Regional Geology of the Northern Carnarvon Basin

Basin Outline

The Carnarvon Basin is the southernmost component of the Late Paleozoic to Cenozoic Westralian Superbasin that underlies the northwestern continental margin of Australia from North West Cape in the south to the Arafura Sea in the north. The basin can be divided into northern and southern components. The offshore Northern Carnarvon Basin covers approximately 535000 km^2 with water depths up to 3500 m and comprises up to 15000 m of largely Mesozoic sedimentary rocks. The Southern Carnarvon Basin consists of Paleozoic depocentres, with Permian to Ordovician strata being exposed onshore.

The offshore part of the Northern Carnarvon Basin evolved from a pre-rift, predominantly sag-type basin in the Late Paleozoic, through a tectonically active period of syn-rift sub-basins in the Jurassic, to a passive margin carbonate shelf in the from the Late Cretaceous (**Figure 1**). The geological evolution of the basin has been discussed in detail by many authors, and the summary presented below is derived from the work of Kopsen and McGann (1985), Boote and Kirk (1989), Hocking (1990), Jablonski (1997), Westphal and Aigner (1997), Tindale et al (1998), Bussell et al (2001), Norvick (2002) and Longley et al (2002).

The offshore part of the Northern Carnarvon Basin comprises the inboard Exmouth, Barrow, Dampier and Beagle sub-basins, and outboard the Exmouth Plateau, including the Rankin Platform, Kangaroo Syncline and Wombat Plateau (**Figure 2**). The tectonic elements of the region are dominated by a northeasterly trend that developed as a result of rift tectonism initiated in the Early Jurassic and continuing until the Late Jurassic. Proximal basin-bounding faults are similarly oriented, and subsequent tectonic movements have variably inherited this structural alignment. The last major rift-related tectonism occurred in the Valanginian, preceding the final continental separation of Greater India from Australia .

As a result of the Jurassic and Early Cretaceous rift tectonism, the Barrow and Dampier sub-basins formed a northeast-trending graben, bounded on the distal side by the buried fault escarpment of the Rankin Platform and the Exmouth Plateau. The oceanic crust of the Argo, Cuvier and Gascoyne abyssal plains bound the distal area of the Exmouth Plateau and the Exmouth Sub-basin.

Basin Evolution and Tectonic Development

The Paleozoic evolution and stratigraphy of the offshore part of the Northern Carnarvon Basin is relatively poorly known, mainly because the Mesozoic has been the exploration target to date. The Mesozoic and Cenozoic successions are divided into several megasequences, variably influenced by tectonic phases associated with major rifting and sea-floor spreading. A generalised stratigraphy of the basin is shown in **Figure 1** and comprises the following megasequences:

> Pre-rift Active Margin (Triassic to mid-Pliensbachian)

> Early Syn-rift (mid-Pliensbachian to mid-Callovian)

> Main Syn-rift (mid-Callovian to latest Tithonian)

> Late Syn-rift Barrow Delta (latest Tithonian to mid-Valanginian)

> Post-rift Active margin (mid-Valanginian to mid-Santonian)

> Passive Margin (mid-Santonian to Miocene)

Depositional environments and hydrocarbon generation, migration and entrapment are strongly controlled by rift-related tectonism in the basin. During the pre-rift phase, marine and fluvio-deltaic sediments were deposited in a broad basin. This basin subsequently fragmented into smaller depocentres in which marine and deltaic sediments were deposited during the early syn-rift phase and restricted marine sediments accumulated during the main syn-rift phase. During the late syn-rift phase, various marine sediments were deposited within the framework of the large-scale Barrow Delta system. In the post-rift phase, transgressive shaly marine deposition prevailed. During the subsequent passive margin phase, a variety of marine carbonate sediments accumulated in open marine shelfal environments.

Clastic sediments were predominantly sourced from the southeastern cratonic flank throughout the Mesozoic and Cenozoic evolution of the basin (Longley et al, 2002). However, in the Triassic, sediments may also have been delivered into the Northern Carnarvon Basin from regions to the north and east (Norvick, 2002; Jablonski and Saitta, 2004). In addition, reworked sediments were supplied from uplifted areas within the basin, formed during tectonic uplift in the Jurassic and syn-depositional inversions in the Cretaceous.

Pre-rift Active Margin (Triassic to mid-Pliensbachian)

A regional marine transgression, as a result of post-rift sagging of the previous Paleozoic rift cycle, commenced at the beginning of the Triassic, leading to the deposition of the Locker Shale unconformably on Permian sediments (**Figure 1**). The Locker Shale accumulated in broad, relatively unfaulted downwarps and grades upwards into the fluvio-deltaic Mungaroo Formation, which is composed of thick sandstone sequences and claystones with minor coals. The fluvio-deltaic system prograded to the northwest where it covered much of the offshore part of the Northern Carnarvon Basin. The Mungaroo Formation represents deposition in a broad, low relief, rapidly subsiding coastal plain, which included an extensive swamp system that was cross-cut by fluvial channels. The Mungaroo Formation also contains distinct limestone units.

The fluvial sandstones of the Mungaroo Formation form the principal reservoir facies of the giant gas accumulations on the Rankin Platform. The uppermost, marine part of the Mungaroo Formation consists of shoreline sandstones and claystones. The uppermost part of the Mungaroo Formation is absent due to erosion in the eastern part of the Rankin Platform (around the North Rankin gas field). In contrast, this part of the formation is well preserved on the western distal portion of the Rankin Platform where it is one of the major reservoirs in the Gorgon and other nearby gas accumulations (**Figure 3**).

Throughout much of the Triassic, the onshore portions of the Northern Carnarvon Basin and the onshore Pilbara Block underwent active uplift and erosion, providing sediment sources for the Locker Shale and Mungaroo Formation. However, some of the large sediment volume in the Mungaroo Delta, which stretched across the Exmouth Plateau, may have been derived from much further away. Sandy sediments from eastern and central Australia may have been delivered via transcontinental river systems emerging into the Westralian Superbasin through the onshore Canning Basin. Other potential sediment source areas lay to the north (Argo Land/West Burma) and south (Greater India) of the Exmouth Plateau in the Triassic prior to rifting (Norvick, 2002; Jablonski and Saitta, 2004).

However, whatever the various contributions, the abundant clastic sediment supply was disrupted by the end of the Triassic and there was a shift to more marine facies (Hocking, 1990). On the Wombat Plateau, drilling during Leg 122 of the Ocean Drilling Program, revealed Mungaroo Formation fluvio-deltaic siliciclastics capped by latest Triassic reefal limestones (von Rad et al, 1992a and b).

Marking rapid subsidence in the latest Triassic and into the Early Jurassic, the transgressive Brigadier Formation and Murat Siltstone were deposited in a marine shelf environment and comprise thinly bedded marine siltstones, claystones and marls. The Brigadier Formation is well preserved below a widespread Late Jurassic unconformity in the outer part of the Northern Carnarvon Basin, and the top of the formation represents the maximum flooding surface of the Early Jurassic marine transgression. Within the Kangaroo Syncline in the southern Exmouth Plateau, the preserved Early to Middle Jurassic section, including the Brigadier Formation, is thicker than on the Rankin Platform (Bussell et al, 2001). Thin, reservoir-quality sandstones on some horst blocks along the Rankin Platform are known as the North Rankin Formation.

Early Syn-rift (mid-Pliensbachian to mid-Callovian)

The pre-rift active margin to syn-rift transition is represented by the rift-onset Pliensbachian unconformity (JP1 seismic horizon; **Figure 1**). Extensional rift-faulting and warping produced northeast-trending tilted fault blocks, horsts and graben (Barber, 1988). The development of the Exmouth, Barrow and Dampier sub-basins and Rankin Platform was initiated during this early syn-rift phase, and these elements remained tectonically active throughout the Jurassic.

The early syn-rift mega-sequence (mid-Pliensbachian to mid-Callovian) comprises restricted marine claystones of the Athol Formation and deltaic sandstones of the Legendre Formation. The Legendre Delta developed in the early Bathonian in the Dampier Sub-basin, but sedimentation ceased by the early Callovian.

Main Syn-rift (mid-Callovian to latest Tithonian)

The mid-Callovian unconformity surface (JC seismic horizon; **Figure 1**) defines the boundary between the early syn-rift (mid-Pliensbachian to mid-Callovian) and main syn-rift (mid-Callovian to latest Tithonian) megasequences. This unconformity represents the onset of the continental breakup of the northwest Australian margin (Jablonski, 1997). Claystones of the transgressive Callovian Calypso Formation were deposited in the Barrow and Dampier sub-basins over the unconformity surface.

Major rift-faults developed along the northern edge of the Exmouth Plateau in the Callovian, but continuous oceanic crust was not created until the Late Oxfordian (Norvick, 2002). The basal Oxfordian unconformity ('Breakup Unconformity'; JO seismic horizon; **Figure 1**) represents this phase of continental breakup and the onset of sea-floor spreading to form the Argo Abyssal Plain.

The term'Main Unconformity' (MU seismic horizon; **Figure 1**) has been used widely to refer primarily to the basal Oxfordian (JO) unconformity. In practice, however, this horizon is often a composite sequence boundary, ranging in age from basal Jurassic in one part of the basin to Aptian in another (Jablonski, 1997). For instance, in some areas on the Rankin Platform, the Norian Mungaroo Formation underlies the Albian Windalia Radiolarite or Gearle Siltstone, indicating that the Main Unconformity represents a 92 million year hiatus (Newman, 1994). A large and inconsistent time break at the Main Unconformity has led to confusion regarding the nature and timing of erosion. Because of the diachronous nature of the unconformity surface, the composite Main Unconformity is also called the'Intra-Jurassic unconformity' (IJU seismic horizon; **Figure 1**) (Sibley et al, 1999).

Following continental breakup, active faulting continued in the Late Jurassic. This resulted in uplift and tilting of the shelf and the Rankin Platform. Reworked sediments were deposited in depocentres adjoining the uplifted areas. Tectonic subsidence rates far exceeded sedimentation rates in regional depocentres, resulting in a thick succession of the deep-water Dingo Claystone, which gradually filled the graben depocentres and progressively overlapped the flanks of high blocks (Tindale et al, 1998). This deep-water marine sedimentation was confined to the graben depocentres of the Barrow, Dampier and Exmouth sub-basins. The Oxfordian maximum flooding phase of the graben system provided a favourable depositional environment for high quality, oil-prone source rocks (Norvick, 2002).

Although marine claystones dominate the main syn-rift (mid-Callovian to latest Tithonian) megasequence, paradoxically this is also the time when reservoir-quality turbidite, submarine fan, shoreline and fluvial sandstones were deposited locally at the edge of tectonically active graben.

On the eastern portion of the Exmouth Plateau, Late Jurassic deposition of sandy shelfal facies occurred within restricted shallow basins. The Kangaroo Syncline was also tectonically active during the Late Jurassic across the southern Exmouth Plateau and northern Exmouth Sub-basin, in response to footwall uplift of the Triassic tilted fault blocks on the Rankin Platform. The uplift created a hinterland that provided a source for coarse clastic sediments eroded from the Mungaroo Formation and transported into the shallow marine environment of the syncline. By the Tithonian, the gradual subsidence and peneplanation of the provenance area limited clastic input to the syncline (Jenkins et al, 2003).

Oxfordian shallow-marine sandstones (Jansz Sandstone) represent the major reservoir interval in a stratigraphic trap(Jenkins et al, 2003) for the giant Jansz/Io gas accumulation (**Figure 1** and **Figure 3**) The Biggada Sandstone, Dupuy and Angel formations are other significant reservoir-quality sandstones deposited in this megasequence. For example, turbidite sandstones of the Angel Formation, which are the major oil- or gas-bearing reservoirs in the Dampier Sub-basin, were deposited in the Tithonian when reactivation of horsts and graben resulted in further erosion of marginal areas with reworking of quartz-rich sandstones (Hocking, 1990).

Further inshore, an Oxfordian shallow-marine sandstone (Linda Sandstone) was deposited in the eastern Barrow Sub-basin, which has traditionally been viewed as a deep-water depocentre. Late Jurassic shore-face and shallow-marine sandstones may be aligned parallel to shorelines elsewhere in the Northern Carnarvon Basin (Moss et al, 2003).

Late Syn-rift Barrow Delta (latest Tithonian to mid-Valanginian)

Latest Jurassic uplift and erosion marked the onset of late syn-rift (latest Tithonian to mid-Valanginian) sedimentation. The large Barrow Delta system abruptly and briefly developed in the Northern Carnarvon Basin during this tectonically quiescent phase. The Barrow Delta was extensive, and its sediments are up to 2500 m thick. The delta prograded in two major phases, and two main delta lobes were developed. The initial depositional phase occurred over the Exmouth Sub-basin in response to a prominent supply of sediment from the south. The delta then prograded rapidly to the north over a thick pile of turbidites and pro-delta shales to a maximum northward limit roughly west from Barrow Island across to the Exmouth Plateau. On the Exmouth Plateau, the Barrow Group consists of turbidites, basin floor fans and fluvio-deltaic sediments of the lower Barrow Delta lobe. A turbidite fan forms the sandstone complex at the Scarborough gas accumulation (**Figure 3**) to the north of the delta front (Norvick, 2002).

While the Barrow Delta resumed progradation in the late Berriasian, erosion of the lower delta lobe occurred in the inshore part of the Exmouth Sub-basin. The new depocentre of the delta retreated 250 km to the east and extended beyond the eastern limit of the first phase. As a result, a back-stepped delta (upper Barrow Delta lobe) developed in the Barrow and Dampier sub-basins. The second phase of delta progradation reached its northern limit around the Gorgon horst.

The sediments of the lower (or western) Barrow Delta lobe are collectively known as the Malouet Formation comprising bottom-set submarine fan sandstones and pro-delta claystones, and those of the upper (or eastern) lobe are known as the Flacourt Formation, comprising basinal turbidites, fore-set claystones and top-set sandstones. The boundary between the two lobes is markedly diachronous and cannot always be picked as a continuous regional seismic horizon (Baillie and Jacobson, 1997). The lower Barrow Delta lobe contains approximately 75% of the sediments deposited by the Barrow Delta system (Ross and Vail, 1994). Barrow Group sandstones are predominantly quartzose with minor clay matrix and are weakly cemented by calcite, pyrite or siderite. Porosity and permeability in these sandstones tend to be excellent in the outer part of the Northern Carnarvon Basin.

Sandy units within the top Barrow Group are variously named, and their nomenclature is somewhat confusing. They include; the top-sandstone of the Barrow Group, top-sandstone of the Flacourt Formation, Zeepaard Formation, and Flag Sandstone. The Zeepaard Formation was deposited across wide areas of the Barrow and Exmouth sub-basins, Rankin Platform and Exmouth Plateau as progradational top-set units of the Barrow Delta in front of multiple distributaries at slightly different times in the early Valanginian. In contrast, the Flag Sandstone was deposited as a submarine fan sandstone in the northeastern proximal part of the Barrow Sub-basin, in front of the last fore-set of the Barrow Delta.

Sediment supply to the Barrow Delta system ceased due to the disruption of a major fluvial distributary system in the Valanginian, when continental breakup commenced to the southwest of the Exmouth Plateau (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-rift Active Margin (mid-Valanginian to mid-Santonian)

After tectonic uplift and faulting associated with the separation of Greater India and Australia in the Valanginian, a large portion of the Northern Carnarvon Basin was subjected to peneplanation. This event was followed by regional post-rift sag sedimentation in the offshore part of the basin from the mid-Valanginian to mid-Santonian.

Post-rift marine deposition commenced on the Valanginian unconformity surface (KV seismic horizon; **Figure 1**), and the Birdrong Sandstone and glauconitic Mardie Greensand were deposited in smaller deltas. This localised sedimentation cycle was followed by the basin-wide deposition of the transgressive marine Muderong Shale, Windalia Radiolarite and Gearle Siltstone. The Muderong Shale is a regional seal, but also contains economically important petroleum-bearing marine sandstones such as the *M. australis* Sandstone (also known as the Stag Sandstone) and Windalia Sandstone in the Barrow and Dampier sub-basins. These diachronous sandstones overlie the intra-Valanginian unconformity and are characteristically glauconitic.

The Windalia Sandstone of the Muderong Shale has historically been a major exploration target in the Barrow Sub-basin. More than 90% of the initial oil reserves of the Barrow Island oil field, which is the largest in the Northern Carnarvon Basin, are contained within this sandstone (Ellis et al, 1999).

Passive Margin (mid-Santonian to Miocene)

Siliciclastic sedimentation ceased by the mid-Santonian, as a result of tectonic stability and a decreasing supply of terrigenous sediments. Shelfal carbonate sediments were deposited on the passive continental margin in the Late Cretaceous and Cenozoic, as the whole region continued to subside after cessation of the rifting process. On the deep-water Exmouth Plateau, sedimentary section deposited during this period was relatively thin, as subsidence rates outstripped sediment input. Towards the end of the Cretaceous, however, the Kangaroo Syncline on the Exmouth Plateau became the major depocentre of the Northern Carnarvon Basin.

During the Campanian, uplift of the hinterland resulted in a phase of inversion in the Exmouth Sub-basin and Exmouth Plateau, forming the Exmouth Plateau Arch. This tectonic event also marked the onset of transpressional structural growth of pre-existing rift-related structures within the Barrow and Dampier sub-basins (Longley et al, 2002).

In the Miocene, a major compressional event associated with the collision of the Australia-India and Eurasia plates affected the entire northwest Australian margin, including the Northern Carnarvon Basin (Longley et al, 2002). This event caused tilting, inversion, renewed movement on faults, and the creation of new strike-slip or wrench faults (Malcolm et al, 1991). This is also the time when many structural traps within the Cretaceous and Cenozoic strata were formed.

Regional Hydrocarbon Potential

The Carnarvon Basin is currently Australia's most prolific hydrocarbon-producing basin; 76.3 MMbbl (12.4 GL) of oil, 1022 Bcf (28.9 Bcm) of gas and 38 6 MMbbl (6.1 GL) of condensate were produced in 2007 (Department of Mines and Petroleum, Western Australia, 2008).

This represents more than half of Australia's total hydrocarbon production. During the 2007-08 fiscal year, 18 new field wildcats were drilled in the offshore Northern Carnarvon Basin and there were 51 producing fields, including Barrow Island (Department of Industry and Resources, Petroleum and Royalties Division, 2008).

The majority of the hydrocarbons discovered to date in the Northern Carnarvon Basin are hosted by highly porous reservoirs beneath the Early Cretaceous Muderong Shale, which forms the regional seal. The presence of this effective regional seal is a major contributing factor to exploration success in the basin (Baillie and Jacobson, 1997). One of the notable exceptions is the Barrow Island oil field, where the oil-bearing Windalia Sandstone of the Muderong Shale is top-sealed by the Aptian Windalia Radiolarite. Another exception is the Maitland gas accumulation, in which a Paleocene sandstone is the reservoir. Intra-formational seals are also an important element of hydrocarbon accumulations in the basin, resulting in stacked hydrocarbon-bearing reservoirs beneath a regional unconformity surface. Individual pools in gas accumulations on the Rankin Platform are top-sealed by a combination of the regional seal and intra-formational claystones. **Figure 3** shows the major oil and gas accumulations discovered, to date, in the Northern Carnarvon Basin.

The main trap styles in the basin are drape anticlines, horsts, fault roll-over structures and stratigraphic pinch-outs beneath the regional seal. The stratigraphic level of top-porosity, ranging from the Late Triassic Mungaroo Formation to the Early Cretaceous Mardie Greensand beneath the regional seal, generally becomes progressively younger in the landward direction.

Hydrocarbon Families and Source Rocks

Two broad hydrocarbon families are recognised in the Northern Carnarvon Basin - one gas prone and derived from Triassic fluvio-deltaic facies, and the other oil prone and sourced from Late Jurassic marine sediments. The giant gas fields on the Exmouth Plateau are considered to have been charged from the deeply buried coals and carbonaceous claystones of the deltaic Mungaroo Formation. Peak gas generation from these Triassic source rocks is interpreted to occur now at depths greater than 5000 m below the sea floor (Bussell et al, 2001). The Rankin Platform is assumed to have access to this active gas source and geochemical studies (Boreham et al, 2001; Edwards and Zumberge, 2005; Edwards et al, 2007) are consistent with these giant gas accumulations being sourced from deltaic Triassic to Middle Jurassic source rocks. However the Rankin Platform fields may also have contributions from late gas generation from the Jurassic in the adjacent Barrow and Dampier depocentres.

The Late Jurassic Dingo Claystone is the principal source for oil in the Northern Carnarvon Basin. It is a fine-grained marine unit deposited in deep water and partly restricted marine environments in the Exmouth, Barrow and Dampier sub-basins. Biomarker and other geochemical studies of the Northern Carnarvon Basin oils indicate that although they are derived from a marine source rock there was also a significant contribution from terrestrial organic matter (Summons et al, 1998) and that the Oxfordian interval (*W. spectabilis* biozone) is the particularly organic rich part of the Dingo Claystone (van Aarssen et al, 1996). Hydrocarbon generation from the Dingo Claystone commenced in the Exmouth Sub-basin and southern parts of the Barrow Sub-basin in the Early Cretaceous with the loading of the Barrow Delta (Tindale et al, 1998; Smith et al, 2003). Further north in the Barrow Sub-basin, beyond the main delta front, significant oil expulsion may have occurred as early as the Late Cretaceous. In contrast, the main phase of generation in the Dampier Sub-basin was in the Cenozoic, in response to the progradation of the carbonate shelf.

These two broad hydrocarbon families are overwhelmingly dominant in the Northern Carnarvon Basin and are considered to be the source of almost all the commercially developed accumulations found to date. Geochemical studies have recognised some vagrant oils which do not fall into these families (Summons et al, 1998). The oil accumulation at Nebo in the Beagle Sub-basin is interpreted as being derived from an Early to Middle Jurassic lacustrine source rock and the original oil discovery onshore at Rough Range, on the margin of the Exmouth Sub-basin, has also been interpreted as having a lacustrine source (Edwards & Zumberge, 2005).

Regional Petroleum Systems

The USGS analysis (Bishop, 1999) of the petroleum systems of the Northern Carnarvon Basin mapped a'Locker-Mungaroo/Barrow' Petroleum System across most of the basin out to the margins to the Exmouth Plateau. However there is no geochemical evidence of a contribution from the Early Triassic marine Locker Shale, and the Mungaroo Formation fluvio-deltaic facies are now considered to as the primary source of the large gas fields. Given the low geothermal gradient on the Exmouth Plateau, basin modelling indicates that it is not impossible that deeply buried Locker Shale has contributed to the hydrocarbon charge. Exploration has recently extended the proven extent of the retitled'Locker/Mungaroo-Mungaroo/Barrow' Petroleum System further north on the Exmouth Plateau with the Thebe 1 and Martell 1 gas discoveries (**Figure 2**).

From the regional perspective of the North West Shelf the'Locker/Mungaroo-Mungaroo/Barrow' Petroleum System can be considered as part of the Westralian 1 Petroleum Supersystem (Bradshaw et al, 1994; Edwards et al, 2007). This Supersystem includes giant gas accumulations sourced mainly from deltaic Triassic to Early-Middle Jurassic source rocks in the Bonaparte, Browse and Northern Carnarvon basins. Similar carbon isotopic profiles are seen in the gases and associated condensates from fields in the Westralian Superbasin as far apart as Sunrise in the Bonaparte Basin, Torosa (Scott Reef) in the Browse Basin and North Rankin in the Northern Carnarvon Basin. This similar geochemistry reflects similar source facies deposited in fluvio-deltaic environments throughout the Westralian Superbasin in the

Triassic to Middle Jurassic (Edwards and Zumberge, 2005; Edwards et al, 2007).

The oil prone'Dingo-Mungaroo/Barrow' Petroleum System (Bishop, 1999) has a more limited distribution than the'Mungaroo-Mungaroo/Barrow' Petroleum System, being restricted to the Exmouth, Barrow and Dampier sub-basins. The proven extent of this system has encroached further to both the south and north with oil discoveries in the Exmouth Sub-basin and at Mutineer/Exeter in the northern end of the Dampier Sub-basin. From the regional perspective of the North West Shelf the'Dingo-Mungaroo/Barrow' Petroleum System can be considered as part of the Westralian 2 Petroleum Supersystem (Bradshaw et al, 1994; Edwards and Zumberge, 2005; Edwards et al, 2007). Geochemically similar oils are recognised in the Northern Carnarvon, Bonaparte and Papuan basins, all derived from Late Jurassic marine source rocks deposited in incipient rifts that developed along the northern and north-western continental margin during Gondwana break-up.

Exploration History

The first flow of oil to the surface in Australia was recorded in 1953 at Rough Range 1 in the onshore Northern Carnarvon Basin, on the eastern edge of the Exmouth Sub-basin. However, the success of Rough Range 1 (an oil flow of 500 bopd) was not repeated with the next wells drilled on the structure, a surface anticline located to the south of Exmouth Gulf (Bradshaw et al, 1999). The sustained success that established the Northern Carnarvon Basin as a major hydrocarbon province came in the offshore, in the 1960s and early 1970s, with WAPET's island and shallow water drilling program (Mitchelmore and Smith, 1994). Giant discoveries were made in 1964 with a billion barrels of oil-in-place at Barrow Island in the Barrow Sub-basin and multi-Tcf gas fields were discovered on the Rankin Platform in 1971. The Legendre 1 oil discovery in 1968 demonstrated that the Dampier Sub-basin was also oil-prone; and the Beagle Sub-basin was added to the list of proven hydrocarbon-bearing areas in the Northern Carnarvon Basin with the Nebo 1 oil discovery in 1993.

Two major exploration campaigns have focussed on the deepwater Exmouth Plateau, the first in 1979 to 1980 for oil targets, and the second currently underway searching for gas. A giant gas accumulation in an Early Cretaceous Barrow Group basin floor fan was discovered in the Scarborough 1 well in 1980 (**Figure 3**). One of the largest discoveries yet made in the Northern Carnarvon Basin is Jansz, a super-giant gas field in a new play type drilled in 2000 on the Exmouth Plateau in the Northern Carnarvon Basin (Jenkins et al, 2003). Other recent large gas discoveries have been made at Wheatstone, Pluto, Xena, Chandon and Clio.

In 2007 BHP Billiton drilled Thebe 1 and intersected a gross gas column of 73 m in the Triassic Mungaroo Formation. Thebe is a multi-Tcf field and the most northerly occurrence of gas found to date on the Exmouth Plateau. In early 2009 Woodside Petroleum Ltd announced the discovery of gas at Martell 1 in the petroleum exploration permit WA-404-P, to the north of the Jansz field (Woodside Petroleum Ltd, 2009). Inboard, Hess Corporation, a new explorer to the area, commenced drilling in petroleum exploration permit WA-390-P. The permit, located southwest of the giant Jansz field, was awarded in 2007 with an aggressive work program including a 16-well drilling commitment. The first 3 wells have all been gas discoveries (Hess Corporation, 2008). Further inboard in petroleum exploration permit WA-356-P, located between the Gorgon and Pluto fields, Apache Corporation has made 6 gas discoveries on the Julimar trend (Apache Corporation, 2008).

3D seismic and AVO technology are key exploration tools and contribute to high success rates (Longley et al, 2002; Korn et al, 2003; Williamson and Kroh, 2007). The Northern Carnarvon Basin has continued to yield oil discoveries, with the extension of the productive oil trend in the Dampier Sub-basin north to the Mutineer/Exeter field. In the Exmouth Sub-basin, the 1999 Enfield discovery has been followed by a string of oil finds including Coniston, Laverda, Stybarrow, Ravensworth and Stickle, and oil production is now established in this sub-basin from the Enfield, Stybarrow and Eskdale fields.

Hydrocarbon Reserves

Table 1: Initial hydrocarbon reserves for Northern Carnarvon Basin

Field	Oil	Condensate	Gas	Gas	Source
	MMbbl	MMbbl	Bcf	MMboe1	
Agincourt	3.6	0.0	1.0	0.2	DMP
Albert	0.7		0.1	0.0	DMP
Angel		84.5	1850.5	314.6	DMP
Artreus	0.3		0.1	0.0	DMP
Australind			7.3	1.2	DMP
Bambra	8.0	0.6	15.8	2.7	DMP
Bambra East		0.9	44.9	7.6	DMP
Barrow Island	355.3	0.0	182.6	31.0	DMP
Blencathra	4.4		0.0	0.0	DMP
Brunello		7.7	302.4	51.4	DMP
Caribou		0.2	8.8	1.5	DMP
Chamois	2.3		0.4	0.1	DMP
Chandon		11.0	2150.1	365.5	DMP
Chinook/Scindian	38.3		81.7	13.9	DMP
Chrysaor		16.1	1875.2	318.8	DMP
Clio		20.0	3145.2	534.7	DMP
Corvus		0.2	25.1	4.3	DMP
Cossack	93.9	0.2	17.6	3.0	DMP
Cowle	3.4	0.0	3.0	0.5	DMP
Crest	1.7		2.1	0.4	DMP
Crosby	57.8		0.0	0.0	DMP
Dionysus		11.6	1508.0	256.4	DMP
Dixon	6.0	3.8	134.2	22.8	DMP
Dockrell		5.6	247.2	42.0	DMP
Doric		0.4	3.6	0.6	DMP
Double Island	4.9	0.0	1.6	0.3	DMP
East Spar		14.3	243.0	41.3	DMP
Echo/Yodel		61.1	438.3	74.5	DMP
Egret	12.3	0.6	21.2	3.6	DMP

Endymion		0.4	24.5	4.2	DMP
Enfield	89.9		9.6	1.6	DMP
Eskdale	4.1		0.4	0.1	DMP
Eurytion		1.4	536.8	91.3	DMP
Exeter	16.8		0.1	0.0	DMP
Flinders Shoal			17.7	3.0	DMP
Gaea		3.4	116.5	19.8	DMP
Geryon/Callirhoe		8.8	2387.3	405.8	DMP
Gipsy	2.5	0.0	3.3	0.6	DMP
Goodwyn		365.0	7112.1	1209.1	DMP
Goodwyn S	2.4	9.6	205.0	34.8	DMP
Gorgon		121.0	17198.4	2923.7	DMP
Griffin	149.6		68.2	11.6	DMP
Gudrun	0.8		0.3	0.0	DMP
Gungurru	1.2		7.4	1.3	DMP
Harriet	51.9	0.4	52.4	8.9	DMP
Harrison	4.0		0.0	0.0	DMP
Hermes	79.1	0.3	28.4	4.8	DMP
Iago		10.9	1066.5	181.3	DMP
Io		9.4	3641.0	619.0	DMP
Jansz			13843.5	2353.4	DMP
John Brookes		14.4	1360.4	231.3	DMP
Julimar		6.7	365.5	62.1	DMP
Julimar East		6.4	368.3	62.6	DMP
Keast		2.1	134.2	22.8	DMP
Kultaar		0.4	26.5	4.5	DMP
Lady Nora		12.5	413.9	70.4	DMP
Lambert	34.8	0.2	10.9	1.9	DMP
Lambert Deep		2.3	261.3	44.4	DMP
Laverda	30.2				DMP
Lee		2.0	50.6	8.6	DMP

Legendre North	43.9		47.9	8.1	DMP
Legendre South	5.0		21.5	3.7	DMP
Linda		2.2	49.8	8.5	DMP
Little Sandy	0.6		0.4	0.1	DMP
Macedon			652.0	110.8	DMP
Maenad		0.9	244.0	41.5	DMP
Maitland		1.9	88.6	15.1	DMP
Mohave	0.9		0.6	0.1	DMP
Moondyne	7.7		0.0	0.0	DMP
Mutineer	43.0		0.3	0.1	DMP
Narvik	0.0		24.2	4.1	DMP
Nasutus	2.5		8.5	1.4	DMP
North Alkimos	0.0		0.5	0.1	DMP
North Rankin		209.8	12324.2	2095.1	DMP
Orthrus		2.2	852.0	144.8	DMP
Oryx	3.2		0.4	0.1	DMP
Pedirka	2.5	0.0	1.0	0.2	DMP
Pemberton		5.7	227.9	38.7	DMP
Persephone		17.4	766.1	130.2	DMP
Perseus		284.3	10712.2	1821.1	DMP
Pluto		0.0	4619.2	785.3	DMP
Pueblo		3.0	82.6	14.0	DMP
Rankin/Sculptor		3.1	80.9	13.8	DMP
Ravensworth	54.5		0.0	0.0	DMP
Reindeer		2.3	447.4	76.1	DMP
Roller	45.3		25.0	4.3	DMP
Rose		1.4	39.6	6.7	DMP
Rough Range	0.1		0.0	0.0	DMP
Sage	4.7		0.0	0.0	DMP
Saladin	98.5		58.7	10.0	DMP

Scarborough			5191.3	882.5	DMP
Searipple		4.6	33.7	5.7	DMP
Simpson	5.8	0.0	2.8	0.5	DMP
Skate	1.7	0.1	4.3	0.7	DMP
Skiddaw	4.0		0.0	0.0	DMP
South Chervil	0.6		9.5	1.6	DMP
South Plato	4.5	0.0	1.6	0.3	DMP
Spar		6.5	249.0	42.3	DMP
Stag	62.1		13.2	2.2	DMP
Stickle	35.0		0.0	0.0	DMP
Stybarrow	74.8		1.0	0.2	DMP
Tanami	3.2	0.1	3.2	0.5	DMP
Taunton	3.3	0.1	2.8	0.5	DMP
Tidepole		16.0	519.1	88.3	DMP
Tusk	1.8		0.4	0.1	DMP
Urania		0.2	196.6	33.4	DMP
Van Gogh	56.0				DMP
Victoria	0.3		0.2	0.0	DMP
Vincent	73.0				DMP
Wanaea	286.9	2.1	345.0	58.6	DMP
Wandoo	94.7		31.5	5.4	DMP
West Cycad	1.5		0.5	0.1	DMP
West Tryal Rocks		38.0	2560.3	435.3	DMP
Wheatstone		26.0	3951.7	671.8	DMP
Wilcox		19.5	328.4	55.8	DMP
Wonnich		3.0	158.2	26.9	DMP
Woollybutt	41.6		4.6	0.8	DMP
Xena		5.0	488.1	83.0	DMP
Yammaderry	5.4		3.4	0.6	DMP
Zephyrus	0.5		0.1	0.0	DMP

[1] Conversion factor for gas is 1 Bcf gas ≡ 0.17 million barrels of oil. All reserves are P50. All developed field resources. The initial recoverable resource estimates are at 31 December 2007

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Figures

Figure 1:	Regional stratigraphy of the Northern Carnarvon Basin, AGSO 1996 Time Scale (Young and Laurie, 1996).
Figure 2:	Structural elements of the Northern Carnarvon Basin showing the 2009 Release Areas (after Stagg et al, 2004).
Figure 3:	Major oil and gas accumulations in the Northern Carnarvon Basin indicating age of main reservoir.

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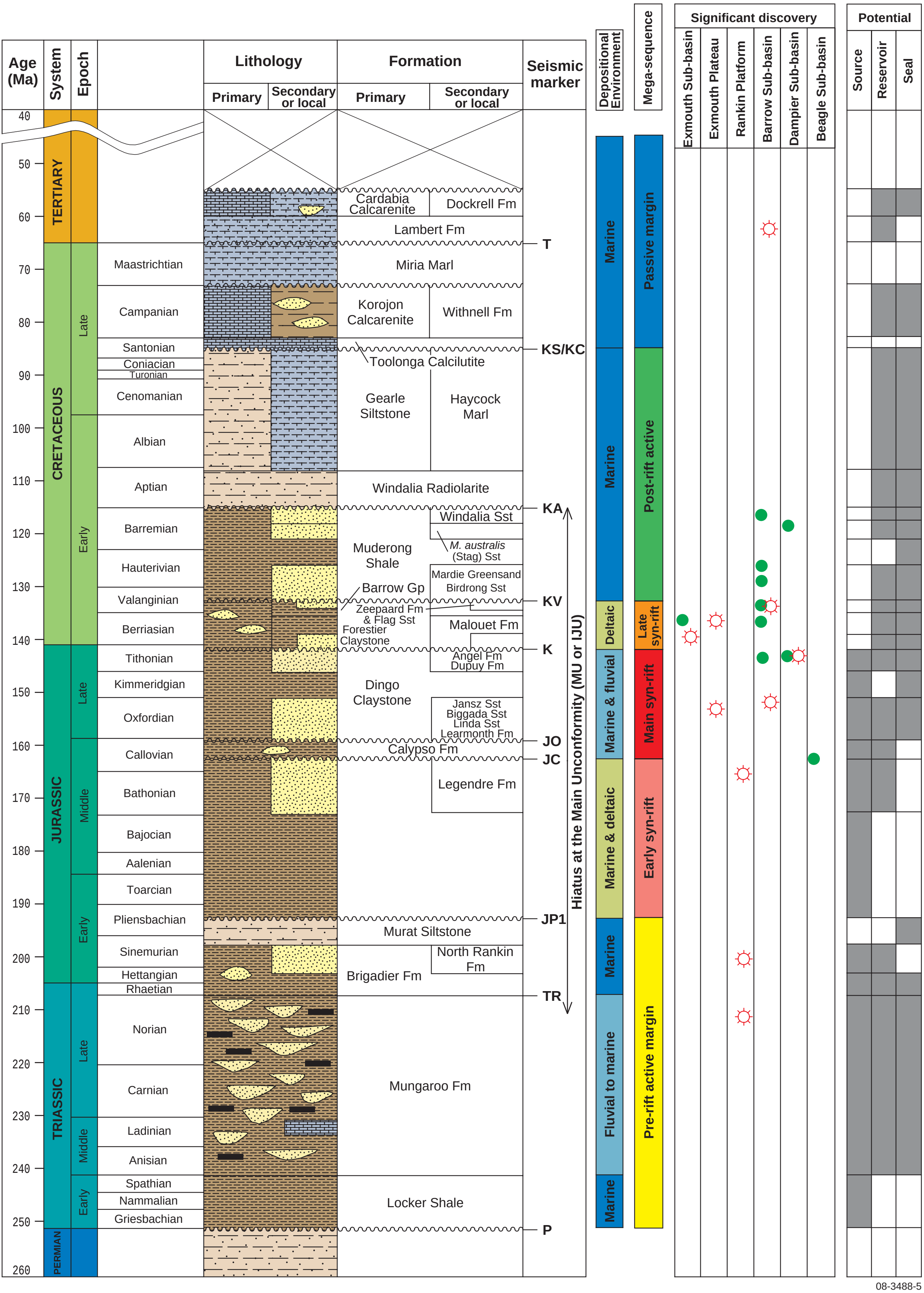

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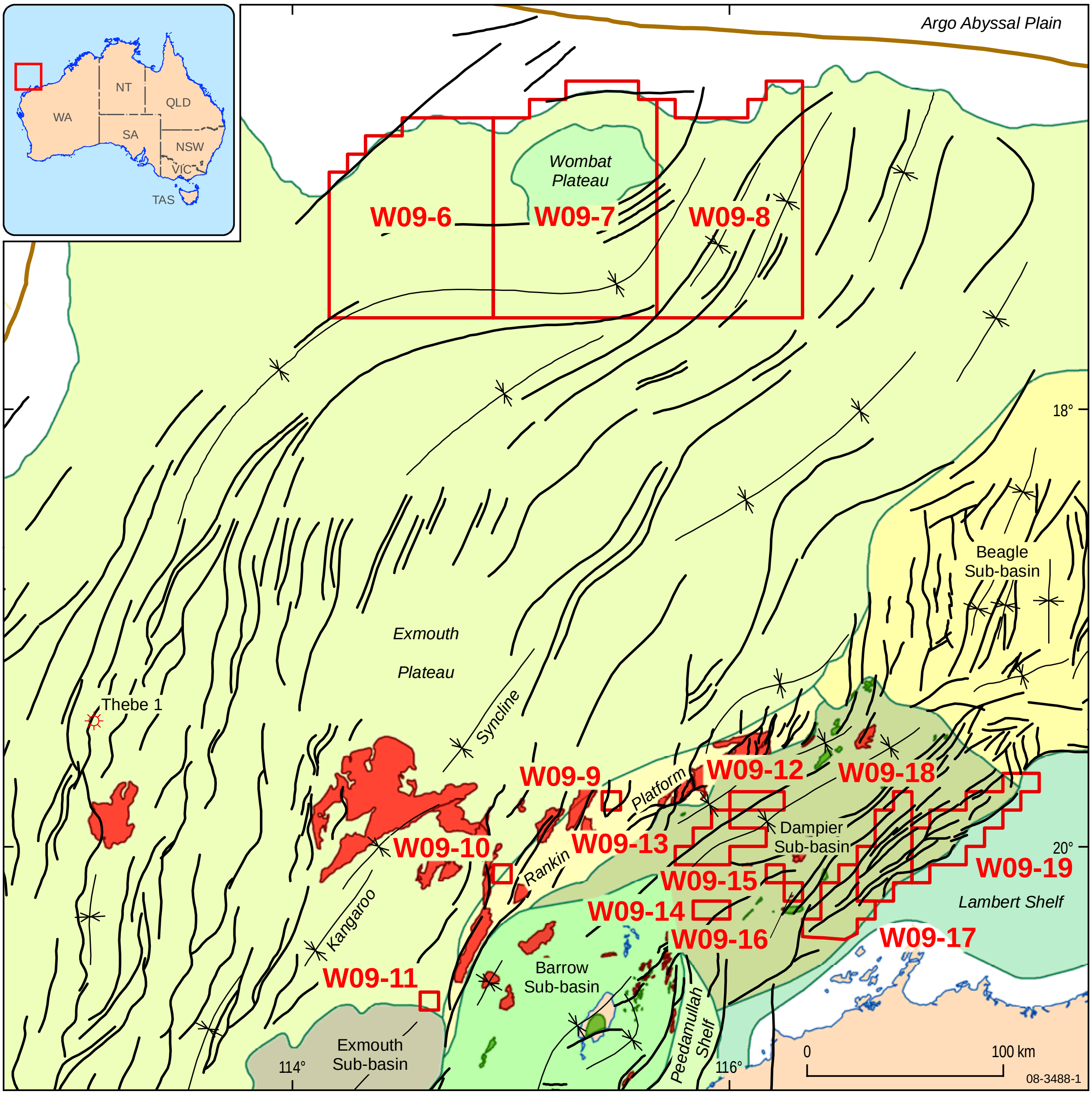


Where well symbol information is sourced from publicly available "open file" data, it has been provided by Geoscience Australia from Well Completion Reports. These symbols were generated from open file data as at 31 March 2009. Where well symbol information is not publicly available from titleholders' data, the information has been extracted from other public sources. Field outlines are provided by GPinfo, an Encom Petroleum Information Pty Ltd product. Field outlines in GPinfo are sourced, where possible, from the operators of the fields only. Outlines are updated at irregular intervals but with at least one major update per year.

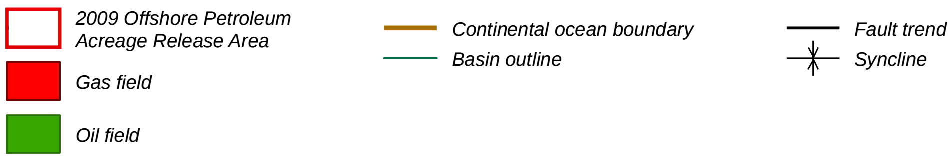
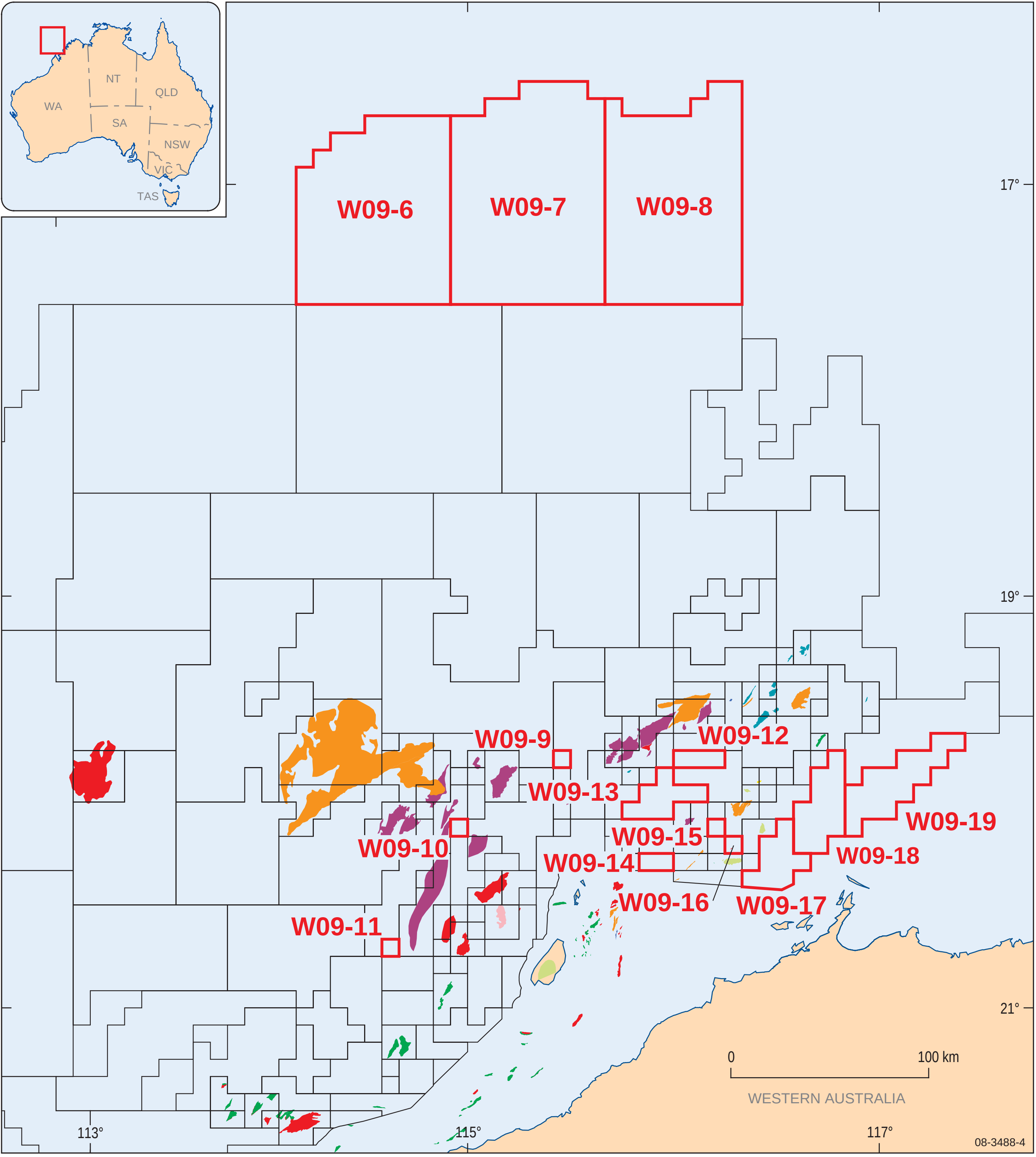


Figure 2. Structural elements of the Northern Carnarvon Basin showing the 2009 Release Areas, from Stagg et al (2004).



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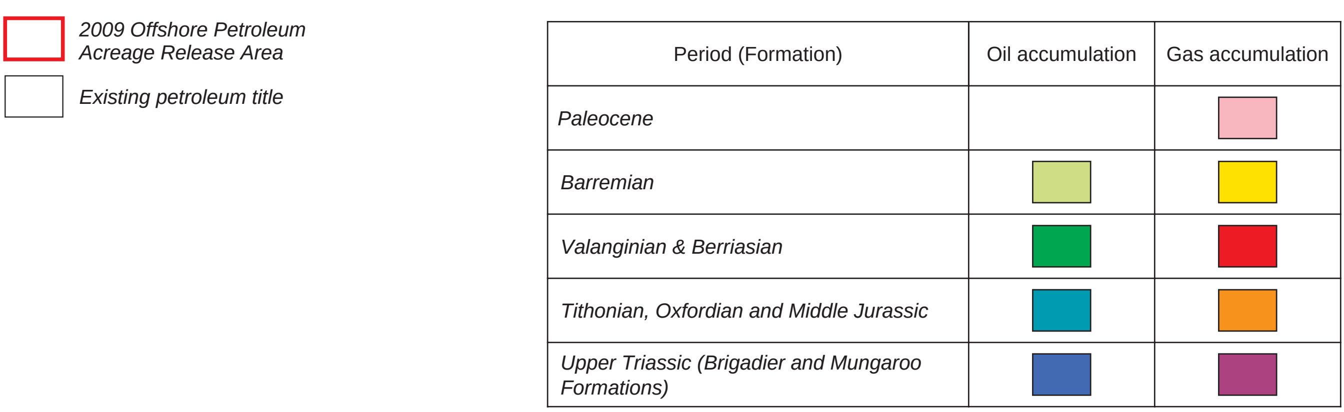

Figure 3. Major oil and gas accumulations in the Northern Carnarvon Basin indicating age of main reservoir.