Regional Geology of the Bight Basin

Basin Outline

The Jurassic-Cretaceous Bight Basin is a large, mainly offshore basin situated along the western and central parts of the continental margin of southern Australia , in water depths of less than 200 m to over 4000 m. The basin extends from south of Cape Leeuwin in the west to south of Kangaroo Island in the east, where it adjoins the Otway Basin (Bradshaw et al, 2003; **Figure 1**). To the south, the uppermost sequences of the Bight Basin onlap highly extended continental crust and rocks of the continent-ocean transition on the abyssal plain between Australia and Antarctica (Sayers et al, 2001). The Bight Basin is overlain unconformably by the dominantly cool-water carbonates of the Cenozoic Eucla Basin. The basin contains five main depocentres-the Ceduna, Duntroon, Eyre, Bremer and Recherche sub-basins (**Figure 1** and **Figure 2**). The most prospective depocentre, the Ceduna Sub-basin, occurs in the eastern part of the Bight Basin. To the north and east of the main depocentres, a thin Bight Basin succession overlies Proterozoic basement (including the Gawler Craton and Albany-Fraser Orogen) and deformed Proterozoic-Early Paleozoic rocks of the Adelaide Fold and Thrust Belt (AFTB) (**Figure 2**). Basement trends have had a profound influence on the structural development of the Bight Basin, controlling the location and orientation of early basin-forming structures (Stagg et al, 1990; Totterdell et al, 2000; Teasdale et al, 2003; Totterdell and Bradshaw, 2004).

Basin Evolution and Tectonic Development

The Bight Basin is one of a series of Mesozoic to Cenozoic depocentres that developed along Australia's southern margin during the breakup of eastern Gondwana (Fraser and Tilbury, 1979; Bein and Taylor, 1981; Willcox and Stagg, 1990; Stagg et al, 1990; Hill, 1995; Totterdell et al, 2000; Norvick and Smith, 2001; Teasdale et al, 2003; Totterdell and Bradshaw, 2004). The basin evolved through repeated episodes of extension and thermal subsidence leading up to, and following, the commencement of seafloor spreading between Australia and Antarctica (Totterdell and Bradshaw, 2004). The tectonostratigraphic development of the basin can be described in terms of four basin phases that reflect those different tectonic drivers (**Figure 3**; Totterdell et al, 2000). Deposition in the basin took place during a global, first order, transgressive-regressive cycle, as shown on the sea-level curve in **Figure 3**.

Mid Jurassic-Early Cretaceous extension and post-rift subsidence

The Bight Basin was initiated during a period of Middle-Late Jurassic to Early Cretaceous upper crustal extension (Basin Phase (BP) 1; **Figure 3**). At this time a convergent margin existed on the eastern side of the continent. Incipient rifts were developing between Australia and Antarctica, India and Antarctica, and India and Western Australia, the extensional systems forming a triple junction (Norvick and Smith, 2001). Rifting along this system eventually resulted in sea-floor spreading between India and Australia/Antarctica, but the rift along the southern margin failed at that time. In the Bight Basin, a northwest-southeast to north-northwest to south-southeast extension direction, superimposed on east-west and northwest-southeast-oriented basement structures, resulted in oblique to strongly oblique extension and the formation of en-echelon half graben in the Eyre, inner Recherche, eastern Ceduna and Duntroon Sub-basins (**Figure 2**). The inboard rift systems are illustrated in **Figure 4**, **Figure 5** and **Figure 6**, which also show the stratigraphy and structural architecture of the Bight Basin. The areal extent of the early extensional structures beneath the Ceduna Sub-basin cannot be determined due to the thickness and nature of the sedimentary section. The anomalously thick nature of the sub-basin may indicate, however, that Jurassic-Early Cretaceous rifts are present at depth.

The Early Cretaceous was characterised by post-rift thermal subsidence in the Bight Basin (BP 2; **Figure 3**). By the mid-Cretaceous, open ocean lay to the west and a seaway extended along the margin to the eastern Bight Basin area. The rocks deposited during the initial extensional phase and the subsequent period of thermal subsidence were largely non-marine, with some marine influence becoming evident late in BP 2 (Late Aptian), in wells located on the inboard margins of the basin.

Mid Cretaceous accelerated subsidence

An abrupt increase in subsidence rate in the mid-Albian (Totterdell et al, 2000; Totterdell and Bradshaw, 2004) signalled the start of the third basin phase (BP 3; **Figure 3**). This period of accelerated subsidence, which continued until the commencement of sea-floor spreading between Australia and Antarctica in the Late Santonian, coincided with a period of rising global sea level (**Figure 3**). This combination of factors resulted in a high rate of creation of accommodation, the first major marine flooding event in the basin and the widespread deposition of marine silt and shale of the Albian-Cenomanian Blue Whale Supersequence. Progradation of deltaic sediments into a narrow seaway (White Pointer Supersequence) commenced in the Cenomanian. Rapid deposition resulted in a short-lived period of shale mobilisation and growth faulting throughout the northern half of the Ceduna Sub-basin (**Figure 2**, **Figure 5** and **Figure 6**). The Cenomanian deltaic facies include a broad band of coaly sediments in the inner part of Ceduna Sub-basin. The White Pointer Supersequence is overlain by the marginal marine, deltaic and open marine sediments of the Turonian-Santonian Tiger Supersequence. In wells, the Tiger Supersequence is dominated by mudstone and a few thick sandstone units, while on seismic data, it has a largely flat-lying, aggradational character.

Australian-Antarctic sea-floor spreading and post-breakup subsidence

The commencement of ultra-slow to very slow seafloor spreading in the latest Santonian was followed by a period of thermal subsidence and the establishment of the southern Australian passive margin (BP 4; **Figure 3**). This phase is represented by the latest Santonian-Maastrichtian Hammerhead Supersequence, a sand-rich deltaic system characterised by strongly prograding stratal geometries (**Figure 5** and **Figure 6**). Because of the slow rate of seafloor spreading, the seaway into which the deltas prograded would have been relatively narrow. A dramatic reduction in sediment supply at the end of the Cretaceous saw the abandonment of deltaic deposition. Regional uplift resulted in the erosion of the Hammerhead Supersequence, and much of the underlying Tiger Supersequence from the Eyre Sub-basin, and the progressive erosion of the Cretaceous section across the Madura Shelf.

From the late Paleocene to present, the largely cool-water carbonates of the Eucla Basin accumulated on a sediment-starved passive margin. In the middle Eocene (around 45 Ma) there was a dramatic increase in the rate of spreading (Tikku and Cande, 1999), which resulted in widespread subsidence of the margin.

Regional Hydrocarbon Potential

Regional Petroleum Systems

The thick sedimentary succession in the Bight Basin and its evolution from local half-graben depocentres during the Jurassic, to an extensive sag basin in the Early Cretaceous and passive margin during the Late Cretaceous to Holocene, implies that there is significant potential for the presence of multiple petroleum systems. Regional sequence stratigraphic analysis (Totterdell et al, 2000) suggests the presence of at least eight potential source rock intervals at different stratigraphic levels. These include Late Jurassic syn-rift lacustrine shale, Early Cretaceous fluvial and lacustrine deposits, Aptian-Albian marginal marine to coastal plain mudstone and coal, Albian-Cenomanian and Turonian-Santonian marine shale, Cenomanian deltaic and shallow marine shale and coal, and Santonian-Campanian prodelta shales (**Figure 3**).

While the Jurassic-Early Cretaceous non-marine source intervals are important in the shallower, more proximal parts of the basin, the key to the petroleum prospectivity of the region resides in Late Cretaceous marine and deltaic facies. Recent dredging of Late Cenomanian-Turonian organic-rich marine rocks has confirmed the presence of high quality source rocks in the basin and has significantly reduced exploration risk. Excellent reservoir rocks and potential intraformational seals are present in the Late Cretaceous deltaic successions, and regional seals could be provided by Late Cretaceous marine shales. Early Cretaceous potential reservoir rocks could be of importance in the proximal parts of the basin, however, seal is a risk in this area of the basin. Interpretation of seismic data illustrate numerous play types in the basin and some structures show amplitude anomalies, providing many exploration targets.

Exploration History

The frontier Bight Basin covers some 804000 km^2 but, in nearly 50 years of exploration there have only been ten wells drilled and less than 100000 line-km of seismic recorded in the entire offshore portion of the basin. The majority of these wells have been drilled in water depths of less than 250 m (**Figure 7**) along the margins of the basin, where the source rock quality of middle to Late Cretaceous marine deposits has been reduced by the influx of terrigenous organic matter into proximal depositional facies. More distal facies are found in the Ceduna Sub-basin, the thickest depocentre, which covers an area of 126300 km^2 (**Figure 2** and **Figure 7**). Five wells have been drilled in the Ceduna Sub-basin. Three of these wells (Platypus 1, Greenly 1 and Borda 1) were originally assigned to the 'Duntroon Basin', but due to reinterpretation of basin boundaries (Bradshaw et al, 2003), they are now located in the Ceduna Sub-basin. With the exception of Gnarlyknots 1/1A, the wells were drilled in relatively shallow water near the basin margin and the deeper part of the sub-basin remains untested (**Figure 7**). **Figure 8** presents an assessment of the reasons for failure of the wells drilled to date in the Bight Basin.

Exploration of the Bight Basin began in 1960 when OEL 25 in the Duntroon Sub-basin was awarded to the Australian Pacific Oil Co. Ltd, Burmah Oil Company and Murphy Corporation. Subsequently, the region has experienced several phases of exploration. Significant campaigns include those by Shell Development (Australia) Ltd (Shell) from the mid 1960's to mid 1970s, Esso Exploration and Production Australia Inc. (Esso) between 1979 and 1983, BP Petroleum Development Pty Ltd (BP) in the 1980s, BHP Petroleum (Aust.) Pty Ltd (BHP) in the early 1990s and more recently by Woodside Energy Ltd (Woodside) and its joint venture partners from 2000 to 2007.

In 1966, Shell was awarded OEL 38, covering most of the Bight and Duntroon basins. During 1968 and 1969 OEL 38 was converted to Exploration Petroleum Permits (EPP) 5, 6 and 7, covering much of the previous licence area. A substantial area of deeper water in the Bight Basin was awarded as EPPs 10 and 11 (O'Neil, 2003). Between 1966 and 1976 Shell carried out 10 seismic surveys (R1 - R10) across the basin, acquiring 23172 line-km of 2D seismic reflection data with magnetics also recorded along most of the deep water lines. In addition, 16000 km of regional aeromagnetic data were recorded over OELs 33 and 38 in early 1966. Three exploration wells were also drilled: Echidna 1 and Platypus 1 in 1972 and Potoroo 1 in 1975 (**Figure 7**). Echidna 1 in the Duntroon Sub-basin tested a large faulted anticline, primarily targeting reservoirs in the Southern Right - Wobbegong supersequences; Platypus 1 was drilled on the eastern flank of the Ceduna Sub-basin and targeted a range of reservoirs with fault related closure within the Late Cretaceous to Cenozoic section; and Potoroo 1, drilled in the northern Ceduna Sub-basin, tested a structure within the White Pointer Supersequence with dip closure against a major basement-involved fault (Messent, 1998). Although all three wells failed to discover commercial hydrocarbons they significantly advanced the stratigraphic knowledge of the basin. Encouragingly, oil indications (cut and fluorescence) were recorded from the Bronze Whaler Supersequence in Echidna 1, while an anomalously high gas reading was recorded in the White Pointer Supersequence in Potoroo 1 (Messent, 1998).

Esso Exploration and Production Australia Inc. (Esso), in joint venture with Hematite Petroleum Pty Ltd (Hematite), concentrated their exploration efforts on the Eyre Sub-basin (**Figure 1**), holding permits WA-125P and WA-126P between 1979 and 1983. The joint venture acquired a total of 4073 line-km of good quality seismic data over two surveys (E79A and E82A) recorded in 1979 and 1982 respectively, and drilled a single exploration well in 1980 (Bein and Taylor, 1981). Jerboa 1 (**Figure 7**), was dry with minor oil and gas indications but, significantly, a 15 m net palaeo-oil column extending over the interval 2470-2495 mKB within basal sandstone of the Sea Lion Supersequence was interpreted during a later evaluation of the well (Liu and Eadington, 1998; Ruble et al, 2001).

Exploration in the Bight Basin was lacklustre during the early 1980s. BP and Hematite were granted EPP 16 over the central part of Bight Basin in 1980, acquiring 2188 line-km of seismic data before surrendering the permit in 1982 (Stagg et al, 1990). Outback Oil Co. NL (Outback) was awarded EPP 19 over the western Duntroon Sub-basin in 1981 and acquired 539 line-km of seismic data in the following year. The contractor Geophysical Service Inc. (GSI), recorded an additional 827 line-km of seismic data in adjacent permits on a non-exclusive basis, however interest in the area was so low that most of the data was left unprocessed and the permit was surrendered in 1984 (Stagg et al, 1990, O'Neil, 2003).

In 1982, EPP 21 covering the central Duntroon Sub-basin was granted to a joint venture, ultimately operated by BP after a farm-in in 1985. In 1983, the joint venture acquired 2102 line-km of seismic data in conjunction with a geochemical hydrocarbon seepage sniffer survey, with a further 1017 line-km of seismic data acquired in 1984 (Stagg et al, 1990; O'Neil 2003). These surveys defined several large prospects in the Duntroon and Ceduna Sub-basins, leading to the drilling of Duntroon 1 in early 1986 (**Figure 7**). The well was dry and subsequent mapping indicated that the well was drilled off-structure on the flank of a large faulted closure (O'Neil, 2003).

After an exploration hiatus through the late 1980s, BP flew an Airborne Laser Fluorosensor (ALF) survey in early 1990. The survey covered the entire inboard Bight Basin and was conducted as part of a regional evaluation prior to an anticipated offshore acreage release. A total of 27624 line-km of data were recorded at a line spacing of 5 km over an area of approximately 108508 km^2 (Mackintosh and Williams, 1990). The initial results were poor with two definite, but weak fluors detected, however reprocessing and reinterpretation of the data recorded a total of 941 confident fluors (Cowley, 2001). The fluors were concentrated in three regions in the Ceduna Sub-basin, one in the vicinity of Greenly 1 and two other dense, but less confidently interpreted areas approximately 50 km south and approximately 100 km southwest of Potoroo 1.

A new phase of exploration began in 1991, when BHP was awarded EPP 25 and EPP 26 covering the Ceduna and Duntroon sub-basins. In 1991, 1046 line-km of seismic data acquired by the EPP 21 joint venture were reprocessed and from 1991 to 1995 three new seismic surveys (DH91, DH92 and HD95) acquired 10579 line-km of high quality seismic data. These new data indicated that all prior drilling in the region had been sited on invalid structures (O'Neil, 2003). BHP drilled three wells in 1993: Borda 1 and Greenly 1 within the Ceduna Sub-basin, and Vivonne 1 in the Duntroon Sub-basin (**Figure 7**).

Although all three wells were plugged and abandoned, their results were encouraging and emphasise the complex structural history of the basin. Borda 1 was designed to test a Late Cretaceous to Cenozoic play sealed by Cenozoic marls, similar in style to the highly productive Gippsland Basin play. The most likely cause of failure was the presence of thick Late Cretaceous claystones, which inhibited vertical migration from the Bronze Whaler Supersequence to reservoirs in the Wobbegong Supersequence (Messent, 1998). Greenly 1 tested a basal Late Cretaceous play, reaching a total depth of 4860 mRT. A Repeat Formation Test (RFT) at 4209 mRT recovered oil and gas. and numerous oil indications were encountered from 3430-4524 mRT and 4770-4818 mRT (Messent, 1998). These represent the first major indications of hydrocarbons, identifying a valid source rock, which significantly upgraded the prospectivity of the Ceduna Sub-basin. Vivonne 1 tested a Late Cretaceous play and reached a total depth of 3000 mRT. The lack of a suitable migration pathway from the Bronze Whaler Supersequence is thought to have contributed to the failure of this well (Messent, 1998).

The latest phase of exploration commenced in 2000 when three exploration permits EPP 28, EPP 29 and EPP 30 were awarded to a joint venture comprising Woodside Energy Ltd (operator), Anadarko Australia Co. Ltd and PanCanadian Petroleum Corp. (now EnCana Corp.). The permits were surrendered in 2007 after the acquisition of a large quantity of seismic data and the drilling of one exploration well, Gnarlyknots 1A in 2003 (**Figure 7**). The Flinders 2D Seismic Survey acquired a total of 15636 line-km of high quality, full fold data across the three permits. The seismic grid ranges in density from 4 x 4 km in the west to 4 x 8 km in the northern and eastern portions of the survey area and the recording parameters were set in order to capture any potential AVO effects (Bruins et al, 2001). The Gnarlyknots 1A well was plagued by mechanical problems and eventually abandoned due to bad weather (1500 m above the prognosed total depth). Although Gnarlyknots 1A failed to encounter any significant hydrocarbons, the well produced several encouraging results. These include excellent quality sandstone reservoirs, marine shale top seals and thermogenic hydrocarbon shows, which indicate the presence of a mature source rock down-dip (Tapley et al, 2005). In early 2006, Woodside acquired 1250 km^2 of 3D seismic data (Trim 3D Seismic Survey) over EPP 29. This survey overlies the northern portions of the current Release Areas S09-4 and S09-5 (**Figure 7**).

Exploration permit EPP 31, located partially over the Ceduna Sub-basin and Duntroon sub-basins, was awarded to the Woodside-Anadarko-EnCana joint venture for a period of six years from June 2001. The joint venture acquired 1925 line-km of 2D seismic data (Whidbey 2D Marine Seismic Survey) and reprocessed older seismic data over the permit. The adjacent permit, EPP 31, was awarded to Santos Offshore Pty Ltd in late 2002, who acquired 514 line-km of 2D seismic data in 2003 (2003 Duntroon Basin, EPP 32 Marine Seismic Survey). Both permits were surrendered in 2007.

Geoscience Australia (GA) and its predecessor agencies have a long history of research in the Bight Basin, conducting several gravity and magnetic surveys and acquiring over 28000 km of regional seismic data. More recently, GA carried out an integrated basin study of the eastern Bight Basin (1998-2003) using regional seismic and well data. Resulting petroleum system and play modelling predicted numerous potential petroleum systems in Jurassic and Cretaceous age depocentres from the Eyre, Duntroon and

Ceduna sub-basins (Blevin et al, 2000; Totterdell et al, 2000, Struckmeyer et al, 2001). These studies were followed by a marine survey (Bight Basin Geological and Sampling Survey) in 2007 (Totterdell, in press), which targeted and recovered potential source rocks of late Cenomanian to early Turonian age from the northwestern edge of the Ceduna Sub-basin (Totterdell et al, 2008) (**Figure 7**).

Figures

Figure 1:	Location of the Bight Basin, with component sub-basins (after Totterdell and Bradshaw, 2004).
Figure 2:	Structural elements of the eastern Bight Basin (after Bradshaw et al, 2003).
Figure 3:	Bight Basin stratigraphic correlation chart showing basin phases and predicted source rock intervals (modified from Blevin et al, 2000 and Totterdell et al, 2000). The sea-level curve (Haq et al, 1988) is modified to the time scale of Gradstein et al (2004).
Figure 4:	Cross-section through the Eyre Sub-basin, Madura Shelf and Ceduna Sub-basin, showing supersequences. Refer to Figure 2 for location of cross-section (after Totterdell and Bradshaw, 2004).
Figure 5:	Cross-section through the Madura Shelf, northern Ceduna Sub-basin and Recherche Sub-basin, showing supersequences. Refer to Figure 2 for location of cross-section (after Totterdell and Bradshaw, 2004).
Figure 6:	Cross-section through the Madura Shelf, Ceduna Sub-basin and Recherche Sub-basin, showing supersequences. Refer to Figure 2 for location of cross-section (from Totterdell and Krassay, 2003a).
Figure 7:	Location of seismic lines and wells in the eastern Bight Basin.
Figure 8:	Bight Basin well analysis summary.

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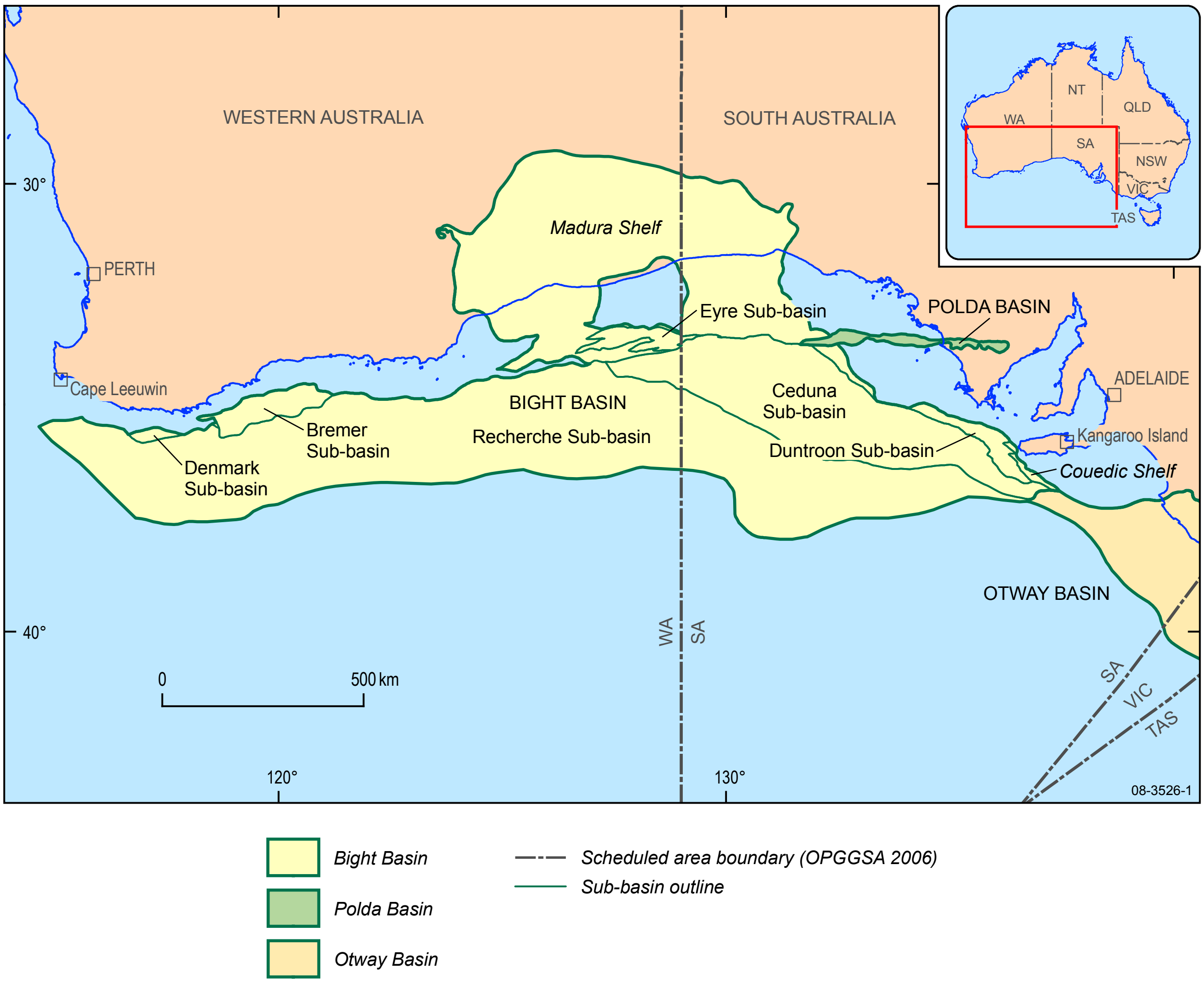

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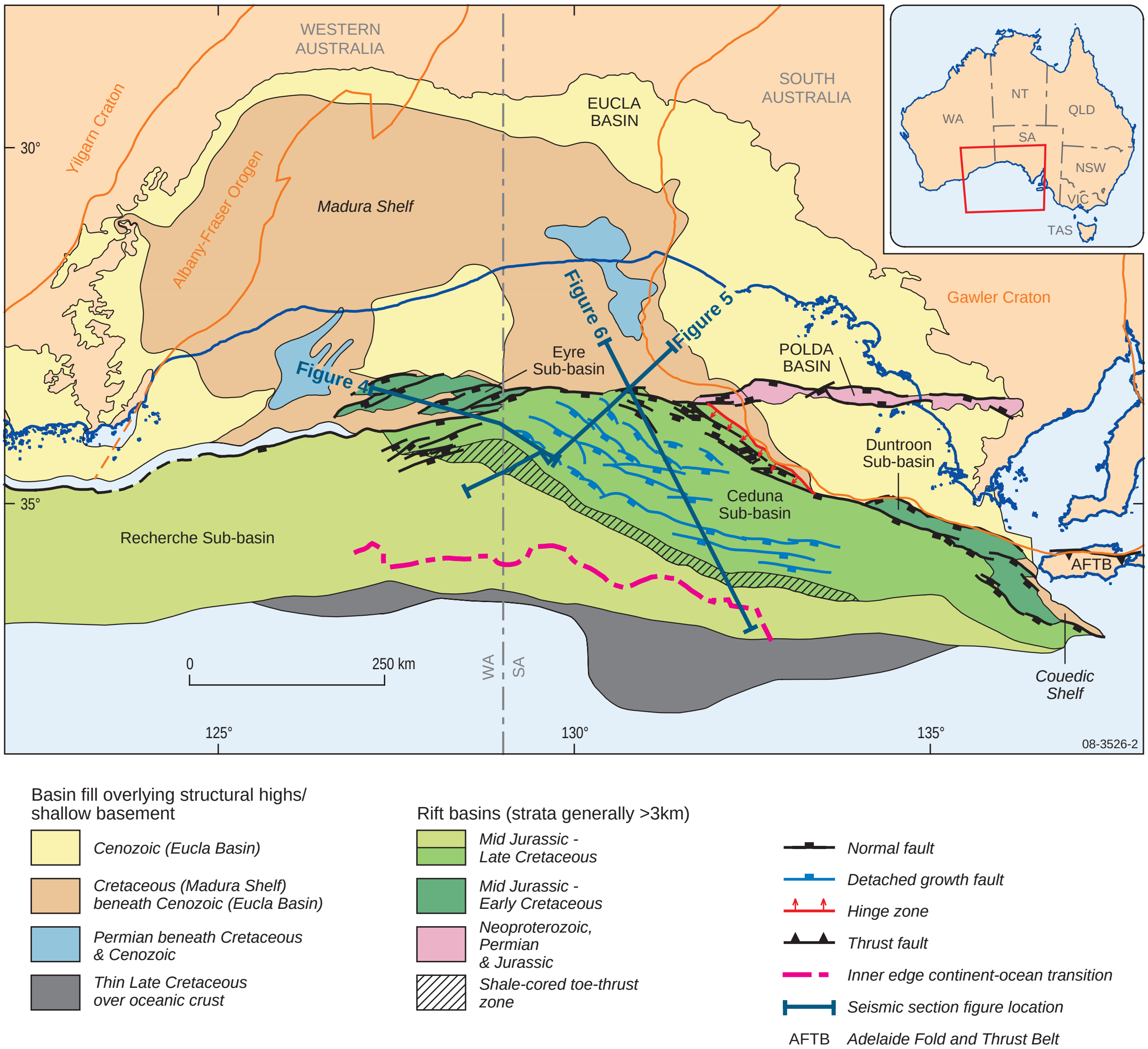
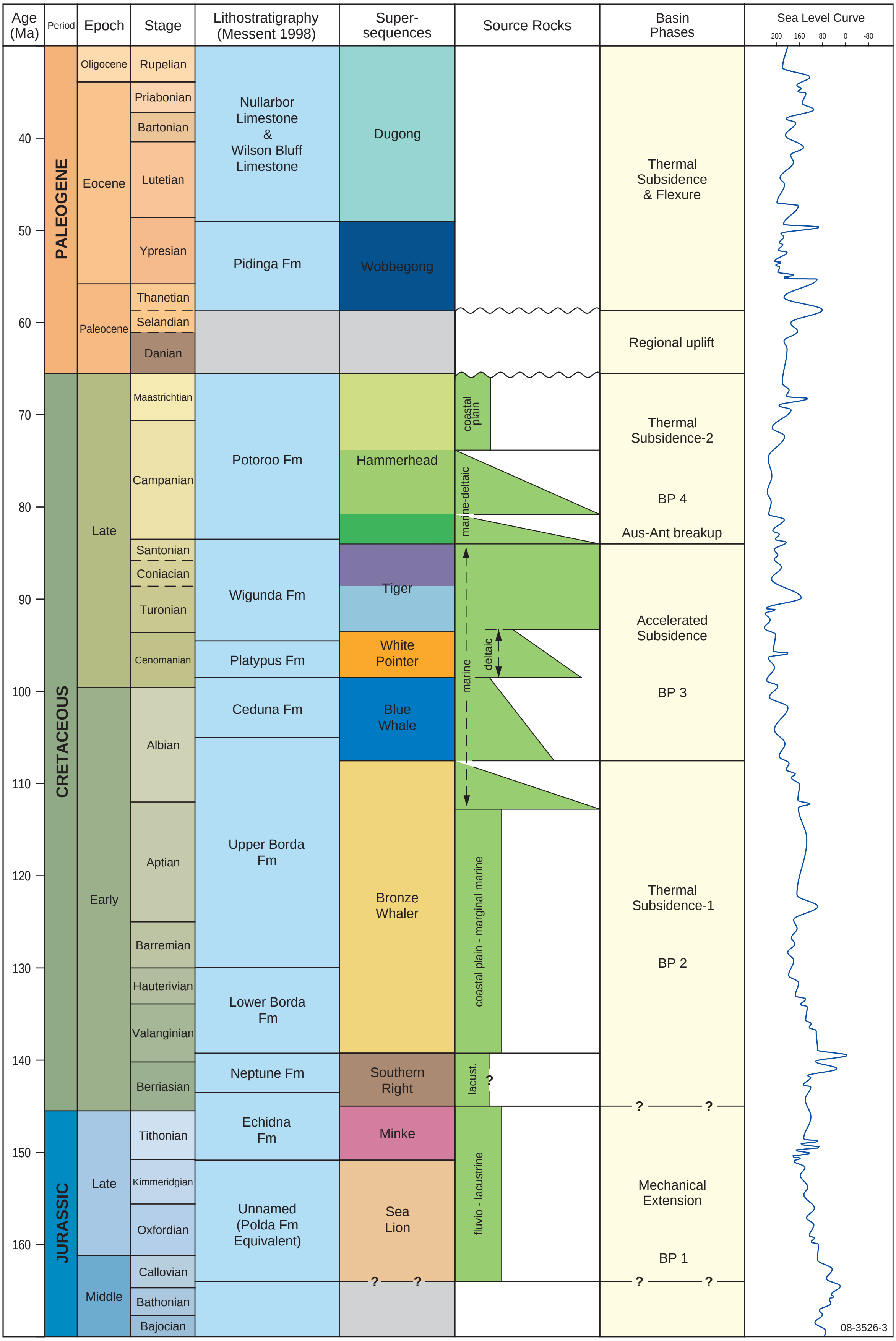


Figure 2. Structural elements of the eastern Bight Basin (after Bradshaw et al, 2003).



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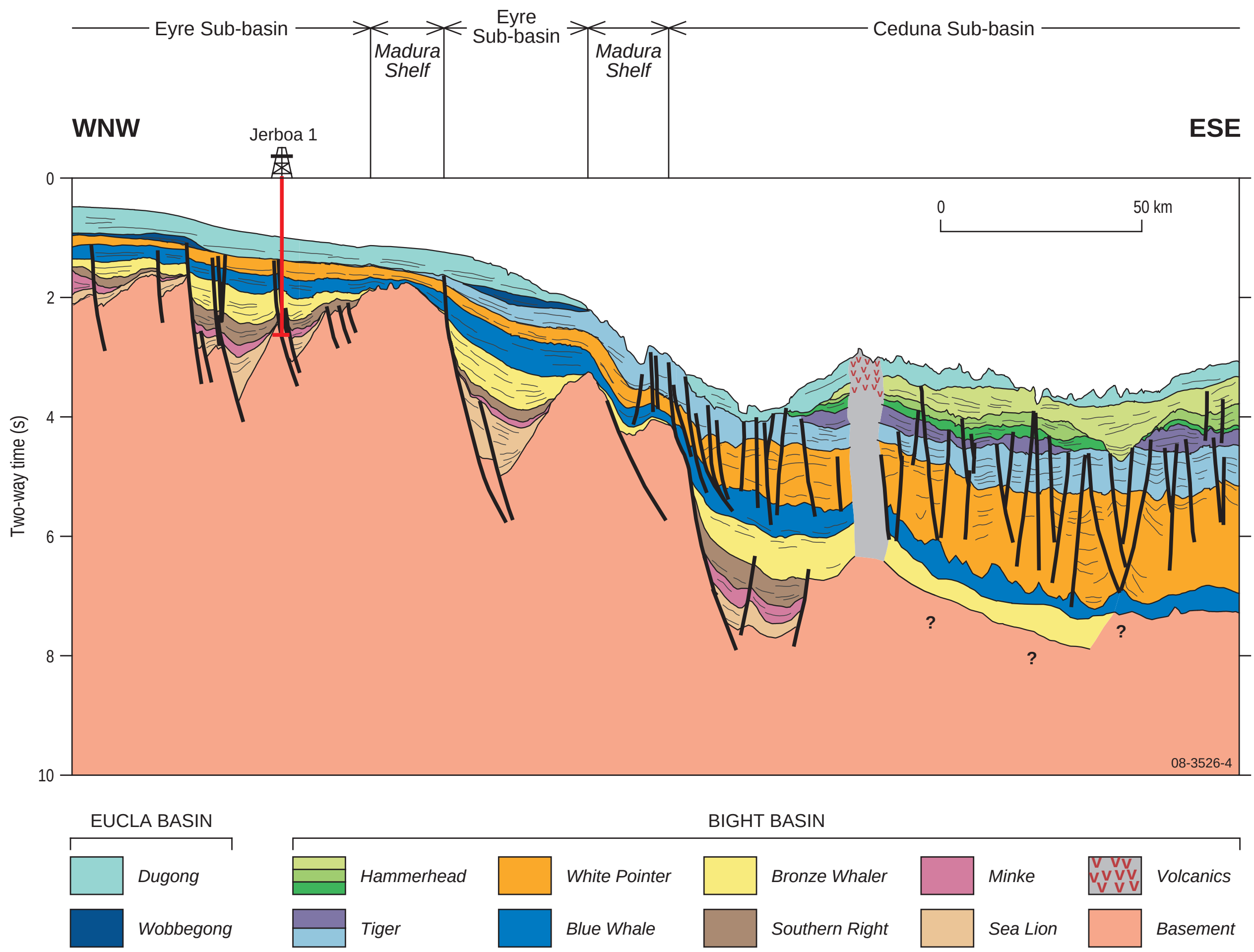

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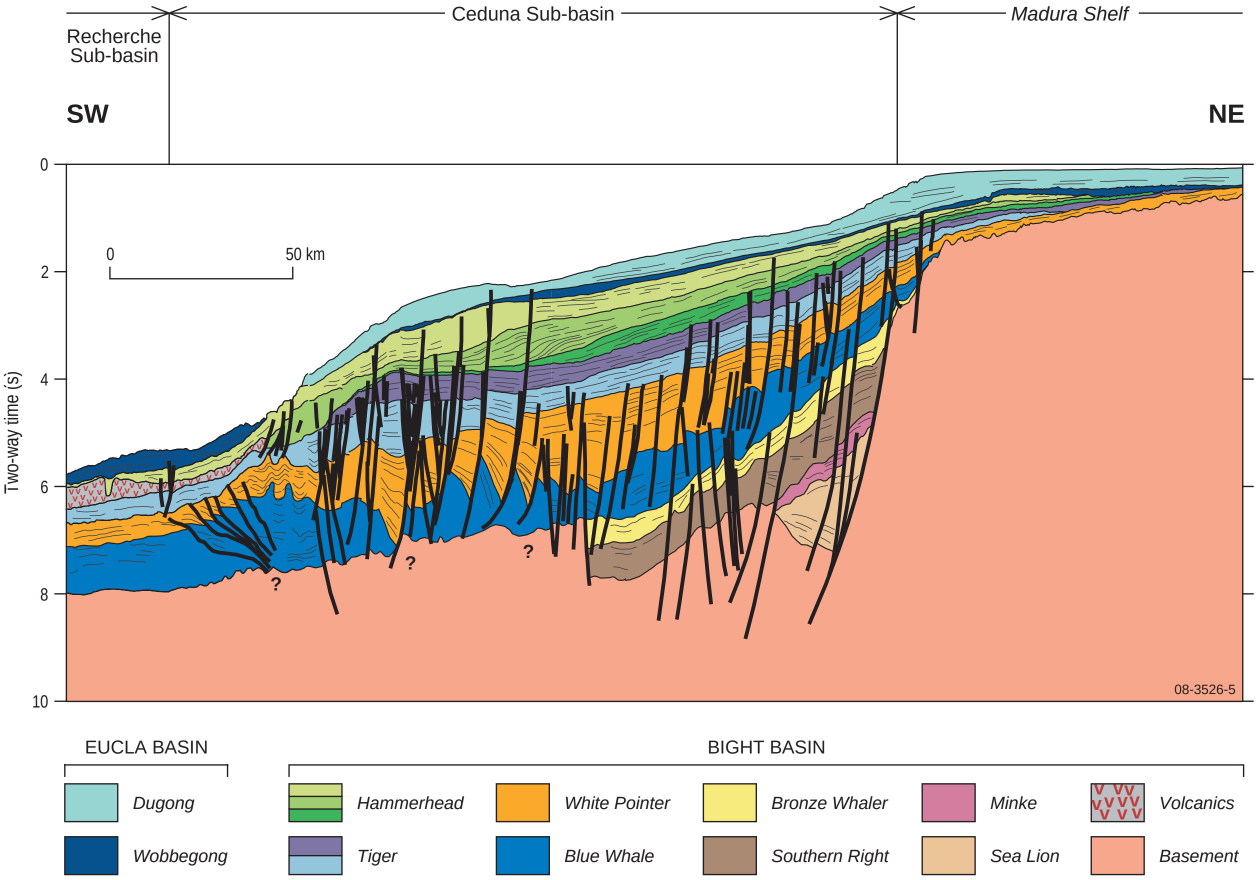


Figure 5. Cross-section through the Madura Shelf, northern Ceduna Sub-basin and Recherche Sub-basin, showing supersequences. Refer to Figure 2 for location of cross-section (after Totterdell and Bradshaw, 2004).

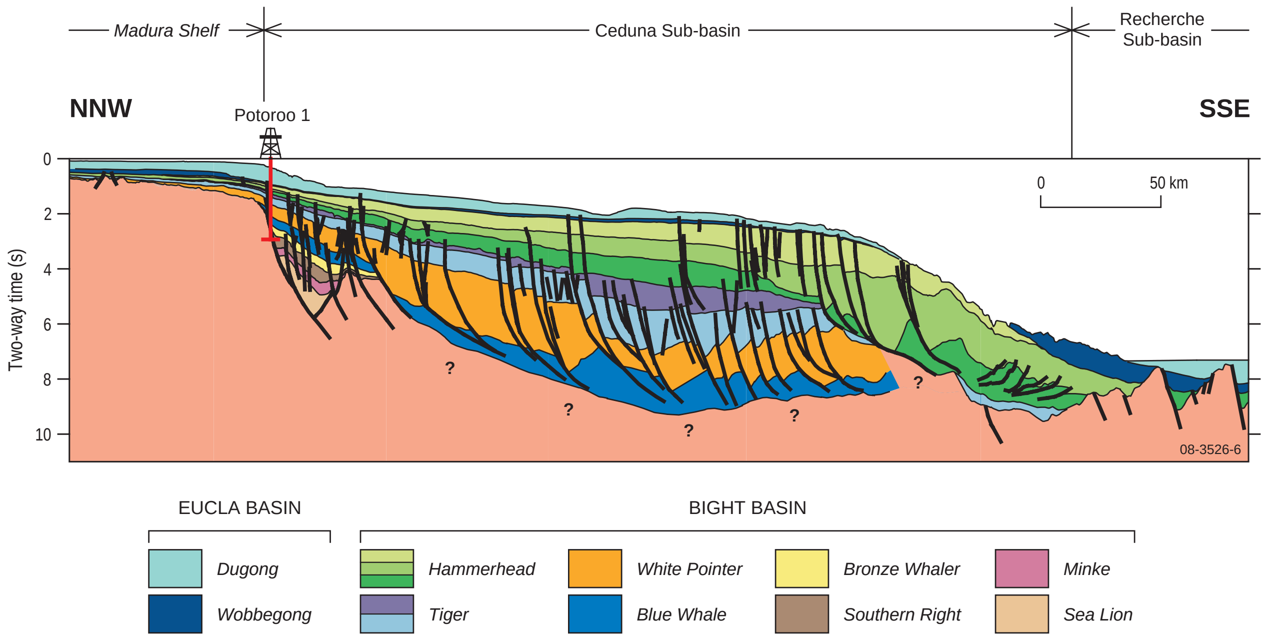
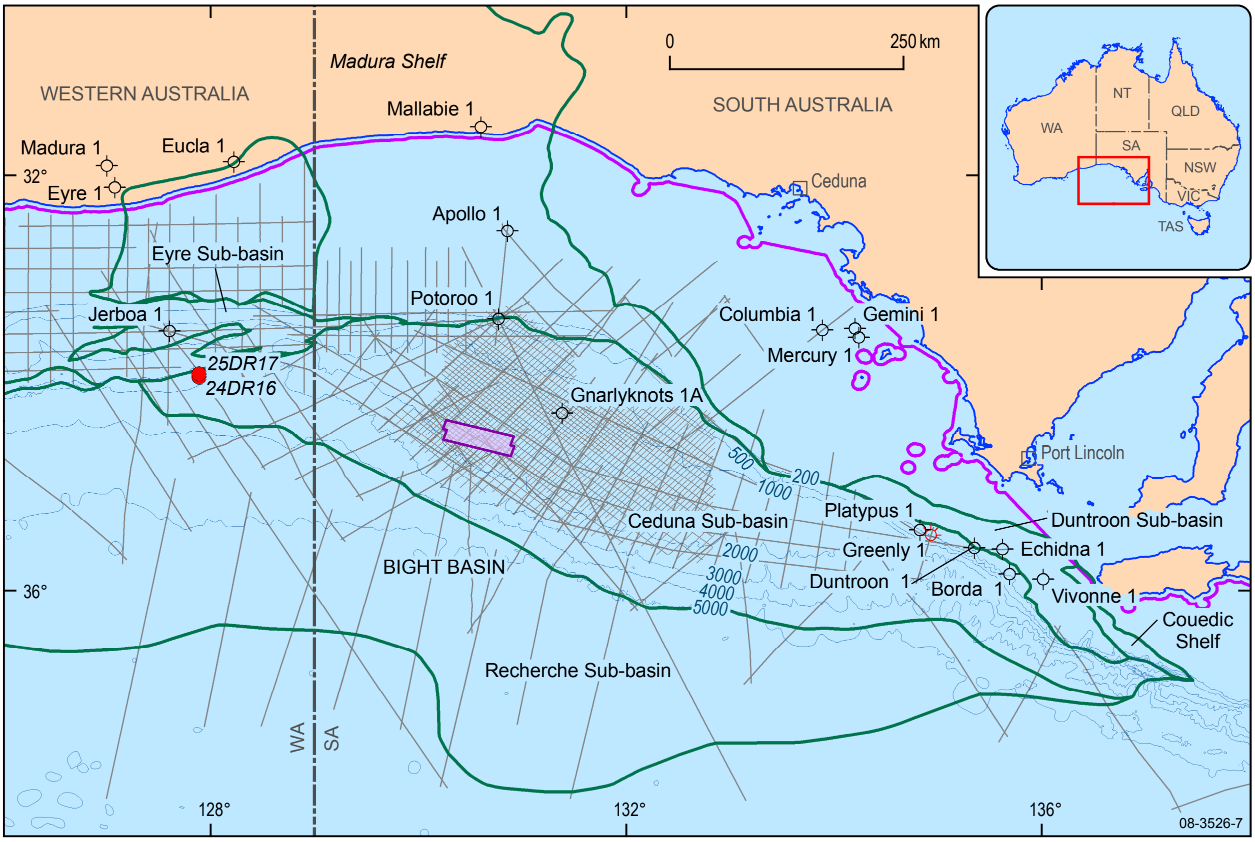


Figure 6. Cross-section through the Madura Shelf, Ceduna Sub-basin and Recherche Sub-basin, showing supersequences. Refer to Figure 2 for location of cross-section (from Totterdell and Krassay, 2003a).



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.

3D Trim seismic survey
Basin outline
2D seismic survey line
Limit of Coastal Waters
Bathymetry contour (depth in metres)
Scheduled area boundary (OPGGSA 2006)
Petroleum exploration well - Dry hole
Petroleum exploration well - Gas show
Potential source rocks dredge sample location

Figure 7. Location of seismic lines and wells in the eastern Bight Basin.

BIGHT BASIN WELL ANALYSIS SUMMARY

Geological setting & wells	Target P - primary S - secondary		Structure Style	Risk elements: Structure	Seal - Fault breach	Seal - Quality	Reservoir	Source	Maturity	Migration	Timing	Comments & Issues of concern
Eyre Sub-basin												
Jerboa 1	P	Bronze Whaler Supersequence	Basement drape	Green	Red	Green	Green	Green	Green	Green	Green	Good evidence from GOI analysis that hydrocarbons were originally present and subsequently lost during Late Cretaceous faulting.
Ceduna Sub-basin												
Potoroo 1	P	White Pointer Supersequence	Fault block	Yellow	Green	Green	Red	Yellow	Yellow	Red	Yellow	Primary cause of failure was lack of reservoir at the primary target horizon.
Platypus 1	P	Tiger Supersequence	Fault block	Red	Yellow	Green	Green	Green	Yellow	Yellow	Yellow	Probable cause of failure is lack of a valid structure.
	S	Wobbegong & Hammerhead supersequences	Fault block	Red	Yellow	Red	Green	Green	Yellow	Yellow	Yellow	
Greenly 1	P	White Pointer Supersequence	Fault block (low side)	Red	Red	Green	Red	Green	Green	Green	Yellow	Well originally planned to test rollover anticline, but was actually drilled on the hanging wall of a fault block.
Borda 1	P	Dugong Supersequence	Faulted anticline	Green	Green	Green	Green	Yellow	Yellow	Red	Yellow	Thick underlying shales have prevented hydrocarbons migrating into trap.
Gnarlyknots 1/1A	P	Tiger Supersequence	Fault block	Green	Red	Green	Green	Yellow	Green	Green	Green	Main cause of well failure is lack of suitable cross-fault seals.
Duntroon Sub-basin												
Duntroon 1	P	White Pointer Supersequence	Tilted fault block	Red	Yellow	Green	Yellow	Yellow	Yellow	Red	Yellow	Cause of failure unclear, but probably invalid structure, and location in a migration shadow.
Echidna 1	P	Southern Right Supersequence	Faulted anticline	Red	Yellow	Green	Red	Green	Green	Green	Yellow	No reservoir present in primary target, and presence of a valid trap is unlikely.
	S	Wobbegong Supersequence	Faulted anticline	Red	Yellow	Yellow	Green	Green	Green	Green	Yellow	
Vivonne 1	P	Hammerhead & Wobbegong supersequences	Tilted fault block	Green	Green	Yellow	Green	Green	Green	Red	Red	Failure most likely due to lack of suitable migration pathway and poor timing of structure vs expulsion.
Madura Shelf												
Apollo 1	P	Wobbegong Supersequence	Faulted anticline	Red	Yellow	Red	Green	Red	Red	Red	Yellow	Failure due to lack of structure, seal and mature sources

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Green: *Low risk element - Adequate properties* — Yellow: *Poorer quality or uncertain presence* — Red: *High Risk - Inadequate element*

Figure 8. Bight Basin well analysis summary.