1 well upon being acquired by Mobil in the late 1990s. Farther south, WAPET drilled shallow stratigraphic tests on anticlinal structures without discovering any hydrocarbons. The most prolific drilling (16 wells) was carried out by WAPET on Dirk Hartog Island (Mory et al, 2003).

By the mid-1970s exploration in the Southern Carnarvon Basin almost ceased, mainly because successes in the adjacent Northern Carnarvon Basin attracted most of the region's exploration focus. At the end of the 1970s the Geological Survey of Western Australia (GSWA) carried out mapping of the onshore part of the basin which was synthesized by Hocking et al (1987).

From the 1990s there has been some revival of exploration activity in the Southern Carnarvon Basin. Empire Oil and Gas NL drilled Carlston 1 in 2002 on the basis of seismic data acquired in 1994 in the northern part of the Gascoyne Sub-basin. The Carlston prospect was drilled to evaluate Devonian reefal objectives, of a similar age to those productive in the Canning Basin, but no hydrocarbons were recovered. In late 1993, GSWA commenced a program to re-evaluate the petroleum potential of the Southern Carnarvon Basin, including drilling of eleven stratigraphic wells. In the following decade a series of reports were published on individual sub-basins or areas (Merlinleigh Sub-basin: Mory and Backhouse 1997; Iasky et al, 1998; Gascoyne Sub-basin: Iasky and Mory, 1999; Ghori, 2002; Ghori et al, 2005; Mory et al, 2003; Byro Sub-basin: Mory, 1996; Bernier Ridge: Lookwood and D'Ercole, 2004).

In 2008 Empire Oil drilled two wells in the northern Gascoyne Sub-basin. Lake Macleod 1 tested a Devonian four-way dip closure over a Silurian fault block, while Star Finch 1 tested a reverse faulted anticlinal structure formed by mid-Miocene compression (ABNNewswire, Press Releases, 2008). No hydrocarbons were discovered in either prospects (Upstream, 2008).

Exploration in the offshore part of the basin began in the middle to late 1960s with a regional aeromagnetic survey followed by regional seismic surveys. The first offshore well in the Southern Carnarvon Basin (Pendock 1a) was drilled in 1969 by Genoa Oil (Geary, 1970) in the northern part of the Bernier Platform. The well had minor oil shows in the Devonian and Silurian, but none in the Birdrong Sandstone, which was the primary target. Also, no postulated Mesozoic section was intersected. In the early 1970s Ocean Ventures carried out several seismic surveys in the southern part of the Gascoyne Sub-basin before drilling Edel 1 (1972). This well tested an anticline mapped at an interpreted Jurassic or Triassic horizon, but no hydrocarbons were found. The well intersected Cenozoic strata overlying Ordovician Tumblagooda Sandstone intercalated with volcanic rocks (Crostella, 2001). Pendock 1a and Edel 1 remain the only two wells drilled in the offshore Southern Carnarvon Basin.

In the late 1980s and 1990s a number of 2D surveys were carried out in the northern part of the basin. The most significant include Capricorn (1982), Cuvier (1992), Rundle (1993-94) and Carnarvon Terrace 2D (1998). In 2001–2002 Shell Australia and Woodside Energy Ltd began exploration near the border between the southern Exmouth and Gascoyne sub-basins. They acquired regional 2D seismic grid (Coverack 2D) and 3D seismic data north of Pendock 1a (Coverack 3D). With these surveys, Woodside delineated the Birdrong Sandstone play tested by Herdsman 1 in 2003.

The offshore Southern Carnarvon Basin remains under-explored. Since the Drilling of Herdsman 1 in 2003 several seismic surveys have been conducted to improve the coverage and quality of data available across the basin. In 2008-2009, under the Offshore Energy Security program Geoscience Australia acquired regional seismic data in frontier areas of the Western Australian margin (GA survey 310), including the outboard part of the Southern Carnarvon Basin (**Figure 9**). Subsequently, in 2009, Searcher Seismic shot a regularly spaced 25x25 km regional grid of 2D seismic over the western part of the Bernier Platform (**Figure 9**, Searcher Seismic, 2010). Other datasets acquired in this period include swath bathymetry, dredge samples, gravity and magnetic records (GA Marine Reconnaissance Survey 2476; Daniell et al, 2009) and SAR data (Logan et al, 2010). The Rocket 2D seismic survey (**Figure 9**), acquired by Spectrum Geo in 2015, consists of 8292 line km of modern, long-offset data covering much of the Bernier Platform (Phase 1) and central Houtman sub-basin (Phase 2). The Rocket 2D data has revealed geometries that indicate the presence of an offshore basin below a 'thin rugose basalt layer' on the Bernier Platform (O'Neill et al, 2016). In 2016, Spectrum Geo also reprocessed 3455 line km of data from Geoscience Australia's 2014-15 GA-349 2D survey across the adjacent northern Houtman Sub-basin. The result is an integrated regional coverage of modern data providing improved seismic imaging of this underexplored region. These datasets provide an opportunity to re-evaluate the petroleum potential of this frontier area.

## Regional petroleum systems

The hydrocarbon prospectivity of the Southern Carnarvon Basin is relatively poorly understood. While the onshore part of the basin has been assessed in some detail (Ghori et al, 2005), including available data from Western Australia's first oil producing well Rough Range 1, only two wells, Edel 1 and Pendock 1, provide limited geological control. Herdsman 1, located in the southernmost part of the Exmouth Sub-basin, provides additional information about the Mesozoic section.

The region has potentially two active petroleum systems: Paleozoic and Mesozoic. So far no commercial discoveries from Paleozoic petroleum systems have been found in the Southern Carnarvon Basin, however oil and gas shows were detected in a number of wells. Within the Paleozoic Gascoyne Sub-basin and Bernier Platform, source rocks are present in the Silurian and Upper Devonian. Effective reservoirs and seals are present both in the Paleozoic and the post-breakup Cretaceous succession. The Mesozoic petroleum system of the southern Exmouth Sub-basin of the Northern Carnarvon Basin includes potential source rocks in the Triassic Mungaroo Formation and Jurassic Dingo Formation with multiple reservoir and seal units in the Triassic, Jurassic and Cretaceous. The potential of the Mesozoic petroleum system in the southernmost part of the Exmouth Sub-basin has not been proven. A test of a valid structure at Herdsman 1 suggests that the thickness of the Mesozoic succession is a critical factor for hydrocarbon generation in this part of the basin.

## Well control

### Herdsman 1 (2003)

Herdsman 1 was drilled in 2003 by Woodside Energy Ltd within the Exmouth Sub-basin in the Northern Carnarvon Basin, in a water depth of 556.7 m (**Figure 1, Figure 2**), approximately 227 km north of Carnarvon and 46 km north of Pendock 1. Herdsman 1 is the southernmost well in the Exmouth Sub-basin (Woodside Energy Ltd, 2003a). The well tested a structural closure over a tilted fault block with the primary targets in the Lower Cretaceous Birdrong Sandstone and Middle Jurassic Learmonth Formation.

The well reached a total depth of 2010 mRT intersecting Cenozoic, Cretaceous and Jurassic sections. The deepest units intersected were the Jurassic Athol (1397.7–1462.7 mRT) and Learmonth (1462.7 mRT to TD) formations (Woodside Energy Ltd, 2003a). The Jurassic section was thinner and sandier than anticipated. The Learmonth Formation penetrated in this well comprises a lower non-marine medium-grained sandstone package (>80 m) and a locally carbonaceous claystone interval (115 m) that grades upwards into a non-marine medium-grained sandstone package (352 m). The overlying Athol Formation comprises 65 m of silty claystone grading into argillaceous siltstone deposited in a non-marine to marginal marine environment. The Cretaceous breakup unconformity separates the Athol Formation from the overlying Birdrong Sandstone (1367.7–1397.7 mRT), a non-marine to near-shore sandstone containing minor silt. The Birdrong Sandstone is in turn overlain by the 57.5 m of Muderong Shale, 51.5 m of Windalia Radiolarite, 285 m of Gearle Siltstone followed by undifferentiated Upper Cretaceous and Cenozoic carbonates.

No indications of hydrocarbons were seen in the Birdrong Sandstone and it was evaluated as water-bearing. Reservoir quality was good with an average porosity of 28% and a net-to-gross ratio of 87%. The secondary objective, the Learmonth Formation sandstones, were penetrated about 390 metres shallower than expected, due to more extensive erosion at the breakup unconformity. The Learmonth Formation is also evaluated as water bearing with good reservoir properties (average porosity of 26% and a net-to-gross ratio of 86%).

The Herdsman trap was interpreted to be valid. The lack of hydrocarbon charge was thought to be due to the absence of Jurassic source rocks at this location and extensive erosion during the Valanginian. It has been suggested that if Jurassic source rocks are present, they are small in volume and are insufficiently buried to have matured (Woodside Energy Ltd, 2003a). Low reservoir temperatures (40 to 60 °C) were also confirmed. However, spore colouration indicated the section is marginally mature for oil at the base of the Cretaceous interval and is mature for both oil and gas generation in the Jurassic interval. This is confirmed by the vitrinite reflectance analysis which found the lower part of the section to be quite mature (Woodside Energy Ltd, 2003a).

Geochemical analyses were performed by Geotech on four sidewall core samples from 1428 to 1920 mRT and cuttings from 1950 to 1955 mRT (Woodside Energy Ltd, 2003a). The sidewall cores yielded 0.64 to 3.10% Total Organic Carbon (TOC), the maximum occurring at 1,895 mRT. The Hydrocarbon Indices (HI) are very poor ranging from 47 to 157, with the lowest at 1895 mRT, suggesting gas source potential only.

Fluid Inclusion Stratigraphy (FIS) was performed on cuttings from 1090 to 2010 mRT by Fluid Inclusion Technologies Inc (Woodside Energy Ltd, 2003a, Appendix 3). Results of this work suggest that very poor Lower Jurassic or Upper Triassic source rocks were mature some time before the Valanginian breakup. The migrated compounds were limited in volume and consisted of wet gas and possibly other liquids. Very high net-to-gross ratio in the Learmonth Formation strata provides effective pathways for migration but is unfavourable for trap formation. Any traps that might have existed were disrupted by the Valanginian tectonism. The remaining traces of hydrocarbons have been biologically altered due to temperatures less than 80°C (Woodside Energy Ltd, 2003a).

## Edel 1 (1972)

Edel 1 was drilled in 1972 Ocean Ventures Pty Ltd to test a structural closure that was mapped by the Bernier Marine Seismic and Magnetometer Survey. The well was spudded in 310 ft (95 m) water depth (**Figure 1** and **Figure 2**) and reached TD at 9021 ft (2750 m). The main exploration objective were the Triassic-Jurassic sandstone sequences, as those encountered previously in Pendock 1A. Drilling difficulties were reported in the section downward from 1162 ft (354 m) which comprises a sequence of interbedded sandstones and volcanic horizons.

K/Ar radiometric dating of seven volcanic intervals between 1700 ft (518 m) and 8020 ft (2445 m) yielded absolute ages ranging from 241 ( $\pm 7$ ) to 260 ( $\pm 5$ ) million years and place the lower section of Edel 1 into the Upper Permian (Lopingian) to Middle Triassic (Anisian).

The geological section penetrated by Edel 1 comprises Quaternary/Paleogene sediments to 1162 ft (354 m) which are unconformably underlain by Cretaceous siliciclastics down to 3050 ft (930 m). The remaining downhole section is represented by the “Edel Formation” (Ocean Ventures, 1972) a thick succession of interbedded sandstones and volcanic dykes and sills. Only a few reservoir quality sandstones were encountered. The average porosity was assessed as being below 10%, with individual intervals reaching 18–23% in the Cretaceous and up to 20% in the Mesozoic sections. Measured permeabilities are less than 1mD. Since no hydrocarbons were encountered, no formation tests were run and the well was plugged and abandoned.

## Pendock 1A (1969)

Pendock 1 and Pendock 1A were drilled in 1969 by the Canadian Superior Oil (Aust.) Pty Ltd. Both wells were located approximately 181 km north of the town of Carnarvon within the Gascoyne Sub-Basin of the Southern Carnarvon Basin (**Figure 1** and **Figure 2**). Pendock 1 was drilled in a water depth of 132.6 m (10.4 mKB) and reached a TD of 242.6 mKB. Indications of excessive deviation and drill string hang-ups led to abandoning the well and spudding of Pendock 1A approximate 12 m away from the original location (Canadian Superior Oil (Aust.) Pty Ltd, 1970). Pendock 1A was drilled in 131.1 m water depth and reached a TD of 2501 mKB. The well tested a large anticlinal structure beneath the breakup unconformity interpreted from seismic data. The primary target was the Lower Cretaceous Birdrong Sandstone and the secondary targets were possible Triassic to Jurassic sandstone intervals.

The lower 651 m of Pendock 1A penetrated the Upper Ordovician to Silurian Dirk Hartog Formation. Above the Dirk Hartog Group the well intersected 184.7 m of the Lower Devonian Nannyarra Formation, 558.1 m of Devonian Gneudna Formation, and 77.1 m of the Mississippian Moogooree Limestone. Within the Devonian Gneudna Formation the well encountered a dense dolomite unit containing abundant stromatoporoids and corals, which was interpreted to represent a reef or a carbonate bank deposit.

The breakup unconformity at the top of the Moogooree Limestone suggests erosion or non-deposition from Cisuralian to lowest Cretaceous. The presence of Mesozoic strata has been incorrectly inferred from the aeromagnetic data, which indicated over 5000 m of sediments at this location. Above the breakup unconformity, the well intersected 202 m of the Aptian to Cenomanian Winning Group, including only 7.3 m of the Birdrong Sandstone. The upper part of the well intersected 685 m of Upper Cretaceous to Holocene carbonates.

Minor shows of oil were found in the Devonian and Silurian section (**Figure 10**). Oil stains were detected in the Nannyarra Formation (1718 mKB) and the overlying Point Maud Member of the Gneudna Formation (1409 and 1413 mKB, respectively). Oil staining and fluorescence were also detected within the Coburn Formation of the Dirk Hartog Group (e.g. 2,201 mKB). Methane gas shows occurred throughout the Paleozoic with the maximum readings in the interval 2121–2124 mKB (GENOA Oil N.L., 1970: Canadian Superior Oil (Aust.) Pty Ltd, 1970). Hydrocarbon shows in the Paleozoic imply this interval is prospective elsewhere in the basin. Rock-Eval of a limited number of samples from the Silurian/Devonian source interval indicated that these rocks are thermally immature. More recently work has shown that the Gneudna Formation is currently mature at Pendock 1A (Ghori et al, 2005).

Although Pendock 1A failed to intersect anticipated Triassic and Jurassic strata, minor shows encountered in the Devonian and Silurian succession provide important information about a possible Paleozoic petroleum system in this region.



## Petroleum Systems Elements

Sources	<ul style="list-style-type: none"> <li>• Silurian (Llandoveryan–Ludlowian) shallow marine Coburn Formation</li> <li>• Devonian (Frasnian) shallow marine Gneudna Formation</li> <li>• Permian (Sakmarian–Artinskian) shallow marine sediments of the Wooramel and Byro groups</li> </ul>
Reservoirs	<ul style="list-style-type: none"> <li>• Upper Ordovician Tumblagooda Sandstone ('red beds')</li> <li>• Devonian (Frasnian) shallow marine Gneudna Formation</li> <li>• Permian (Sakmarian–Artinskian) Moogooloo Sandstone</li> <li>• Cretaceous coastal to near-shore Birdrong Sandstone (Valanginian) and Windalia Sandstone Member (Aptian) of the Winning Group</li> </ul>
Seals	<ul style="list-style-type: none"> <li>• Devonian (Frasnian) uppermost part of Gneudna Formation, thick marine shales and marls</li> <li>• Carboniferous to Permian Lyons Group</li> <li>• Cretaceous Muderong Shale (Valanginian), Windalia Radiolarite (Aptian) and Gearle Siltstone (Albian)</li> </ul>
Traps	<ul style="list-style-type: none"> <li>• Rotated fault blocks, horst blocks, inversion anticlines, stratigraphic pinchout and reefs</li> </ul>

## Source Rocks

The best Paleozoic source rocks are within the Silurian Coburn Formation, and Devonian Gneudna Formation (Ghori et al, 2005; **Figure 10**). Silurian–Devonian source rocks have been shown to have good potential for both oil and gas generation. Silurian source beds have organic richness of over 7% TOC, potential yield (S1 + S2) of up to 38 mg/g, and hydrogen index of up to 505 mgHC/gTOC. The main source rocks in the Gascoyne Sub-basin are organic rich and oil-prone laminated mudstones within carbonate facies of the Devonian Gneudna Formation. Devonian source beds have organic richness of up to 13.5% TOC, potential yield of up to 40 mg/g, and hydrogen index of up to 267 mgHC/gTOC. However, all of these source rocks are thin and probably of limited extent. Maturity and petroleum generation modelling of the Paleozoic succession (Ghori et al, 2005) showed that the maturity of these units progressively increases from immature in the south-southeast to mature in the north-northwest, commensurate with increasing depth of burial.

The presence of Triassic and Jurassic source rocks is inferred from the northern part of the Exmouth Sub-basin, where they charge a number of commercial accumulations. These may include organic-rich units of the Lower Triassic Locker Shale and deltaic Upper Triassic Mungaroo Formation. The Upper Jurassic Dingo Claystone is the principal source for oil in the Exmouth Sub-basin (Tindale et al, 1998), however it is not clear how far south it extends as this unit is missing at Herdsman 1.

## Reservoirs and seals

The Paleozoic succession contains a number of potential reservoir and seal units (**Figure 10**). The Ordovician red beds (Tumblagooda Sandstone) has variable porosity and permeability, although even at depths greater than 1000 m porosity is typically good, with an average of 13%. The Gneudna Formation provides the prime reservoir potential, with the reefal Point Maud Member demonstrating favourable reservoir properties. Seal is inferred to be provided by thick marine shales and marls of the upper Gneudna Formation overlying the Point Maud Member.

The Triassic Mungaroo Formation and Lower Cretaceous Birdrong Sandstone are the main reservoir units in the Mesozoic succession (**Figure 10**). The Birdrong Sandstone overlies the breakup unconformity, has excellent reservoir characteristics and hosts a number of oil and gas accumulations both onshore and offshore in the Northern Carnarvon Basin. The Birdrong sandstone has been the prime exploration target in the area. The Dingo Claystone, Muderong Shale, Windalia Radiolarite and Gearle Siltstone are possible seals in the Mesozoic succession (**Figure 10**). The Muderong Shale and Gearle Siltstone are proven effective seals in the northern Exmouth Sub-basin (Iasky et al, 2003).

## Timing of generation

Burial, thermal and erosional histories are complex and poorly constrained in the Gascoyne Sub-basin (Iasky et al, 2003). Geohistory modelling by Ghori et al (2005) indicated that petroleum generation and migration from Silurian and Devonian source rocks peaked during the Permian, whereas generation from Permian source rocks peaked during the Triassic. Therefore, in the Gascoyne Sub-basin, mid-Carboniferous to Cisuralian structures are the most prospective, although there is the risk of breaching during later tectonic events.

On the Bernier Platform there is some controversy as to how much of the Triassic and Jurassic section was eroded during the uplift preceding the Valanginian breakup (Lockwood and D'Ercole, 2004). Maturity of the source rocks would depend on the thickness of the eroded section. In the model with major erosion during the Permian, the maximum rate of hydrocarbon generation from Silurian and Devonian source rocks occurs at the end of the Permian (Iasky et al, 2003). For the model with major erosion during the Early Cretaceous the peak of hydrocarbon generation for these units extends from the Permian to Middle Jurassic. If no deposition occurred between the Permian and Cretaceous, peak hydrocarbon expulsion may have occurred more recently which would result in filling of Miocene structures only.

In the Exmouth Sub-basin, the thickness of the Mesozoic synrift succession and the presence of good source rocks in the area are the main risk. Maximum thickness of the Jurassic rocks is interpreted to be up to 5-6 km in the northern part of the Gascoyne Sub-basin. These rocks are buried deep enough to have generated oil before the breakup (Partington et al, 2003). However, across the basin, thickness of the interpreted Jurassic succession is highly variable, which suggests that some of the Jurassic source rocks would have generated much later. The inferred Triassic succession is buried up to 8 km below the breakup unconformity and is also likely to have generated hydrocarbons (Partington et al, 2003), whereas the underlying Paleozoic section is likely to be mostly overmature.

## Play types

The Paleozoic Gascoyne Sub-basin hosts a number of structural and stratigraphic plays. Structural plays include fault block and Miocene reactivation anticline plays (**Figure 11** and **Figure 12**). Paleozoic traps include Ordovician, Silurian and Devonian reservoir rocks in rotated fault blocks created by mid- to Lopingian and Late Jurassic rifting. Such traps may be effective if sealed by intraformational shales. Low dips and small fault displacements imply that such traps may be quite large (Mory et al, 2003). In the northern part of the sub-basin, east of Pendock 1a, there are a few untested faulted anticlines, in which reefal carbonate facies of the Point Maud Member of the Gneudna Formation may be sealed intraformationally (Iasky et al, 2003). In the southwestern offshore Bernier Platform, there are fault block plays in which the Kockatea Shale seals the Tumblagooda Sandstone. These traps could have been charged by hydrocarbons that migrated updip from more deeply buried sections of the Kockatea Shale in the Abrolhos Sub-basin (Mory et al, 2003).

The main objective for petroleum exploration in the Gascoyne Sub-basin has been the Birdrong Sandstone, sealed by the Muderong Shale in Miocene anticlinal structures formed as a result of normal fault inversion. A few untested Miocene structures have been identified by Iasky et al (2003) in the northern part of the area surrounding Pendock 1a. A likely problem with the Birdrong Sandstone is that a strong artesian flow could flush hydrocarbons from all but the most robust traps (Mory et al, 2003).

Possible stratigraphic plays in the Gascoyne Sub-basin include incised channels filled by Birdrong Sandstone and sealed by the Muderong Shale. In the northern part of the sub-basin there may be additional traps in which the Birdrong Sandstone is missing, thereby allowing the Muderong Shale to seal dipping Paleozoic reservoir rocks (Iasky et al, 2003). Mobil (1994) suggested some of the stratigraphic traps may be charged by long-distance migration from the Mesozoic source rocks in the adjacent Exmouth Sub-basin.

The most likely plays in the Merlinleigh Sub-basin are anticlines, fault dependent closures, and stratigraphic traps. A number of anticlines have been identified from seismic and outcrop data (Mory et al, 2003), but their extent at depth is unclear. Fault plays are present throughout the Merlinleigh Sub-basin and along the eastern margin, they are proximal to Devonian source rocks that are presently in the oil generation window. Farther west, such traps may be prospective for gas. In the Gneudna Formation, carbonate sections, if lenticular, could form stratigraphic traps charged from intraformational shales. The underlying Nannyarra Sandstone may also have potential in fault block traps.

## Critical risks

The prime risks for Paleozoic plays are the volume of available source rock, trap integrity because of the long period of preservation required, and relative timing of generation versus trap formation (Ghori et al, 2005). Some of the trapped hydrocarbons from Silurian-Lower Devonian sources are likely to have been lost during Permian and Valanginian rifting and Miocene inversion (Partington et al, 2003).

## Geoscience Australia data

### 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](#).
- [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.

## 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 Southern Carnarvon Basin (**Figure 13**). The information is provided in support of business decisions with respect to planned exploration and development activities. The Southern Carnarvon 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 Southern Carnarvon 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 Southern Carnarvon 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 300km 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<sup>2</sup> 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 km<sup>2</sup> 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 km<sup>2</sup> 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 km<sup>2</sup> 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<sup>2</sup> 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 Southern Carnarvon Basin; 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<sup>2</sup> and a water depth range between 15 m and 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 Southern Carnarvon 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 visiting 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; and
- general use in the remainder of the park.

## **Heritage**

There are no shipwrecks listed in the release area. However, the HMAS Sydney, a naval cruiser wrecked in 1941, is located south of the release area in 2470 m water depth (coordinates: 26.24 °S, 111.22 °E). 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 South Carnarvon Basin area:

- the Western Deepwater Trawl Fishery operates in water deeper than 200 metres 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 (370.4 km) from the coast; and
- 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 in February to 22.4 °C in July. Average minimums are 23 °C and 11 °C 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 (Foster et al, 2014). 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 (Bosserele et al, 2012, Li et al, 2012).

## Seabed environments

The seabed of the South Carnarvon Basin is situated in water depths that range from ~200 m on the outer continental shelf to over 2000 m on the continental slope (Daniel et al, 2009). The sea floor morphology of the continental slope is characterised by the extensive Carnarvon Terrace and a series of slope-confined canyons that incise the lower slope (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 Southern Carnarvon 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 72 sample observations are held within the national marine sediments database (MARS: <http://www.ga.gov.au/oracle/mars>).

## Ecology

The Southern Carnarvon Basin overlaps the transition between the North-West and South-West Marine Region Marine Regions. The Carnarvon Shelf runs along the coast of Western Australia and supports Ningaloo Reef, a World Heritage Area and Australia's longest fringing reef that is protected by the Ningaloo Marine Park. The aggregation of whale sharks at and around Ningaloo Reef is amongst the highest known density of whale sharks in the world, while Shark Bay and adjacent waters support one of the world's largest remaining dugong populations. At the smaller scale of provincial bioregions (IMCRA 4.0), the Southern Carnarvon Basin is significant because it contains habitats, species and ecological communities associated with the Central Western Shelf Province, Central Western Transition and Central Western Shelf Transition Provinces (Commonwealth of Australia, 2005).



The northern region of Carnarvon Shelf is generally dominated by tropical species, whereas the southern region (~200 km to the south) has a higher number of temperate species (van Keulen and Langdon 2011). Across the region, near-shore areas of Ningaloo Reef support hard corals (van Keulen and Langdon 2011), whereas offshore areas support diverse assemblages of sponges and octocorals (Heyward et al, 2010; Schönberg and Fromont, 2012). The Carnarvon Shelf supports highly diverse macrofaunal and infaunal assemblages, comprising many rare species and spanning a range of phyla, trophic guilds and habitat preferences (Przeslawski et al, 2013).

Sampling of deep-water (641–4827 m) benthic habitats surrounding the Southern Carnarvon Basin 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). Deposit-feeding holothurians (sea cucumbers) were the most common taxa observed, with occurrences higher up the slope margins than on the Cuvier Plateau. However, few research surveys have been undertaken to examine many offshore environments of the Southern Carnarvon Basin and as a result the benthic ecology for these areas remain largely unknown.

## 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 Southern Carnarvon Basin, its main geological provinces and the distribution of petroleum exploration wells.
- Figure 2** Structural elements map for the Southern Carnarvon Basin showing the location of petroleum wells and location of cross-sections in Figures 5, 6, 7 and 11.
- Figure 3** Bouguer gravity image of the Southern Carnarvon Basin showing the correlation between gravity anomalies and major depocentres within the basin. Tectonic elements of the Southern Carnarvon Basin based on current interpretation and compilation from Hocking et al (1987), Lockwood and D'ercole (2004) and Woodside (2003b, 2003c).
- Figure 4** Geological cross-sections of the main structural provinces within the Southern Carnarvon Basin (modified from Hocking et al, 1987). See Figure 2 for location of cross-sections.
- Figure 5** Seismic line gpctr-93-0405 showing tectonic relationship between the Northern and Southern Carnarvon basins. Line location shown on Figure 2.
- Figure 6** GA-acquired seismic line s310/42 across boundary between Exmouth Sub-basin and Gascoyne Sub-basin, showing structural architecture below regional Cretaceous unconformity. Line location shown on Figure 8.
- Figure 7** Seismic line (wg98ct-4) across the boundary between the Bernier Platform and the Mesozoic depocentre of the southern Exmouth Sub-basin. Line location shown on Figure 2.
- Figure 8** Generalised stratigraphy of the Southern Carnarvon Basin (after Gradstein et al, 2004 and Ogg et al, 2008).
- Figure 9** Map showing seismic data coverage in the Southern Carnarvon Basin.
- Figure 10** Stratigraphic chart for the Southern Carnarvon Basin showing petroleum systems elements and possible play types (Geologic Time Scale after Gradstein et al, 2004 and Ogg et al, 2008).
- Figure 11** Seismic line (Cuvier seismic survey, line 92m-126) across the northern Bernier Platform showing potential Paleozoic plays. 1 - Miocene anticline, 2 - Paleozoic horst block, 3 - Devonian reef (modified from Geary, G., 1994). Location of the seismic line is shown on Figure 2.
- Figure 12** Generalised cross-section showing conceptual plays across the Southern Carnarvon Basin and southernmost Northern Carnarvon Basin. Source rock intervals: SR1 - Coburn Formation, SR2 - Gneudna Formation, SR3 - Locker Shale, SR4 - lacustrine shales of Mungaroo Formation, SR5 - Dingo Formation
- Figure 13** Map showing marine reserves, marine parks, multiple use zones and ecological features in the Southern Carnarvon Basin