



# Regional Geology of the Northern Carnarvon Basin

The Northern Carnarvon Basin represents the westernmost offshore province of Australia's North West Shelf comprising also the Browse, Roebuck, Offshore Canning and Bonaparte basins (**Figure 1**). The Northern Carnarvon Basin covers an area of approximately 535 000 km<sup>2</sup>, predominantly offshore, in water depths of up to 4500 m (**Figure 2**). It contains a Paleozoic, Mesozoic and Cenozoic sedimentary succession up to 15 000 m thick, which is dominated by deltaic to marine siliciclastics and shelfal carbonates of Mesozoic to Cenozoic age. Two Mesozoic petroleum supersystems (Westralian 1 and Westralian 2) have been identified and numerous commercial oil and gas discoveries have been made within the basin. The basin is Australia's premier hydrocarbon producing province and contains an established network of oil, condensate and gas production infrastructure (**Figure 4**). As of May 2022, the total proved and probable reserves for the Northern Carnarvon Basin are 3140 PJ (534 MMbbls) of oil and natural gas liquids and 50 982 PJ (45.33 Tcf) of natural gas and ethane (EnergyQuest, 2022).

## Basin outline

The Northern Carnarvon Basin is the westernmost province of the late Paleozoic to Cenozoic basins that form the northwest continental margin of Australia (Bradshaw et al, 1988). The basin is bounded to the northeast by the Roebuck and offshore Canning basins, to the southeast by the Pilbara Block, to the south by the Bernier Platform, Gascoyne Sub-basin and Merlinleigh Sub-basin of the Southern Carnarvon Basin, to the southwest by the Cuvier Abyssal Plain, and to the northwest and north by the Gascoyne and Argo abyssal plains, respectively. The sedimentary fill in the basin is up to 15 km thick and dominated by deltaic to marine siliciclastics and shelfal carbonates of Mesozoic to Cenozoic age.

## Tectonic framework

The Northern Carnarvon Basin evolved from a broad intracontinental basin in the late Paleozoic, through syn-rift sub-basins in the Jurassic, to a passive margin carbonate shelf in the Cenozoic. The regional geology, structural evolution, and petroleum potential have been discussed by many authors, including Kopsen and McGann (1985), Boote and Kirk (1989), Hocking (1990), Stagg and Colwell (1994), Jablonski (1997), Romine et al (1997), Westphal and Aigner (1997), Driscoll and Karner (1998), Bussell et al (2001), Longley et al (2002), Barber (2013), and Tao et al (2013). A regional tectonostratigraphic model of the North West Shelf, which includes the Northern Carnarvon Basin, has been developed by Marshall and Lang (2013).

The offshore basin consists of three broad structural zones (**Figure 3**):

- an inboard, structural high (Lambert and Peedamullah shelves);
- a central zone of large depocentres (Beagle, Dampier, Barrow and Exmouth sub-basins); and
- a large outboard area (Exmouth Plateau) and its uplifted inboard margin (Rankin Platform).

The oceanic Argo, Cuvier and Gascoyne abyssal plains are the boundaries to the distal margins of the Exmouth Plateau.

Multiple phases of extension, which culminated in the Jurassic to Early Cretaceous breakup of the northwest Australian continental margin, produced a dominant northeast structural grain, which is evident from the alignment of major faults and depocentres. A secondary, north to north-northwest trend is also apparent, particularly in accommodation zones and associated faults that link the northeast-trending *en echelon* faults.

Comprehensive summaries of the petroleum geology are presented by Tindale et al (1998) for the Exmouth Sub-basin, Stagg et al (2004) for the Exmouth Plateau, Nishimori (1999) and Jablonski et al (2013) for the Rankin Platform, Hearty et al (2002) for the Barrow Sub-basin, Woodside Petroleum Ltd (1988) and Barber (1994a) for the Dampier Sub-basin, and Blevin et al (1994) and Lech (2013) for the Beagle Sub-basin.

### ***Beagle Sub-basin***

The Beagle Sub-basin (**Figure 7**) is a structurally complex, northerly trending series of fault blocks, anticlines and troughs. This structural trend is oblique to the regional northeast trend that dominates the other sub-basins inboard of the Rankin Platform. The sub-basin developed through several pre-, syn- and post-rift phases (Lech, 2013). Lateral fault movements dominated the sub-basin's tectonic evolution in conjunction with localised areas of extension and compression (Blevin et al, 1994). The sedimentary succession attains a thickness of up to 12 km, and is dominated by Triassic to Middle Jurassic sediments (**Figure 22**). In contrast to the other sub-basins, the Upper Jurassic succession is either thin or absent. The sedimentary succession in the Beagle Sub-basin is bounded to the south and southeast by shallow basement of the Pilbara cratonic block, while to the west and northwest it is bounded by the continental Exmouth Plateau.

### ***Dampier, Barrow and Exmouth sub-basins***

The Dampier, Barrow, and Exmouth sub-basins are a series of large rift depocentres (**Figure 3, Figure 5, Figure 8, Figure 9, Figure 10**), which contain a predominantly Triassic, Jurassic and Lower Cretaceous sedimentary succession (**Figure 14, Figure 15, Figure 16b, Figure 18, Figure 19, Figure 20**). Maximum sediment thickness exceeds 10 km in the Dampier and Exmouth sub-basins and 15 km in the Barrow Sub-basin. The Barrow Delta dominates the Lower Cretaceous succession in the Exmouth and Barrow sub-basins (Tindale et al, 1998). By contrast, in the Dampier Sub-basin, marine environments prevailed during the Upper Jurassic and Lower Cretaceous, resulting in the deposition of fine-grained claystones. The sub-basins comprise a series of *en echelon* troughs separated by structural highs, with an overall northeast trend formed by oblique extension (Romine et al, 1997).

The sub-basins are separated by large Paleozoic–Triassic fault blocks that have been internally faulted, uplifted or rotated. Examples include the Alpha Arch between the Exmouth and Barrow sub-basins, the Sultan Nose between the Barrow and Dampier sub-basins (Polomka and Lemon, 1996) and the De Grey Nose between the Dampier and Beagle sub-basins (**Figure 5**).

The sub-basins are separated from the structural highs of the Rankin Platform and Exmouth Plateau to the northwest, and the Lambert and Peedamullah shelves to the east and south, by major extensional fault systems. The Rankin fault system separates the Rankin Platform from the Dampier Sub-basin (Stagg and Colwell, 1994), and the Flinders and Sholl Island fault systems separate the Peedamullah and Lambert shelves from the Barrow and Dampier sub-basins (Kopsen and McGann, 1985). Broad marginal terraces, overlain by predominantly Triassic to Cenozoic sediments have formed over down-faulted or rotated blocks along the faulted margins. These include the Enderby Terrace (**Figure 5**) in the Dampier Sub-basin and the Bruce and North Turtle terraces in the Beagle Sub-basin. From the Silurian to the Late Permian, the terraces were major extensional depocentres. Due to a general westward shift in the locus of extension, they were only moderately affected by subsequent Mesozoic rifting events (Hocking, 1990; Polomka and Lemon, 1996).

### ***Exmouth Plateau***

The Exmouth Plateau (**Figure 5, Figure 11, Figure 12**) is a subsided continental platform that is characterised by a faulted, predominantly Triassic sedimentary succession attaining a maximum thickness of up to 15 km. Jurassic sediments are generally either thin or absent. The major structural elements of the plateau comprise the Rankin Platform (**Figure 13**), the Kangaroo Syncline, the Investigator Sub-basin and the Wombat Plateau (Tindale et al, 1998; Stagg et al, 2004; **Figure 5**). The dominant structural trend varies between north and northeast, reflecting the interplay between the oblique extensional vectors and the pre-existing structural grain of the basement (Stagg et al, 2004).

### ***Lambert and Peedamullah shelves***

The Lambert and Peedamullah shelves form a rift shoulder to the Northern Carnarvon Basin (**Figure 2, Figure 5**). They comprise planated Precambrian cratonic basement mantled by landward-thinning, dominantly Cretaceous–Cenozoic sedimentary rocks up to 2 km thick. Silurian–Permian successions underlie parts of the Peedamullah Shelf.

## Basin evolution and stratigraphy

The generalised stratigraphy of the basin, shown in **Figure 6**, can be related to six tectonic phases, which, in turn, are related to the rifting phases that culminated in the continental breakup of the west Australian margin in the Middle–Late Jurassic and Early Cretaceous:

1. Pre-rift (Silurian to Toarcian)
2. Early syn-rift (Toarcian to earliest Callovian)
3. Main syn-rift (earliest Callovian to Berriasian)
4. Late syn-rift Barrow Delta (Berriasian to Valanginian)
5. Post-breakup subsidence (Valanginian to mid-Santonian)
6. Passive margin (mid-Santonian to present)

Hydrocarbon generation, migration and trap formation in the basin have been strongly controlled by syn-rift structuring and deposition and post-rift reactivation.

### *Pre-rift (Silurian to Toarcian)*

The onset of rifting of the Sibumasu Block from Gondwana (Metcalf, 1999) resulted in widespread deposition from the late Carboniferous, and initiation of the Westralian Superbasin, which includes the Northern Carnarvon Basin (AGSO North West Shelf Study Group, 1994). By the late Permian, northeast-trending depocentres had formed, where shallow marine clastics and carbonates were then deposited (Longley et al, 2002). At the beginning of the Triassic, a regional marine transgression deposited the Locker Shale, a predominantly marine claystone and siltstone with minor paralic sandstone and shelfal limestone (**Figure 6**). The Locker Shale grades upwards to the Middle–Upper Triassic Mungaroo Formation; a thick succession of sandstone, claystone and minor coal that was deposited in a fluvio-deltaic environment. The Mungaroo Delta prograded to the northwest and covered much of the offshore Northern Carnarvon Basin. The Mungaroo Formation consists of shoreline sandstone, shallow marine claystone and minor limestone. The Middle Triassic Cossigny Member of the Mungaroo Formation comprises a paralic siltstone, claystone and limestone unit that is a significant regional seismic marker, particularly in the Beagle Sub-basin (**Figure 6**). Fluvial and shoreline sandstones of the Mungaroo Formation host the giant gas accumulations on the Rankin Platform. The formation is also considered to contain the primary gas-prone source rocks in the Barrow, Dampier and Exmouth sub-basins and the Exmouth Plateau.

Deposition throughout the Triassic occurred within broad, gently structured downwarps. The large volume of the Mungaroo Delta sediments suggests that some clastics may have been delivered via transcontinental river systems from central Australia, Argo Land, West Burma and/or Greater India (Jablonski and Saitta, 2004).

Thinly bedded shelfal siltstone, claystone and marl of the Brigadier Formation and Murat Siltstone were deposited in response to rapid subsidence from the latest Triassic to the Early Jurassic (**Figure 6**). On the Wombat Plateau, Upper Triassic reefal limestone caps the Mungaroo Formation (von Rad et al, 1992a, 1992b). In the outer part of the basin, the Brigadier Formation is well preserved and is particularly thick in the Kangaroo and Victoria synclines (**Figure 5**) on the eastern Exmouth Plateau where it may also have gas potential (Bussell et al, 2001; Jablonski et al, 2013). In the Barrow and Dampier sub-basins, the Brigadier Formation is considered to be both a gas source and a reservoir. Thin, reservoir-quality sandstones preserved on some horst blocks along the Rankin Platform are known as the North Rankin Formation (Seggie et al, 2007).

In the Beagle Sub-basin, the Fitzroy Movement formed a series of structural highs and lows that isolated it from the Dampier Sub-basin during the Late Triassic (Blevin et al, 1994; Smith et al, 1999).

By the Pliensbachian, continued rifting resulted in the present day structural configuration of the Northern Carnarvon Basin. Major bounding faults (e.g. Rosemary, Flinders and Rankin fault systems) developed and delineated the Barrow, Dampier and Exmouth sub-basins, the Rankin Platform, and the Lambert and Peedamullah shelves (**Figure 2**, **Figure 5**). Oblique extension, combined with the pre-existing Proterozoic to Paleozoic northerly structural grain, resulted in *en echelon* faulting and compartmentalisation of the sub-basins (Romine et al, 1997). The formation of tilted fault blocks, horsts and graben strongly controlled the pattern of deposition (Barber, 1988). The large amount of subsidence that is observed, relative to faulting, suggests that lower crustal processes also played a major role during extension (Stagg and Colwell, 1994; Driscoll and Karner, 1998).

### ***Early syn-rift (Toarcian to earliest Callovian)***

The Toarcian to earliest Callovian syn-rift succession comprises restricted marine claystone and siltstone (Athol Formation) and regressive deltaic sandstone (Legendre Formation; **Figure 6**). By the Bathonian, the Legendre Delta had expanded westward from the Beagle Sub-basin into the Dampier Sub-basin and across the Rankin Platform. Sediment was supplied from fault blocks and platforms on the margins of the depocentre. The Athol and Legendre formations are the likely source of some of the hydrocarbon accumulations in the Dampier Sub-basin and in the southern Beagle Sub-basin (Thomas et al, 2004; Edwards and Zumberge, 2005; Jablonski et al, 2013). It hosts, and is the source of, the gas in the Reindeer and Saffron–Rosemary accumulations (Thomas et al, 2004).

### ***Main syn-rift (earliest Callovian to Berriasian)***

During the Callovian to Oxfordian, Argo Land separated from Australia and seafloor spreading commenced in the Argo Abyssal Plain (Jablonski, 1997). Uplift and erosion associated with initial extension produced the Callovian unconformity. This was followed by the main phase of syn-rift deposition in the Northern Carnarvon Basin that commenced with the deposition of the transgressive Callovian Calypso Formation claystone and sandstone in the Barrow and Dampier sub-basins (**Figure 6**). Major rift-related faults developed along the northern edge of the Exmouth Plateau at this time.

In parts of the basin, the basal Oxfordian unconformity or the ‘Breakup Unconformity’ corresponds to the so-called ‘Main Unconformity’. However, elsewhere, the latter is a diachronous sequence boundary, of earliest Jurassic to Aptian age (Newman, 1994; Jablonski, 1997), and is also referred to as the ‘Intra-Jurassic Unconformity’ (Sibley et al, 1999).

Post-breakup faulting during the Late Jurassic uplifted and tilted the Exmouth Plateau and the Rankin Platform and allowed them to supply sediment to adjacent depocentres. Rapid tectonic subsidence resulted in the deposition of a thick, deep marine succession (Dingo Claystone; **Figure 6**). This unit progressively filled and overlapped the flanks of the Barrow, Dampier and Exmouth sub-basins (**Figure 14, Figure 15**; Tindale et al, 1998). During the Oxfordian, a maximum flooding phase provided a favourable depositional environment for high-quality, oil-prone source rocks (Longley et al, 2002). At the depocentre margins, reservoir-quality turbidite, submarine fan, shoreline and fluvial sandstones were deposited.

Over parts of the Exmouth Plateau, shallow-marine sandstones were deposited within restricted depocentres during the Late Jurassic. The Kangaroo Syncline formed on the Exmouth Plateau in response to extensional reactivation of tilted Triassic fault blocks on the Rankin Platform (Jenkins et al, 2003). Coarse clastic sediments derived from the erosion of the Mungaroo Formation in uplifted areas were transported into the syncline until the Berriasian. Upper Jurassic sandstones constitute significant petroleum reservoirs in parts of the Northern Carnarvon Basin. These include turbiditic sandstones of the Biggada, Eliassen, Dupuy and Angel formations, and the shallow-marine to shoreline Jansz Sandstone (Jenkins et al, 2003; Moss et al, 2003; **Figure 6**). The Angel Formation is the main oil- and gas-bearing reservoir unit in the Dampier Sub-basin, and the Jansz Sandstone hosts the giant Io–Jansz gas accumulation on the Exmouth Plateau.

Deposition was terminated during the early Berriasian by a further episode of uplift and erosion that marked the final major pulse of rifting between Greater India and Australia.

### ***Late syn-rift Barrow Delta (Berriasian to Valanginian)***

The late syn-rift phase (Berriasian to Valanginian) was dominated by the Barrow Delta. The delta system covered a large area and resulted in the deposition of the Barrow Group (**Figure 6**), which attains a thickness of up to 2500 m. Initial deposition occurred in the Exmouth Sub-basin, fed by sediments from the south. The delta initially prograded northward, to the west of Barrow Island and across to the Exmouth Plateau, to form the lower Barrow Delta lobe. Approximately 75% of the Barrow Delta succession is attributed to the lower lobe (Ross and Vail, 1994). A second progradational phase commenced in the late Berriasian and formed the upper Barrow Delta lobe in the Barrow and Dampier sub-basins, 250 km to the east of the delta’s earlier depocentre. As the delta prograded northward towards the Gorgon Horst, the lower Barrow Delta lobe was eroded in the shoreward part of the Exmouth Sub-basin.

The sediments of the lower (or western) Barrow Delta lobe are collectively known as the Malouet Formation, and those of the upper (or eastern) lobe as the Flacourt Formation. The boundary between the two lobes is markedly diachronous (Baillie and Jacobson, 1997). Dominant facies include basin-floor fan sandstones, pro-delta to fore-set claystones, and top-set sandstones. Barrow Group sandstones are predominantly quartzose, weakly cemented, with excellent porosity and permeability. The giant Scarborough gas accumulation is hosted within a Barrow Group basin-floor fan sandstone (Tao et al, 2013). The sandstones above the Barrow Group are known locally as the Flag Sandstone and Zeepaard Formation (**Figure 6**). The Flag Sandstone was deposited as a basin-floor fan in the northeast part of the Barrow Sub-basin. In the early Valanginian, deposition of progradational top-set units of the Zeepaard Formation was widespread within the Barrow and Exmouth sub-basins and on the Rankin Platform.

Sediment supply to the Barrow Delta system ceased due to the commencement of continental breakup to the southwest of the Exmouth Plateau during the Valanginian (Hocking, 1990). The Exmouth Sub-basin and Exmouth Plateau were tectonically inverted during breakup, but subsidence and marine sedimentation continued throughout the Barrow and Dampier sub-basins.

### ***Post-breakup subsidence (Valanginian to mid-Santonian)***

Continental breakup and the onset of seafloor spreading in the Gascoyne and Cuvier abyssal plains during the Valanginian, resulted in widespread peneplanation in the Northern Carnarvon Basin and the formation of the Valanginian unconformity. Rapid subsidence following breakup resulted in a widespread transgression and the deposition of a fining-upward marine sequence over the unconformity surface.

Deposition in localised paralic and shelfal environments gave rise to the Birdrong Sandstone and the glauconitic Mardie Greensand. This was followed by the basin-wide deposition of the transgressive Muderong Shale, Windalia Radiolarite and Gearle Siltstone (**Figure 6**). The Muderong Shale forms a regional seal, and for the Barrow Sub-basin, hosts commercial oil accumulations within glauconitic sandstones of the *M. australis* Member. In the Dampier Sub-basin, oil is found in the Windalia Sand Member (**Figure 6, Figure 18**), which contained over 90% of the initial oil reserves of the Barrow Island oil field (Ellis et al, 1999). During the early Santonian, uplift in the southern Exmouth Sub-basin formed the Novara Arch and caused erosion of the Gearle Siltstone (Tindale et al, 1998).

### ***Passive margin (mid-Santonian to present)***

By the mid-Santonian, tectonic stability and a decreasing supply of terrigenous sediment caused siliciclastic sedimentation to cease. Prograding shelfal carbonates were deposited on the passive continental margin in the Late Cretaceous and Cenozoic.

During the Campanian, a period of regional compression resulted in uplift of the hinterland and structural inversion in the Exmouth Sub-basin. Further west, compression led to the formation of the Exmouth Plateau Arch and Resolution Arch and inversion of the Kangaroo Syncline (**Figure 5**; Tindale et al, 1998). Pre-existing rift-related structures experienced transpressional reactivation within the Dampier and Barrow sub-basins and led to the formation of Barrow Island (Longley et al, 2002; Cathro and Karner, 2006). During the Oligocene and Miocene, prograding shelfal carbonates continued to be deposited (Tindale et al, 1998).

In the Miocene, a major compressional event associated with the convergence of the Australian and Eurasian plates affected the entire northwest Australian margin, including the Northern Carnarvon Basin (Longley et al, 2002). This event caused tilting, inversion and renewed faulting (Malcolm et al, 1991; Cathro and Karner, 2006) and led to the formation of many structural traps within the Cretaceous and Cenozoic sections.

## **Exploration history**

The stratigraphic position and location of discoveries and exploration wells in the Northern Carnarvon Basin are shown in **Figure 2** and **Figure 6**, current permits and operators are shown in **Figure 17**.

The first flow of oil from a well to the surface in Australia was recorded in 1953 at Rough Range 1 in the onshore Exmouth Sub-basin. Oil flowed at a rate of 500 bopd (79.5 kl/d) from the Lower Cretaceous Birdrong Sandstone. Subsequent appraisal drilling on the Rough Range feature failed to replicate the initial success (Bradshaw et al, 1999; Ellis and Jonasson, 2002).

Exploration in the offshore Northern Carnarvon Basin during the 1960s and early 1970s established the basin as a major hydrocarbon province (Mitchellmore and Smith, 1994). The giant Barrow Island oil accumulation was discovered in 1964 (Ellis et al, 1999), and the Griffin oil accumulation was discovered in 1974. In 1968, the discovery of oil in Legendre 1 stimulated exploration in the Dampier Sub-basin. In 1972 and 1973, further discoveries were made at Angel and Lambert. A series of multi-Tcf gas discoveries were made on the adjacent Rankin Platform (Goodwyn, North Rankin/Perseus and Rankin; **Figure 23**; Barber, 1994a, 1994b; Thomas et al, 2004). In 1972, gas discoveries were made in Triassic sandstones at West Tryal Rocks 1 in the Barrow Sub-basin. In the same year, the first gas shows were recorded in the Exmouth Sub-basin by West Muiron 1.

Significant gas discoveries were made in the late 1970s to early 1980s. In 1979, a giant gas accumulation within a Lower Cretaceous Barrow Group basin-floor fan sand was discovered at Scarborough 1, in relatively deep water on the Exmouth Plateau. Scarborough is estimated to hold 7.3 Tcf (206.7 Bcm) of gas (Woodside Petroleum Ltd, 2019a). The gas discovery at Spar 1 (1976), in the Barrow Sub-basin, was also made in Lower Cretaceous sandstones. Discovered in 1981, the Gorgon field is one of the largest gas accumulations in the basin, and has a resource of 16.8 Tcf (475.7 Bcm) of gas and 121 MMbbl (19.2 GI) of liquids for a total of 2976.2 MMboe (Barber, 2013).

From the early 1980s to the mid-1990s, a number of predominantly medium-sized oil and gas discoveries were made in the Barrow and Dampier sub-basins as a result of 2D seismic surveys that were acquired with high line densities (Longley et al, 2002). These included South Pepper, Chervil, Harriet, Outtrim, Rosily and Saladin in the southern Barrow Sub-basin (Baillie and Jacobson, 1997); East Spar and Wonnich to the northwest of Barrow Island; Scindian/Chinook on the Alpha Arch; and Cossack, Talisman, Stag, Wanaea and Wandoo in the Dampier Sub-basin (Vincent and Tilbury, 1988; Bint, 1991). During this period, Maitland 1 (1992) discovered gas in a sandstone near the base of the Paleocene in the Barrow Sub-basin (Sit et al, 1994). In 1993, the oil discovery in Nebo 1 stimulated exploration interest in the underexplored Beagle Sub-basin (Osborne, 1994). In 1982, oil was discovered in Novara 1 in the Exmouth Sub-basin; however, the biodegraded nature of the Novara oil (16.7°API; Smith et al, 2003) proved to be a disappointment. Exploration on the Rankin Platform and adjacent Exmouth Plateau continued to target Triassic fault block and intra-Triassic plays. This resulted in the discovery of Chrysaor in 1994–1995 and Dionysus in 1996.

Major discoveries continued from the mid-1990s to the mid-2000s, punctuated by that of the giant Io–Jansz gas accumulation in 2000 on the Exmouth Plateau. The primary reservoir at Io–Jansz is an Oxfordian shallow-marine sandstone (the ‘Jansz Sandstone’; **Figure 6**). The gas is thought to have migrated into the Oxfordian sandstone after spilling from a gas-charged Triassic reservoir at Geryon (Jenkins et al, 2003). The Io–Jansz accumulation constitutes the largest gas resource discovered in the basin. It is estimated that the Io–Jansz feature holds 20.1 Tcf (569.2 Bcm) of gas and 16 MMbbl (2.5 GI) of liquids, for a total of 3436.3 MMboe (Barber, 2013).

Between the mid-2000s and mid-2010s commercialisation of discoveries were a focus. Large numbers of ‘step-out’ exploration wells, extension/appraisal and development wells were drilled to delineate and develop accumulations. The relatively high well and seismic data density/coverage over much of the basin is such that the Dampier and Barrow sub-basins, the Rankin Platform and parts of the Exmouth Plateau and Exmouth Sub-basin are now considered to constitute mature exploration provinces. With the application of modern 3D seismic acquisition, seismic reprocessing, and specialised techniques such as seismic amplitude-vs-offset (AVO) modelling, drilling success rates (particularly on the Exmouth Plateau) have improved (Kingsley and Tilbury, 1999; Longley et al, 2002; Korn et al, 2003; Williamson and Kroh, 2007).

In 2015 International Ocean Discovery Program (IODP) Expedition 356 sampled the western Australian margin from Fremantle to Darwin (International Ocean Discovery Program, 2015). Several shallow holes were drilled in the Northern Carnarvon Basin and provide some insight into the shallow sedimentary section and seafloor conditions.

Between 2015 and April 2021, twelve exploration wells were drilled in the offshore Northern Carnarvon Basin. Davis 1 (Santos, 2016a) and Spartan 1A (Australian Pipeliner, 2016a) are reported gas discoveries, and Outtrim East 1B (Carnarvon Petroleum Ltd, 2016) is a reported oil discovery for the Barrow Sub-basin. Snapshot 1 was drilled in 2016 on the central Exmouth Plateau and is a gas discovery (NOPTA, 2018). Woodside's Swell 1A, drilled in 2017, is a reported tight gas discovery for the Exmouth Sub-basin, although not commercially recoverable (Woodside Petroleum Ltd, 2019a). Reported dry holes include: Levitt 1 (Karoo Gas Australia Ltd, 2015) and Hyde 1A (Energy News Bulletin, 2016a) for the eastern Exmouth Plateau; Driftwood 1/ST1 (Offshore Energy Today, 2016) for the Barrow Sub-basin; Skippy Rock 1/Stokes 1 (Woodside Petroleum Ltd, 2016c) for the Beagle Sub-basin; and Achnar 1 in on the far eastern Rankin Platform/Dampier Sub-basin (Woodside Petroleum Ltd, 2020). Recently Ferrand 1 (2018) drilled on the Exmouth Plateau was reported as a gas discovery (Woodside Petroleum Ltd, 2019a), appraisal well Corvus 2 (2019) encountered a significant gas resource in the Dampier Sub-basin (Santos, 2019) and Ironbark 1 (2020) was reported as dry (Energy News Bulletin, 2021a).

To July 2022, three exploration wells have reached completion in 2022 in the Northern Carnarvon Basin: Dancer 1 (Santos) in the Dampier Sub-basin, Kanga 1 (SapuraOMV) on the Rankin Platform and Sasanof 1 (Western Gas) on the Exmouth Plateau. All three wells were deemed dry. Drilling of exploration well Yoorn 1 is anticipated to commence later in 2022 (Santos, 2021), the first of a possible three well campaign in the Dampier Sub-basin. Woodside's exploration well in the Barrow Sub-basin, Gemtree A is planned to drill in 2023 (Woodside Petroleum Ltd, 2022a). Woodside has approval to drill up to five further exploration and appraisal wells in WA-28-P but these are dependent on results of Achnar 1 (PESA News, 2019), no decision has been announced.

In the late 2000s to early 2010s several regional 2D deep-seismic surveys have been acquired in the Northern Carnarvon Basin. The Petroleum Geo-Services 2007–2010 “New Dawn” NWS Australia MC2D survey covers the Bonaparte, Browse, Roebuck and Northern Carnarvon basins (Petroleum Geo-Services, 2014) and employed a seismic broadband technique to provide a good mid-crustal view of regional structure. The WestraliaSPAN survey was completed in 2013 and comprises 11 500 km of deep-crustal 2D seismic over the Exmouth Plateau, and the Browse and Bonaparte basins (Ion Geophysical, 2013).

In the last six years four 3D marine seismic surveys (MSS) were conducted in the basin (NOPIMS, 2022): Schlumberger's 2017 Exmouth SLB15 MC3D MSS in the Exmouth Sub-basin and Exmouth Plateau for which a new 3D Petroleum System Model, related data and interpretation is available from the [National Offshore Petroleum Information Management System](#) (NOPIMS; Schenk et al, 2020; Geoscience Australia, 2020a); Quadrant's 2017 Bianchi/Hockey 3D MSS in the Barrow and Exmouth sub-basins (NOPSEMA, 2020a, 2020b); CGG Services' 2018-2019 Davros Extension MC3D MSS in the Dampier Sub-basin and Rankin Platform/Exmouth Plateau; and Petroleum Geo-Services' 2019 Mawson/Rollo MC 3D MSS on the Exmouth Plateau. In the first half of 2020 Woodside Energy acquired four ‘time lapse’ or 4D MSS (Pluto, Harmony, Laverda and Cimatti) all on the Rankin Platform and Exmouth Plateau to inform current and future reservoir management decisions (Woodside Petroleum Ltd, 2019b).

TGS's planned 2020–2023 Capreolus-2 MC3D MSS will cover much of the Beagle Sub-basin and parts of the Lambert Shelf and Bedout Sub-basin, with up to 27 649 km<sup>2</sup> of planned acquisition, specific commencement dates are yet been determined (NOPSEMA, 2020c).

### ***Dampier and Beagle sub-basins***

In the Dampier Sub-basin, re-evaluation of early discoveries on the Enderby Terrace and the testing of new play concepts led to the discoveries of oil at Chamois, Oryx, Sage and Tusk, and gas at Reindeer–Caribou and the nearby Corvus accumulation (Seggie et al, 2003; **Figure 4, Figure 8, Figure 18**).

During 2012, two wells were drilled southwest of the Legendre accumulation. Hoss 1 encountered oil shows and Jalfrezi 1 contained oil and gas shows. Winchester 1/ST1, drilled towards the western margin of the Dampier Sub-basin, encountered 58 m of net gas pay in the Jurassic Angel and Triassic Mungaroo formations (Santos, 2013a, 2013b).



The northern extent of production in the Dampier Sub-basin was extended from the Mutineer and Exeter oil accumulations (discovered by Pitcairn 1 in 1997 and Exeter 1 in 2002, respectively; Auld and Redfearn, 2003) into the adjacent Beagle Sub-basin by the discovery of oil at Fletcher 1 (2007) and Finucane South 1A (2011) by Santos Offshore Pty Ltd (Department of Mines and Petroleum, 2011). The resultant fields have been delineated by several extension/appraisal wells (**Figure 7**). In March 2014, Santos spudded Vanuatu 1 in WA-54-L (the Fletcher–Finucane production licence), which was plugged and abandoned as a dry hole.

In 2015, three 3D seismic surveys were conducted in the Dampier and Beagle sub-basins: the multi-client Capreolus 3D seismic survey, covering 22 132 km<sup>2</sup> across the boundary between the Roebuck and Northern Carnarvon basins (including the northern Beagle Sub-basin; Polarcus Ltd, 2015), was conducted by Polarcus Seismic Limited; CGG Services (Australia) Pty Ltd completed Phase 1 of the 11 000 km<sup>2</sup> Davros 3D seismic survey; and the Rosemary 3D seismic survey acquired 9400 km<sup>2</sup> of 3D seismic data over the Dampier Sub-basin, the southern Beagle Sub-basin, the southern Rankin Platform and the northernmost Barrow Sub-basin. In 2018–2019 CGG Services (Australia) Pty Ltd completed the 8072 km<sup>2</sup> Phase 2 of the Davros MC3D seismic survey which covers much of the Dampier Sub-basin, as well as areas of the central and north-eastern Rankin Platform (NOPSEMA, 2020d). TGS's planned Capreolus-2 3D MSS will cover much of the Beagle Sub-basin (NOPSEMA, 2020c).

Skippy Rock 1 and Stokes 1 were drilled by Woodside in the eastern Beagle Sub-basin in 2016, both were declared dry holes (Woodside Petroleum Ltd, 2016c). In 2019, two wells were drilling in the Dampier Sub-basin. Santos drilled Corvus 2, to appraise the Corvus oil discovery drilled by Apache in 2000, and announced a significant gas resource that includes 245 m of net pay between 3360 and 3998 in North Rankin and Mungaroo formation reservoirs (Santos, 2019a). Achernar 1, drilled by Woodside to a TD of 3285 m, intersected high porosity sands in the targeted North Rankin Formation reservoir, but was water bearing and was plugged and abandoned a dry hole (Woodside, 2020).

Carnarvon Petroleum derisked several prospects on the inboard Dampier Sub-basin as part of their Cerberus Project (Carnarvon Petroleum Ltd, 2017). These include the Kes and Honeybadger prospects, with are both Lower Triassic plays targeting stratigraphic traps with turbidite channel reservoirs sealed by the Locker Shale, as well as the Belfon prospect, which is targeting a titled fault block structural play with Permian Kennedy Formation reservoir also sealed by the Locker Shale (Carnarvon Petroleum Ltd, 2017). The permits covering these prospects are now held by Coastal Oil and Gas P/L. Santos has current interests in the Dampier Sub-basin with the award of WA-546-P in 2020 and WA-549-P in 2021, recent drilling and up to three further wells planned. Completed in early 2022, Dancer 1 targeting wet gas in the Jurassic Legendre Formation in WA-1-P at a planned total depth of 3604 m (Oil & Gas Today, 2021a), but came up dry (Energy News Bulletin, 2022a). Yoorn 1 located in WA-499-P northeast of the Campbell field, is anticipated to be drilled in the second half of 2022, with follow up wells Jelen 1 and Parnassus 1 planned for 2023 (Energy News Bulletin, 2022a).

Exploration interest in the Beagle Sub-basin is high, with the award in 2019 of WA-541-P to Santos and BP and WA-542-P to Equinor (now held by Finder). Further acreage nominations and releases followed in 2019, 2020 and 2021, with Finder awarded WA-547-P in 2021 and BP awarded WA-551-P in 2022. Heightened exploration interest in the Beagle Sub-basin is part of a broader exploration resurgence in the central NWS following the discovery of oil at Phoenix South 1 in 2014, and subsequent hydrocarbon discoveries in the Bedout Sub-basin (**Figure 7**). Further details on these discoveries and the prospectivity of the relatively underexplored central NWS are presented in the documentation of the [Regional Geology of the Roebuck Basin](#) (Geoscience Australia, 2020b).

### ***Barrow Sub-basin***

The Barrow Sub-basin, Barrow Island and the inshore part of the Barrow Island Trend have been foci of exploration since 1964 (**Figure 4**, **Figure 9**). Oil production commenced on Barrow Island in 1966 (Ellis et al, 1999).



In 2013, Apache drilled Bianchi 1, 6.4 km north of the Zola 1 gas discovery. Wireline logging and pressure data confirmed the presence of 112 m of net gas pay in the Triassic Mungaroo Formation (Apache Corporation, 2013a). In 2014, although no exploration wells were drilled in the Barrow Sub-basin, TGS acquired 2129 km<sup>2</sup> of new 3D seismic data (Huzza MC3D survey) across numerous permits in the southern part of the sub-basin. This was followed by the acquisition of 192 km<sup>2</sup> of multi-client 3D seismic data (Huzza Phase 2 MC3D survey) over the adjacent margins of the Barrow and Exmouth sub-basins. In 2015, Phase 1 of the Davros (~11 000 km<sup>2</sup>) multi-client 3D seismic survey was conducted and included areas of the northern Barrow Sub-basin. In early 2017, Quadrant completed the Bianchi/Hockey 3D seismic survey, covering ~1600 km<sup>2</sup> across the central Barrow Sub-basin and parts of the southern Rankin Platform and northern Exmouth Sub-basin (NOPSEMA 2017b).

In 2016, Davis 1 was drilled by partners Quadrant Energy and Santos, which tested the northern extension of the Maitland field; with Santos reporting the well as a gas discovery, as it encountered hydrocarbons in the 'Maitland sandstone' (Santos, 2016a). Outtrim East 1 was then drilled by partners Carnarvon Petroleum and Quadrant Energy, in the southern part of the basin, to test the eastwards extent of the Outtrim 1 oil discovery, particularly for sandstones of the Lower Cretaceous Barrow Group (Oil & Gas Journal, 2016). Driftwood 1 was spudded in August 2016 by Quadrant Energy to test Lower Cretaceous sandstones, but failed to find hydrocarbons (Offshore Energy Today, 2016). Also in 2016, Spartan 1/1A was drilled by partners Quadrant Energy and Santos, east of the Maitland gas field, and is a gas discovery (Australian Pipeliner, 2016a).

Exploration activity continues in the Barrow Sub-basin, notable recent events and planned activities include: Award of WA-543-P to Santos in late 2020, with an exploration well included in the work program out years'. Drilling of exploration well Eagle 1 by SapuraOMV in state waters in mid-2021. The well located ~13 km east of Outtrim, targeted gas in the Triassic Mungaroo Formation (Oil & Gas Journal, 2020a), no results have been disclosed. Carnarvon Petroleum are targeting gas with a planned exploration well in the Palmerston prospect, a Triassic Mungaroo Formation fault block structure in WA-155-P, comparable to the setting of the Zola 1 gas discovery to the north (Tap Oil Ltd, 2016; Oil & Gas Journal, 2020a). Carnarvon Petroleum hold a 70% interest in the Palmerston prospect, part of the broader Outtrim Project that includes further Mungaroo Formation targets (the Belgravia and Belgravia-East prospects; Carnarvon Petroleum, 2020).

### ***Exmouth Sub-basin***

In 1998 and 1999, respectively, the Vincent and Enfield oil discoveries were made in the Exmouth Sub-basin (**Figure 4, Figure 10, and Figure 19**). In 2000, these successes were followed by the Laverda and Scafell oil discoveries. Between 2003 and 2007, numerous successful wells were drilled; these included Bleaberry West, Eskdale, Crosby–Harrison–Ravensworth–Stickle, Langdale, Skiddaw and Stybarrow. Cimatti 1 was drilled by Woodside to test a prospect within tie-back distance to Enfield and intersected a gross 15 m oil column in the Macedon Formation, before being sidetracked as Cimatti 2 to further appraise the discovery. To the north of Cimatti 1, Furness 1 (2010) and Crusader 1 (2011) were drilled by BHP Billiton Petroleum Pty Ltd and Apache. In 2011, Woodside drilled Opel 1 in a separate fault block on the western flank of the Laverda accumulation and encountered oil (Woodside Petroleum Ltd, 2011a).

Exploration wells spudded in the Exmouth Sub-basin during 2012 and 2013 did not encounter commercial hydrocarbons. Palta 1 was drilled by Shell Development (Australia) Pty Ltd in the southern portion of the sub-basin. The well was plugged and abandoned after it failed to encounter significant hydrocarbon shows (Offshore Energy Today, 2013). Other wells drilled during 2013 included: Gumbo 1 (dry well) by Woodside on the northwest flank of the sub-basin, 8 km from the Ragnar 1A gas discovery; Minarelli 1 (dry well) located near the edge of the Enfield oil accumulation (Woodside Petroleum Ltd, 2013a, 2013b); and BHP Billiton's Stybarrow East 1 (oil shows), drilled northeast of the Stybarrow oil accumulation.

In 2014, two exploration wells were drilled and one 3D seismic survey was undertaken in the Exmouth Sub-basin. BHP Billiton drilled Rydal 1 which encountered non-commercial hydrocarbons. Woodside then drilled Toro 1, which intersected approximately 150 m of gross (65 m of net) gas pay within the Mungaroo Formation (Woodside Petroleum, 2014a). During early 2014, Woodside acquired the Babylon 3D seismic survey (1266 km<sup>2</sup>) within exploration permit WA-483-P, on the eastern margin of the sub-basin (Woodside Petroleum Ltd, 2014c).

In 2015–16, a single exploration well, Malaguti 1, was drilled by Woodside in the sub-basin and was declared a dry hole. In 2017, the only exploration well to be drilled in the Northern Carnarvon Basin was Swell 1/1A in the Exmouth Sub-basin. The well was spudded in August 2017 by partners Woodside and Kufpec, targeting a Triassic tilted fault block play with Mungaroo, Brigadier and Barrow formation reservoirs, and was reported as a tight gas discovery, although not commercially recoverable (Woodside Petroleum Ltd, 2017a, 2018). The 70% Carnarvon Petroleum held Belgravia and Belgravia east prospects, in WA-155-P ~20 km southwest, and ~650 m updip of Swell 1/1A, are targeting structures in the Triassic Mungaroo Formation (Carnarvon Petroleum Ltd, 2020).

In early 2017, the Exmouth SLB15 MC3D seismic survey was completed for Schlumberger over multiple permits in the Exmouth Sub-basin and Exmouth Plateau, covering an area of ~12 000 km<sup>2</sup> (NOPSEMA, 2020a; Schlumberger Ltd, 2017). This data allowed work that revealed new insights into the architecture and tectono-stratigraphic evolution of the Exmouth Sub-basin and was used to produce a basin wide 3D Petroleum System Model that, together with related data and interpretation, is available via NOPIMS (Schenk et al, 2020; Geoscience Australia, 2020a).

### ***Rankin Platform and Exmouth Plateau***

In recent years, growing demand for LNG in the Asia–Pacific region has stimulated exploration on the Rankin Platform and adjoining Exmouth Plateau (**Figure 4, Figure 11, Figure 12, Figure 13, Figure 19, Figure 23**). Most wells have tested Triassic fault blocks with top and intra-Mungaroo Formation objectives.

On the northern Rankin Platform (**Figure 13**), exploration drilling by Woodside has sought to extend the area of known accumulations by drilling wells such as Ananke 1 (2012) and Goodwyn North 1 (2013). In the central part of the Rankin Platform (in the vicinity of the Iago, Pluto and Wheatstone gas fields discovered between 2000 and 2005), Eris 1 (2009), Emersons 1 (2011) and Xeres 1A (2011) were also drilled by Woodside. In 2015 Woodside drilled Pyxis 1, just north of the Pluto field on the Exmouth Plateau, and intersected approximately 18.5 m of net gas within the Jurassic sandstone target (Woodside Petroleum Ltd, 2015a). Apache made several significant oil discoveries in the Mungaroo Formation (Balnaves 1–4 and Balnaves Deep 1; Apache Corporation, 2011a) in reservoirs that are distinct from those that host the nearby Julimar and Brunello gas accumulations (discovered in 2007 and 2008, respectively). The appraisal wells Balnaves Deep 2 and 3 were drilled in 2012 and development drilling was undertaken at Balnaves in 2014. Early in 2014, Apache Energy continued drilling in the Balnaves area with Balnaves West 1, which was plugged and abandoned as a dry hole. Between 2012 and 2014, numerous development wells were drilled at Brunello by Apache, at Wheatstone by Chevron and at Goodwyn, Xena and Tidepole by Woodside.

To further assess the Goodwyn accumulation, Woodside acquired the ~4000 km<sup>2</sup> Fortuna 3D seismic survey across multiple permits on the northern Rankin Platform in 2014. During 2015, the Dunnart 2D seismic survey was also collected over the western Dampier Sub-basin, the central Rankin Platform and Exmouth Plateau, including over the Jansz gas discovery, while the Davros 3D seismic survey (Phase 1 in 2015; Phase 2 in 2018–19) also included areas in the central and north-eastern Rankin Platform. The Northern Carnarvon Basin MC3D multi-client survey commenced in June 2015, with data collection over large areas of the Exmouth Plateau. Over late 2015 to early 2016, Woodside undertook the Pluto four-dimensional time-lapse marine seismic survey (Pluto 4D MSS), on the Rankin Platform and Exmouth Plateau, to better characterise the Pluto gas reservoir (Woodside Petroleum Ltd, 2016a).

In 2012, on the southern Rankin Platform, Chevron drilled Pontus 1, which encountered 97 ft (30 m) of net gas pay. During 2014, development drilling at Gorgon continued. Zola 1/ST1, to the south of, and on trend with, the Gorgon field, encountered 100 m of net gas pay over a 400 m gross interval within the Mungaroo Formation (Apache Corporation, 2011b). Drilled in 2013, Apache's Olympus 1 discovered gas in the Cretaceous lower Barrow Group and in the Triassic Mungaroo Formation (Johns and Despland, 2014). The recent Bianchi/Hockey 3D seismic survey, collected in 2017, covers the southern tip of the Rankin Platform, over the Zola, Bianchi and Antiope gas accumulations (NOPSEMA, 2020b).

Further west, on the central Exmouth Plateau (**Figure 11**, **Figure 12**), the Maenad and Orthrus gas accumulations were discovered in 1999–2000, to the south of the Io–Jansz accumulation. Subsequent gas discoveries at Achilles 1 and Acme 1 led to an increase in the known gas reserves on this part of the plateau. Over 2010–2011, extension and appraisal drilling by Chevron continued at Acme West 1 and 2, Clio 3, Iago 5 and Geryon 2. Also drilled by Chevron in 2010, Orthrus 2 intersected a deeper gas pool to the Orthrus gas accumulation (Department of Mines and Petroleum, 2011). Success at Satyr 1, drilled in 2009, led to further extension and appraisal drilling at Satyr 2, 3 and 4. These wells confirmed the presence of 128 ft (39 m), 243 ft (74 m) and 220 ft (67 m) of net gas pay, respectively. Satyr 5 was drilled in 2015, and was plugged and abandoned as a dry hole. Chevron drilled Dino North 1 and Isosceles 1 in the area in 2014 and 2015, respectively, both of which encountered gas (Chevron Australia Pty Ltd, 2015).

To the southwest of Io–Jansz are the Briseis, Glencoe and Nimblefoot gas discoveries, made by Hess in 2008 (**Figure 12**). Gas is trapped in the post-Callovian section, although at Briseis 1 there is additional pay in the Triassic Mungaroo Formation (Smallwood et al, 2010). Between 2009 and 2011, Hess drilled 16 wells within WA-390-P, of which 13 are gas discoveries. More recent drilling on the central plateau includes extension and appraisal drilling in 2012 by Hess at Glencoe (Glencoe 2/RE) and exploration drilling by Chevron at Cloverhill 1 in 2014, approximately 20 km north of Glencoe 1.

Exploration on the southern margin of the Exmouth Plateau includes the acquisition of Woodside's Centaurus 3D survey in WA-478-P (801 km<sup>2</sup>) (Woodside Petroleum Ltd, 2014c) and the discovery of the Tallaganda and Bunyip gas accumulations. BHP Billiton drilled Tallaganda 1 in 2012 and intersected gas in the Triassic Mungaroo Formation (Tap Oil Limited, 2012). To its south, Bunyip 1 was drilled in 2014 and encountered hydrocarbons (BHP Billiton, 2014).

Just to the north of the giant Io–Jansz field, the gas discoveries at Larsen 1, Larsen Deep 1, Martell 1, Martin 1, Noblige 1, Remy 1A (Woodside Petroleum Ltd, 2011b) and, most recently, Ferrand 1 (intersecting a 69 m gross gas column; Woodside Petroleum Ltd, 2019a) have extended the northerly limit of known gas accumulations on the central Exmouth Plateau. Gas discoveries just west of the Io–Jansz gas accumulation include Chevron's Chandon 1 (2006) and Yellowglen 1 (2009) and, more recently, Elfin 1 (2013). The latter intersected 132 ft (40 m) of net gas pay in upper Mungaroo Formation sandstones (Chevron Australia Pty Ltd, 2013b).

In 2011, three wells were drilled in the north and east of the Exmouth Plateau (**Figure 12**). La Rocca 1 was drilled by Apache Northwest Pty Ltd and Galahad 1 and Gawain 1 were drilled by ENI Australia Ltd. In 2012, Woodside sought to define the extent of these gas plays on the plateau and drilled Banambu Deep 1. In 2014, CNOOC Limited acquired a ~2000 km<sup>2</sup> 3D seismic survey in exploration permit WA-484-P. The most northeasterly well on the plateau, Levitt 1 drilled by Quadrant Energy in 2015, encountered no hydrocarbons in the targeted Jurassic reservoir, and was plugged and abandoned (Karoo Gas Australia Ltd, 2015). In 2016, Hyde 1A, drilled to the southwest of Levitt 1, also encountered no hydrocarbons, though the Joint Venture partners have identified several other surrounding leads and prospects (Energy News Bulletin, 2016a).

To the central western limit of the Exmouth Plateau (**Figure 11**), gas discoveries at Brederode 1, Kentish Knock 1, Guardian 1, and Thebe 1 and 2 extended the western limit of known gas accumulations on the outer plateau. In 2012, the discovery in upper Mungaroo Formation sandstones of 45.5 m of net gas pay at Arnhem 1 (Chevron Australia Pty Ltd, 2012), and 75 m of net gas pay at Kentish Knock South 1 (Chevron Australia Pty Ltd, 2013a), have confirmed the extent of these gas plays. The presence of gas south of the Scarborough accumulation was confirmed by the intersection of 60 m of net gas pay in Barrow and Mungaroo sands at Pinhoe 1 (Chevron Australia Pty Ltd, 2012). Also in the area are Chevron's Lymphstone 1 and Blake 1 gas discoveries, drilled in 2014. In early 2016, Hess drilled Snapshot 1, midway between the Io–Jansz and Scarborough fields, and discovered gas (NOPTA, 2018).

The exploration wells that have been drilled farthest to the west on the Exmouth Plateau are Tiberius 1, Alaric 1, Cadwallon 1, Genseric 1 and Vos 1, which were all drilled by Woodside between 2010 and 2012 (**Figure 11**). Alaric 1 intersected a 185 m gross gas column (Woodside Petroleum Ltd, 2010) and Cadwallon 1 intersected a 27 m gross gas column (Woodside Petroleum, 2011a). Gas discoveries by Alaric 1, in a reported Triassic target, and Cadwallon 1 suggests that the petroleum plays present on the central and eastern parts of the plateau extend to the deep-water western margin. Vos 1 (drilled by Chevron) encountered 138 m of net gas pay (Chevron Australia Pty Ltd, 2011) and also confirmed the prospectivity of the western margin of the Exmouth Plateau. During 2014, Chevron drilled Royal Oak 1 in WA-367-P, which was a reported gas discovery. In 2014–15 Shell completed its DAB 3D seismic program which comprised data from the Dirk 3D, Adventure 3D and Bart 3D seismic surveys in WA-491-P, WA-439-P and WA-496-P, respectively.

To date, three wells have been drilled on the Rankin Platform and Exmouth Plateau this decade. In late 2020 BP, in co-ordination agreement with Cue, Beach Energy and New Zealand Oil and Gas, drilled Ironbark 1 targeting multiple objectives within the Triassic Mungaroo Formation north of the North Rankin gas field (Energy News Bulletin, 2020a). The well was reported dry after reaching a total depth of 5618 m, one of the deepest exploration wells drilled in Australia (Energy News Bulletin, 2021a). In mid-2022 SapuraOMV drilled Kanga 1 in WA-412-P on the Rankin Platform, along trend from the North Rankin and Perseus gas fields. The well targeted the Jurassic Legendre Formation in a horst structure (Oil & Gas Journal, 2020b), but came up dry. Also in mid-2022, Sasanof 1 was drilled by Western Gas, with a planned total depth of ~2500 m. The Sasanof prospect is a large, seismic amplitude supported, structural-stratigraphic trap in Lower Barrow Group (Cretaceous) reservoir sandstones. Unrisked P50 prospective resources were estimated at 7.2 Tcf gas and 176 MMbbls condensate (Western Gas, 2022). The well failed to encounter significant hydrocarbons (Energy News Bulletin, 2022b).

Woodside's proposed well Gemtree-A, targeting the Gemtree prospect in WA-49-L for tie-back to Wheatstone infrastructure, is planned for drilling in 2023 after being deferred from drilling in 2020 due to challenging operating conditions (Oil & Gas Today, 2021b; Woodside Petroleum Ltd, 2022a). Further prospects across the Exmouth Plateau and Rankin Platform, include Woodside's Braastad prospect outboard of the Io-Janz gas field, which has potential to tie-in to the Pluto LNG project if successful (NOPSEMA, 2015), and Cue Energy's Sherlock prospect to the north of the Goodwyn gas field. The Sherlock prospect has a primary target below the base Cretaceous and a secondary target in the Mungaroo Formation, with both targets pursuing gas (Cue Energy Resources Ltd, 2014, 2018).

## Production and development

The Northern Carnarvon Basin is one of Australia's most prolific hydrocarbon-producing basins. The basin is estimated to contain 22.2 Bboe (3529.7 GL) resources (Barber, 2013). Most of the offshore part of the basin is located in Commonwealth waters and is currently under title (**Figure 17**).

In the 12 months to March 2022, the Northern Carnarvon Basin accounted for 51.1% of total petroleum production in Australia, producing 48.0% of total oil and NGL, and 51.8% of total natural gas (EnergyQuest, 2022). For the Northern Carnarvon and Roebuck basins collectively, to the end of 2020:

- 11 888 PJ (2021.7 MMbbl) of oil had been produced, and remaining reserves (2P) and contingent resources (2C) were 1105 PJ (187.9 MMbbl) and 1907 PJ (324.3 MMbbl), respectively;
- 6562 PJ (1116 MMbbl) of condensate had been produced, and remaining reserves (2P) and contingent resources (2C) were 3010 PJ (511.9 MMbbl) and 2296 PJ (390.6 MMbbl), respectively;
- 41 192 PJ (36.62 Tcf) of natural gas had been produced, and remaining reserves (2P) and contingent resources (2C) were 49 527 PJ (44.04 Tcf) and 56 994 PJ (50.68 Tcf), respectively (Geoscience Australia, 2022).

The main currently producing areas/hubs in the Northern Carnarvon Basin (**Figure 4**), as documented by APPEA (2016) and EnergyQuest (2022), are:

- North West Shelf Venture's (NWS Venture) North West Shelf Project (NWSP) located primarily on the northern Rankin Platform (fields: Angel, Goodwyn, North Rankin, Perseus, Searipple, Cossack, Wanaea, Lambert, Hermes and Persephone);
- Pluto LNG project on the Rankin Platform/Exmouth Plateau (fields: Pluto and Xena);
- Wheatstone LNG project on the Rankin Platform/Exmouth Plateau (fields: Wheatstone, Iago, Julimar and Brunello);

- Greater Gorgon LNG project on the Rankin Platform and Exmouth Plateau (fields: Gorgon and Janz-lo);
- Devil Creek project (tied in to Reindeer field), Stag, and Wandoo in the Dampier Sub-basin, plus Fletcher/Finucane (tied in to Mutineer/Exeter) in the Beagle Sub-basin;
- Barrow and Varanus islands in the Barrow Sub-basin (fields: Barrow Island, John Brookes, Halyard, Spar, East Spar and Wonnich); and
- Pyrenees, Macedon, Vincent and Van Gogh/Coniston in the Exmouth Sub-basin.

Of the above, seven produce natural gas—the NWSP, Pluto, Wheatstone, Gorgon, Varanus Island Gas Hub, the Devil Creek Gas Plant and the Macedon Domestic Gas Project. The remaining facilities produce oil, including the NWSP.

For major Northern Carnarvon Basin offshore producing fields/hubs, the latest total petroleum production figures for the 12 months to March 2022 are available from EnergyQuest's June 2022 Energy Quarterly (EnergyQuest, 2022). They are listed here in descending order:

- NWSP: 165.68 MMboe;
- Gorgon: 157.56 MMboe;
- Wheatstone: 114.99 MMboe;
- Pluto: 52.63 MMboe;
- John Brookes, Halyard, Spar: 17.03 MMboe;
- Macedon: 12.24 MMboe;
- Vincent/Greater Enfield: 11.34 MMboe;
- Reindeer: 7.94 MMboe;
- Pyrenees: 4.53 MMboe;
- Van Gogh/Coniston: 4.46 MMboe;
- Wandoo: 1.33 MMboe;
- Stag: 807 000 boe;
- Other: 1.223 MMboe.

In total, in the 12 months to March 2022, the Northern Carnarvon Basin produced 28.38 MMbbl (166.89 PJ) of oil, 366.2 PJ (326 Bcf) of conventional gas, 43.573 Mt of LNG, 393 000 t of LPG, and 44.7 MMbbl (262.87 PJ) of condensate, for a total petroleum production of 551.76 MMboe (EnergyQuest, 2022).

### ***Rankin Platform and Exmouth Plateau***

The NWS Venture is one of the world's largest consortia of LNG producers. The offshore production facilities are operated by Woodside Energy Pty Ltd with joint venture partners, BP Developments Australia Pty Ltd, Chevron Australia Pty Ltd, Japan Australia LNG (MIMI) Pty Ltd and Shell Development (Australia) Pty Ltd. The fields and facilities constitute Australia's largest oil and gas resource development (NWSP) and account for more than a quarter of Australia's oil and gas production. Gas from a series of offshore production facilities is transported to the Karratha Gas Plant for processing via two sub-sea pipelines (**Figure 4**). The NWSP remained the largest overall petroleum producer in Australia with 165.68 MMboe produced in the 12 months to March 2022, consisting of 14.32 Mt (794 PJ) of LNG, 11 PJ (10 Bcf) of conventional gas, 4.69 MMbbl (27.58 PJ) of oil and 20.58 MMbbl (121.01 PJ) of condensate (EnergyQuest, 2022). The Persephone Project—part of the NWS Project—is a Woodside development involving a 7 km subsea tie-back from the Persephone gas-condensate field to the North Rankin Complex platforms (Woodside Petroleum Ltd, 2014b). The field commenced production in July 2017 (Oil & Gas Journal, 2017).

The Pluto LNG Project is operated by Woodside Energy Pty Ltd (with joint venture partners Kansai Electric Power Australia Pty Ltd and Tokyo Gas Pty Ltd) and consists of a 4.9 MMtpa single train LNG plant located on the Burrup Peninsula (Burrup Park [Pluto] LNG plant; **Figure 4**), supplied with gas from the Pluto and Xena fields (Woodside Petroleum Ltd, 2016b). The plant commenced processing gas from Pluto in March 2012. In the 12 months to March 2022, the project produced 7.6 PJ (7 Bcf) of conventional gas, 5.052 MMt (280 PJ) of LNG and 3.39 MMbbl (19.93 PJ) of condensate (EnergyQuest, 2022).

The Gorgon LNG project, which sources gas, condensate and LNG from the Gorgon and Janz-Io accumulations (**Figure 4**), is the largest single resource development in Australia's history (Maffei et al, 2013). The project is operated by Chevron Australia Pty Ltd, with joint venture partners ExxonMobil Pty Ltd, Shell Australia Pty Ltd, Osaka Gas Pty Ltd, Tokyo Gas Pty Ltd and JERA Pty Ltd. Production facilities include a three-train LNG plant on Barrow Island with a capacity of 15.6 MMtpa, a 300 TJ/d domestic gas plant to supply the Western Australian markets, a 2.1 km long loading jetty for transport to international markets and a large-scale carbon dioxide reinjection project (Chevron Australia Pty Ltd, 2017a). The project shipped its first LNG cargo from Train 1 in March 2016, followed by Train 2 in October 2016 and Train 3 in March 2017 (Chevron Australia Pty Ltd, 2017b). The Gorgon domestic gas plant, located on Barrow Island, came online in December 2016 (Chevron Australia Pty Ltd, 2017a). Phase 2 of the Gorgon project, which involves drilling of 11 new wells and construction of pipelines and other subsea infrastructure commenced in mid-2019 (Offshore Energy Today, 2019a). In the 12 months to March 2022 Gorgon produced 69.3 PJ (62 Bcf) of gas, 14.58 Mt (808.2 PJ) of LNG and 7.13 MMbbl (41.92 PJ) of condensate (EnergyQuest, 2022).

The Wheatstone LNG project sources gas, LNG and condensate from the Wheatstone, Iago, Julimar and Brunello fields (**Figure 4**). The project is operated by Chevron Australia Pty Ltd, with equity participants Kufpec Australia Pty Ltd, Woodside Energy Pty Ltd, PE Wheatstone Pty Ltd (part owned by JERA Pty Ltd) and Kyushu Electric Power Company (Chevron Australia Pty Ltd, 2017c). The project uses a two-train plant, with a combined capacity of 8.9 MMtpa, at Ashburton North Strategic Industrial Area, 12 km west of Onslow (**Figure 4**), as well as a domestic gas plant. The first shipment of LNG was made in 2017, and the first condensate shipment followed in February 2018 (Chevron Australia Pty Ltd, 2017c; Energy News Bulletin, 2018). Production in the 12 months to March 2022 was 68.6 PJ (61 Bcf) of gas, 9.6 MMt (533 PJ) of LNG and 12.35 MMbbl (72.62 PJ) of condensate (EnergyQuest, 2022).

### ***Dampier and Beagle sub-basins***

The Santos operated Reindeer/Devil Creek development supplies gas and condensate from the Reindeer field to the domestic market via an offshore pipeline and Devil Creek processing plant. The processing plant is located onshore, south of Karratha, and consists of two-trains designed to process 215 TJ of gas per day (Santos, 2011, 2020; **Figure 4**).

Oil has been produced from the Stag oil field since May 1998. The field has produced up to 8800 bopd (1400 kl/d), although it is now producing 3400 bopd (540 kl/d) as reported after purchase of the field and associated infrastructure by Jadestone Energy (Jadestone Energy Australia Pty Ltd, 2017). Production continues following completion of infill drilling in 2019 (Oil and Gas Journal, 2019) with 807 000 bbls of oil produced in the 12 months to March 2022 (EnergyQuest, 2022).

The Wandoo oil field is operated by Vermilion Energy Inc. and produces via the Wandoo A monopod and the Wandoo B platform. Production rates for the field are expected to be maintained at 6000 bbls/d (954 kl/d) (Vermilion Energy, 2020). Production in the 12 months to March 2022 was 1.33 MMbbl of oil (EnergyQuest, 2022).

### ***Barrow Sub-basin***

The Barrow Island production facilities (**Figure 4**), on Barrow Island, are operated by Chevron with partners Santos and ExxonMobil. The Barrow Island oil field is the largest oil accumulation in Western Australia. In 1999, in-place reserves were 1250 MMbbl (198.7 GL) of oil and 580 Bcf of gas (16.4 Bcm; Ellis et al, 1999). Since production commenced in 1967, over 327 MMbbl (52 GL) of oil has been produced (Chevron Australia Pty Ltd, 2018). Production is mostly via horizontal wells, collected at eight gathering stations, and stored on the island before transfer via an offshore tanker mooring.

The Varanus Island Gas Hub is operated by Santos, and is located approximately 75 km offshore (NOPSEMA, 2020e). It is the production facility for the Harriet, East Spar and John Brookes fields as well as other nearby producing fields, and has infrastructure that has the capacity to produce up to 390 TJ of gas per day, producing 17.3 MMboe in 2017 (Santos, 2019b). Oil is transferred to tankers for export while gas is transported onshore via two 100 km pipelines that connect to the Dampier to Bunbury Natural Gas Pipeline (DBNGP) and Goldfields Gas Pipeline. Santos' Greater East Spar offshore installation project seeks to connect the Spar 2 well, drilled in 2010, to the existing Halyard subsea facilities (NOPSEMA, 2020f). In August 2017, the project had its environmental plan approved, with installation activities completed in late 2017 (NOPSEMA, 2020f).

### ***Exmouth Sub-basin***

The Woodside operated Pyrenees Project produces oil from the Crosby, Ravensworth and Stickle fields through the Pyrenees Venture FPSO facility (**Figure 4**). In the 12 months to March 2022, oil production from the Pyrenees Project was 4.53 MMbbl (26.64 PJ; EnergyQuest, 2022). The Macedon Project, also operated by Woodside, produces gas from the Macedon, Wildbull, Tanglehead and Moondyne fields, with a gas production capacity of 200 MMcfd (5.7 Mm<sup>3</sup>/d) (Offshore Technology, 2016a). A pipeline connects the Macedon Gas Plant to the DBNGP (Apache Corporation, 2013b) for supply to the domestic market (**Figure 4**). Natural gas production in the 12 months to March 2022 was 71.2 PJ (63 Bcf; EnergyQuest, 2022).

The Enfield oil field reached the end of its life in 2018 and has been decommissioned by Woodside. Production via the Nganhurra FPSO commenced in June 2006, going on to produce a total of more than 80 MMbbl (Woodside Petroleum Ltd, 2019c).

The Vincent oil field is operated by Woodside in conjunction with partner Mitsui E & P Australia Pty Ltd (Offshore Technology, 2016b). Production is via the Ngujima-Yin FPSO, which commenced in August 2008. The Van Gogh oil field is an extension of the Vincent oil field and commenced production in February 2010 via the Ningaloo Vision FPSO. The Coniston and Novara oil fields are operated by Santos and commenced production in 2015, via subsea tie-backs to the Ningaloo Vision FPSO (NOPSEMA, 2020g). Environmental approval to drill additional wells as part of the Van Gogh/Coniston development to boost production has been granted (NOPSEMA, 2020g).

The Greater Enfield Project is a Woodside development that provides a 31 km subsea tie-back of the Laverda Canyon, Norton over Laverda, and Cimatti oil fields to the Ngujima-Yin FPSO, which is serving the Vincent oil field (Offshore Technology, 2016c; Woodside Petroleum Ltd, 2016a). The Greater Enfield drilling campaign included twelve development wells and subsea tie-back, with first oil produced in 2019 (Offshore Energy Today, 2019b). In the 12 months to March 2022, oil production from Vincent and Greater Enfield was the highest for the Northern Carnarvon Basin, with 11.34 MMbbl (66.68 PJ) produced (Energy Quest, 2022).

### ***Development status***

Currently there are three development projects in various stages of progress in the Northern Carnarvon Basin: NWS Venture's Greater Western Flank, Scarborough (including the Pluto LNG expansion project) and Equus.

The NWS Venture's Greater Western Flank (GWF) Project Phases 1 and 2 will maintain offshore supply to the Karratha Gas Plant for both domestic gas and LNG (Woodside Petroleum Ltd, 2011c). Phase 1 commenced production in 2015 (Woodside Petroleum Ltd, 2016d) and brings the Goodwyn and Tidepole gas and condensate accumulations through a sub-sea tie-back to the Goodwyn-A platform. The US \$2 billion GWF Phase 2 project develops 1.6 Tcf (45.3 Bcm) of gas (Woodside Petroleum Ltd, 2015b), consisting of the development of the Keast, Dockrell, Sculptor, Rankin, Lady Nora and Pemberton accumulations via sub-sea tie-backs to Goodwyn-A. First gas from this second phase of the GWF development was produced in October 2018 (Woodside Petroleum Ltd, 2019d). Planning for a third phase of the project (GWF-3) together with the Lambert Deep Project is underway, with proposed drilling of three development wells at the GWF and one development well at Lambert Deep to be tied back, subsea, to existing infrastructure (Oil & Gas Today, 2021c).



Woodside and joint venture partners are progressing plans to expand their Pluto LNG facility into a regional LNG production hub, the Burrup Hub. The vision includes North West Shelf (NWS) Project Extension; the Pluto–Karratha Gas Plant (KGP) Interconnector; and development of Pluto Train 2 and the Scarborough field (**Figure 2**). Pluto Train 2 has a planned capacity of 5 Mtpa, and will allow development of the Scarborough gas field via a 430km pipeline to the onshore facilities on the Burrup Peninsula (Woodside Petroleum Ltd, 2022b). Front-end engineering design (FEED) activities were conducted in 2019, with final investment decisions (FID) approving the US \$12 billion Scarborough and Pluto Train 2 developments announced in November 2021 (Woodside Petroleum Ltd, 2021). The Pluto–Karratha Gas Plant (KGP) Interconnector, transporting gas from new facilities at Pluto LNG to the KGP, has a capacity of more than 5 Mtpa and achieved start-up in Q1 2022 (Woodside Petroleum Ltd, 2022b).

Development of the Pyxis Hub, the next major source of gas for the Pluto LNG facility, began in 2020 following FID in 2019. The project will develop Pyxis, Pluto North, and Xena 2 fields via subsea tieback and will support the broader Burrup Hub (Offshore Energy Today, 2019c).

The Equus Gas Project began after Hess discovered gas at Glencoe 1, midway between the Scarborough and Ilo–Jansz gas fields, in 2008. Hess had proposed to develop the discoveries and began front-end engineering studies (Hess Corporation, 2016) before the undeveloped project was acquired by Western Gas (Energy News Bulletin, 2017b). The acquisition includes four permits and a retention lease covering 11 gas-condensate fields, with estimated resources of more than 2 Tcf (56.6 Bcm) of gas and 402 MMbbls (63.9 GL) of condensate (Energy News Bulletin, 2017b). In 2019 Western Gas completed its development plan that includes FPSO and FLNG facilities and a tie-in to the DBNGP. Project financing plans are underway and first domestic gas supply is expected in 2024 (Western Gas, 2019).

DUET has approved use of the depleted onshore Tubridgi gas reservoir (**Figure 4**) as a large gas storage facility to serve the northern Carnarvon region (Australian Pipeliner, 2016b; Energy News Bulletin, 2017a). Work on an expansion project began in late 2018 to increase injection and withdrawal capacity to 90TJ/day and 60TJ/day, respectively (Australian Gas Infrastructure Group, 2020).

## Regional petroleum systems

Two Mesozoic petroleum supersystems have been identified within the Northern Carnarvon Basin. Bradshaw (1993) and Bradshaw et al (1994, 1997) developed a petroleum system and supersystem framework that linked Australian basins by age, facies, tectonic history and hydrocarbon generation history. Each petroleum system within a supersystem is defined by a combination of play elements separated by either tectonic and/or climatic events. The petroleum systems of the Northern Carnarvon Basin were characterised by Spencer et al (1993, 1994 and 1995) and Bradshaw et al (1994) as belonging to the Westralian 1 and Westralian 2 supersystems.

On the basis of a USGS resource assessment analysis, Bishop (1999) further defined the two petroleum systems in the Northern Carnarvon Basin using the source–reservoir couplet nomenclature of Magoon and Dow (1994):

- The ‘Locker/Mungaroo–Mungaroo/Barrow’ Petroleum System.
- The ‘Dingo–Mungaroo/Barrow’ Petroleum System.

These systems are considered to source the majority of the commercial petroleum discoveries within the basin.

The gas-prone ‘Locker/Mungaroo–Mungaroo/Barrow’ Petroleum System covers most of the basin and extends to the margins of the Exmouth Plateau. The primary source rock for this petroleum system is the Upper Triassic deltaic Mungaroo Formation (and marine equivalents) with a possible secondary contribution from organic-rich marine units in the Lower Triassic Locker Shale. The majority of recent exploration on the Exmouth Plateau has been based on a model that invokes gas charge from deeply buried coals and carbonaceous claystones within the Mungaroo Formation.

From a regional perspective, the ‘Locker/Mungaroo–Mungaroo/Barrow’ Petroleum System can be considered part of the Westralian 1 Petroleum Supersystem (Bradshaw et al, 1994; Edwards and Zumberge, 2005; Edwards et al, 2007). This supersystem includes giant gas accumulations that have been predominantly sourced from fluvial-deltaic Triassic to Lower–Middle Jurassic source rocks in the Bonaparte, Browse and Northern Carnarvon basins. Similarities between carbon isotopic profiles of gases and condensates within the Westralian Superbasin reflect recurring organofacies that existed in the fluvial-deltaic environments developed from the Triassic to the Middle Jurassic (Edwards and Zumberge, 2005; Edwards et al, 2006).

The oil-prone ‘Dingo–Mungaroo/Barrow’ Petroleum System (Bishop, 1999) is restricted to the Exmouth, Barrow and Dampier sub-basins, and is principally sourced from the Upper Jurassic Dingo Claystone. It can be considered part of the Westralian 2 Petroleum Supersystem (Bradshaw et al, 1994) as geochemically similar oils are recognised in the Northern Carnarvon, Bonaparte (Vulcan Sub-basin and Laminaria High) and Papuan basins (AGSO and GeoMark, 1996; Edwards and Zumberge, 2005).

Some oils and condensates that could not be attributed to either of these two petroleum systems have been termed ‘vagrants’ by Summons et al (1998) and used as evidence that additional source rocks have been generating hydrocarbons within the basin. For example, lacustrine sources have been ascribed to the Nebo 1 oil accumulation in the Beagle Sub-basin, and to oils recovered at Parrot Hill 1 and Rough Range 1/1A in the onshore Exmouth Sub-basin (Longley et al, 2002; Edwards and Zumberge, 2005).

## Petroleum Systems Elements

### *Beagle Sub-basin*

Sources	<ul style="list-style-type: none"> <li>• Potential Upper Jurassic marine Dingo Claystone</li> <li>• Lower–Middle Jurassic marine and deltaic Murat Siltstone, and Athol and Legendre formations</li> <li>• Presumed Lower—Middle Jurassic deltaic coals or lacustrine mudstones</li> <li>• Upper Triassic fluvial-deltaic to marine Brigadier Formation</li> <li>• Middle–Upper Triassic fluvial-deltaic Mungaroo Formation</li> <li>• Lower Triassic Locker Shale</li> </ul>
Reservoirs	<ul style="list-style-type: none"> <li>• <i>M. australis</i> Member and other sandstone units within the Lower Cretaceous marine to marginal marine Muderong Shale</li> <li>• Lower Cretaceous marine to fluvial-deltaic sandstones of the Forestier Claystone (Barrow Group equivalents)</li> <li>• Upper Jurassic Angel Formation turbidites</li> <li>• Middle–Upper Jurassic fluvial-deltaic to marine Legendre and Calypso formations</li> <li>• Lower–Middle Jurassic marginal marine Athol Formation</li> <li>• Lower Jurassic fluvial-deltaic to marginal marine North Rankin Formation</li> <li>• Upper Triassic fluvial-deltaic to shallow marine Brigadier Formation</li> <li>• Middle–Upper Triassic fluvial-deltaic to marginal marine Mungaroo Formation</li> <li>• Potential Lower Triassic marginal marine transgressive sand underlying the Locker Shale</li> </ul>
Seals	<p><i>Regional seals</i></p> <ul style="list-style-type: none"> <li>• Lower Cretaceous marine Muderong Shale</li> <li>• Middle Triassic marine Cossigny Member of the Mungaroo Formation</li> </ul> <p><i>Intraformational seals</i></p> <ul style="list-style-type: none"> <li>• Lower–Upper Cretaceous marine Gearle Siltstone</li> <li>• Lower Cretaceous marine to fluvial-deltaic Forestier Claystone</li> <li>• Upper Jurassic marine Dingo Claystone</li> <li>• Middle–Upper Jurassic marine to marginal marine Calypso Formation</li> <li>• Lower–Middle Jurassic marine to marginal marine Athol Formation</li> <li>• Lower Jurassic marine Murat Siltstone</li> <li>• Lower Triassic Locker Shale (untested)</li> </ul>
Traps	<ul style="list-style-type: none"> <li>• Cenozoic incised valley and channel stratigraphic traps</li> <li>• Lower Cretaceous unconformity and basement onlap stratigraphic traps</li> <li>• Upper Jurassic–Lower Cretaceous submarine fan, shoreline and estuarine sandstone stratigraphic traps</li> <li>• Middle Jurassic to Lower Cretaceous horst, tilted fault block and low-side rollover traps</li> <li>• Triassic to Lower Cretaceous anticlines and faulted anticline traps</li> <li>• Middle Jurassic to Lower Cretaceous drape and anticline traps over Triassic to Jurassic fault blocks</li> <li>• Middle–Upper Triassic Mungaroo Formation pinch-out traps</li> <li>• Triassic transgressive sandstone stratigraphic traps at the base of the Locker Shale</li> </ul>

### Dampier Sub-basin

Sources	<ul style="list-style-type: none"> <li>Upper Jurassic marine Dingo Claystone</li> <li>Lower–Middle Jurassic marine and deltaic Murat Siltstone and Athol and Legendre formations</li> <li>Triassic fluvial-deltaic sediments of the Mungaroo Formation</li> <li>Potential Lower Triassic Locker Shale</li> </ul>
Reservoirs	<ul style="list-style-type: none"> <li><i>M. australis</i> Member and other sandstone units within the Lower Cretaceous marine to marginal marine Muderong Shale</li> <li>Upper Jurassic Angel Formation turbidites</li> <li>Middle–Upper Jurassic fluvial-deltaic to marine Legendre and Calypso formations</li> <li>Lower–Middle Jurassic marginal marine Athol Formation</li> <li>Lower Jurassic fluvial-deltaic to marginal marine North Rankin Formation</li> <li>Upper Triassic fluvial-deltaic to shallow marine Brigadier Formation</li> <li>Middle–Upper Triassic fluvial-deltaic to marginal marine Mungaroo Formation</li> <li>Potential Lower Triassic marginal marine transgressive sand underlying the Locker Shale</li> </ul>
Seals	<p><i>Regional seals</i></p> <ul style="list-style-type: none"> <li>Lower–Upper Cretaceous marine Gearle Siltstone</li> <li>Lower Cretaceous marine claystones of the Muderong Shale</li> <li>Lower Triassic Locker Shale (untested)</li> </ul> <p><i>Intraformational seals</i></p> <ul style="list-style-type: none"> <li>Upper Jurassic condensed marls and claystones of the Dingo Claystone</li> <li>Lower–Middle Jurassic marine to marginal marine Athol Formation</li> <li>Lower Jurassic marine Murat Siltstone</li> </ul>
Traps	<ul style="list-style-type: none"> <li>Lower Cretaceous <i>M. australis</i> Member stratigraphic trap</li> <li>Lower Cretaceous low-side rollover structures and faulted horst blocks</li> <li>Upper Jurassic–Lower Cretaceous drape structures</li> <li>Upper Jurassic–Lower Cretaceous submarine fan stratigraphic traps</li> <li>Middle Jurassic faulted anticlines</li> <li>Upper Triassic–Lower Jurassic horst and tilted fault-blocks and associated drapes</li> </ul>

### Rankin Platform

Sources	<ul style="list-style-type: none"> <li>Lower–Middle Jurassic marine and deltaic Murat Siltstone and Athol and Legendre formations</li> <li>Triassic fluvial-deltaic sediments of the Mungaroo Formation</li> </ul>
Reservoirs	<ul style="list-style-type: none"> <li>Upper Jurassic shallow marine and basin-floor fans of the Angel Formation</li> <li>Middle Jurassic deltaic Legendre Formation</li> <li>Lower Jurassic North Rankin Formation</li> <li>Upper Triassic shallow marine-deltaic Brigadier Formation</li> <li>Middle–Upper Triassic fluvial-deltaic to marginal marine Mungaroo Formation</li> </ul>
Seals	<p><i>Regional seal</i></p> <ul style="list-style-type: none"> <li>Lower Cretaceous marine claystones of the Muderong Shale</li> </ul> <p><i>Intraformational seals</i></p> <ul style="list-style-type: none"> <li>Lower Cretaceous distal marine claystones of the Barrow Group (Forestier Claystone equivalents)</li> <li>Upper Jurassic condensed marls and claystones of the Dingo Claystone</li> <li>Triassic fluvial-deltaic claystones of the Mungaroo Formation</li> </ul>
Traps	<ul style="list-style-type: none"> <li>Lower Cretaceous basin-floor fan stratigraphic traps</li> <li>Upper Jurassic structural traps</li> <li>Lower to Middle Jurassic tilted fault blocks</li> </ul>

	<ul style="list-style-type: none"> <li>• Tilted Triassic fault blocks and associated drapes</li> </ul>
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### ***Barrow and Exmouth sub-basins***

Sources	<ul style="list-style-type: none"> <li>• Upper Jurassic marine Dingo Claystone</li> <li>• Lower–Middle Jurassic marine and deltaic Murat Siltstone, and Athol and Legendre formations</li> <li>• Middle–Upper Triassic fluvial-deltaic Mungaroo Formation</li> </ul>
Reservoirs	<ul style="list-style-type: none"> <li>• <i>M. australis</i> Member (Barrow Sub-basin) and other sandstone units, including Mardie Greensand Member (Exmouth Sub-basin), within the Lower Cretaceous marine to marginal marine Muderong Shale</li> <li>• Lower Cretaceous fluvial-deltaic Barrow Group, including Malouet and Flacourt formations and Flag Sandstone</li> <li>• Upper Jurassic marine Dupuy and Biggada formations</li> <li>• Middle–Upper Triassic fluvial to marginal marine Mungaroo Formation</li> </ul> <p><i>Barrow Sub-basin</i></p> <ul style="list-style-type: none"> <li>• Lower Jurassic fluvial-deltaic to marine North Rankin Formation</li> <li>• Upper Triassic fluvial-deltaic to marine Brigadier Formation</li> <li>• Potential Lower Triassic basal transgressive sandstone underlying the Locker Shale</li> </ul> <p><i>Exmouth Sub-basin</i></p> <ul style="list-style-type: none"> <li>• Lower Cretaceous deltaic Zeepaard Formation</li> <li>• Lower Cretaceous coastal to nearshore Birdrong Sandstone</li> </ul>
Seals	<p><i>Regional seal</i></p> <ul style="list-style-type: none"> <li>• Lower Cretaceous marine Muderong Shale</li> </ul> <p><i>Intraformational seals – Barrow Sub-basin</i></p> <ul style="list-style-type: none"> <li>• Paleocene Dockrell Formation</li> <li>• Lower–Upper Cretaceous marine Gearle Siltstone</li> <li>• Lower Cretaceous Windalia Radiolarite</li> <li>• Upper Jurassic marine Dingo Claystone</li> <li>• Lower–Middle Jurassic marine to marginal marine Athol Formation</li> <li>• Lower Jurassic marine Murat Siltstone</li> <li>• Lower Triassic Locker Shale (untested)</li> </ul> <p><i>Intraformational seal – Exmouth Sub-basin</i></p> <ul style="list-style-type: none"> <li>• Upper Triassic fluvial-deltaic Mungaroo Formation</li> </ul>
Traps	<p><i>Barrow Sub-basin</i></p> <ul style="list-style-type: none"> <li>• Paleogene stratigraphic traps</li> <li>• Lower Cretaceous stratigraphic traps (e.g. <i>M. australis</i> Member), low-side rollover structures and faulted horst blocks</li> <li>• Upper Jurassic–Lower Cretaceous drape structures and submarine fan stratigraphic traps</li> <li>• Middle Jurassic faulted anticlines</li> <li>• Upper Triassic–Lower Jurassic horst and tilted fault-blocks and associated drapes</li> </ul> <p><i>Exmouth Sub-basin</i></p> <ul style="list-style-type: none"> <li>• Cretaceous inversion anticline structural/stratigraphic traps</li> <li>• Complex Jurassic structural/stratigraphic traps</li> <li>• Tilted Triassic fault blocks and associated drapes</li> </ul>

## Exmouth Plateau

Sources	<ul style="list-style-type: none"> <li>• Triassic fluvial-deltaic sediments of the Mungaroo Formation</li> <li>• Potential Lower Triassic Locker Shale</li> </ul>
Reservoirs	<ul style="list-style-type: none"> <li>• Lower Cretaceous basin-floor fans and turbidites in the Barrow Group</li> <li>• Upper Jurassic upper–lower shoreface Jansz Sandstone</li> <li>• Potential Upper Triassic carbonate reefs</li> <li>• Upper Triassic shallow marine-deltaic Brigadier Formation</li> <li>• Middle–Upper Triassic fluvial-deltaic to marginal marine Mungaroo Formation</li> </ul>
Seals	<p><i>Regional seals</i></p> <ul style="list-style-type: none"> <li>• Lower Cretaceous marine claystones of the Muderong Shale</li> <li>• Potential Lower Triassic Locker Shale</li> </ul> <p><i>Intraformational seals</i></p> <ul style="list-style-type: none"> <li>• Lower Cretaceous distal marine claystones of the Barrow Group (Forestier Claystone equivalents)</li> <li>• Upper Jurassic condensed marls and claystones of the Dingo Claystone</li> <li>• Triassic fluvial-deltaic claystones of the Mungaroo Formation</li> </ul>
Traps	<ul style="list-style-type: none"> <li>• Upper Cretaceous turbidite sandstones combined structural and stratigraphic traps</li> <li>• Lower Cretaceous basin-floor fan stratigraphic traps</li> <li>• Upper Jurassic shoreface sandstone stratigraphic traps</li> <li>• Potential Upper Triassic pinnacle reefs</li> <li>• Tilted Triassic fault blocks and associated drapes</li> </ul>

## Source Rocks

The primary gas-prone source rocks across much of the Northern Carnarvon Basin, particularly the Barrow, Dampier and Exmouth sub-basins, are inferred to be the Triassic fluvial-deltaic sediments of the Mungaroo Formation, with a secondary contribution from the overlying Lower–Middle Jurassic marine and deltaic Murat Siltstone and Athol/Legendre formations (**Figure 6**). Geochemical studies indicate that the gas accumulations on the Rankin Platform accessed both Triassic and Lower–Middle Jurassic source rocks in the adjacent Barrow and Dampier sub-basins (Boreham et al, 2001; Edwards and Zumberge, 2005).

The giant gas accumulations of the Exmouth Plateau are inferred to have been primarily charged from deeply buried coal and carbonaceous claystone in the Mungaroo Formation (Cook et al, 1985; Bussell et al, 2001). A secondary contribution from the Locker Shale has not been discounted.

The principal oil-prone source rock in the Northern Carnarvon Basin is the Upper Jurassic Dingo Claystone (**Figure 6**). The unit was deposited in deep water, restricted marine conditions within incipient rifts that developed along the northern and northwestern continental margin during the breakup of Gondwana. The Oxfordian interval (*W. spectabilis* biozone) is a particularly organic-rich part of the Dingo Claystone (van Aarssen et al, 1996; Thomas et al, 2004). Biomarker and geochemical studies of oils derived from the marine Dingo Claystone indicate that there is a significant supplementary contribution from terrestrial organic matter preserved within the marine claystones (Summons et al, 1998; Edwards and Zumberge, 2005; van Aarssen et al, 1994, 1996).

Potential source rock units in the Beagle Sub-basin are assumed to be at similar stratigraphic levels to the Dampier Sub-basin, but well data indicate that the Dingo Claystone is often thin or absent, and source quality of the Mungaroo Formation and the underlying Locker Shale (**Figure 6**) is poor (Surdam and Warne, 1984). The Lower–Middle Jurassic Murat Siltstone and Athol/Legendre Formation claystones are the prime potential source units within the Beagle Sub-basin, given their thickness, distribution and inferred maturity level (Blevin et al, 1994). However, the oil recovered at Nebo 1 was sourced from either oil-prone deltaic coals or lacustrine mudstones of presumed Early–Middle Jurassic age, and, with the exception of some oils e.g. Exeter/Mutineer (Preston and Edwards, 2014), is distinct from most oils in the Dampier Sub-basin and other basins of the North West Shelf (Edwards and Zumberge, 2005).

## Reservoirs and seals

Reservoir rocks in the Northern Carnarvon Basin are dominated by fluvial-deltaic and marginal marine sandstones within the Triassic Mungaroo Formation, the Bajocian–Callovian Legendre Formation (in the Beagle and Dampier sub-basins), and the Berriasian–Valanginian Barrow Group (in the Barrow and Exmouth sub-basins and the Exmouth Plateau) (**Figure 6**). The Upper Triassic shallow-marine to deltaic Brigadier Formation and the Lower Jurassic fluvial-deltaic to marginal marine North Rankin Formation also provide reservoir units across the Northern Carnarvon Basin. In addition, Upper Triassic carbonate reefs may constitute valid reservoirs on the outboard Exmouth Plateau (Grain et al, 2013).

Most hydrocarbon discoveries within the basin are hosted by sand reservoirs either beneath or within the Lower Cretaceous Muderong Shale. The marine claystones of this unit form an effective regional seal which has contributed to high exploration success rates in parts of the basin (Baillie and Jacobson, 1997). Notable exceptions occur in the Beagle Sub-basin, where the Middle Triassic Cossigny Member of the Mungaroo Formation acts as a regional seal, and in the Barrow Sub-basin, where top-seals are formed by the Aptian Windalia Radiolarite (Barrow Island oil field; Ellis et al, 1999) and the Paleocene Dockrell Formation (Maitland gas field; Sit et al, 1994).

Intraformational seals commonly form stacked hydrocarbon-bearing reservoirs in the basin. Gas accumulations on the Rankin Platform are top-sealed by a combination of regional seals and intraformational claystones. Significant intraformational seals occur within the Berriasian–Valanginian Barrow Group, Forestier Claystone and equivalents, the Toarcian–Callovian Athol and Legendre formations, and the Triassic Mungaroo Formation. The Lower Triassic Locker Shale may also act as a seal to older reservoir targets in the inboard areas.

## Timing of generation

Hydrocarbon generation from the Dingo Claystone commenced in the Exmouth Sub-basin and southern parts of the Barrow Sub-basin in the Early Cretaceous as a consequence of sediment loading by the Barrow Delta (Tindale et al, 1998; Smith et al, 2003). In the Beagle Sub-basin, hydrocarbon generation from Lower–Middle Jurassic source rocks began prior to the deposition of the Lower Cretaceous Muderong Shale regional seal. Loading of the sub-basin during the Cenozoic, due to the deposition of a carbonate wedge, has driven late-stage maturation. As a result, there is the possibility that hydrocarbons generated during the Cenozoic have been trapped and preserved (Lech, 2013). The main phase of hydrocarbon generation in the Dampier Sub-basin was also driven by the progradation of a Cenozoic carbonate shelf across the sub-basin (Thomas et al, 2004). On the Exmouth Plateau, peak gas generation from the Mungaroo Formation is currently expected at depths of over 5000 m below the sea floor (Cook et al, 1985; Bussell et al, 2001).

## Play types

The main structural trap styles in the basin are horsts, tilted fault blocks, drapes and fault-related roll-over anticlines. Stratigraphic traps in the basin are formed by basin-floor and turbidite fan sands, and unconformity pinch-outs and onlaps (**Figure 24**, **Figure 25**). Upper Triassic pinnacle and patch reefs (such as those intersected in ODP holes on the Wombat Plateau; Williamson et al, 1989) have been identified as potential new plays across parts of the central Exmouth Plateau (**Figure 26**). Structural compartmentalisation of the basin has resulted in complex trap evolution, migration and charge histories.

## Critical Risks

### *Beagle Sub-basin*

The discovery of a small oil accumulation at Nebo 1 and production from Fletcher/Finucane (Santos, 2015b) proves the existence of active petroleum systems within the central and southwestern Beagle Sub-basin. However, the hydrocarbon potential of the remainder of the Beagle Sub-basin is unproven. The general absence of significant hydrocarbon shows across the other wells is possibly due to a lack, or thin development, of adequate regional-scale source rocks, resulting in a high charge risk. There are also risks associated with vertical and lateral migration, seal integrity and timing of fault movement, with fault-trap breaching of seals by late-stage faulting and inadequate migration pathways suggested to explain several well failures.



Furthermore, the obliquely extensional to transtensional structural development of the sub-basin during the Mesozoic, along with Cenozoic reactivation, has significant implications for local exploration concepts and increases complexities in trap development and preservation. The traditional extensional horst-and-graben rift-related play concepts developed for the Dampier Sub-basin are unlikely to extend without considerable modification into the Beagle Sub-basin, and should be re-evaluated in terms of the effects of transpressional-transtensional evolution of the associated faults.

### ***Dampier Sub-basin***

In parts of the Dampier Sub-basin, trap integrity and reservoir preservation constitute significant exploration risks. Variable sandstone distribution and porosity within fine-grained deep-water sediments can also be problematic. Exploration risks associated with the inboard areas of the Dampier Sub-basin include hydrocarbon migration distance, biodegradation of oil in shallow reservoirs and the potential absence of a competent seal. Late gas flushing of oil reservoirs is also considered an exploration risk in some areas.

In the northwest part of the sub-basin, diagenesis of Jurassic sandstones as a result of increased burial depth may adversely impact on reservoir porosity and permeability.

### ***Rankin Platform***

Charge is not considered to be an exploration risk on the Rankin Platform and in surrounding depocentres. Instead, trap integrity, and reservoir distribution and quality constitute the primary exploration risks. Reservoir quality is enhanced in the shallower Triassic reservoirs, and sandstone distribution is a risk for the Upper Jurassic and younger plays which rely on discontinuous sandstones within fine-grained deep water deposits. Gas flushing is a major risk to the preservation of any early oil charge, such as the hydrocarbon indications in Carey 1 (2008) which were interpreted to be residual oil.

### ***Barrow Sub-basin***

A successful petroleum system is well established in the Barrow Sub-basin, with trap geometry, reservoir occurrence and quality remaining the main risks. Reservoir quality is enhanced in the shallower Triassic and Barrow Group reservoirs, and sandstone distribution is a risk for the Upper Jurassic and younger plays which rely on discontinuous sandstones within fine-grained deep water deposits. The seal lithologies throughout the lower Barrow Group and Dupuy Formation are variable and can be unexpectedly thin, thereby providing inadequate seal for commercial quantities of hydrocarbons. As with other areas of the basin, gas flushing is a major risk to the preservation of any early oil charge. A present-day overpressured zone is present at about 2650–4650 m, within the thick Jurassic section and lower part of the Cretaceous Barrow Group. This overpressured zone is associated with vitrinite reflectance values of 0.8–2.2% and an increased volume of gas-generating organic matter within sealed conditions, resulting in sustained, deep overpressure since the Cenozoic, which represents a drilling hazard (He and Middleton, 2002).

### ***Exmouth Plateau***

The full areal extent of the petroleum system(s) present on the northern and western parts of the Exmouth Plateau is yet to be determined. Continued exploration success on the Exmouth Plateau will be dependent most likely on the delineation of competent traps that have access to charge from either the gas-prone Mungaroo Formation or the unproven underlying Locker Shale. Seismic and well data indicate that traps tested by several wells on the plateau have been breached (e.g. Jupiter 1). Trap breach has been identified as a significant exploration risk on the northern part of the plateau and is a possible explanation for the occurrence of hydrocarbon-bearing structures that are not filled to spill point (Longley et al, 2002).

Reservoir quality is generally better in the shallower Triassic reservoirs. For Upper Jurassic and younger deep-water, basin-floor fan sand and turbidite plays, the distribution of reservoir quality sandstones within fine-grained deposits can be problematic. Structurally controlled targets are also dependent upon the complexities of fault-linkages between the various phases of breakup-related extension in the Middle–Late Jurassic and Early Cretaceous (Yang and Elders, 2016), and its implications for secondary migration pathways.

## Geoscience Australia products and data

A range of Geoscience Australia's publications, data and products cited throughout the text are available via the links provided in the [references](#). Themes include basin geology, stratigraphy, organic geochemistry, petroleum systems and prospectivity.

- [Exmouth Sub-Basin Regional Study and Petroleum Systems Model](#) – a new 3D Petroleum System Model for the Exmouth Sub-basin, related data and interpretation is available from [NOPIMS](#) or [ausgeodata@ga.gov.au](mailto:ausgeodata@ga.gov.au). The data and models cover the area from the Exmouth SLB15-MC 3D-MSS Seismic Survey and is built on interpretation of the entire Mesozoic succession and has improved understanding of fault timing and the complex resulting structure.

### 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 [Energy](#) and [Acreage Release](#) personas that allow access to a wide range of geological and geospatial data. Themes include source rock geochemistry, petroleum wells, stratigraphic information, province and basin geology, geophysical survey data coverage and other fundamental geospatial and administrative datasets.
- The [National Petroleum Wells Database](#) application provides access to Geoscience Australia's Oracle petroleum wells databases. Data themes include header data, biostratigraphy, organic geochemistry, reservoir and facies, stratigraphy, velocity and directional surveys. Data is included for offshore and onshore regions, however scientific data entry is generally limited to offshore wells and is dependent on Geoscience Australia's project activities.

## Marine environment information

The following section contains information about the existing marine parks, their special habitat zones and physiographic features within the Northern Carnarvon Basin (**Figure 27**). The information is provided in support of business decisions with respect to planned exploration and development activities. Potential hazards of note include tropical cyclones.

### Australian marine parks

Australian Marine Parks (Commonwealth 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 of the marine environment, cultural heritage, and sustainable use of the area. Links to these management plans are provided for each marine park or marine park network in the Northern Carnarvon 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 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.

Six of the marine parks within the North-west Marine Parks Network overlies or intersect the Northern Carnarvon Basin: Montebello Marine Park, Argo-Rowley Terrace Marine Park, Eighty Mile Beach Marine Park, Dampier Marine Park, Ningaloo Marine Park, and Gascoyne 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>

#### *Montebello Marine Park*

The [Montebello Marine Park](#) is located offshore of Barrow Island and 80 km west of Dampier extending from the Western Australian state water boundary, and is adjacent to the Western Australian Barrow Island and Montebello Islands Marine Parks. The marine park covers an area of 3413 km<sup>2</sup> and water depths from less than 15 m to 150 m.

#### **Statement of significance**

The Montebello Marine Park is significant because it contains habitats, species and ecological communities associated with the Northwest Shelf Province bioregion. It includes one Key Ecological Feature: the ancient coastline at the 125 m depth contour (valued as a unique seafloor feature with ecological properties of regional significance). The marine park provides connectivity between deeper waters of the shelf and slope, and the adjacent Barrow Island and Montebello Islands Marine Parks. A prominent seafloor feature in the park is Tryal Rocks consisting of two coral reefs that are close together. The reefs are emergent at low tide.

The Montebello 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).

### *Argo-Rowley Terrace Marine Park*

The [Argo-Rowley Terrace Marine Park](#) is located approximately 270 km north-west of Broome, Western Australia, and extends to the limit of Australia's exclusive economic zone. It is adjacent to the Mermaid Reef Marine Park and the Western Australian Rowley Shoals Marine Park. The Argo-Rowley Marine Park covers an area of 146 003 km<sup>2</sup> and water depths 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 bioregions. 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 upwellings that result in localised higher levels of biological productivity.

The Argo-Rowley 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).

### *Eighty Mile Beach Marine Park*

The [Eighty Mile Beach Marine Park](#) is located approximately 74 km north-east 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 a water depth ranges between less than 15 m and 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 bioregion, 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 Eighty Mile Beach 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).

### *Dampier Marine Park*

The [Dampier Marine Park](#) is located approximately 10 km north-east of Cape Lambert and 40 km from Dampier extending from the Western Australian state water boundary. The marine park covers an area of 1252 km<sup>2</sup> and a water depth range between less than 15 m and 70 m.

#### **Statement of significance**

The Dampier Marine Park is significant because it contains habitats, species and ecological communities associated with the Northwest Shelf Province bioregion. It provides protection for offshore shelf habitats adjacent to the Dampier Archipelago, and the area between Dampier and Port Hedland, and is a hotspot for sponge biodiversity. The marine park includes several submerged coral reefs and shoals including Delambre Reef and Tessa Shoals.

The Dampier 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).

### *Ningaloo Marine Park*

The [Ningaloo Marine Park](#) stretches approximately 300 km along the west coast of the Cape Range Peninsula, and is adjacent to the Western Australian Ningaloo Marine Park and Gascoyne Marine Park. It covers an area of 2435 km<sup>2</sup> and a water depth range of 30 m to more than 500 m.

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

#### **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 Ningaloo 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.

### *Gascoyne Marine Park*

The [Gascoyne Marine Park](#) is located approximately 20 km off the west coast of the 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. It covers an area of 81 766 km<sup>2</sup> and water depths between 15 m and 6000 m.

The Gascoyne 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).

#### **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 bioregions. 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.

## **Western Australian marine parks**

Western Australia contains 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. Five of these marine parks overly or intersect the Northern Carnarvon Basin: the Rowley Shoals Marine Park, Eighty Mile Beach Marine Park, Montebello/Barrow Islands Marine Conservation Reserves, Muiron Islands Marine Management Area, and Ningaloo Marine Park.

### *Rowley Shoals Marine Park*

The [Rowley Shoals Marine Park](#) protects the Rowley Shoals, which comprise three reef systems, 30–40 km apart. The park was designed to complement the adjacent Commonwealth-managed Mermaid Reef Marine Park. The marine park is located approximately 300 km north-west of Broome.

The Rowley Shoals have been described as the most perfectly formed shelf atolls in Australian waters. The marine reef fauna of the Rowley Shoals is considered to be exceptionally rich and diverse, including species typical of the oceanic coral reef communities of the Indo-West Pacific. As many of these species are not found in the inshore tropical waters of northern Australia, such populations are of regional significance. The Rowley Shoals are also regionally significant as their position in the headwaters of the Leeuwin Current suggest they are an important source of invertebrate and finfish recruits to areas further south.

The Shoals are also of international significance as, given the low level of pressures on the Shoals, they are an important global benchmark for Indo-West Pacific reefs. The major activities in the area are nature-based tourism and recreational fishing, primarily by charter.

The zoning scheme for the Rowley Shoals Marine Park comprises:

- two sanctuary zones
- three recreation zones
- general use in the remainder of the park

Sanctuary zones provide areas of for the protection of biodiversity that are representative of the major habitats and communities found in the park, in which the influence of humans is minimised. The recreation zones have the primary purpose of providing opportunities for recreation, including fishing (subject to conservation measures). Petroleum drilling and production is not permitted in recreation zones. General use zones provide for recreational and commercial activities to occur, provided that these are compatible with the overall maintenance of the park's value and in accordance with permitted activities listed in the [management plan](#).

### *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 marine 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, while 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 will be 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.

### *Montebello/Barrow Islands Marine Conservation Reserves*

The [Montebello/Barrow Islands Marine Conservation Reserves](#) protect a unique combination of offshore islands, intertidal and subtidal coral reefs, mangroves, macroalgal communities, and sheltered lagoons that are located in the headwaters of the Leeuwin Current. The reserves lie approximately 1600 km north of Perth, and are in the Pilbara Offshore marine bioregion seaward of the ten metre depth contour between North West Cape and Cape Keraudren.

The reserves protect island complexes that comprise a broad range of habitats, flora, and fauna, which are typical of the Pilbara Offshore bioregion. The structural variety of the substrate types in the reserves combine with local oceanographic conditions to create exceptional habitat diversity, and these habitats are species-rich. Five of the six species of marine turtle found in Western Australia have been found in the reserves and of these, the green, hawksbill, and flatback turtles regularly nest on the sandy beaches of islands in the reserves. Occasional nesting of loggerhead turtles has been observed on Barrow Island. Whales, dugongs, and at least 15 seabird species are also found in the area.

The zoning scheme for the Montebello/Barrow Islands Marine Conservation Reserves comprises:

- two sanctuary zones
- two recreation zones
- one special purpose zone (benthic protection)
- eleven special purpose zones (pearling)
- general use in the remainder of the park

Sanctuary zones provide for the maintenance of environmental values and are managed for nature conservation, excluding human activities that are likely to adversely affect the environment. They afford the highest level of protection for vulnerable or specific habitats and/or species. Special purpose zones are managed for a particular priority purpose or use, such as a seasonal event (e.g. whale watching) or a particular commercial activity (e.g. pearling). And use incompatible with the specific priority purpose is not allowed in these zones. Recreation zones provide for conservation and compatible activities, including recreational fishing. Petroleum exploration and production is not permitted in these zones. General use zones are all areas of the marine reserve not covered in the other categories. Conservation of natural values remains the priority in these areas, however activities including petroleum exploration and production are permitted, provided they do not compromise the ecological values of the reserves.

### *Muiron Islands Marine Management Area*

The [Muiron Islands Marine Management Area](#) protects a very diverse marine environment, with coral reefs, filter-feeding communities, and macroalgal beds. The management area is located off the North West Cape of Western Australia, approximately 1200 km north of Perth.



The management area comprises North and South Muiron islands, as well as Sunday Island. These islands are important seabird and green turtle nesting areas.

Three conservation (flora and fauna protection) areas have been established in the management area. They are located at the north-east corner of South Muiron Island, the south-east corner of North Muiron Island and an area surrounding Sunday Island. These areas provide protection of representative of seaward and landward coral reef and deeper water habitats on the eastern and western sides of the islands. All fishing activities are excluded from the conservation areas. Passive nature-based tourism, some recreational activities, boating, and approved scientific (non-destructive) research are permitted. Petroleum exploration and development proposals will be subject to assessment.

### *Ningaloo Marine Park*

The [Ningaloo Marine Park](#) protects Ningaloo Reef, which is the largest fringing coral reef in Australia. The marine park is located off the North West Cape of Western Australia, approximately 1200 km north of Perth.

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. These values contribute to the Ningaloo Marine Park being regarded as the State's premier marine conservation icon. The Ningaloo area has high cultural significance to the Traditional Owners, and also is an important recreation area for nature-based tourism.

The zoning scheme for the Ningaloo Marine Park comprises:

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

Sanctuary zones provide for the maintenance of environmental values and are managed for nature conservation, excluding human activities that are likely to adversely affect the environment. They afford the highest level of protection for vulnerable or specific habitats and/or species. Special purpose zones are managed for a particular priority purpose or use e.g. protection of seafloor environments. Recreation zones provide for conservation and compatible activities, including recreational fishing. Petroleum exploration and production is not permitted in these zones. General use zones are all areas of the marine reserve not covered in the other categories. Conservation of natural values remains the priority in these areas, however activities including petroleum exploration and production are permitted, provided they do not compromise the ecological values of the reserves.

## **Biologically important areas**

The Northern Carnarvon Basin overlaps or is close to the following biologically important areas:

- The Brown Booby, Greater Frigatebird, Lesser Crested Tern, Lesser Frigatebird, Little Tern, and Redfooted Booby breeding, foraging, and resting areas lie to the south on the Kimberley coasts and islands
- To the south Humpback Whale breeding, calving and nursing areas are located off the Kimberley Coast
- Pygmy Blue Whales migration areas
- Whale Shark foraging in the areas, particularly along the 200 m isobath
- Green Turtles nesting on Browse Island and Scott Reef

- The Australian Snubfin, Indo-Pacific Humpback, Indo-Pacific Spotted Bottlenose dolphin breeding, calving and foraging areas around Kimberley sounds

The [National Conservation Values Atlas](#) and the [Atlas of Living Australia](#) provide further information and visualisations concerning animals and plants recorded in the Northern Carnarvon Basin region.

## Heritage

The Ningaloo marine area and coastline is World, National and Commonwealth Heritage listed. The Dampier Archipelago and Murujuga, also known as the Burrup Peninsula, are National Heritage listed.

Australia protects its shipwrecks and associated underwater heritage through the [Underwater Cultural Heritage Act 2018](#). There are no historic shipwreck protected zones located within the Northern Carnarvon Basin, however there are several shipwrecks within the basin that are not associated with a defined protected zone. These can be identified using the [Australian National Shipwreck Database](#) map search tool.

## Fisheries

The following Commonwealth fisheries are within the Northern Carnarvon Basin area:

- The North West Slope Trawl Fishery operates in the area between 200 m water depth to the outer limit of the Australian fishing zone. The fishing season runs year round.
- The Western Deepwater Trawl Fishery, operated in waters deeper than 200 m, offshore Exmouth to Augusta. The fishing season runs year round.
- The Southern Bluefin Tuna Fishery covers the entire sea area around Australia, out to 200 nm from the coast. The fishing season runs for 12 months, starting on 1 December.
- Western Tuna and Billfish Fishery operates in the Australian Fishing Zone and adjacent high seas. The fishing season runs year round.

The Government of Western Australia manages both [commercial](#) and [recreational](#) fisheries in the waters overlying the Northern Carnarvon Basin. Three of Western Australia's major commercial fisheries occur in the area: the Shark Bay Prawn, Exmouth Gulf Prawn, and Shark Bay Scallop fisheries. Other commercial fisheries in the region target tropical finfish, demersal scalefish, and mackerel (Fletcher et al, 2017). The basin also overlaps areas used by the pearling industry, which is Western Australia's second most valuable fishing industry.

## 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.

## Oceanic regime

The oceanic regime of the Pilbara to Gascoyne shelf is characterised by the general poleward flow of surface currents, with the seasonal poleward-flowing Leeuwin Current strongest in autumn, and diminished in strength during the wet monsoon season. Surface waters, generally sourced from the north, are warm, nutrient poor and of slightly lowered salinity compared to average marine values (Waite et al, 2007). Tidal ranges are small in Exmouth Gulf (microtidal, <2 m) and increase to macrotidal ranges close to Broome (Dix, 1989). Inshore of Barrow Island tidal heights are of 3–4 m (Dix, 1989).

The region supports mesotrophic ecosystems (intermediate productivity, surface chlorophyll-*a* between 0.1 and 1.0 mg/m<sup>3</sup>) in winter and spring, while the deeper offshore regions shift to oligotrophic systems (low primary productivity, surface chlorophyll-*a* <0.1 mg/m<sup>3</sup>) in summer and autumn.

## Seabed environments: regional overview

The Exmouth Plateau and the adjacent shelf regions are located on the southwestern section of the extensive Australian North West Shelf (NWS). They are characterised by a variety of seabed geomorphic features, the largest of which include terrace, slope, shelf and deep hole/valley (Heap and Harris, 2008). Additionally, canyons supporting good habitat potential are present to the west of Exmouth Gulf (Huang et al, 2018). The continental shelf adjacent to Exmouth Gulf is 50 km wide, and is the narrowest section of the NWS.

Sediment on the NWS generally consists of medium- to coarse-grained bioclastic material with a carbonate content that is commonly between 60% and 90% (McLoughlin and Young, 1985). This shelf is a region of net sediment loss to deeper water, resulting in areas rich in 'relict' material (James et al, 2004; Margvelashvili et al, 2006). In shallow waters on the Carnarvon shelf, including, for example, around Barrow Island, shelf sediments are generally composed of carbonate sand and gravel (Dix, 1989). Several major seafloor sedimentary facies are present. These include a calcareous tube and pelagic facies, an ooid-peloid facies, a relict and biofragmental facies and a large benthic foraminiferal facies (James et al, 2004). Relict particles, largely deposited during the most recent rapid sea-level rise following the Last Glacial Maximum (~18 000 years before present), contribute >25% to 50% of the sediments on the mid to inner shelf (mid to inner ramp) (James et al, 2004). Shallow water environments are dominated by the geomorphic feature 'shelf' and by banks/shoals.

The sections of the basin overlying the Exmouth Plateau are located in water depths of 950–1600 m. In comparison with the adjacent shelf areas, the Exmouth Plateau and surrounds are relatively poorly known. To a large extent, modern sediment is composed of hemipelagic plankton ooze that is moderately high in carbonate (>55% CaCO<sub>3</sub>), and low in terrestrial sediment (Veeh et al, 2000; Baker et al, 2008). Sediment textures on the Exmouth Plateau are largely sandy mud and muddy sand, while further inshore, toward Barrow Island, gravelly textures are more common (Baker et al, 2008). Four sedimentary facies have been documented: 1) shelly carbonate sand facies in <200 m water depth; 2) foraminiferal oozes and sands containing pteropod pieces in 200–800 m water; 3) foraminiferal oozes and sands in 800–4500 m water; and, 4) siliceous clays in water depths >4500 m (Colwell and von Stackelberg, 1981). The composition of sediment at the seabed is strongly influenced by depth and currents, with increasing proportions of siliceous sediment as depths increase towards the abyssal zone. The presence of clay minerals and the general sandy composition overall, at depth, strongly suggests the influence of bottom currents. The clays present are most likely from the early Holocene rather than modern terrestrial sources (Gingele et al, 2001).

## Ecology

The ecological knowledge of this region is limited to the shelf and Ningaloo canyons that link the Cuvier abyssal plain and Cape Range Peninsula. Patches of coral reefs and rhodolith (marine red algae) beds can occur in shallow water on the inner shelf (Brooke et al, 2009), while deeper shelf water (>40 m) are dominated by sponges and soft corals, which provide habitat for other organisms (Brooke et al, 2009; Schoenberg and Fromont, 2011). These environments also support diverse assemblages of small macrofauna and infauna dominated by crustaceans (Przeslawski et al, 2013). The benthic invertebrate megafauna of the upper continental slope, off the Cape Range peninsula, may be distinct from those along the rest of the slope in the North-West bioregion, showing more similarity to those in the South-West bioregion (Williams et al, 2010). Video transects from the lower continental slope along the Cuvier margin (2123–4660 m) reveal scattered benthic invertebrates and demersal fish, with the nearshore mouth of the Cloates Canyon home to comparatively higher abundances of suspension feeders, particularly gorgonians (Daniell et al, 2009). Steep canyon habitats support high benthic invertebrate abundance and likely represent biologically significant areas of the Gascoyne Marine Park (Post et al, 2022). There have been no targeted surveys over the vast abyssal plains of this region, so that the understanding of this environment is limited to the knowledge of other regions, notably, the assumption that the abyssal plain supports cosmopolitan deep-water communities with patches of highly diverse and specialised communities supported by rocky outcrops, hydrothermal vents and whale falls (Levin et al, 2001).

## Quaternary geological history

Previous work on emergent Miocene terraces at Cape Range indicate that coastal uplift has occurred prior to and during the Quaternary (Allen, 1993; Denniston et al, 2013), and Pliocene–Pleistocene initiated neotectonic reactivation is continuing (Whitney et al, 2016). Evidence from a number of Ocean Drilling Program (ODP) sites located on or near the Wombat and Exmouth plateaus indicate that near-continuous sedimentary successions have accumulated during the Quaternary (Wells and Chivas, 1994; Sinha et al, 2006). Findings from these cores, combined with late Quaternary regional climate reconstructions (Denniston et al, 2013), suggest arid conditions during glacial intervals and more humid conditions during interglacials over the past 550 thousand years (Stuut et al, 2014). During the glacial–interglacial cycles of the middle and late Pleistocene, the Exmouth Plateau was exposed to varying amounts of terrestrially sourced clays and to changing marine currents (Gingele et al, 2001; Sanchez et al, 2016), while the shelf was subaerially exposed for varying periods down to the present 125 m isobath.

Several flat-topped carbonate platforms of the Pliocene–Pleistocene, which formed on topographic highs afforded by lowstand delta lobes, were subsequently drowned by either preferential compaction of the underlying strata, or by tectonic subsidence (Sanchez et al, 2016) and are no longer growing. The modern monsoon system probably commenced in this region at approximately 13 000 years before present (BP), and evidence for the influence of the El Niño–Southern Oscillation (ENSO) is present from 5000 years BP (De Deckker et al, 2014). The detailed local climate record of Denniston et al (2013) indicates increased early Holocene rainfall, followed by a middle Holocene rainfall peak, a significant decline until approximately 1500 years BP, then a resurgence of wetter conditions.

Core recently collected during IODP Expedition 356 on the NWS has undergone preliminary analysis (Gallagher et al, 2017) and will provide a 5 million year history of the Indonesian Throughflow, Australian monsoon and subsidence on the northwest shelf of Australia.

## 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 2017.

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. AusSeabed is currently focussed on enabling accessibility of bathymetry data in Australian waters, however the long-term goal is to establish a comprehensive online platform containing data and information, including tools, to support data collectors and users in connecting with the broader seabed mapping community. This platform will also include derived data products such as morphological and geomorphological maps of the sea floor.

## Other online information resources

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

- [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

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